PHYSICAL AND GEOTECHNICAL INFLUENCES ON PEAT INSTABILITY

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ABSTRACT

There is an urgent need to develop robust tools and policies for stability and hazard risk assessments in order to manage upland peat landslides in locations such as the British Isles where they have frequently occurred and caused harm to the environment. One of the particular difficulties is that reliable values of peat strength are difficult to obtain.

The objectives of this research were to establish the nature of any relationships between the strength characteristics and the botanical, physical and chemical properties of the peat, and to determine whether palaeobotanical analyses of samples of the basal peat can provide a reliable indication of potential instability in upland blanket bogs. The research was carried out at the Straduff Townland (Co. Sligo), Slieve Anierin (Co. Leitrim) and Slieve Rushen (Co. Cavan) landslides, all located in northwest Ireland, from the margins of which monolith and core peat samples were collected. Standard and validated paleobotanical, chemical and geotechnical protocols, modified or refined where necessary to suit the nature of the peat, were used in the study. The triaxial, direct shear and tensile strength tests were conducted using experimental very low stress conditions in order to fully replicate *in-situ* conditions. The reliability of the measured strength parameters was examined by performing deterministic and probabilistic stability analyses of the failed slopes using industry-standard „limit equilibrium" software (SLOPE/W). The nature, extent and spatial distribution of the hydrocarbons unexpectedly found in the basal peats during the fieldwork were also investigated.

This research found that blanket peat dominated by monocotyledons (with mainly *E. vaginatum*) is likely to be susceptible to failure because its „effective structural properties", specifically the high degree of humification and low fibre content of its basal peat, cause it to have very low strength and also therefore a very low bearing capacity. Furthermore, monocotyledons or its remains in peat have morphological, chemical, biological features that can promote bogflow-type failure. These may include for example (i) their parallel and elongated leaf veinations that promote flow, (ii) the genesis of hydrocarbons such as bitumen from their lignified tissues and (ii) being host to a hydrocarbon-producing aphid *Colopha compressa*. Laboratory measurements of undrained strength of the weak basal peats were consistently < 3 kPa, and deterministic stability analyses revealed that the value of the tensile strength can be used as an indicator of the undrained shear strength. A new classification (i.e. „the modified fibre content scheme") and a modified procedure for assessing upland peat failure for construction projects has been proposed based on peat fibre and humification characteristics and their apparent influences on peat strength. Deposits of hydrocarbons such as bitumens within the basal peat constitute a previously unrecognised factor that probably contributed to the occurrence of the studied landslides due to their hydrophobic properties.

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CHAPTER ONE - INTRODUCTION

The physical and geotechnical characteristics of the basal peat, commonly identified as factors contributing to peat mass movement (Dykes and Warburton, 2007a) are critical to an adequate understanding of, and an ability to analyse and model, the stability of peat deposits. This research aimed to investigate the influences of the botanical, physical and some chemical properties of peat on blanket bog instability.

In general, mass movements are relatively common and constitute a major geohazard in many countries around the world. A „mass movement‟ is defined as the detachment and down slope transport of soil and rock materials under the influence of gravity (Chorley *et al.*, 1984). Mass movements have led to losses in terms of human life (e.g. Petley, 2012) and infrastructure (e.g. the Landova mass movement in 1997 that destroyed 150 houses: Lee and Jones, 2004).

Mass movements involving peat have also occurred around the world (e.g. Dykes, 2008a) and have been well documented for several centuries (Feehan and O`Donovan, 1996). They have commonly been reported as „peat slides‟, „bog bursts‟, „bogflows‟, „bog slides‟, „peaty-debris slides‟ or „peat flows‟ (Dykes and Warburton, 2007a). Despite this, the fundamental controls on this type of shallow instability are still poorly understood (Tallis, 2001). Dykes and Selkirk-Bell (2010) showed that around 25% of known global mass movements involving blanket peat have occurred in the British Isles. They are associated with blanket bogs on hillslopes with gradients generally ranging from 2 to 10 degrees in the uplands of Ireland, northern England (Carling, 1986) and subantarctic islands (e.g. Bailey, 1879; Barkly, 1887; Campbell, 1981; Nel *et al.*, 2003). Numerous peat mass movements have occurred in other countries including Germany (Vidal, 1966), Switzerland (Feldmeyer-Christe, 1995), Canada (Hungr and Evans, 1985), Argentina (Gallart *et al.*, 1994) and Australia (Tranter, 1999).

Like all mass movements, peat failures have caused impacts to the environment. These include:

(1) significant damage to the built environment including roads, railways, canal embankment and buildings (e.g. the landslides that occurred on 19 September 2003 at Dooncarton Mountain, Co. Mayo, Ireland: Dykes and Warburton, 2008a),

(2) pollution of water and damage to fauna and flora (e.g. landslides that occurred on 19 September 2003 at South Mainland, Shetland, Scotland: Nettleton *et al.*, 2005; Dykes and Warburton, 2008b),

(3) blockage or diversion of rivers by materials displaced by landslides (e.g. landslide that occurred on 16 October 2003 at the Derrybrien, Co. Galway: Lindsay and Bragg, 2004) and

(4) release of greenhouse gas from within the peat matrix (DEFRA, 2012) as result of peat disturbances. The potential hazard from peat landslides was brought to widespread attention in 2003 in the British Isles following the peat failure events at Dooncarton Mountain and Derrybrien

that caused over £3 million of damage to property and infrastructure, as well as severe pollution of freshwater and marine fisheries.

Peat mass movements are promoted by (1) climate change with increases in winter precipitation and seasonality (Heathwaite, 1993; Evans *et al.*, 1999; Tallis *et al.*, 1997; Warburton *et al.*, 2004) or (2) anthropogenic influences including peat extraction (Sollas *et al.*, 1897; Alexander *et al.*, 1985) and new developments like windfarms for example (Lindsay and Bragg, 2004). Climate change scenarios that predict more frequent „extreme" rainfall events (IPPC, 2007), and the increasing construction of upland windfarms (Kunz *et al.* 2007; Drewitt *et al.*, 2006) may significantly increase the risk of peat failure. There is therefore an urgent need to develop robust stability and risk assessment tools and policies for blanket mires in the British Isles. Some issues needing further investigations (Dykes, 2008d) relate to: (1) the difficulties associated with the classification of peat for engineering purposes due to its heterogeneous nature; (2) the difficulties associated with the determination of the liquid limit of peat that is known to sometimes exceed the natural water content; (3) the difficulties associated with peat strength measurement; and (4) the fact that there are almost no data to show how peat strength relates to any other physical properties or indeed botanical properties. It is known that conventional soil mechanics used to predict slope failure may not apply to peat. This is because methods used for measuring strength properties and the assumptions behind the modelling of slope stability may be inadequate for peat stability assessment.

1.1-JUSTIFICATION FOR THIS RESEARCH

The structure of peat affects the retention or expulsion of water in the system, gives it strength and differentiates one peat type from another (MacFarlane and Radforth, 1968). Therefore, a peat strength model suitable for assessing peat instability should take into account its structural features. This is particularly important for bogflows (and bog slides to some extent) because their failure mechanisms involve the lower part of the catotelm, as opposed to some other types of peat landslides whose failure mechanisms involved the mineral substrates. Like any soil, peat may be regarded as a system comprising two or three spatially coexistent phases (i.e. a solid phase, a liquid phase and usually a gas phase). However, unlike mineral soils, in its microscopic aspect, the solid phase of peat is in itself a secondary system of biological entities consisting of cellular structures containing liquid and/or gas (MacFarlane, 1968), which gives peat different strength properties and stability conditions. Some knowledge of the relation between these phases, as well as of the structure (i.e. refers to the morphology and arrangement of the constituent peat elements, both in the macro- and microscopic aspects) of the solid and liquid phases, is fundamental to an understanding of peat instability. Any attempt to understand „bogflows" or „bog slides" must therefore take account of the botanical, bulk physical and geotechnical properties of the peat deposit as well as smaller-scale structures within the peat (Dykes and Kirk, 2006).

Peat typically contains about 88-97% water by volume (Eggelsmann *et al.* 1993; Warburton *et al.*, 2004), 2-10% dry matter and 1-7% gas (Ivanov, 1981). The fabric and structure of peat are largely determined by its vegetation constituents and compression history (Landva and Pheneey, 1980; Gavrilchik *et al.*, 1996; Evans and Warburton, 2001). This has implications for the variability of peat properties (Hobbs, 1986). Some physical properties that may be related to peat instability are the water content (Mp), the bulk density (γ), the ash content (A_c), the hydraulic conductivity (k), the degree of humification, the fibre content and the macrofossil content. These parameters directly or indirectly affect the peat structure and texture and could potentially influence its strength. The common physical properties of peat such as water content, loss on ignition, permeability and bulk density have been frequently investigated for upland peat instability assessment. However, they appear to be unrelated to each other within any given mass of blanket peat.

Peat is also made of the full range of chemical compounds found in the parent plants and these compounds also determine the structure of peat. Different chemical and biochemical processes (Clymo, 1983; Sikoro and Keeney, 1983; Gorham *et al.*, 1985; Shotyk, 1988; Ross, 1995; Mitsch and Gosselink, 2000; Charman, 2002) occur within the peat matrix and critically affect the availability and storage of elements in the system. Water passing throughout the peat interacts with interstitial water mediated by biotic factors such as vegetation, detritus, fauna microorganisms and sediments (Howard-Williams, 1985; Ross, 1995; Charman, 2002). Some substances are removed with time (e.g. pigments do not survive in acid peat) and others are formed under the influence of biotic factors (e.g. microorganisms) and abiotic factors such as the formation of open channels within the peat mass.

The presence of deposits of hydrophobic substances such as hydrocarbons (e.g. bitumen) within the basal peat of blanket bogs located on a slope can give rise to discontinuities. Hydrophobic substances (e.g. wax molecules) and lignified tissues contain a high proportion of hydrocarbons like alkanes and phenolic compounds. In physical chemistry (Otter, 2008), it is known that hydrophobic compounds (i.e. which are repelled from water) contain strong covalent carbon-hydrogen bonds. They are therefore very stable and not reactive at room temperature and they require heating for any reaction to occur. For example, alkanes mix well together but they do not with water. This is because alkanes contain non-polar molecules but liquids such as water and methanol contain polar molecules which attract each other and prevent the alkane molecules mixing with them. Such hydrocarbons are therefore lubricant substances and unable to bond with polar molecules. Therefore they can reduce the cohesion and friction between basal peat particles. It is possible that the fluidity and viscosity of hydrocarbon compounds can increase either during a hot summer (which sometimes causes subsurface fires in upland peat: Boyd, 1982; Moore, 1982) or due to the presence of thermophilic fungi (Kuster and Locci, 1964) in the saturated anaerobic underlying peat. Excessive activity of these fungi can raise the temperature within the peat to 70ºC (Clymo, 1983). Although the origin of natural bitumen or petroleum hydrocarbons is complicated (Rongxi *et al.*, 2012) and remains unclear and relatively unstudied on peat, it can be said that based on the chemistry of petroleum hydrocarbons in general, compression or compaction of lignified fibre tissues can lead to the formation of hydrocarbons and the production of bitumens as end products (Bartok and Sarefim, 1991). Meyer and Wallace (1990) also suggested that peat bitumen may form aerobically from plant cells. The occurrence of such hydrocarbons may also have something to do with host organisms that lived in the original plant systems (e.g. the aphid *Colopha compressa* that lives in the root of *Eriophorum vaginatum*: Wheatley *et al.*, 1975). In fact, in order to avoid being entrapped in liquids, aphids that live in plant roots produce wax (Pike *et al.,* 2002) that is made of hydrocarbons and is also ultra-hydrophobic. There are, however, other possible explanations for the genesis of hydrocarbons in peat including the maturity of peat following processes of bitumen fermentation at depth (Rennie, 1810; Kuder and Kruge, 1998).

Physical and chemical properties therefore have major influences on peat structure and texture, which promote „bogflows‟ or „bog slides‟ as defined by Dykes and Warburton (2007b). This study uses standard and validated protocols in order to investigate peat properties controls on blanket peat landform instability. These protocols have been modified or refined where necessary to suit the complex organic nature of peat. The study focuses on British Isles and in particular Ireland where peatlands have frequently failed and caused damage to the environment. It should be noted that most of the more recent Irish failures have been „bogflows‟(e.g. Alexander *et al.*, 1985; 1986; Dykes, 2008d) as presented by Dykes (2008d, 2009), involving the break-out and evacuation of semi-liquid highly humified basal peat from a clearly defined source area (Dykes and Warburton, 2007b). The three chosen sites for this study, which are all bogflows, are Straduff Townland (Co. Sligo), Slieve Anierin (Co. Leitrim) and Slieve Rushen (Co. Cavan) in northwest Ireland (Figure 1.1). The descriptions of the sites are provided in Chapter 3.

1.2- AIMS, OBJECTIVES AND CONTRIBITUTION TO KNOWLEDGE

The aim of this research is to investigate the influences of the botanical, physical and chemical properties of peat on blanket bog instability. This is coupled with the refinement of geotechnical test procedures to facilitate the correlation of geotechnical properties with the corresponding physical characteristics of the peat.

The objectives of this study are:

(1) To establish the nature of the relationship between the strength characteristics and physical properties of the peat;

(2) To determine whether palaeoecological analysis of core samples of peat can provide a reliable indication of potential instability in upland blanket bogs.

(3) To investigate the distribution and characteristics of hydrocarbons in the peat and assess their influences on basal peat instability.

The reviews of Hobbs (1986) and Bell (2000) identified relationships between botanical composition and geotechnical properties as being of fundamental importance to the understanding of factors controlling peat failure, but thus far neither the botanical and chemical composition nor the nature and properties of residual plant remains have been directly correlated with geotechnical properties. Indeed, the composition of peat subjected to geotechnical and chemical analyses has not previously been determined for stability assessment. This study will increase the knowledge and understanding of peat physical and chemical properties control on instability in blanket bogs.

The benefits of an improved understanding of peat instability extend beyond the scientific understanding of peatland environments. It is anticipated that the results in this thesis will contribute to appropriate planning, impact assessment, design and construction of windfarm and forestry works on blanket bogs. It is hoped that the results will aid the integration of land instability hazard assessments with land use planning by providing the basis for a method of assessing potential instability using field data without the need for the extensive excavations.

This project addresses two of the UK‟s priority research areas (as identified by NERC (2013)) by identifying and providing strategies and techniques to address the challenges associated with mitigating hazards that occur as a result of climate change. As such, the findings will inform British and Irish practitioners (e.g. environmental impact specialists and engineers), as well as the international scientific community, of the improved or new means of assessing potential instability.

1.3- ORGANISATION OF THE THESIS

This work contains six chapters including this introduction. Chapter 2 reviews the literature surrounding the research topic. Current gaps in research into peat geotechnical, physical and chemical properties are identified. Chapter 3 presents the methods used to investigate the properties of peat. Chapter 4 synthesises and discusses the results of the investigations carried out at the chosen sites. Chapter 5 discusses the results of the investigations, explaining the implications and meanings of the study findings. Finally, Chapter 6 presents (i) the conclusions of the research and its limitations and possible improvements and applications and (ii) the recommendations arising from the study and potential avenues for future research. Appendices A and B include supplementary information relevant to Chapters 3 to 5.

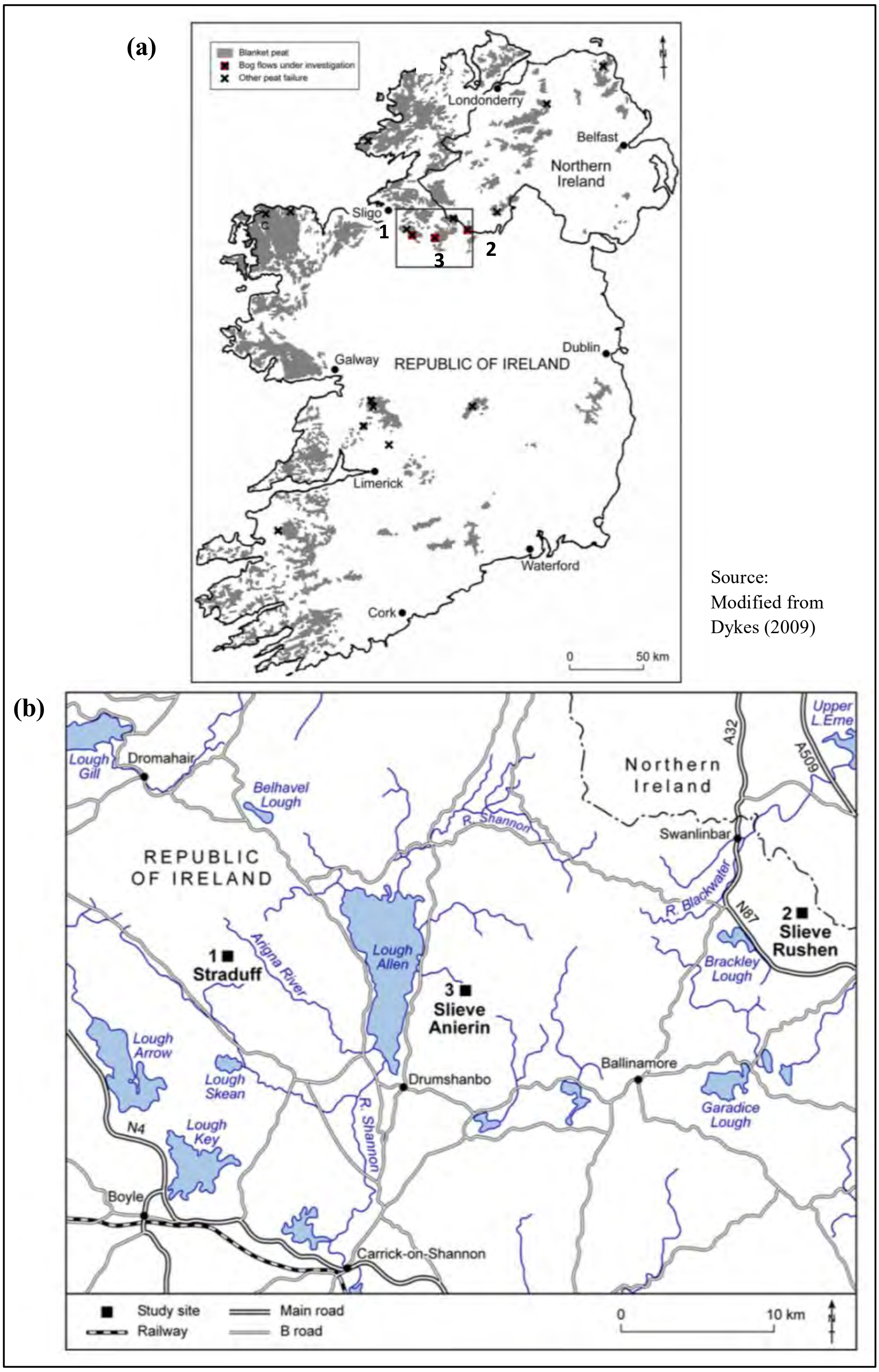

Figure 1. 1. Location maps of (1) the Straduff Townland landslide, (2) the Slieve Rushen landslide and (3) the Slieve Anierin landslide in (a) Ireland (modified from Dykes (2009)) and (b) the area of northwest Ireland that includes the three study sites.

CHAPTER TWO- LITERATURE REVIEW

This chapter aims to identify gaps in the research into blanket bogs instability with respect to the properties of the peat. It will introduce the origins and characteristics of peat deposits and then outline the fundamentals of landslide science. This will be followed by a review of peat classification systems for describing peat in the field and previous research into peat properties in general, and at or near the study sites in particular.

2.1- INTRODUCTION

An overview of current knowledge on peatlands in general can be found in Charman (2002). Peatlands can be defined as ecosystems where in excess of 0.3-0.4 m of peat has formed (Charman, 2002). Although peatland types are variable in terms of flora and fauna, all have one predominant characteristic which is their close interrelationship with the water table, termed „ecohydrology" (Eggelsmann *et al.*, 1993). The dynamics of water supply and loss are fundamental to the development, maintenance and stability of peatlands (Ivanov, 1981; Hughes and Heathwaite, 1995). Understanding mire processes and stability therefore requires knowledge of its hydrology and physical properties (Eggelsmann *et al.*, 1993).

The hydrology of peatlands

Figure 2.1 shows the different components of water storage in a peatland water balance (Gilman, 1997). The main compartments of the peatland water balance include atmospheric inputs, the peat matrix, the adjacent mineral material and the hydrological network, which includes pipes and channels (Eggelsmann *et al.,* 1993). The important water balance processes are precipitation of atmospheric moisture, seepage of liquid water through the peat (which acts as a porous medium), pipe (or fissure) flow which is not directly open to the atmosphere, diffuse surface runoff, unconfined channel flow and evapotranspiration (Ingram, 1983). Peatlands store a great quantity of water and contain very large quantities of bound water, amounting to as much as 97% on a volume basis, depending on peat type and level of decomposition (Heathwaite, 1993; Warburton *et al.*, 2004). Most of the water in a mire is stored in the catotelm (i.e. the underlying and unsaturated layer (Ivanov, 1981)). Within the catotelm, water is held as intracellular, interparticle or absorbed water (Burt, 1995). However, only a very small proportion, the intracellular water, is free and can be involved in the seasonal exchange of water. The acrotelm (i.e. the saturated surface layer of a mire soil (Ivanov, 1981)) acts as a temporary water storage reservoir and its capacity depends on the porosity, size distribution and pore architecture, which together determine the proportion of pores that drain at a given water potential (Eggelsmann *et al.,* 1993).

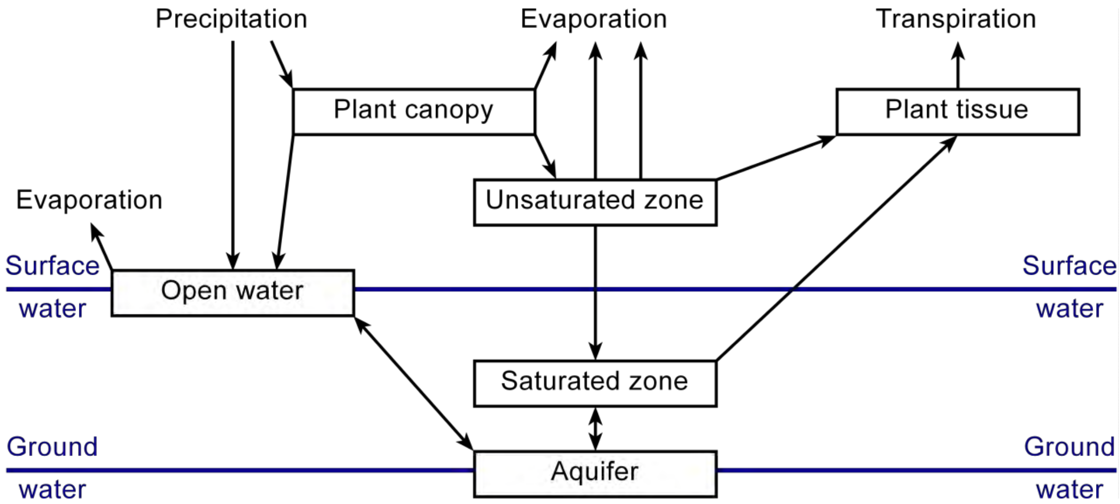

Figure 2. 1. Components of water storage in a peatland water balance (after Gilman, 1997).

The water potential quantifies the tendency of water to move from one area within the peat to another due to osmosis, gravity, mechanical pressure, or capillary forces. It can help to understand the movement of water within the peat. The diplotelm model also enables the understanding of natural or anthropogenic changes to the peat landform system through processes of hydrological and biological changes (Kirkby *et al.*, 1995). Diplotelmic mires can be defined as mires in which both the acrotelm and the catotelm are present as opposed to „haplotelm" in which only the catotelm remains (Ingram, 1978). Ivanov (1981) presented the characteristics of diplotem model components (i.e. the acrotelm and catolelm) as shown in Table 2.1. Citing Ingram (1983), Holden and Burt (2002) represented a conceptual diplotemic model (Figure 2.2) of runoff production in North Pennine blanket peat in which a discontinuity in hydraulic conductivity exists between the acrotelm and the catotelm. The hydrology therefore influences the peat landform and different site conditions (i.e. including the climate, the geology and geomorphology) give rise to different peatland types.

Table 2. 1. Characteristics of the acrotelm and catotelm (Ivanov, 1981).

Acrotelm (upper layer)	Catotelm (lower layer)
(1) intensive exchange of moisture with the atmosphere and surrounding area	(1) very slow exchange of water with the subjacent mineral strata and surrounding area
(2) frequent fluctuations in water table level and changing moisture content	(2) constant or little-changing water content
(3) high hydraulic conductivity and water yield, declining rapidly with depth	(3) very low hydraulic conductivity (2-5 orders of magnitude less than the acrotelm)
(4) periodic access of air to pores, clearing them of water	(4) very limited access of air to pores
(5) aerobic microorganisms, facilitating rapid decomposition and transformation into peat of each year`s dying vegetation	(5) few aerobic microorganisms and other kinds; and slow decomposition.
(6) Living plant cover	

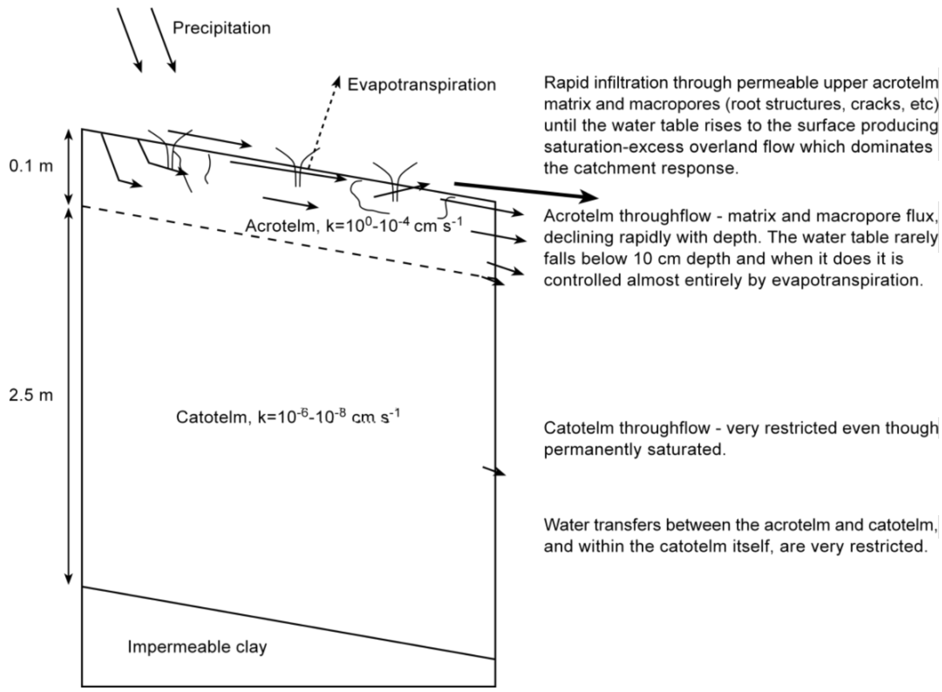

Figure 2. 2.Conceptual model of runoff production in North Pennine blanket peat (Fig. 1 in Holden and Burt, 2002).

Distribution and classification of peatlands

Peatlands are regionally variable because their development is determined by environment factors combined with the intensity and histories of human influences (Charman, 2002). Therefore, variability in criteria used for defining peat and peatlands in different countries and disciplines has led to different and sometimes confusing terminologies, published peatland distribution data and classification systems. Peatlands cover around 3% of the global land surface (Tallis, 1997). Figure 2.3 represents a distribution of peatlands internationally, showing that most peatlands are located in the northern hemisphere of the globe.

The hydromorphological system (Charman, 2002) distinguishes between ombrotrophic (i.e. peatland systems that receive all of their water from the atmosphere (Charman, 2002); e.g. blanket mires), mineratrophic peatlands (i.e. peatlands that receive water from outside their confines, from groundwater or surface runoff; therefore they tend to be alkaline and richer in nutrients (Charman, 2002)) and is the most used classification system in many applications.

Blanket mires represent the most extensive type of peatlands within the British Isles and are restricted to wet and cool oceanic climates. They are ombrotrophic peatlands that can cover large areas of upland and coastal regions (Whittow, 1984). They occur in areas with impermeable substrates where they lie like blankets over flat or slightly sloping terrains (Taylor, 1983).

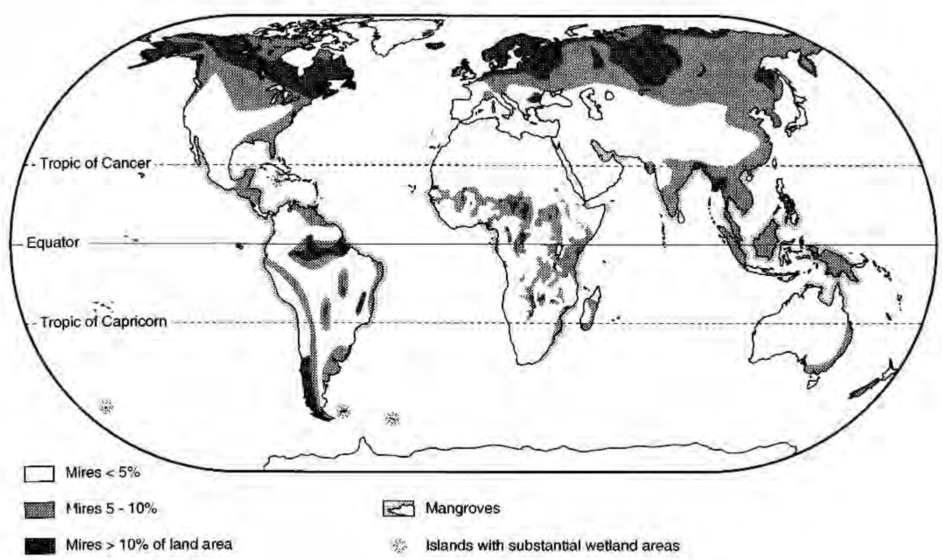

Figure 2. 3. The world distribution of mires (Fig. 1.9 in Charman, 2002).

With the exception of the Ruwenzori Mountain in Uganda with altitude reaching 2000 m (Charman, 2002), blanket mires are restricted to temperate hyperoceanic areas (Lindsay *et al.*, 1988; Doyle, 1997; Charman, 2002). Climatic conditions in areas where blanket peat generally form are often mild, wet and windy with precipitation exceeding 1200 mm per annum and the number of rainy days exceeding 200 per year. The total amount of rainfall is less important than the distribution of rainfall episodes throughout the year. The warmest month of the year has an average temperature of 15°C (Lindsay *et al.*, 1988; Charman, 2002; Dykes and Selkirk-Bell, 2010). Blanket mires are also relatively unconstrained by terrain topography with uniform vegetation and ubiquitous cover (Goode and Ratcliffe, 1997; Moore, 1984).

Blanket mires occur on landscapes wherever slope gradients remain less than 15 degrees and in some places, such as parts of western Ireland, they may occasionally cover slopes steeper than 20 degrees (Doyle, 1997). Typically, such blanket mires occupy coastal plains and inter-montane valleys along the Atlantic seaboards and on plateau areas in the mountain regions (Doyle, 1997). Taking into consideration the altitude which influences the plant cover along the slope, Schouten (1984) differentiated Irish blanket bogs into lowland blanket bogs (0-150 m above OD), highland blanket bogs (i.e. located at 150-300 m above O.D.) and mountain blanket bogs (i.e. located >300 m above O.D.). In general, the area of blanket mires in the British Isles is approximately 25,000 km^2, which is about 10% of the global total and is thus of considerable international importance (Clymo, 1983; Tallis, 1997; Yeloff *et al.*, 2006). Most blanket mires are located in the north and west, extending from Devon in the south to Shetland in the north (JNCC, 2012).

Peatlands are under threat from degradation and their futures are uncertain with problems likely to be exacerbated by climate change (Warburton *et al.*, 2004). Climate change scenarios predict an increase in winter precipitation and seasonality that could lead to increases in peat erosion, pollution of controlled waters (Evans and Warburton, 2001) and destabilisation of blanket peat (Heathwaite, 1993; Evans *et al.*, 1999). Lowland peatlands are completely destroyed by different anthropogenic influences including agriculture, afforestation and commercial peat extraction. Peatlands including upland bogs are also susceptible to erosion (DoE, 1995) which has increased in intensity over the last 200 years (Evans and Warburton, 2001). Peat extractions can also induce peat mass movements (Alexander *et al.*, 1985) which are common phenomena associated with blanket mires on hillslopes.

Table 2.2 presents the current extent of blanket mires in the British Isles. The vast majority of blanket bog is found in Scotland. Although they are all located in the British Isles, these blanket bogs may have formed from different plants and, as such, may have different structural and strength properties.

Table 2. 2. Distribution of blanket bogs in the British Isles (Tallis, 1998).

Country	Area in ha	Reference	Definition
England	214 000	DOE (1994)	>1.0 m depth
Wales	78 000	Yeo (1997)	>0.9 m depth
Scotland	1 056 000	DOE (1994)	>1.0 m depth
Northern Ireland	131 000	Foss and O`Connel (1996)	>0.3 m depth
Republic of Ireland	775 000	Foss and O`Connel (1996)	>0.3 m depth
Total	2 254 000		

2.2- PEAT MASS MOVEMENTS

Although earlier research suggested that 80% of all known peat mass movements have occurred in the British Isles (i.e. with 60% in Ireland and 20% in England and Scotland: Dykes and Kirk, 2006), an inventory survey of the subantarctic islands recently indicated that there may be several hundred peat landslides, perhaps three times more than in the British Isles (Dykes and Selkirk-Bell, 2010). Summaries of some known peat failure sites are presented by Kirk (2001), the Geological Survey of Ireland „Landslide Working Group" (Creighton, 2006) and Dykes (2008a, 2009). As noted by Boylan *et al.* (2008), who analysed peat slide causal factors and fatalities, over 70 instances of peat slope failures have been reported in Ireland. Climate change and new windfarm developments could give rise to more. In fact, there has been a resurgence of interest in peat mass movements recently due to the occurrence of several catastrophic peat landslide events in the UK and Ireland. These include the multiple peat failures on Dooncarton Mountain, County Mayo, western Ireland, on 19 September 2003 (Tobin, 2003; Duggan, 2004); the Channerwick, South Shetland peat slides also of 19 September 2003 (Dykes and Warburton, 2008b) and the Derrybrien bog failure in County Galway on 17th October 2003 (Bragg, 2007).

The events outlined in the previous paragraph have coincided with new research which aims to examine the fundamental characteristics of peat mass movement events, the characteristics of the peat matrix in terms of physical compositions and to move away from the purely descriptive and case-by-case approach which had previously dominated the literature (Mills, 2002). The assessment of slope stability for any purpose requires a proper understanding of four related groups of topics presented in Table 2.3 (Petley, 1984). This study deals with some aspects of topics 1-4 specified, some of which remain poorly understood with respect to peat as discussed in Chapter 1. The uncertainties involved in the understanding of these topics render peat slope stability assessment particularly challenging. For example, there are no classifications of peat for stability assessment. Even more problematic, methods for measuring peat strength and for stability analysis may be inappropriate for the fibrous and organic nature of peat, as further discussed in the following sections.

Table 2. 3. Factors needed for assessing slope stability (Petley, 1984).

Slope stability assessment method
(1) Recognition and classification of various types of mass movements that can occur on a slope; their characteristic morphological features; their geological settings; their rates of displacement and the cause(s) of failure.
(2) Classification and precise description of the materials involved in a mass movement, and the quantitative measurement of their relevant properties.
(3) Determination of methods of calculation of the stability of a slope in terms of the types of failure, real or anticipated, and the material properties.
(4) Correlation between field observations and the results of stability calculations based on measured properties of the materials involved in a mass movement.

2.2.1- Classification of peat for stability assessment

Several mass movement classifications exist based on the original scheme developed by Sharpe (1938). Selby (1993) described some criteria used to classify different types of mass movements including the geometry of the failed mass, the material involved, mode of deformation, velocity and mechanism of the movement and the water content of the failing slope. Table 2.4 presents some mass movement classifications which all have some limitations. Dykes and Warburton (2007a) proposed the use of clearly defined terms (Table 2.5) that can be readily applied and used to understand peat mass movements. The scheme does not, differentiate between lowland, highland, mountain blanket bogs as defined by Schouten (1984) for Ireland, for example. These blanket peats showed different plant types (as result of different climatic and topography conditions) that may accumulate and form peats with different structures and textures, and different strength properties. Paleobotanical studies of these different types of blanket bogs as defined by Schouten have not been specifically investigated, therefore their macrofossil contents can not be compared. The strength property of peat can determine its susceptibility to failure under specific conditions and also its failure mechanism.

2.2.2- Mass movement causal factors

The causal factors of landslides are the preparatory (or background) and external (or triggering) factors (Crozier, 1986). Factors contributing to low or high soil shear stress which influence slope stability in general are summarised in Table 2.6

Table 2. 4. Some mass movement classification systems limitations in terms of peat landslides.

Author	Criteria	Limitations
Sharpe, 1938	Process	Peat failure not included - excludes materials properties
Varnes, 1978	Process and material	Peat failure not included - excludes organic soils
Crozier, 1973	Morphometric	
Cruden and Varnes, 1996	Genetic	Does not accommodate characteristics of peat failure
Hungr *et al.*, 2001	Taxonomy	Require knowledge of failure and movement mechanisms
Hutchinson, 1988	Peat morphology and also subdivided by factors unique to peat	Bog slide, flow and burst included in translational slides – potentially inappropriate amalgamation of different process types
Dykes and Warburton, 2007a	Peat deposit and failure morphology	Exclude creep movements. Classification for peat movements only. The classification does not differentiate between lowland, highland, mountain blanket bogs as defined for example by Schouten (1984) for Ireland.

Although most of the mechanisms described in this table are also relevant to peat, the assessment of a peat-covered slope for mass movements is highly complex partly because current knowledge of causal factors and failure mechanisms remains rudimentary. Like all peatlands, blanket bogs are living landform systems, the development and stability of which depends on various factors as presented in Figure 2.4 and explained by Charman (2002). The hydrological, geochemical, biological and physical processes determine the hydrological, chemical biological and physical properties of peat. Peat mass movement site factors are site conditions that have developed so as to render a slope susceptible to failure under the influence of a specific trigger event, the latter normally being an external influence acting on the slope as explained by Dykes and Kirk (2006). Dykes (2008c) presented a literature review of natural and anthropogenic causal factors of Irish peat landslides. He recommended that in the absence of quantitative research on peat geotechnics and failure mechanism, the resulting risk factors should be used for hazard management purposes. It has also been noted that sites of peat mass movements share several common characteristics that appear to predispose them to failure, as presented in Table 2.7 (Tomlinson and Gardiner, 1982; Carling, 1986; Warburton *et al.*, 2003).

Although the peatland formation process is strongly influenced by climatic conditions, its morphology depends on various external factors and interrelated internal processes within the peat. Peat structure depends on its degree of humification, its fibre content and its water content.

The microorganisms in peat play a major role in peat humification and structure and, thus, peat strength properties. As noted by Pigott *et al.* (1992), a complicating factor in the understanding of landslides in peat is the presence of fibres and the natural heterogeneity of the material. The reinforcing effect of fibres, particularly in the upper less humified layers can sometimes increase stability (Dykes, 2008d). However the nature of peat can vary significantly with depth.

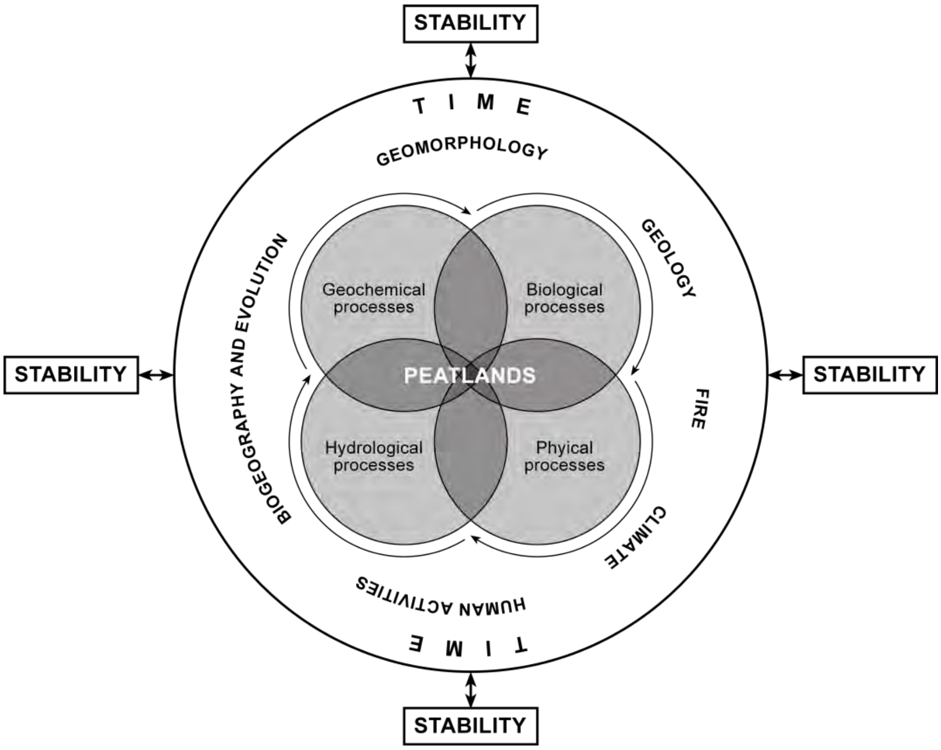

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Figure 2. 4. Main internal and external influences on peat landform development (from Charman, 2002; Figure 2.1)

Site factors that promote peat failure may include, but are not limited to, the bedrock geology, botanical properties of peat, geomorphological factors, hydrology and hydrogeology and land cover as presented and explained in Table 2.7. These factors can act together at the same site to trigger a landslide, which renders the determination of the primary causal factor particulary challenging.

Table 2. 5. Peat mass movement classification system used in this study (after Dykes and Warburton, 2007a).

Type	Peatland type	Location of failure surface or zone	Example	Possible causes
Bog burst	Raised bog	(lower) Catotelm	The lowland raised bog that burst on 26 January 1744 at Pilling Moss, Lancashire, U.K. (Dykes and Warburton, 2007a).	Unknown structure and processes hidden within the peat and triggered by intense rainfall or rapid snowmelt (Tallis, 2001) or peat weakness cause by peat cutting.
Bogflow (or „Bog flow")	Blanket bogs	(lower) Catotelm	The three study sites	Properties of basal peat Low tensile strength at the base of the peat profile
Bog slide	Blanket bogs	(lower) Catotelm	The 1945 bog slide at Meenacharvy Townland, Co. Donegal, Ireland (Bishopp and Mitchell, 1946; Dykes, 2008a).	Discontinuity between peat layers
Peat slide	Blanket bogs	Interface between base of peat and substrate material (± a few mm)	The 19 September 2003 peat slides on South Shetland, Scotland (Dykes and Warburton, 2008b).	Low cohesion between the mineral substrate and the overlaying peat, impermeability of the mineral substrate. High tensile strength throughout the peat profile.
Peaty-debris slide	Blanket bogs	Within substrate material below base of peat	The 25 October 1998 landslide on the north side of Cuilcagh Mountain, Co. Fermanagh, Northern Ireland (Dykes and Kirk, 2002).	Properties of mineral substrate.
Peat flow	Fen, intermediate blanket bogs and any other type of peat	Various/ unknown	The Wingecarribee Swamp peat flow of 9 August 1998, New South Wales, Australia (Beder, 2001).	High pore water pressures. Head-loading.

Table 2. 6. Factors influencing soil shear strength (Selby, 1993).

High shear stress			Low shear stress		
Type	**Mechanism**		**Type**	**Mechanism**	
Removal of lateral support	(i)	Stream, water, or glacial erosion	Composition and texture	(i)	Weak material such as volcanic tuff and sedimentary clays
	(ii)	Sub aerial weathering, wetting, drying and frost		(ii)	Loosely packed materials
	(iii)	Slope steepness increased by mass movements		(iii)	Smooth grain shape
	(iv)	Quarries and pits, and removal of toe slopes by human activities		(iv)	Uniform grain size
Overloading	(i)	Weight of rain, snow, talus	Relict structures	(i)	Joints and other planes of weakness
	(ii)	Fill, waste piles, structures		(ii)	Beds of plastic and impermeable soils
Removal of underlying support	(i)	Undercutting by running water	Physico-chemical reactions	(i)	Cation (base) exchange
	(ii)	Sub aerial weathering, wetting and drying, frost action		(ii)	Hydration of clays
	(iii)	Subterranean erosion, squeezing out of underlying plastic soils		(iii)	Drying of clays
	(iv)	Mining activities, creation of lakes, reservoirs		(iv)	Solution of cements
Lateral pressure	(i)	Water in interstices	Effects of pore water	(i)	Buoyancy effect
	(ii)	Freezing of water		(ii)	Reduction of capillary tension
	(iii)	Swelling by hydration of clay		(iii)	Viscous drag of moving water on soil grains, piping
	(iv)	Mobilisation of residual stresses	Change in structure	(i)	Spontaneous liquefaction
Increase of slope angle	(i)	Regional tectonic tilting		(ii)	Progressive creep with re-orientation of clays
	(ii)	Volcanic processes		(iii)	Reactivation of earlier shear planes
Transitory stresses	(i)	Earthquakes-ground motion and tilt	Vegetation	(i)	Removal of trees: (a) Reducing normal loads; (b) Removing apparent cohesion of tree roots; (c) Raising of water tables; (d) Increased soil cracking
	(ii)	Vibration from human activity – blasting, traffic, machinery			

Table 2. 7.Site factors for peat mass movements.

Factors	**Components or examples**	**Comments**
Bedrock geology	The stratigraphy, structure, texture, mineralogy and the degree of weathering	Some peat slides are caused by a combination of excess subsurface water pressures developed in sandy or buried soil horizons over the iron pans and the thinner overburden of peat or peaty soil which is associated with steep planar slops and steeper slope segments below the major slope convexities (Dykes and Warburton, 2007b). When a peat layer overlies an impervious or very low permeability clay or mineral base (hydrological discontinuity), water could enter the interface through preferential flow pathways during intense rainfall, be unable to percolate into the underlying mineral material and therefore cause „rafting" of the overlying peat down slope (e.g. Hart Hope peat slide: Warburton *et al.*, 2003; the Shetland islands peat slides: Dykes and Warburton, 2008b).
Properties of peat	Stratigraphy, structure, texture, thickness and plant species composition	This is under investigation as part of this study.
Geomorphology	Slope elevation, gradient and aspect, down slope profile and cross-slope profile	Slope form has an important influence on both hillslope hydrology and stability (Crozier, 1986; Warburton *et al.,* 2004). The physical characteristics of the slope are very important because they might make it prone to failure if triggered by other external factors. Many peat failure sites have been found to have a convex or concave slope or a slope with a break of slope at the head (or toes) of the landslide (Tomlinson and Gardiner, 1982; Carling, 1986; Warburton *et al.*, 2004; Dykes and Kirk, 2006; Boylan *et al.*, 2008). Depending on the nature and properties of the materials a break of slope for example could lead to possible removal of down slope support for the peat. A convex slope at the head may also contribute to the creation of tension cracks within the peat (Mitchell, 1938; Alexander *et al.*, 1986).
Hydrology and hydrogeology	Slope drainage patterns, subsurface pipes, water table levels and permeability	Hydrological processes are fundamental in determining the spatial and temporal occurrence of peat slides (Warburton *et al.,* 2004). It was suggested that shear failure by loading, possibly buoyancy effects, basal liquefaction and surface or marginal rupturing could lead of peat failure. Naturally occurring excess water pressures at, or close to, the base of the peat can cause simple buoyancy or uplift.
Occasionally human activities	Turf cutting can release the basal near-liquid peat (Dykes, 2008c). The dumping of peat spoil or other material onto *in-situ* peat	Additional anthropogenic factors that might promote peat failure may include undercutting of slopes, burning, and drainage for agriculture for example and new developments on upland like windfarms among others.
Land cover	The vegetation type and land use	The removal of trees where present could influence the shear strength of soil.

Influence of hydrology, geomorphology and geology

Geomorphology creates diversity in the hydrological characteristics of the landscape which may influence the accumulation of water and drainage on the surface of the peatland. Table 2.8 details the slope gradients of some bogflows (including the study sites) reported by Dykes (2008a, 2009) and some possible causal factors for those landslides.

Several authors (e.g. Clymo, 1983; Carling, 1986; Alexander *et al.*, 1986; Boylan *et al.*, 2008) discussed the hypothesis that the mass movement of blanket peat is primarily a naturally occurring phenomenon that relates to intrinsic thresholds in peat-covered hillslopes, which are conditioned by their slope gradients and peat depths. Published accounts of peat landslides (i.e. Colhoun *et al.*, 1965; Tomlinson, 1981; Dykes, 2009; Feehan and O"Donovan, 1996; Yang and Dykes, 2006; Dykes, 2008b; Dykes, 2008c) also revealed that bogflows have occurred on blanket peats with average peat depths < 4 m and slope gradients at the head of the source areas < 6º as presented in Table 2.8. This review suggests that there may be a gradient control over the primary failure mechanism. Evans and Warburton (2007) also reported that bog bursts often show lower minimum slope angles (i.e. 1º-2º) compared with peat slides with higher minimum slope angles (i.e. 3º-4º). They also suggested that peat slides occur with smaller peat depths (i.e. 1.0 m- 2.0 m) than „bursts" and flows (i.e. peat depths between 1.5 m- 9.0 m). Dykes (2008a) further suggested that bogflows occur at consistently lower gradients than bog slides. This later suggestion was quantitatively demonstrated by Dykes and Selkirk-Bell (2010) (Table 5a). However, there is as yet insufficient explanation of the processes that are involved to confirm the general validity of this relationship. There is also no agreement on the maximum gradient and depth of peat that may theoretically accumulate on upland blanket mires or other peatland types (Clymo, 1983). Furthermore this review also suggests that the mechanism of failure at the study sites may not be entirely controlled by the slope gradient ranges shown in Table 2.8 because other types of peat landslides (e.g. bog slides and peaty-debris slides) have occurred on slopes with similar gradient ranges (e.g. 4° to 8°: Bolyan *et al.*, 2008; 3° to 30°: Dykes and Jennings, 2011, Table 1). The most important finding from this synthesis is that bogflows occur on slope angles of more than 2°.

A significant change of slope gradient on a blanket bog covered slope is another geomorphological factor that can promote peat instability. Escarpment bogflows (e.g. Straduff Towland and Slieve Anierin; Table 2.8) are frequent and occur as result of the loss of basal support at the escarpment edges due to drying, for example. It has been suggested that in some cases, the firm lower wall of drier peat gave way, and failure propagated upslope by retrogressive unloading of the adjacent bog (Dykes and Kirk, 2006). It should be noted that the bogflow type of failure has also occurred on blanket bog areas with no escarpments (e.g. the Slieve Rushen study site).

Table 2. 8.Site factors and possible landslide trigger factors at some Irish bogflows.

Bogflow		**Altitude (m above OD)**	**Maximum peat depth (m)**	**Slope gradient at the source area or down gradient to crest of escarpment**			**Surface waters/ (0-50 m)**	**Bedrock (B) / Surface (S) Topography[10]**	**Drift geology**	**Basal peat**	**Dry (D) / High rainfall (HR) [10]**	**Season [10]**	**Others factors**
Ref.[1]	**Name**			**At the head**	**Middle**	**Escarpment**							
11	1945 Straduff	400	(3.2) [2]	2.0-2.5	2.5-12	15-17	n/d	n/d	**Clay** (70%) rich drift	U	U	U	U
12	1963 Glendun	370	(1.2)[3]	2.5-3.5	3.0	4.0	n/d	Concave	Schists, silt and granites	U	HR	Autumn	U
14	1980 Carrowmaculla	240	(3.0)[4]	4.0	4.0-5.5	none	Drains & ditches	Convex	Sandy-**clay**	Not very weak	HR	Autumn	Burning
15	1984 Straduff	390	(3.2)[2]	> 2.0	>2.0	>2.0	n/d	Convex (B)	Same as (11)	Weak/ greasy	D/HR	Autumn	Burning
16	1985 Tullynascreen	250	(2.0)[5]	3.5	3.5	10.0	n/d	Convex	Rich in **clay**	U	U	Spring	Peat extractio n
17	1986 Conaghra	150	(3.0)[6]	2.5	2.5-6.0	none	Drains & ditches	Convex	n/d	U	U	Winter	U
19	1988 Slieve Bloom	490	(n/d)[7]	4.5	5.0-9.0	none	Ditches	Convex (S)	n/d	U	U	U	U
20	1990s Slieve Rushen	390	3.4	5.5	1.5	none	none	Break at the head, then planar	Sandstones in **clay** matrix	Slurry/ greasy	U	U	U
21	1990/91 Straduff	410	(3.0)[8]	5.0	2.0-4.0	12.0	none	Convex	n/d	Slurry	D/HR	U	U
27	1997-1998 Slieve Anerin	440	3.4	4.0	4.0	20.0	none	Convex (B)	Sandstones in **clay** matrix	Slurry/ greasy	U	U	U
29	2000s Maghera	380	(3.0)[9]	4.0	2.0-3.0	10.0-20.0	Drains & ditches	Convex (S)	Sandy substrate	Slurry	U	U	U
35	2008 Straduff	400	3.0	5.5	2.5-6.0	23.0-28.0	Ditches	Convex (B)	Sandstones in **clay** matrix	Slurry/ greasy	HR	Summer	U

<u>Notes</u> 20, 27 & 35 are the study sites for this thesis and the site conditions presented are discussed in Chater 4, nd = Not determined, U = Unknown, [1]Dykes (2008a, 2009 (11, 16 & 35)), [2 and 5] Alexander *et al.* (1985), [3]estimated from depth of the flow source area (Colhoun *et al.*, 1965), [4]Tomlinson (1981), [6]Dykes (2009), [7]Feehan and O‟Donovan (1996), [8]Yang and Dykes (2006), [9]Dykes (2008b) and [10] Dykes (2008c).

The geometric configuration (or topography) of the slope and its peat cover (i.e. convex, concave or with a break of slope at the head or toe; Table 2.8) has been identified as a peat failure site factor by different authors because it influences the site hydrological processes (i.e. including drainage patterns and tension within the peat: Alexander *et al.*, 1986) that can promote peat instability. Dykes and Kirk (2001) and Dykes (2008c) presented a summary of some peat landslide types including bogflows with convex and concave downslope forms. Reviewing the works of Wilson and Hegarty (1993), Mitchell (1938), Hendrick (1990), Walker and Gunn (1993) and Tomlinson and Gardiner (1982), Dykes and Kirk (2006) suggested that planar or convex slopes, or planar slopes with a convex break, are the usual topographic locations of peat failures, some of which may also coincide with natural surface drainage lines or flushes (Selkirk, 1996; Warburton *et al.*, 2003, 2004). This conclusion was drawn because no „clear causal link" between concave slope form and peat failure mechanism was provided in the studies reviewed. Supporting this point, Dykes (2008c) further reviewed the natural and anthropogenic peat failure causal factors in Northern Ireland and the Republic of Ireland and suggested that bog slides tend to be associated with concave slope forms and bogflows with convex slope forms or escarpments.

Convex land forms promote drainage processes on hillslopes (Gerrard, 1992), which may influence the structure and strength of peat. Water tends to flow away from convex slope areas to lower elevations on hillslopes. Peat erosion, for example, can therefore occur when water flow rates and volumes are high or where there are surface and subsurface irregularities like cracks, and so promote peat instability. It should be noted however that in some cases, as peat is eroded, instability becomes less likely due to the removal of mass from the slope. During intense and frequent rainfall events, water can accumulate in concave surface and bedrock areas of the slopes (Gerrard, 1992) and promote peat instability by increasing tension or water pressures in/or on the peat, leading to an increase in normal stresses and peat failure. For example, where tension cracks exist, the condition of the peat may be different upslope and downslope of the line of fracture. Water draining from the upslope peat or from precipitation could accumulate in the fracture line therefore increasing pressure on the downslope peat, which could promote peat failure by loading. The failure location in the bog that is situated downslope of the line of fracture is very much influenced by the properties of the peat or of the mineral substrate. Other hydrological mechanisms could occur when water drains from areas where the bedrock is convex in shape to locations where it is concave or planar and cause a reduction of unsaturated peat strength (i.e. increase peat liquefaction in concave areas) especially for the basal peat which has low liquid limit. This phenomenon can lead to the collapse of the peat mass and peat failure.

The underlying geology of a peatlands must also be relatively impermeable to ensure sufficient water retention within the peat. The common characteristic of most bogflow sites is that their mineral substrates are rich in clay particles, as also encountered at the Carrowmaculla landslide (Tomlinson, 1981), which can form impermeable surfaces underneath the peat. Stratigaphic surveys of some bog failures (Table 2.8) have revealed thick clay layers below affected peats (e.g. maximum of 0.55 m at the 1984 Straduff Townland bogflow: Alexander *et al.*, 1986; and at least 1.5 m thick at the Cuilcagh Mountain landslide: Dykes and Kirk, 2001). Carling (1986) suggested that the weathering and stability of the impermeable clay may be a constraining factor limiting peat thickness on some steep slopes. It was also reported that organic dispersing agents leaching from the peat can induce interparticle repulsions in the clays and consequently lead to loss of strength and peat failure. However, the evidence presented by Dykes (2008a, 2009) and Dykes and Jennings (2011) revealed that the landslides under investigation as part of this study were bogflows, suggesting that failure occurred within the peat and not at the interface between the mineral substrate and the peat.

Influences of geochemical processes, biogeography and evolution

Geochemical processes determine the chemistry and hydrochemistry of peat, including the degree of humification and the fibre content which are important structural properties of peat. As discussed in Chapter 1 (Section 1.1), different chemical and biochemical processes occur within the peat matrix and critically affect the structure, texture and the strength of peat. External and internal factors related to any peatland also change over time and critically affect peat structure. Peatlands have evolved over millennia and their ecologies today depend to a large extent on this long-term development (Charman, 2002). Furthermore, although few ecosystems actually record past events faithfully over thousands of years, many ecosystems have some dependence on past events (Charman, 2002). In a global context, biogeography and evolution determines which plants are present to begin the peat formation process. Since plants differ both in productivity and decay rates, this can be an important determinant of peat landform development (Charman, 2002). For example, some species of *Sphagnum* have greater decay rates than others. Different plant types and species may have different peat growth models (Eggelsmann *et al.*, 1993) and will therefore produce different peat landforms with different physical, chemical and strength properties as a result of variation in the degree of humification and other unknown properties.

Triggering factors: Precipitations and anthropogenic factors

The main external factors that can act on a peat-covered slope to initiate landslides are rainfall (i.e. total amount, intensity and frequency) and anthropogenic influences that increase stress on the slope and promote its susceptibility to failure. Dykes and Warburton (2008b) explained that extreme rainfall generates high and sometimes artesian water pressures within the interface between the peat and the underlying mineral. The pressures can then generate a net upward force at the base of the peat that could uplift the whole mass leading to failure. This is possible because of the low field density of peat that is similar to that of water.

Supporting this point linking peat failure to rainfall, Warburton *et al.* (2004) brought together examples of failures which have occurred in the UK and Ireland as a result of rainfall. A detailed seasonal analysis of 44 recorded UK and Irish peat mass movements (Warburton *et al.*, 2004) showed that roughly half occurred in the late summer months of July and August with 10 scattered through the winter months of November, December and January. As discussed by Warburton *et al.* (2004), peak rainfall intensities for winter failures are not usually reported in studies; however, maximum hourly intensities of 70 mm h^{-1} have been reported for slides occurring in Scotland (Acreman, 1991) and 72 mm h^{-1} for a set of slides in Ireland (Tomlinson and Gardiner, 1982) that occurred in July and August of the respective years. Monthly rainfall totals usually reveal greater than average percentages for the month of failure (Colhoun *et al.*, 1965; Alexander *et al.,* 1986) but interestingly, in some cases, below average values for the months prior to failure (Alexander *et al.*, 1986; Hendrick, 1990) have also been noted.

Because of the incommensurate nature of the data it is difficult to analyse intensities beyond this cursory level. Nevertheless, despite attempts to relate rainfall intensity and duration to shallow landslide activity (e.g. Caine, 1980), it has not always been the case that high intensity rainfall precedes failures and, in one case, the absence of rainfall has been noted (Mitchell, 1938). Warburton *et al.* (2004) suggested that this may relate to crack formation and the setting up of stresses between upper and lower peat layers.

Anthropogenic factors and natural fires can often play a role in the initiation, development and degeneration of peat. Anthropogenic influences can lead to changes in peatland hydrology, ecology and colonisation by new species better adapted to the new environment, chemical status (e.g. changes in nutrient status, mineralisation or change in pH) and therefore changes in its structural and strength properties that are of great importance to peat stability. Furthermore, the texture and structure of peat is determined by climatic factors including the origin/type of constituents‟ plant species, temperature, climate, and humidity (Huat, 2004). The natural development of peat can result in significantly humified or weak layers being present at depth. Occurrences such as ancient peat fires, former slides, or a change in the environment at a particular time during its formation can also result in weak layers or discontinuities in the peat as observed at the 2003 Derrybrien peat failure site (Creighton, 2006).

From the above analyses it can be said that, in order to improve our understanding of peat instability, more specific and detailed studies of the influences of all the factors and processes involved in the formation of the peat landform are needed. Such research remains limited (see Section 2.4) and little such work has focused on the hydrological (e.g. Warburton *et al.*, 2004) and geomorphological (e.g. Evans and Warburton, 2007) processes. Such research could significantly help to improve hazard risk assessment and slope stability assessment methods in order to mitigate or manage the impacts of peat mass movements on the environment.

2.2.3- Impacts on the environment

As summarised by Evans and Warburton (2007), peat mass movements have long- and short-term impacts. Potential receptors of hazards (Table 2.9) from peat failures include, but are not limited to, water and ecological features, geological and geomorphological receptors, ambient air, the built environment, human health and economical losses leading to social and cultural implications. Risks to human health are considered minimal because of the remote location of most upland peats from residential properties. An adequate understanding, and appropriate modelling and management, of blanket peat instability should begin with an adoption of a universal classification of peat for stability assessment purposes.

Table 2. 9. Potential receptors of peat failure hazards.

Receptors	Example of impacts
Water and ecology features	(1) Water pollution and risk to sensitive fauna present (McCahon *et al.*, 1987; Wilson *et al.,* 1996; Tallis, 2001); (2) Alterations of natural drainage channels (Alexander *et al.*, 1986; Coxon *et al.,* 1989); (3) Potential changes to ecosystems (Feldmeyer-Christe, 1995; Feldmeyer-Christe and Köchler, 2002) leading to management problems.
Geomorphology	Changes in the lithology and palaoecological properties of adjacent mires (Ashmore *et al.*, 2000); Geomorphologic changes (Evans and Warburton, 2007).
Ambient air	Emission of greenhouse gas in the environment from the humified organic matter.
Built environment	Damaging to property and infrastructure (Colhoun *et al.*, 1965; Long and Jennings, 2006).
Human health	Peatlands are generally very remote from residential areas, risk to human health is considered to be very low although few fatalities have occurred (e.g. the bog located a short distance from Ballaghhline, west Clare, in 1900; Kilroe, 1907; On the subantarctic islands, two people were killed in Port Stanley by the 1886 bogflow; Dykes and Selkirk-Bell, 2010).
Economy	Economic losses (Coxon *et al.,* 1989) and future liability problems arising from inadequate peat failure risk assessments.

2.3- DESCRIPTION /CLASSIFICATION OF PEAT IN THE FIELD

Peats are highly heterogeneous, making classification difficult. Hence, existing methods for peat description are very variable depending on the subject area, the country and the purpose of the study. Earlier organic soil classifications quoted by Farnham and Finney (1965) were based on topographical-geographical, surface vegetation chemical properties, botanical origin, morphology and genetic processes. Following their review of classification systems for organic soils, Farnham and Finney (1965) created a new classification in which organic soils were divided into three peat classes (i.e. fabric, hemic and sapric peat) based on fibre content greater than 0.1 mm. Various other simple geotechnical properties including the water content and loss on ignition (i.e pH) have been further used to categorise and define peat (Hobbs, 1986). The most common geotechnical peat property used for classification remains the ash content (Landva *et al.*, 1983; Carlsten, 1993) and the most common peat classification systems used internationally are the Radforth system

(Radforth, 1952), the Troels-Smith system (Troels-Smith, 1955) and the von Post system (von Post, 1924). The current Scottish Executive guideline (2006) recommends the use of the two latter classifications for peat failure hazard assessment. These systems are all subjective; therefore experience is needed for their accurate and consistent application in the field.

The Radforth system is based on the structure of peat and was developed for Canadian muskeg (i.e. swamp or bog formed by an accumulation of *Sphagnum* moss, leaves, and decayed matter resembling peat) because of problems associated with trafficability (i.e. is the ability of a given vehicle to traverse a specified terrain), construction and foundation engineering.Very little botanical knowledge is involved (Landva *et al.*, 1983). The system divides peat into three main categories with 17 subdivisions and uses the concepts „woody‟ and „non-woody‟ to characterise the peat. The plant cover/topsoil is also divided into nine different classes based on the structure. This system is not readily applicable to the British Isles (Hobbs, 1986) where environmental settings are different from those of Canada.

The von Post system is the best known classification system and is the most widely used in Europe. It was originally designed to aid the development of an inventory of Swedish peat resources and was oriented towards horticulture, agriculture and forestry requirements. As suggested by Hobbs (1986), peats are composed of the partly decomposed remains of plant communities containing varying morphology and texture. MacFarlane (1986) stipulated that the structure of peat affects the retention or expulsion of water in the system, gives it its strength and ultimately differentiates one type of peat from another. The von Post classification system therefore attempts to describe peat and its structure in quantitative terms. Different modifications have been carried out on this system for geotechnical use. Landva and Pheeney (1980) and Hobbs (1986) extended the von Post system to provide a means of correlating the types of peat (i.e. by direct examination of peat fabric and structure) with their physical, chemical and structural properties. Properties defined include the humification (scale: H1-10), the wetness (scale: B1-5), the fine fibre (scale: F0-3), the coarse fibre (scale: R0-3), wood and shrub remnants (scale: W/N0-3), vertical and horizontal tensile strengths (TV/TH0-3), the smell and the plasticity (scale: 0 -1) and the acidity (scale: acid pH_L , neutral pH_o and alkaline pH_n). The smell, the acidity and the pH are not often determined in the field probably due to the fact that they are not often discussed or interpreted in most studies or also because links to peat instability has not been established. Magnan (1994) further reduced the von Post system to three classes: fibrous, semi-fibrous and amorphous peats, similar to the modern Swedish system (Larsson, 1990; Long, 2005). However, this later classification has not been often used in the literature, especially for the purpose of stability assessment

The Troels-Smith classification system is a Danish system based on morphological characteristics of the peat. This system was designed in 1955 and was an attempt to create a „universal classification system based on a purely descriptive approach‟. This system has been rarely used in geotechnical applications. Although also subjective, this system is a logical, versatile and flexible description method. It recognises that sediments are often mixtures of elements (Birks and Birks, 1980). The system describes the humicity (i.e. the degree of humification of the peat), the physical features (i.e. the appearance and mechnanical properties; Troels-Smith, 1955) and the component parts (i.e. the nature, as well as the proportion, of the elements of which the deposit is composed; Troels-Smith, 1955) of the deposits.

The humicity (*Huminositet*), which is defined as „the degree of disintegration of organic substance, regardeless of the way this disintegration has taken place, and what substances resulted from it" (Troels-Smith, 1955), is described using a 5 -class scale, derived from the von Post 10 -class scale of the degree of humification (i.e. 0 (von Post H1-2), 1 (von Post H3-4), 2 (von Post H5-6), 3 (von Post H7-8) and 4 (von Post H3-4)).

The physical features used are,

(1) the degree of; (i) darkness (*Nigor*), (ii) stratification (*Strat.*), (iii) elasticity (*Elasticitas*) and (iv) dryness (*Siccitas*),

(2) the structure of peat (e.g. granular, fibrous), and

(3) the sharpness of the boundary between peat strata (*Limes*).

Peat colour (i.e. represented as the degree of darkness) throughout the peat profiles reflects the combination of different factors including the original plant assemblage, the degree of peat humification, peat chemical composition (e.g. the proportion of proteins, of iron oxides), peat mineral content (e.g. manganese oxide causes a black colour) and water content (e.g. water content influences the rate of peat oxidation) (Clymo, 1983).

The degree of peat dryness (or wetness) in the field depends on the proportion of water that is held in the intracellular, interparticle spaces or held as absorbed water (Burt, 1995). The proportion of water in each compartment depends on the proportion of plant particles in the peat which, in turn, depends on the degree of humification and the position of the water table that often fluctuates during the year. Frequent fluctuations in water table level and moisture content occur in the acrotelm which critically affect peat properties. Although the water table and the moisture content fluctuations are generally very limited in the catotelm (Table 2.1), they can occur in some eroded or disturbed blanket bogs where preferential flow pathways exist (Tallis, 2001). It should be noted that the water-holding capacity of peat in the laboratory test is not the same as the water content of peat before the removal of the monoliths from the deposits (Davis, 1946). Therefore an assessment is needed *in situ* to characterise the deposit. The „true" field water content is difficult, if not impossible, to measure accurately.

Peat stratigraphy arises from differences in colour, texture and composition of plant remains that accumulate under different environmental conditions (Charman, 2002). A very thin boundary between two consecutive peat units (i.e. peat profile statigraphic zone observed in the field) could represent a discontinuity in the peat accumulation process whereas a thick boundary would indicate a more gradual change in the environmental factors. The degree of peat elasticity is determined by the fabric of the original plant material and its degree of decomposition and compaction. The degree of elasticity could influence the degree of compression or tensile strength of the peat. Peat with low strength often shows low elasticity (Winterkorn and Fang, 1991). MacFarlane (1969) suggested that the spongy or elastic nature of peat means that large deformations occur as the peat develops its inherent resistance to applied force.

The component parts of the deposits include, for example,

i. *Substancia humosa* (i.e. humous substance, homogeneous microscopic structure or completely humified peat),
ii. *Turfa* (e.g. remains of mosses or below ground remains of woody and herbaceous plants, and the stumps of trunks, branches and stems of plant connected to the roots),
iii. *Detritus* (e.g. mostly above ground fragments of ligneous, herbaceous plants and sometimes animal fossils)
iv. *Limus* (e.g. mudlike, heterogeneous and plastic deposit made up essentially of small organic particles of plant and animals arising from the productivity of microorganisms),
v. *Argilla* (e.g. particles of silt and/or clay which are characteristically sticky and plastic) and
vi. *Grana* (e.g. macroscopic particles of sand or gravel).

The assessory elements include, for example, remains of molluscs and shells of molluscs, trunks and cortex of trees, cultural remains (e.g. bones, stones and metals) and miscellaneous (e.g. specific locations where sample of strata were taken if any).

The composition of a stratum is recorded on the basis on a scale of 1 to 4, where 1 indicates approximately 25% and 4 indicates approximately 100% of the component. The trace amount of any component in a stratum is represented by the plus (+) sign. A layer may contain one or more components.

Although describing the peat in the field is necessary to characterise the deposit in its natural state, not all of the properties described in the two later classification systems as recommended in the current Scottish Executive guideline (2006) for example are necessary for peat stability assessment. Furthermore, upland peat constituents are less variable than that of peat from other mineratrophic peatlands with more diverse plant types. Parameters that are the most relevant to peat strength should be identified and used to create a suitable classification for stability assessment. In addition to field description of peat, laboratory measurements are often needed in order to investigate the structural properties of peat or to test for properties (e.g. the Loss on Ignition (LoI) and peat strength) that would be difficult to investigate in the field.

2.4- PEAT PROPERTIES AND CURRENT RESEARCH ON INSTABILITY OF BLANKET MIRES

Stability and engineering works on peat require an assessment of its fundamental physical and geotechnical properties, the latter including its hydrological, structural and strength properties. Peat properties are often related (Clymo, 1983). However, the relationships between most failed blanket peat physical properties have not been investigated. Studies of peat properties have been conducted for engineering purposes across a wide variety of different peatlands (e.g. Berry, 1983; Carlsten, 1993; Helenelund, 1967; MacFarlane, 1969; MacFarlane and Rutka, 1962; Mickeborough, 1961; Miyakawa, 1960; Galvin, 1976; Skempton and Petley, 1970; Kovalenko and Anisimov, 1977; Landva *et al.*, 1983; Marachi *et al.*, 1983; Hobbs, 1986; Bell, 1994, 2000; Islam and Hashim, 2008a,b) but neither their results nor the types of peat tested are relevant to natural instability and botanical characteristics of upland blanket bogs. Most of the properties of Irish blanket peat investigated with reference to natural instability of peat in recent years (Kirk, 2001; Yang and Dykes, 2006; Dykes and Warburton, 2007b, 2008a, b; Dykes, 2008b, d; Dykes and Jennings, 2011) have not been correlated with the tested bog"s botanical properties. Recent investigations of natural peat failures in Ireland have suggested that although engineers engaged in construction projects over peatlands have traditionally used standard geotechnical tests to provide adequate data for their purposes (Hobbs, 1986), these methods may be inappropriate for application to problems involving potential instability of blanket bogs (Dykes, 2008b; Dykes and Warburton, 2008b). As suggested by Mills (2002), due to similarities in local geomorphologic conditions within sites located in the same area, a regional approach to the study of peat mass movements through the comparison of geomorphological, physical and geotechnical properties should perhaps be adopted. The morphological differences between different peatlands types arise from the circumstances surrounding their formation and the plant types constituting the peat. Hobbs (1986) and Bell (1994) presented connections between the morphologies of mires and the properties of peat of concern to engineers in the UK or other countries that have similar topographic and post-glacial climatic histories. A review of these studies revealed that the physical properties of peat (i.e. structure, fabric, degree of humification and proportion of mineral material) influence its plasticity, permeability, compressibility and strength of the peat and its engineering behaviour (Hobbs, 1986) and should be investigated further. Table 2.10 shows the ranges of properties of peat reported in the literature for Irish blanket bogs, some of which will be used for subsequent stability modelling in Chapter 3 (Section 3.3.8).

2.4.1- Physical properties

The water content (Mp), the bulk density (γ), the ash content (A_c), the hydraulic conductivity (k), the degree of humification, the fibre content and the macrofossil content may directly or indirectly affect peat structure and texture and could potentially influence its strength. Some chemical properties of peat, such as the presence of highly hydrophobic substances like hydrocarbons, can also influence its structure and promote upland peat instability as discussed in Chapter 1(Section 1.1).

Water content: Peat is mainly water and most of this water remains fairly static, as its movement through the peat matrix is very slow. The water content varies sharply over small distances due to the variability of plant material present in the peat (Hobbs, 1986). Boelter (1964) showed that a specific change in water table elevation in the horizon containing loose, porous, less humified peat would involve a great deal more water than the same change in horizon of more dense humified and herbaceous peat. He therefore concluded that the hydrological role of any bog or bog area will depend on the type of peat found in the organic profile. Furthermore, citing Boelter and Blake (1964), he emphasised that the volumetric expression of water content is necessary to show accurately the water storage of a peat profile *in situ*. Different peatlands types have different distribution of air, solid and water space, which influence water storage in the acrotlem (Charman, 2002). Charman (2002) demonstrated that natural mire vegetation may not be particularly good at temporary storage of large volume of water, whereas mires that have deeper active surface zone for rooting and aeration have a storage that is greater. Charman (2002) also suggested that peatlands store large volume of water in the catotelm and only a small proportion of this water is involved in the seasonal exchange between peat and the environment.

Values reported in previous works on other bogflows (e.g. Dykes, 2008d), other types of peat failures (e.g. Dykes and Warburton, 2007b; Warburton *et al.*, 2003) and in the studies of Lewis *et al.* (2011) and Wellock *et al.* (2011) are variable (Table 2.10) and are presented in Chapter 4 (Section 4.3). Boylan *et al.* (2008) reported an average water content of 1055 % for a lowland blanket bog in Co. Mayo. He reported water contents ranges from 800 % to 1300 %. Hanrahan (1954) reported water content ranges of 340-1465%, while Galvin (1976) reported a value of 1607% for Irish blanket peat. It can be suggested that peat water content is generally high and cannot be predicted with accuracy. This is partly owing to the variability of the methods used for testing and partly to the variability of the structure of peat itself. Furthermore most studies do not mention if the values reported are field or laboratory saturated water contents of the tested peat samples.

Loss on Ignition: The Loss on Ignition can be defined as a percentage loss in mass of an ignited soil sample to constant mass. Its value depends on the temperature used for combustion. The inorganic part of the plant or extraneous matter is incombustible and ash-forming whereas the organic material of the peat is generally combustible carbonaceous matter. The LoI has many known biases in that during peat combustion and depending on the temperature used some inorganic materials (e.g. such as chemically bound water and calcium carbonate) may be destroyed by volatilisation.

The ash content (i.e. the inorganic content of the peat, which is the amount of matter that remains after combustion (Andrejko *et al*., 1983; Carlsten, 1993)) of peat varies with peatland type as reported by Aston (1909) and Pearsall (1950) for example. Similary to the ash content, the LoI is variable with peat type and depth. For example, Boylan *et al.* (2008) reported an average LoI of 97.9% for the Irish lowland blanket peats cited in the previous Section. Values of LoI for failed upland blanket peats ranged from 98.5% for Cuilcagh Mountain peat (Dykes, 2008d) to 92.7% for Dooncarton Mountain peat (Dykes and Warburton, 2007b) (Table 2.10). Although often high for ombrotrophic peat, the variability of the values of LoI reported in the literature is owing to the variability of methods used for testing and also to the variability of the structures of the peats investigated.

The physical composition of peat deposits varies as a result of their botanical composition, mineral content and degree of decomposition (Eggelsmann *et al.*, 1993). For example, weakly humified peats contain well-preserved and recognisable plant residues whereas highly humified peat consists almost entirely of homogenous, humic substances with only very small quantities of plant tissue remains. It should be noted that two samples with the same ash content or LoI may have different physical, chemical and engineering properties because of the difference in their actual constituents.

Bulk density: Density (γ) is the mass per unit volume (Mg m^{-3}) and the unit weight is the weight per unit volume (usually stated in kN m^{-3}). The dry bulk density (γ_d) is the mass of dry soil divided by its total volume and is also used to characterise peat. When peat materials are dried, their volume is reduced, therefore the bulk density must be calculated on the basis of the wet bulk volume if it is to represent field conditions (Boelter, 1969; Hobbs, 1986).

Table 2. 10. Reported values of physical and geotechnical properties of blanket peat.

Properties	Minimum	Location	Reference	Maximum	Location	Reference
Dry bulk density (g cm^{-3})	0.037	Ireland	Wellock *et al.* (2011)	1.5	Stony River	Yang and Dykes (2006)
Ash content/LoI (%)	1.5/98.5	Cuilcagh Mountain, Ireland	Dykes (2008d)	8.3/92.7	Dooncarton Mountain	Dykes and Warburton (2007b)
Water content (%)	450	Dooncarton Mountain, Ireland	Dykes and Warburton (2007b)	2052	Ballincollig Hill	Dykes and Jennings (2011)
Hydraulic conductivity, k (m s^{-1})- Acrotelm	10^{-4}	North Pennines	Holden and Burt (2002)	10	North Pennines	Holden and Burt (2002)
Hydraulic conductivity, k (m s^{-1})-Catotelm	10^{-8} $<10^{-11}$	Various (e.g. Newfoundland, Moor House in northern England) e.g. Cuilcagh Mountain	Rycroft *et al.* (1975), Hoag and Price (1995), Holden and Burt (2003) Dykes (2008d)	10^{-5}		Rycroft *et al.* (1975)
Cohesion, *c* (kPa)	2	Ireland	Dykes and Warburton (2008b)	11	Ireland	Dykes and Warburton (2008b)
Angle of internal friction (°)	21	Ireland	Dykes and Warburton (2008b)	33	Ireland	Dykes (2008b)
Undrained triaxial strength (kPa)	1.4[a]	Ireland	Jennings (2005)	27	Ireland	Jennings (2005)
Undrained vane strength (kPa)	2	Ireland	Jennings (2005)	40	Ireland	Jennings (2005)
Tensile strength (kPa)	0.1[b]	Dooncarton Mountain	Dykes (2008d)	6.6[c]	Maghera Mountain, Ireland	Dykes (2008d)

<u>Notes</u>
[a] For peat of less than 1.5 m below ground level (middle and surface peat) and 0.8 kPa for peat up to 3.3 m deep.
[b] For the catotelmic peat
[c] For the acrotelmic peat

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Bulk density depends on the amount of compaction, the botanical composition of the materials, their degree of humification, and the mineral and moisture contents at the time of sampling or when saturated. As reported by Hobbs (1986), the bulk density of peat is often related to the organic content, the degree of saturation and the void ratio. All of these parameters may influence peat strength properties directly or indirectly.

The gas content of peat has a great influence on peat density as reported by Hanrahan (1954) who found that the gas content in Irish *Sphagnum* peat may be considerably in excess of 5% of the volume. At full saturation most of the gas could be free, and have a considerable influence on permeability, initial consolidation and pore pressure under load in the field. During construction involving the compression of peat, significant volumes of gases such as sulphuretted and phosphoretted hydrogen (phosphine) as well as methane could be emitted. The field or dry density of peat is low and variable compared with that of mineral soils. The major influence on the specific gravity and the bulk density of peat at water contents above 600 % is the degree of saturation or gas content, which may cause the peat to buoyance under water. The bulk density of peat is however variable with peat type (Clymo, 1983) and with depth. For example, Marachi *et al.* (1983) reported a dry density average value of 0.3 g cm^{-3}. Measurements carried out by Boylan *et al.* (2008) gave a dry density average value of 0.09 g cm^{-3} and Lewis *et al.* (2011) reported bulk density ranges from 0.101 to 0.198 g cm^{-3} with a mean value of 0.133 g cm^{-3} and a standard deviation of 0.03 g cm^{-3}. Pigott *et al.* (1992) also explained that peat bulk density varies with the original plant type and the degree of humification as further discussed in Chapter 4 (Section 4.3).

Saturated hydraulic conductivity: The hydraulic conductivity of a peat deposit, as of any porous medium or soil, is the quantity of water flowing across a unit area whose surface is at every point perpendicular to the gradient of the forces acting upon the flow of liquid, when the gradient of these forces is equal to unity (Ivanov, 1981). This hydraulic conductivity is often formally expressed as Darcy‟s law, as presented by Charman (2002). It depends on pore size, porosity, structure and moisture content (Childs, 1969). It depends on pore size, porosity, structure and moisture content (Childs, 1969). The movement of water in peat is important for ecology, catchment hydrology, and even in determining the shape of raised mires (Ingram, 1982).Water movement through the peat matrix is very slow. Studies have shown peat to be hydraulically anisotropic (Boelter, 1965; Hobbs, 1986; Schotzhauer and Price, 1999, Evans and Warburton, 2007) with the horizontal permeability (kh) generally greater than the vertical (kv) (Beckwith *et al.*, 2003a, Evans and Warburton, 2007). For raised bogs, the ratio $\boldsymbol{log_{10}\frac{kh}{kv}}$ = 0.55 (Evans and Warburton, 2007) and this may not be representative of all peatland types. This ratio may also depend on the methods used for measurements. Recent studies by Lewis *et al.* (2011), who investigated the spatial variability of hydraulic conductivity and bulk density of an upland blanket bog in Ireland, found that the field horizontal hydraulic conductivity could be twice the vertical hydraulic conductivity. The fresher the peat (particularly in the acrotelm), the greater the ratio of horizontal to vertical hydraulic conductivity (Hobbs, 1986). Many studies have reported very low hydraulic conductivities (i.e. < 10^{-11} m s^{-1}.Yang and Dykes, 2006) for layers of peat below 0.4 m depth despite high porosities of between 60-90% (e.g. Rycroft *et al.*, 1975; Holden and Burt, 2003). Evans and Warburton (2007) presented typical values of hydraulic conductivity for ombrotrophic mires in different peat layers recorded on the field using head recovery methods and Lewis *et al.* (2011) also presented a summary of some values found in the literature.Literature values varied from 10^{-6} m s^{-1} (Rycroft *et al.*, 1975; Hoag and Price, 1995; Holden and Burt, 2003) to 10^{-3} m s^{-1} (Rycroft *et al.*, 1975), for the catotelm in blanket bogs. Values of hydraulic conductivity for blanket bogs for the catotelm varied from less than 10^{-11} m s^{-1} (e.g. Cuilcagh Mountain; Dykes 2008d), 10^{-8} m s^{-1} (e.g. Newfoundland, Moor House in northern England; Hoag and Price, 1995; Holden and Burt, 2003; Rycroft *et al.*, 1975) to 10^{-5} (Rycroft *et al.*, 1975). Values for the acrotelm varied from 10^{-4} m s^{-1} (i.e. for North Pennines; Holden and Burt, 2002) to 10 m s^{-1} (i.e. North Pennines: Holden and Burt, 2002) (Table 2.10).

The hydraulic conductivity controls the rate of consolidation and settlement and, therefore, the strength of peat under load (Hobbs, 1986). Hydraulic conductivities of peat are variable because the physical structure and arrangement of the constituent particles in peat greatly influence the size and continuity of pores and/or capillaries. It also varies widely, depending on the amount of mineral matter present in the peat, the degree of consolidation and the extent of peat humification (Gruen and Lovell, 1983). The amount and distribution of water within the microstructures of peat is affected by the degree of decomposition and the arrangement of the plant particles present. The highly colloidal, amorphous peats tend to inhibit water flow, whereas the open-meshed fibrous peats are initially quite permeable. Most water in highly humified peat is held by strong chemical bonds (Clymo, 1983) while in less humified peat, water is held not only as absorbed water but also as intracellular and interparticle waters.

MacFarlane (1969) suggested that the physical structure and the arrangement of constituent particles in peat greatly affect the sizes and continuity of the pores and/or capillaries and such differences result in a wide range of hydraulic conductivities. Different methods used for measurements may also give different results.

Humification: Humification is the process by which organic matter loses its original cellular and tissue structures and is converted into humic substances (humic acid, fluvic acid and humin) that are light or dark brown to black in colour and contain varying quantities of nitrogen. The humification process takes place at the same time as mineralisation. Mineralisation involves all the processes which bring about the conversion of organic matter into simple inorganic compounds. It results in the microbial utilisation of the organic matter and release of carbon oxide. The breakdown of plant material is carried out by microflora, bacteria and fungi which are responsible for the aerobic decay. Therefore, humification is dominant in the acrotelm because it is the biologically active layer (Ingram, 1978). The end products of the biochemical oxidation are carbon dioxide and water.

The variability of the degree of humification with peat depth is often explained by the variability of the environmental, chemical and biological factors that influence plant decay. These factors vary spatially, with peat depth and also with time. The rate at which plant material decays in peat depends on different factors including the temperature, moisture, oxygen supply, the composition of the plant material, the composition and number of peat microorganisms (Egglesmann *et al.*, 1993) and the plant species (Clymo, 1983). In fact, the chemical composition of a plant species is also of paramount importance in determining the rate of its decomposition in a blanket bog. It has been reported, for example, that the rate of decay of *Sphagnum* peat is slower than that of many other plant species owing partly to its low nitrogen content (i.e. less than 1% of dry mass) (Clymo, 1983). The accumulation of blanket peat is primarily the result of the intrinsic slow decay rate of some of the species in the original plant communities (Coulson and Butterfield, 1978). Clymo and Harwad (1982) studied the decay rate of *Sphagnum* sp. and other plants in relation to nitrogen concentration at the Moor House blanket bog. The study confirmed that monocotyledon peat has a higher rate of decomposition compared to *Sphagnum* peat. Hughes *et al.* (2012) used the k-values to show that plant „species signals‟ can influence the results of peat humification. The k-value is the measure that provides an assessment of the inter-species differences in the colouration of the preparations used in peat humification analysis before any humification has occurred. It relates to fresh material and does not take account of the differential decay properties of plant litter, which may also contribute to the species signal (Hughes *et al.*, 2012). Other factors that might influence plant decay include the variability over time of the ratio cutane/cutin from plant tissues within the peat profile as this influences the preservation potential of plant tissues (Tegelaar *et al.*, 1991) and the presence of some microorganisms in peat that can produce hydrocarbons. Humification in the catotelm could be owing to the activity of anaerobic microorganisms during bituminous fermentation (that produces hydrocarbons in some cases) (Rennie, 1810; Jackson *et al.*, 2005). It has also been suggested that the presence of bitumen wax that is viscous in nature, often produced by the aphid *Colopha compressa* living on the roots of *Eriophorum* (Wheatley *et al.*, 1975), may be linked to higher degrees of humification. The quantity of wax, and thus bitumen, in peat is said to increase with age and depth, or perhaps more specifically with humification (Clymo, 1983). As suggested by Pike *et al.* (2002), aphids produce wax that is ultra-hydrophobic in order to avoid being entrapped in liquids. The wax is intentionally synthesized by specialized epidermal cells, which are particularly numerous on the abdominal tergites (Smith, 1999) and the chemical composition of this wax is unrelated to that of the host plant (Brown 1975; Jackson and Blomquist, 1976; Pike *et al.*, 2002).

Physical changes occur in peat owing to the process of humification (Lüttig, 1986). These changes include an increase in humus substances, calorific values, specific gravity, compaction, a decrease in pore space and total moisture content and a change in colour towards dark brown then black. The degree of humification of peat is probably a key property of peat. The degree of humification, based on von Post (Hobbs, 1986) is very variable but typically highly humified at the base (H8-H10) (e.g. Straduff Townland and Ballincollig Hill, Ireland; Dykes, 2008d). Warburton *et al.* (2003) is the only study that has investigated the von Post degree of humification using colour and based on Troels-Smith (1955). The degree of humification influence peat fibre content and is also an important peat characteristic (Malterer *et al.*, 1992).

Fibre content: Farnham and Finney (1965) suggested that peat bulk density or fibre content can provide soil scientists and land managers with significant information about the physical and hydrologic characteristics of the organic soil. The three classes of peat (Section 2.3) differentiated had different bulk densities, hydraulic conductivities, total porosities and water contents. The study showed a relationship between peat fibre content and the studied parameters. These links have not been proven on failed blanket peat.

As far as engineering practice is concerned, the more fibrous the peat, the higher the tensile strength and shear strength, void ratio and water content (Bell, 2000). Cola and Cortellazzo (2005) have attempted to measure the contribution of fibres by carrying out shear strength tests on intact and reconstituted samples without fibres (Boylan *et al.*, 2008). The effect of fibres may also play an important role in stabilising bogs (Long and Jennings, 2006). Owing to the influence of the fibres, peat has unusually high angles of internal friction (Hanrahan, 1954; Hanrahan *et al.*, 1967). Boylan and Long (2010) investigated two peat slope failures in the Wicklow Mountains and showed that (i) the locations where peat failures occurred within the peat were highly humified with relatively low fibre contents (with fibrosity < 5%) and (ii) the fibre content decreased with depth at the study sites. However, the strength properties of the peat analysed were not tested and so a link between the physical and geotechnical properties of the peat failure sites could not be quantitatively demonstrated. Furthermore, the degree of humification was determined using the von Post method, which is also subjective.

Macrofossil content: The reviews of Hobbs (1986) and Bell (2000) identified relationships between botanical composition and geotechnical properties as being of fundamental importance to the understanding of factors controlling peat failure, although no such relationships had been established prior to the present research. The fabric and structure of peat is determined by its plant composition. Botanical investigations for engineering purposes have been carried out in an unsystematic manner and have included very little botanical characterisation of the peat. These investigations have included visual descriptions or classifications of peat using botanical origins (e.g. Kivinen, 1954 in Finland; Davis, 1946; Rigg, 1958) or descriptions of plant remains in peat during sampling using the von Post system. None of these studies followed published palaeoecological methods (e.g. Birks and Birks, 1980) or were linked to peat strength properties.

Information about the past history of a mire ecosystem is contained as preserved plant and animal remains in its peat deposits. Components of this sub-fossil record often used in investigations are macrofossils and microfossils. Macrofossils are site-specific and thus give clues to past surface vegetation patterns while microfossils can be allochthonous. Plant macrofossils are preserved in the form of remains large enough to be visible without a microscope with a median size ranging from 0.5 to 2 mm (Birks, 2007). Unlike microfossils, many macrofossils can be identified to species level, therefore ensuring more accurate palaeoenvironmental reconstructions. Charcoal fragments often occurred in macrofossil analyses as a result of moorland fires (Patterson *et al.*, 1987; Moore, 1982; Boyd, 1982). Macrofossils are not usually transported long distance from the parent material because of their bigger sizes and weights. Peat macrofossils therefore represent the former *in situ* vegetation, with excellent preservation possible in mires such as raised bog deposits. Macrofossil analyses have been carried out across peatlands including fens (e.g. Hughes and Barber, 2003) and blanket peats (e.g. Hammond, 1981; Barker *et al.*, 2000) as well as archaeological deposits (e.g. Chambers *et al.*, 2007). They have been used extensively for different purposes as presented in Table 2.11. The macrofossil content of blanket bog is less variable than that of raised bogs (Conway, 1947; Boatman, 1983, Blackford and Chambers, 1991).

Table 2. 11. Some uses of macrofossil evidence.

Macrofossil evidence
(1) Reconstruction of bog surface wetness and detection of evidence for climate change (van Geel *et al.*, 1996; Barber *et al.*, 1998; Hughes *et al.*, 2000; Mauquoy *et al.*, 2008)
(2) Mire development studies (Hughes and Barder, 2003)
(3) Long-term vegetation development studies to inform conservation management (Chambers *et al.*, 2007)
(4) Investigation of the rate and nature of carbon sequestration in peat deposits (Heijmans *et al.*, 2008)
(5) Reconstruction of archaeological contexts (Mauquoy *et al.*, 2010)

2.4.2- Strength properties and stability assessment

In a geotechnical assessment of peat mass movements, the forces of the mass of peat contributing to instability are identified and are compared with those forces (i.e. the strength of peat) that are available to resist the disturbing forces. Such an analysis must consider the geological and geomorphological of the slope, the nature (structure, texture) of the peat/underlying mineral strata and, most importantly, the local hydrogeology and hydrology as water plays an important role in the triggering of slides. Of great importance to peat instability is the very low unit weight of peat material (Farrell *et al.*, 2006).

Strength properties of peat

The shear strength (kN m^{-2}) is the most important soil property that relates to mass movements (Kenney, 1984; Boylan *et al.*, 2008) and the shear strength of a soil can be defined as the maximum shear stress it can sustain. Engineering practices and stability analyses of peat require knowledge of the shear strength characteristics of material below the surface mat of living vegetation. The determination of the shear strength of peat material is particularly challenging and reliable values of shear strength have been found to be difficult to obtain for several reasons (McFarlane, 1969; Long, 2005). These reasons include: (1) the spongy nature of the peat that leads to large deformation as the peat develops its inherent resistance to applied load; (2) variability of the natural water content over the peat"s existence, in that its natural water content may be from 10 to 100 times (and sometimes more) greater than the natural water content of inorganic soils; (3) its high degree of anisotropy with respect to permeability; and (4) the fact that current standard soil methods do not seem to be appropriate for measuring peat shear strength (this is discussed in Chapter 3; Section 3.3). These test methods can, however, be used to indicate patterns of relative strength variations with depth through the peat deposits (MacFarlane, 1969; Kirk, 2001). Dykes and Kirk (2006) suggested that in blanket peat the shear strength decreases with depth generally. In bog slides and bogflows the lower peat layers clearly failed suggesting higher degrees of humification and lower residual fibre contents than the upper layers. In fact, Hobbs (1986) showed that increasing humification corresponds with lower water contents, lower liquid limits, higher dry bulk densities and lower hydraulic conductivities.

The tensile measurement of peat is a potential indicator of peat strength (Helenelund, 1967; Dykes, 2008d). In view of the complex structure and the fibrous nature of peat, the strength and deformability in tension as well as in compression and shear should be investigated further (Helenelund, 1967; MacFarlane, 1969). Helenelund (1967) designed a lightweight aluminium tension box method suitable for measuring tension tests both in the laboratory and the field then Dykes (2008d) devised a method for the determination of peat tensile strength utilising smaller block samples (0.1 m × 0.1 m, up to 0.06 m thick) in a specially designed laboratory apparatus. The results obtained from a bogflow on Maghera Mountain, Co. Clare, Ireland, using this apparatus demonstrated good reproducibility and consistency with published data. The results of stress-strain measurements from tensile strength tests of peat from Irish blanket bog failures by Dykes (2008d) showed that the strain is proportional to the tensile strength. Shear strength parameters of peat presented in the literature are variable. For example, literature values of cohesion for Irish blanket peat vary from 2 kPa (Dykes and Warburton, 2008b) to 11 kPa (Dykes and Warburton, 2008b). Similary, angles of internal friction for Irish peat vary from 21° (Dykes and Warburton, 2008b) to 33° (Dykes, 2008b). As further presented in Table 2.10, the variability of the strength parameters reported in the literature is owing to the variability of methods used for testing, the effect of fibre reinforcement and to the fact that conventional methods used for mineral soils are often used to measure the strength of peat that has low *in situ* strength, and which structure is organic, compressible and made of cellular entities.

Slope stability assessment method

Peat slides in upland blanket bogs resemble translational planar slides, and as such can be analysed using a relatively simple infinite slope analysis. Shear resistance is often considered in terms of effective stress parameters or in terms of total stress (c_u). The factor of safety (FS) for a planar translation slide in terms of total stresses (Haefeli, 1948; Skempton and DeLory, 1957) is given by Equation 2.1:

$$FS = \frac{c_u}{\gamma z \sin\beta \cos\beta} \tag{2.1}$$

Where:

c_u = Undrained shear strength of the material
γ = Unit weight of the material
z = Depth to the failure surface
β = Slope angle

For an effective stress analysis, and assuming steady seepage of groundwater parallel to the ground surface, the *FS* is given by equation 2.2:

$$FS = \frac{[c' + (\gamma z \cos^2\beta - u)\tan\phi'}{\gamma z \sin\beta \cos\beta} \tag{2.2}$$

Where:

c' = Effective cohesion
ϕ' = Internal friction angle
u = Pore water pressure

The *FS* increases with increasing peat strength and with increasing depth of peat (Dykes *et al.,* 2008) but decreases with increasing unit weight and slope angle (Farrell *et al.*, 2006).
Conventional methods of strength determination using the Mohr–Coulomb Law may not apply to peat. Boylan *et al.* (2008) presents an overview of basic soil mechanics in which he defines and explains some of the limitations (Table 2.12) for peat material. In particular, biochemical decomposition of plant remains leads to the formation of peats, which represent complex colloidal systems with a fabric that is significantly different from that of mineral soils. The validity of shear strength models that were developed for mineral soils when applied to peat is therefore doubtful, as explained by several researchers (e.g. Kovalenko and Anisimov, 1977; Dykes, 2008b; Boylan *et al.*, 2008).
The high effective friction angles are believed to be owing to the reinforcing effects of the predominantly horizontally aligned fibres (Landva and La Rochelle, 1983; Long and Jennings

2006). In the case of bog slides, the effective stresses are generally very low, therefore the contribution to shear strength from the angle of shearing resistance can be very low (Landva *et al.*, 1983; Farrell and Hebib, 1998). The effective strength properties and the effects of fibres also depend on the testing method used (Chapter 3; Section 3.3). The limitations presented in Table 2.12 could also explain the scatter of shear strength values found in the literature as reported by Kirk (2001), Dykes and Kirk (2006), Boylan *et al.* (2008) and Dykes (2008b) and could explain why research on geotechnical analysis of peat mass movements remains rudimentary. Long (2005) summarised some numerical modelling works carried out on peat. The few studies carried out on peat stability assessment include the work of Carling (1986) and Dykes and Kirk (2001), who derived factors of safety for the failed clay beneath peat slides.

Dykes and Kirk (2001) used a finite element model to examine the hydrological conditions of a small peat slide in Northern Ireland. It was concluded that the presence of artificial surface drainage ditches and natural soil pipes within the basal clay were necessary for failure to occur at the site. Citing Den Hann *et al.*(1995), Long (2005) suggested that as far as numerical modelling of peat is concerned, effort must be directed at experimental element testing, constitutive modelling and implementation of the results in finite element codes.

The development of an appropriate strength model for stability assessment should begin with a better understanding of the different forces that occur within the peat during failure as will be explained in Chapter 5 (Section 5.1). The influences of (i) the type and content of fibres, (ii) the degree of humification, (iii) other physical properties and (iv) the slope gradient on peat tensile strength should be quantified and used to develop an appropriate model for stability assessment that can be tested with laboratory measurements.

Table 2. 12. Some limitations of direct application of soil mechanics to peat.

Limitations
(1) Peat constituents are compressible as opposed to mineral soil particles.
(2) Contacts between particles in peat are connections rather than frictional contacts.
(3) It is uncertain whether undrained conditions would exist for many *in situ* strength tests and design situations because of the higher permeability of some peat compared with clay soils.
(4) Consolidation of coarsely dispersed soils during shear leads to a change in the limiting relationship between the principal stresses.
(5) Complex colloidal systems occur in peat therefore the strength of highly decomposed peats is not simply due to the effect of frictional forces.

2.4.3- Chemical properties

No research has been carried out on the chemical properties of peat for peat stability purposes, although chemical substances in peat have been investigated for potential uses in various branches of industry (e.g. Fuchsman, 1980; Zherebtsov *et al.*, 2008, 2009; Luik *et al.*, 2009) or for organic chemistry research purposes (e.g. Guignard *et al.*, 2005; Rurka *et al.*, 2005). The chemistry of peat is very complex, largely influenced by hydrology and geographical location, floristic composition and anthropogenic influences (i.e. drainage, fertilisation and pollution) (Ross, 1995) and also changes with time (Clymo, 1983). Peat is made of the full range of compounds found in the parent plants. These compounds are mostly structural cell-wall carbohydrates. Their nature and concentration in peat are likely to depend on the plant species present. There is, therefore, a close correspondence between the range of compounds constituting peat and the plants from which they are derived, the exact composition being a function of the geological conditions of peat landform and the degree of humificationof the peat (Fuchsman, 1980; Leahy and Birkinshaw, 1992). Peat contains considerable lignin, cellulose and bitumen as typical constituents of original lignocellulosics compounds.

Humic acids and humin often represent the major part of any soil organic matter (Stevenson, 1982) and play a major part in complexation reactions in soil (Haynes and Mokolobate, 2001). However, their chemical structures remain largely unknown, as a consequence of the complexity and heterogeneity of these molecular compounds. The acidity, attributed to the formation of organic acids as end-products of organic matter humification, is the chemical property that is most relevant for engineering purposes with reference to potential aggressive action on structures (BRE, 2005). However, its relevance to natural peat instability has not been investigated.

Directly solvent-extractable lipids are almost always minor components of peat organic matter. Nevertheless, they could provide significant information about the original plant material. Moreover, the study of lipids is essential for understanding the relationship between the different fractions of organic matter, via the comparison of degradation products from humic substances (Guignard *et al.*, 2005).

Of particular significance to peat stability could be the presence and distribution of bituminous wax in peat. This is a complex mixture of true waxes, „asphalt‟ and „resins‟ often produced by the aphid. It contains paraffins, with carbohydrates and secondary amides. Its proportion is said to increase with age and depth, or perhaps more specifically with humification (Clymo, 1983). Bitumen could occur in peat as by-product of organic matter during the process of „bituminous fermentation‟ (Rennie, 1810) at an advanced stage of peat maturation and humification. The chemical genesis of peat bitumen and petroleum hydrocarbons is highly complex and poorly understood, as discussed initially by Rennie (1810). He defined „bituminous fermentation‟ as „a fermentation peculiar to vegetable matter placed in such situation, as not only exclude the external air, and secure the presence of moisture, but prevent the escape of more volatile principles; and which terminates in the formation of those substances termed bitumens‟ (Parkinson, 1833, p.181). Bitumens may therefore contribute to petroleum hydrocarbons formation in peat (Parkinson, 1833). Evidence at previous landslides (e.g. (i) bogflows: Mitchell, 1935; (ii) bog slides: Delap and Mitchell, 1939;

Hendrick, 1990; (iii) peat slides: Dykes and Warburton, 2007b; Dykes and Selkirk-Bell, 2010 and (iv) other peatlands in the British Isles: Hanna, 1993) has suggested similar layers in the basal peats. Rennie (1810, pp.627-628) also reported that highly bitumen-rich peats were found in England, Scotland and Ireland; notably at the „Ince-peat of Lanscarshire, the Caespes bituminosus peat of Morthampton, The clods of Aberdeenshire, the glossy peat near John-o-Groat"s house and some parts of Loch Neagh". No record of the exact location of the sites cited and their original plants was discussed or mentioned. Therefore, link between the original plant species and bitumen production cannot be established. Rennie (1810) did, however, suggest that these weak basal peat layers occurred in a specific class of „peat mosses" which he classified as „highly bituminated peat", associated with particular plant species. He commented that these clods of bitumen could accumulate in the „hollowest" places within these peatlands. It should be noted that greasy but firm basal peats were encountered at the Powerscourt Mountain, Co. Wicklow landslide (Delap and Mitchell, 1939). Greasy layers could also occur in the middle of the peat profile (e.g. Macquarie Island peat: Selkirk, 1996; Dykes and Selkirk-Bell, 2010).

This process of bituminous fermentation in peat, especially in upland peat, has not been discussed in the literature since Parkinson (1833) and remains poorly understood. Leahy and Birkinshaw (1992) and Klavina *et al.* (2011) are some of the few recent works carried out on peat bitumen. Leahy and Birkinshaw (1992) subjected Irish high moor peat to chemical, structural and rheological characterisation. The flow behaviour of the bitumen was that of a yield pseudoplastic fluid which depends on temperature. The rheological properties of the bitumen showed substantial temperature sensitivity as a result of both melting of the crystalline materials and a reduction in the polar interactions in the non-crystalline components. As suggested by Leahy and Birkinshaw (1992), resistance to flow in the liquid component at lower temperatures was due to attractive forces between the polar constituents as well as their high molecular weights. The dominating rheological influence in the bitumen was seen to come from the material in the wax fraction with its high crystalline solids content.

PAHs can occur in peat and they are likely to have evolved *in situ* from algae, spores/pollen and plant cuticles, promoted by the pyrolysis of organic materials at high temperatures during fires. The amounts and types of PAHs produced during the combustion of plant materials depend upon the quantity of material, the character and intensity of burning and the plant species involved (McDonald *et al.*, 2000; Oros and Simoneit, 2001). Some studies of PAHs in environmental media include works of Zaccone *et al.* (2009), Wang (2012), Yunker *et al.* (2002), Lee *et al.* (1982), Budzinski *et al.* (1997), Bucheli *et al.* (2004), Qiao *et al.* (2006), Pontevedra-Pombal *et al.*(2012), Halsall *et al.* (2001) and Baek *et al.* (1991).

2.2.4- Current research on Blanket mires instability

Blanket peat mass movements remained largely unstudied (Mills, 2002) until relatively recently. Detailed analyses of failure mechanisms had been superficial owing to lack of rigorous geomorphology, engineering and physical descriptions of peat. Most research carried out to determine the cause and mechanisms has been based on the analysis of post failure landforms (Tomlinson, 1981; Mitchell, 1938), evidence from eye-witness statements (Kinahan, 1897) and local rainfall records (Colhoun *et al.*, 1965). Previous research carried out on Irish peat landslides comprises geomorphological studies of specific failures site (e.g. Tomlinson, 1981; Alexander *et al.*, 1985, 1986; Dykes, 2008a, 2009) and the more geotechnically focused research into the stability and behaviour of peat materials (e.g. Wyld, 1965; Hanrahan, 1994; Marachi *et al.*, 1982; Jennings, 2005; Yang and Dykes, 2006; Dykes, 2008d; Dykes, 2008b; Dykes *at al.*, 2008; Dykes and Jennings, 2011). General studies include Warburton *et al.* (2004), for example, that reported the hydrological processes control on peat instability and Evans and Warburton (2007) that reported geomorphological influences. As suggested by Creighton (2006) and Dykes (2008b), further research is required to study stable and unstable areas of peat in order to develop methods of reliably determining the stability of peat-covered slopes. In particular, the issues presented in Table 2.13 have been identified as needing further investigation. Although there is an extensive literature on palaoecological evidence of peatland palaeoenvironments (Charman, 2002) none has been directly correlated with peat failure mechanisms. This is particularly important for bogflows and bog slides in which failure occurs within the basal peat, suggesting particularly weak sediments. Furthermore, most of the more recent Irish failures have been „bogflows", (e.g. Alexander *et al.*, 1985; 1986; Dykes, 2008d) as presented by Dykes (2008d, 2009). Recent geotechnical research, carried out on bogflows in particular, includes the works of Yang and Dykes (2006), Dykes (2008d) and Dykes and Jennings (2011) (i.e. discussed in the following sections and in Chapter 4; Section 4.4). With the exception of the last topic (Table 2.13), this project tackles some aspects of all the topics specified. Some of these works have been carried out at or near the chosen study sites (Chapter 3; Figure 3.1) and are discussed in the following sections. A summary of some peat properties and topics investigated are presented in Table 2.14. The properties presented are within the ranges reported in Table 2.10 for blanket bogs in general.

Previous research carried out at or near the Straduff Towland landslide

Previous works carried out at the study site include the geomorphological mapping by Dykes (2008d; 2009) (Chapter 3: Section 3.1) and the geotechnical work carried out by Dykes and Jennings (2011).

Figure 4(a-h) of Dykes and Jennings (2011) shows some of the original geomorphological features of the Straduff Townland landslide. Field morphological evidence suggested it to be a bogflow, i.e. involving *in situ* collapse of peat structure, loss of strength and outflow of basal peat (Dykes, 2009). Dykes (2009) described the peat at the time to be typically 2.5 m deep, varying between 1.8 and > 3 m. Semi-liquid peat slurry (approximately 1.0-1.5 m deep) remained across much of the source area with 0.8-1.2 m thick rafts of acrotelm peat floating in the slurry, typically 60%

submerged with 0.3-0.5 m visible above the slurry surface. This implied that approximately 20,000 m^3 of (semi-liquid) peat had been lost from the source area and moved down the escarpment slope towards and across the road. The mobility of the flow was probably greatly enhanced by additional water from the heavy rain and associated surface runoff. Below the road, the flow followed the same stream channel as the peat failure of 1984 (Alexander *et al.* 1986) for 4.5 km to the Geevagh sports field.

Dykes and Warburton (2007a) classified the 1990/91 landslide as a „bogflow". Yang and Dykes (2006) used peat samples obtained from three failed blanket bogs in Ireland including this Straduff Townland 1990/91 landslide located within 50-100m east of the study site (Figure 3.1) and the Slieve Anierin landslide in order to assess the suitability of liquid limit test as a potentially useful indicator of the susceptibility of peat to failure. Peat has extremely high water content and, as an index property, the liquid limit takes no account of the properties or structures of highly heterogeneous intact peat. From the study of Yang and Dykes (2006), it was concluded that engineering works involving blanket peat deposits cannot rely on published general relationships between the index peat properties. Site-specific peat samples should therefore be used for any blanket bog failure assessment (Dykes, 2008d). Other examples of research on blanket bog failure sites that occurred within 10 km of the study site and on Carrane Hill blanket bog (i.e. where the Straduff landslide is located) includes, for example, that of Alexander *et al.* (1985; 1986). Alexander *et al.* (1986) presented some Straduff Townland (1984) bog failure data including peat index properties (water content and density), bog surface topography, vegetation and mechanisms of peat failure, peat stratigraphy and hydrological information about a stream channel near the site. The stratigraphy survey revealed that the peat was generally coarsely fibrous in the upper 0.75-1.0 m, becoming more finely fibrous, darker and more humified from 1.0-2.5 m, and very well humified and greasy below 2.5 m (Alexander *et al.*, 1986). The survey also revealed that over much of the ridge, the peat appeared to be underlain by a variable depth of drift which analysis revealed to contain up to 70% clay. In some places the clay layer appeared to be absent, most notably from an auger sample taken at the ridge crest some 300 m north-west of the flow"s source (Alexander *et al.*, 1986).

Previous research carried out at or near the Slieve Rushen landslide

The only previous work undertaken on this site is the geomorphological mapping by Dykes (2008a) (Chapter 3: Section 3.1). As described by Dykes (2008a), this bog failure had an unusual character. Dykes (2008a) reported that two tension cracks at the lower western margin coincided with a step in the original ground surface with *in-situ* peat around 1m deeper upslope of this step, thus constituting a line of weakness across the slope. Further downslope, the surface of the flow deposit within the source area became level with the adjacent undisturbed peat. South of this line, the deposition zone was entirely contained beneath the generally intact superficial acrotelm layer of a small basin. The steep outer bank of the raised deposition zone was around 1.5m high along the south-western side and 0.5-1m high elsewhere.

Colhoun *et al.* (1965) carried out a descriptive analysis of the 1965 landslide that occurred on the same blanket bog and which scar has now disappeared. Like most blanket bog mass movements, this landslide was triggered by intense and prolonged rainfall over the period of 8th-22nd January 1965. The landslide was first reported as a “bog burst” and “slide” by Colhoun *et al.* (1965) then “bog slide” by Dykes and Warburton (2007a). A stratigraphy survey showed that peat depths at the 1965 landslide varied from 0.9 to 3 m and that the site was underlain by Carboniferous sandstone. The upper 0.6-1.2 m of brown fibrous peat consisted of undecomposed plant remains, and the lower layers of peat were black and amorphous (Colhoun *et al.*, 1965).

Previous research carried out at or near the Slieve Anierin landslide

The site was first described by Yang and Dykes (2006) and is the only previous work carried out on or near the site. Although the morphological evidence indicated a bogflow type of failure it showed different patterns of tearing and shearing of the acrotelm around the margins of the source area. Like the Straduff Townland landslide, the Slieve Anierin landslide appeared to have involved a naturally occurring failure of the peat margin at the edge of an escarpment. However, whilst the western side and most of the central part of the source area appeared to have involved an outflow of (semi-) liquid catotelm that dragged the acrotelm with it, the latter breaking up and largely being transported from the source area, while the catotelm was intact in the head zone and along the eastern side. Site observations (Yang and Dykes, 2006) indicated that the tensile strength of the acrotelm was sufficiently high to overcome the shearing resistance provided by its contact with the upper catotelm. A narrow (30-50m wide) trail of peat slurry and debris led from the escarpment breach down the slope for about 400 m before entering the Stony River. An exposed peat profile at the margin revealed almost 2 m of peat, suggesting a depth of nearly 2.5 m at the time of failure (Yang and Dykes, 2006). The very thin smear of peat slurry covering the mineral substrate over the lower part of the source area indicated that failure occurred within, or at least involved, this lower layer. The parameter values presented in Table 2.14 were measured as part of the study of peat liquid limits carried out by Yang and Dykes (2006).

Table 2. 13. Further works on peat mass movements identified and the topic addressed by this study.

Objective	Further works identify on peat mass movements	This study
(1)	(i) A classification system should be developed for upland peat stability assessment.	A classification system is proposed for blanket peat stability assessment (Chapter 4).
	(ii) The geotechnical properties of peat, with specific reference to slope instability, should continue to be investigated.	Geotechnical properties of peat have been investigated as part of this study (Chapters 4-5).
	(iii) Fundamental research into the behaviour of peat at low effective stresses with particular reference to its shear strength should continue to be investigated.	Shear stresses of peat have been measured using experimentally very low stress as part of this study (Chapters 4-5).
	(iv) Botanical and chemical controls on the geotechnical properties should be investigated further.	This topic has also been investigated and discussed as part of this study (Chapters 4-5).
(2)	(i)The predicted climate changes (Sweeney *et al.*, 2003) may have significant implications for the stability of the peat slopes in Ireland, which can present hazards requiring robust risk assessment tools in many practical situations.	A model procedure is proposed for blanket bog stability assessment (Chapter 5).
	(ii) Appropriate methods of measuring the strength properties of peat relevant to peat failure, and a reliable method for analysing the stability of blanket bog-covered slopes, should be developed.	A method for stability assessment has been proposed (Chapter 5).
Not Investigated	Monitoring of the behaviour of the blanket bog surface should be carried out over time in other to determine variations in peat moisture contents, water pressures and wet density.	Recommended future work.

Note Objectives; (1) to establish the nature of the relationship between the strength characteristics and physical properties of the peat; and (2) to determine whether palaeoecological analysis of core samples of peat can provide a reliable indication of potential instability in upland blanket bogs, and (3) (Chapter 1: Section 1.3) has not been not been discussed in the literature as possible landslide promoting factor.

Table 2. 14.Properties of the peat at or near the study sites, as presented in previous studies.

Properties	**Landslides**			
	1984 Straduff Townland	**1990/91 Straduff Townland**	**2008 Straduff Townland (this study site)**	**Slieve Anierin (this study site)**
Dry bulk density (g cm^{-3})	0.054 at the top 0.503-0.020 at the base[1]	0.13 [2]	Not determined (n/d)	0.15 [4]
Saturated bulk density (g cm^{-3})	n/d	1.06 [2]	n/d	1.05 [2]
Ash content (%)	n/d	1.47 [2]	n/d	1.60 [2]
Water content (%)	885 at the top 0.5 m; 970 at the base [1]	n/d	760-1335 [5]	n/d
Saturated water content (%)	n/d	930 [2]	933-1399 [5]	900 [2]
Field water content (%)	n/d	918 [2]	760-1036 [5]	
Laboratory saturated hydraulic conductivity (m s^{-1})	n/d	$< 10^{-11}$ [2]	n/d	$< 10^{-11}$ [2]
Shear strength (kPa)	n/d	n/d	Using shear vane; variable with depth 15-27 [5]	n/d
Cohesion(c) (kPa)	n/d	n/d	Modelled values: c = 1.6 or c'' = 1.9 [5]	n/d
Angle of internal friction (º)	n/d	n/d	Modelled value: 30 [5]	n/d
Tensile strength (kPa)	n/d	Decreases with depth mean (2.1-4.5) for 0.5-0.8 m bgl [4]	Decreases with depth (15-1.4) for 0.25-1.5 m bgl [5]	n/d
Type and location of profile description	Peat texture (3.2 m deep) [1]	von Post (1.44 m deep) [3]	von Post (2 m deep) [5]	von Post (2.05 m deep)[2]
von Post (1924) classification for basal peat	n/d	($H_{9-10}B_4$ F_2 R_1 W_0) [3]	($H_{10}B_4$ F_{1-2} R_{0-1} W_0N_0) [5]	H_8B_3 F_2 R_2 W_3 [2]
Type of field surveys previously undertaken	Depth (1-2.5 m) and topography [1]	Geomorphological [3,4]	Geomorphological [3,4]	Geomorphological[4]
Suggested causal factors	Rainfall (16-18 October), clay-rich drift underlying the peat and topography [1]	n/d	13-14 August 2008 intense rainfall [5]	n/d

Notes
[1] Alexander *et al*. (1986), [2] Yang and Dykes (2006), [3] Dykes (2009), [4] Dykes (2008d), [5] Dykes and Jennings (2011).

CHAPTER THREE- METHODS

3.1- SELECTION OF SITES AND DESKTOP STUDIES

This study focuses on blanket bogs in the British Isles where peat failures have frequently occurred and caused damage to the environment. The methods adopted for this study have been refined where necessary on the basis of experience gained using a known landslide in northern England as a training site. The results gathered from the training process are not included in this thesis. The three chosen sites for this study are Straduff Townland (Co. Sligo), Slieve Anierin (Co. Leitrim) and Slieve Rushen (Co. Cavan) in Ireland (Figure 3.1). These failed blanket bogs were chosen because they occurred relatively recently and are classified as „bogflows" on the basis of their field morphologies according to Dykes and Warburton (2007a), although the Straduff Townland failure displayed some features of a „bog slide" (Dykes and Jennings, 2011). The Straduff Townland landslide was triggered by heavy rainfall on 13 August 2008; the exact dates of the other landslides are unknown. Therefore, an assessment of possible influences of factors such as precipitation or high temperatures cannot be completely assessed. The head of the Straduff Townland landslide is located at 54°7.2'N, 8°12.9'W at an altitude of around 400 m, on the summit ridge of Carrane Hill located in the Straduff Townland area. This landslide involved 35,000m^3 of peat and occurred shortly before 22.30h on 13 August 2008. It was one of a localised group of landslides that occurred at about the same time within an area of 12 km^2 centred on the Arigna River valley, between Ballyfarnon, Co. Roscommon and Drumkeeran, Co. Leitrim. Most of these landslides involving hillslope blanket peat were triggered by heavy rain across western Ireland. The mean annual rainfall for the Straduff Townland area is reported to be approximately 1400 mm (Alexander *et al.*, 1986) and the summer of 2008 was wetter than normal in Ireland in general with more than 100 % of normal rainfall (Lennon and Walsh, 2008). Further details of this major weather event are presented by Lennon and Walsh (2008).

The Slieve Rushen landslide involved around 20,000 m^3 is thought to have occurred during the mid- to late 1990s. Its head is located at 54°8.9'N, 7°38.5'W at an altitude of around 390 m. The Slieve Anierin landslide involved around 22,000 m^3 of peat and occurred in late 1997-1998 on a small north-facing plateau within the catchment of the Stony River on the north side of Slieve Anierin (Yang and Dykes, 2006). The head of the landslide is located at 54°6.3'N, 7°58.7'W and at an altitude of approximately 440 m.

After the sites had been selected, desktop studies were carried out in order to assess the environmental settings of the peat failures prior to the site investigations. The main sources of information used for the desktop studies were the Geological Survey of Ireland (GSI) digital and online mapping (GSI, 2012) (Table 3.1), geomorphological maps produced by Dykes (2008a, 2009), the Irish Meteorological Service maps (IMS, 2012), previous on-site research works

(Section 2.4: Chapter 2) and newspaper reports. The site investigations comprised fieldwork and laboratory analyses of peat samples collected from each site. The site photographs (showing the sampling points) are presented in Figures 3.2-3.4.

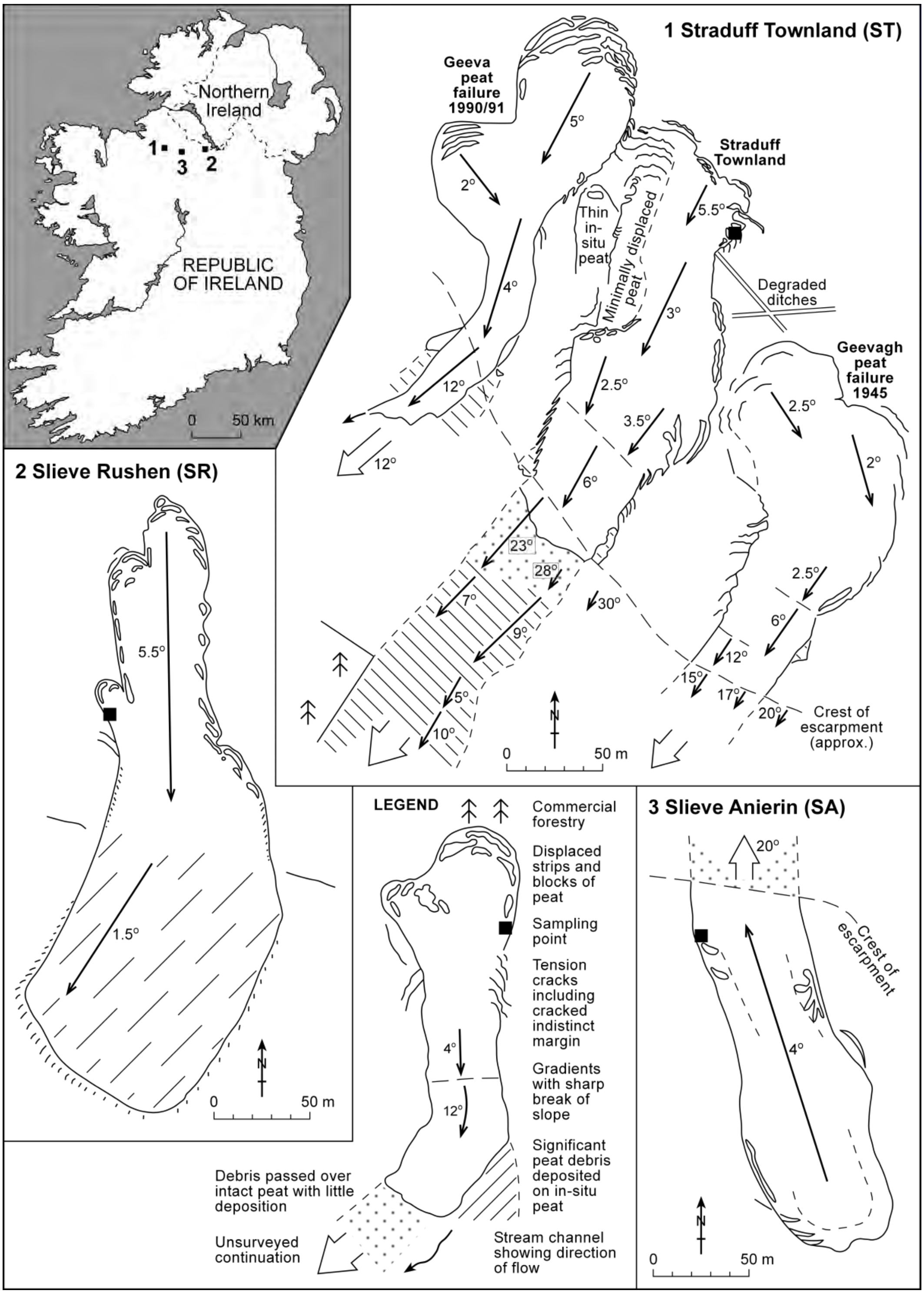
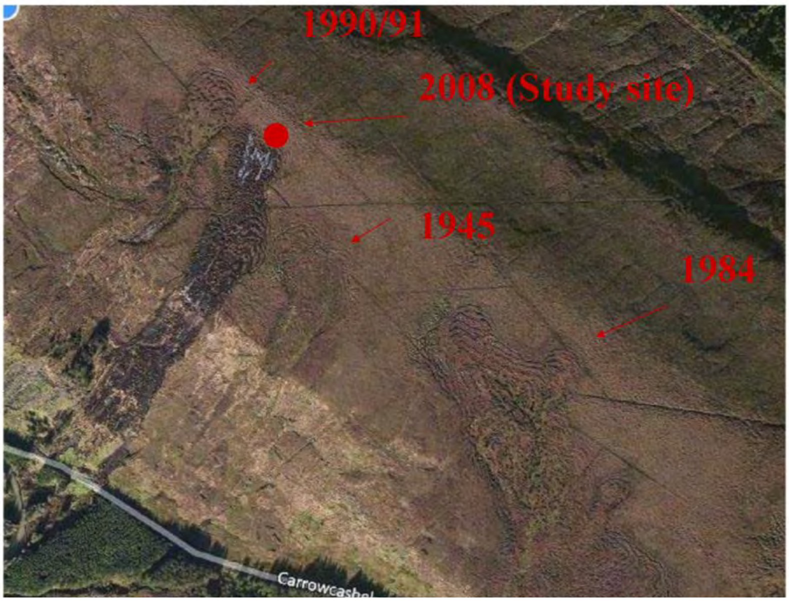


Figure 3.1. Geomorphological maps of (1) the Straduff Townland (or Geevagh) landslide, (2) the Slieve Rushen landslide and (3) the Slieve Anierin landslide showing monoliths sampling points. Source: Modified from Dykes (2009).

(a)

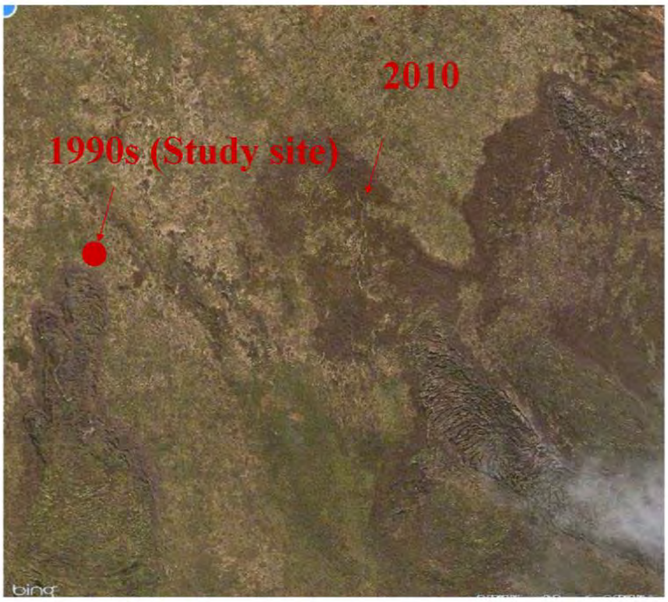


(b)

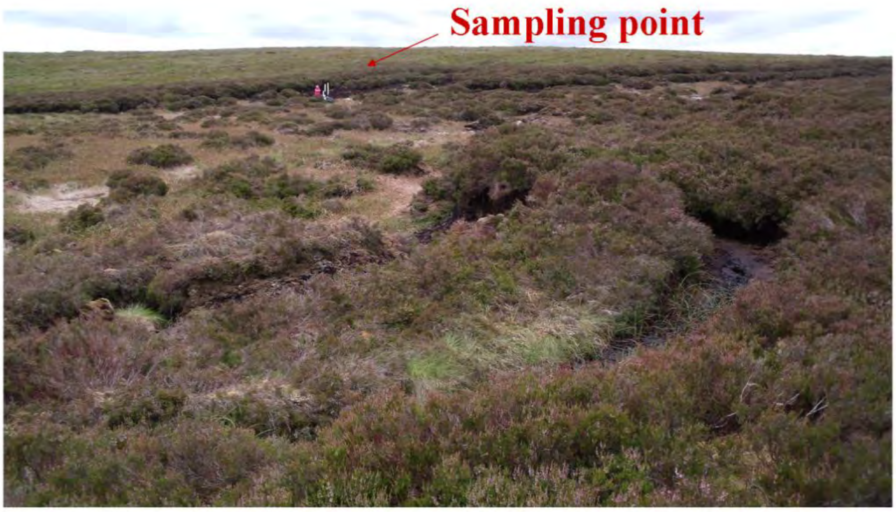
(c)

Figure 3. 2. The Straduff Townland landslide site photographs (a) aerial photo (caption from Bing, 2013; Microsoft corporation @ Nokia), (b) North west corner (Dykes`s Photo showing exposed sandstone at the scar of the landslide) (July 2010) and (c) peat profile (July, 2010).

(a)



(b)



(c)

Figure 3. 3. The Slieve Rushen landslide site photographs (a) aerial photo (caption from Bing, 2013; Microsoft corporation @ Nokia), (b) overgrown scar (Dykes, July 2010) and (c) peat profile (July, 2010).

(a)

(b)

(c)

(d)

Figure 3. 4. The Slieve Anierin landslide site photographs (a) aerial photo (caption from Bing, 2013; Microsoft corporation @ Nokia), (b) view east from margin 150 m south west of head (July 2010), (c) peat profile (July, 2010) with inserted gutter pipes and (d) bitumen-like substances found at the base of peat.

Table 3. 1.Types of the Geological Survey of Irish (GSI) online data.

N	Online map names
1	Caves map
2	Ecology features map
3	Fauna map
4	Geohazards localities map
5	Geology maps
6	Google map
7	Groundwater map
8	Land use map
9	Location (i.e. 1:50,000 Ordnance Survey mapping) map
10	Mining and heritage map
11	River Basin District Boundaries (RBDB) and National Draft Generalised Bedrock (NDGB) map
12	Subsoil type map
13	Vulnerability to pollution map
14	Well maps

3.2- FIELD INVESTIGATION METHODS

At each site under investigation, the peat was described according to the von Post (von Post, 1922; Hobbs, 1986; after Landva and Pheeney, 1980) and Troels-Smith (Troels-Smith, 1955) schemes as these methods provide a quick and reliable means of obtaining first order information on the nature of sediments and stratigraphic changes. As mentioned in Chapter 2 (Section 2.3), the von Post scheme is used to describe the characteristics of peat and its structure in semi-quantitative terms including the humification (H), water content (B), fine fibre (F), coarse fibre (R), wood (W) and shrub (N) remnants, the organic content (N) and tensile strength (TV and TH for vertical and horizontal, respectively). For the degree of humification, which is probably the most used parameter in engineering applications, the system uses a 1 to 10 scale (Table 3.2) where H1 refers to intact plant remains and H10 to completely humified peat.

Table 3.2. Determination of the degree of humification using the von Post system (Landva and Pheeney, 1980).

Scale	Humification	Plant structure	Amorphous material	Nature of extruded material	Nature of residue
H1	None	Easily identified	None	Clear, colourless water	
H2	Insignificant	Easily identified	None	Yellowish water	
H3	Very slight	Still identified	Slight	Brown, muddy water; no peat	Not pasty (i.e. tendency to adhere)
H4	Slight	Not easily identified	Some	Dark brown, muddy water; no peat	Somewhat pasty
H5	Moderate	Recognisable, but vague	Considerable	Muddy water and some peat	Strongly pasty
H6	Moderate strong	Indistinct, more distinct after squeezing	Considerable	About one third of peat squeezed out; water dark brown	
H7	Strong	Faintly recognisable	High	About one half of peat squeezed out; any water very dark brown	
H8	Very strong	Very indistinct	High	About two thirds of peat squeezed out; also some pasty water	Plant tissue capable of resisting decompositi on
H9	Nearly complete	Almost not recognisable		Nearly all peat squeezed out as a fairy uniform paste	
H10	Complete	Not discernible		All the peat passes; no free water visible	

The Troels-Smith classification describes the physical properties (i.e. colour, dryness and stratification), the humicity (i.e. humification) and the composition of sediments (e.g. lake mud, *Sphagnum* peat, sand and silt) (Troels-Smith, 1955). Most constituents are rated on 5-point scale: 0 indicates absence and 4 indicates maximum presence, trace elements (i.e. less than ⅛) are represented by +. It should be noted that this system‟s definition of the degree of humification and the water content refers to the von Post system.

Both classification systems cited above are subjective. The von Post system allows some parameters to be estimated in the field, such as the water content or tensile strength, to be corrected on the basis of subsequent laboratory measurements. It should be noted, however, that field estimates of fibre content and the degree of humification, which are important geotechnical and physical properties, cannot currently be corrected with laboratory measurements. As reported by Hobbs (1986), the system does not differentiate between all types of fibres (i.e. plant root hairs, rhizoids) and does not take into account fibre lengths which influence peat structure and, thus, its strength. The magnitude of the peat shear strength resulting from the influence of fibres depends on the lengths and thicknesses of the fibres and on the shear strength of the peat matrix (Helenelund, 1976). When peat is subjected to tension or shear stresses, some fibres are pulled out of the peat. Shear stresses are therefore developed between these fibres and the surrounding matrix. Flaate (1966) and Helenelund (1976) pointed out that a successful classification system should be complemented with laboratory tests. Therefore, in an attempt to create a more simple classification for peat stability analysis that can be complemented with laboratory measurements, the von Post definition of fine fibre (Fm) and coarse fibre (Rm) has been redefined as explained in Section 3.3.6. These fibres were also estimated in the field at the locations from which the peat material was collected. The following section describes the methods used to survey the study sites.

3.2.1- Site surveys

Stratigraphic and topographic surveys were carried out at each landslide in order to assess the variability of the peat and the morphology of the peat deposit. A gouge auger (0.02 m diameter) was used for the stratigraphic sampling. In order to improve the resolution of the reconstruction of peat morphology at each site, the depth of the peat was established at additional locations by probing with a metal rod. Ground surface elevations, relative to arbitrary local „benchmarks" located above the heads of each landslide, were determined using a Dumpy Level. These elevations represented the peat surface around the landslide source areas and the bedrock or mineral surface within the landslides. Elevations of the mineral surface around each landslide and, hence, the overall morphology of the *in situ* peat mass were determined by surveying the locations at which the peat depth was measured.

The surface vegetation can influence the rate of evaporation of water from the peat therefore its overall water content. Furthermore, the surface vegetation can affect soil shear stress as suggested in Table 2.6. The surface vegetation at each site was determined using a 2 × 2 m quadrat at five undisturbed locations, with one located at the landslide head. The species present within each quadrat were identified and their ground cover values assessed using the DAFOR scale (NCC, 1990) where D = Dominant (50-100 %); A = Abundant (30-50 %), F = Frequent (15-30 %), O = Occasional (5-15 %), R = Rare (< 5%). The plant assemblages at the sites could then be compared with the communities defined by Rodwell (1991). A vegetation survey was not carried out at Slieve Rushen because the site was subjected to a moorland fire between the field site visits in July 1010 and July 2011. The effect of the moorland fire on the structure of the peat sampled at depths more than 0.2 m below ground level appeared to be insignificant. It was anticipated that the lack of vegetation survey at the Slieve Rushen will not affect the results of the research as a whole because the fire had not affected the underlaying peat sampled. Furthermore the vegetation assemblages of upland blanket bogs are not often significantly variable and the surveys were only used to characterise the study sites.

3.2.2- Collection of samples and sampling strategies

Peat samples (Table 3.3) were taken at the „monolith sampling points" and across the sites during the stratigraphy surveys. The „monolith sampling points" were selected where the margins of the landslide source areas (Figure 3.1) were unaffected by tension cracks or other visible disturbance to the *in situ* peat and where the full thickness of the peat was easily accessible, following the approach used by Yang and Dykes (2006). A clean vertical section through the entire depth of the peat was cut, and this peat profile (Figures 3.2c, 3.3c and 3.4c) was described prior to sampling for palaeobotanical, chemical and geotechnical analyses. For palaeobotanical analyses, peat monoliths were cut using opened gutter pipes (0.73 × 0.1 × 0.1 m)(Figure 3.2c). The top 0.1-0.4 m of the peat profile was not sampled. Additional cubic samples of approximately 5 x 10^{-6} m^3 (0.01 m x 0.01 m x 0.05 m) were taken directly from augered cores at intervals of approximately 0.25 m during the stratigraphy surveys for botanical analyses using the method developed by Walker and Walker (1961). It was therefore anticipated that the findings of the study carried out using small sample sizes would not be significantly different from that carried out with bigger sample sizes because the Walker and Walker (1961) method (Section 3.3.7) tests for the frequency of occurrence of different macrofossils in the sample. Furthermore, the objective of the analysis was to determine the dominant macrofossil type across the site.

The geotechnical analyses comprised a series of triaxial, direct shear, tensile strength and permeability measurements of the peat samples from each failure site. Block samples (minimum 0.03 × 0.1 × 0.1 m for the shear box apparatus) and cylindrical samples (0.05 m in length at least and 0.03 m in diameter for triaxial tests) were taken for strength properties measurements. Most geotechnical samples were taken as close as possible to the base of the peat (i.e. approximately within 0.01 m above the peat-mineral interface) where failure occurred, as shown later in Chapter 4 (Section 4.4). With the assumption that the three landslides were similar in term of peat structure, the surface and middle peat was sampled at the Straduff Townland landslide in order to assess the variability of the strength parameters with depth. Other cylindrical samples (0.053 m long × 0.051 m diameter) were taken at 6 locations situated at 0.05 m intervals above the peat profile base for horizontal permeability analyses. All samples were wrapped in clingfilm and aluminium foil and stored at 4ºC in order to minimise oxidation and moisture losses prior to laboratory analyses.

Weak (i.e. sludge-like) and/or greasy layers similar to those observed by Alexander *et al.* (1986) and small patches of bitumen-like substances (Figure 3.4d) were found within the highly humified basal peat in the landslide scar margins during the fieldwork at every site. It was considered that the occurrence of these petroleum hydrocarbons, unexpectedly found in the basal peats in significant quantities, could give rise to weak, low-friction layers or surfaces that could promote instability. Samples of the basal peat were collected across the sites during the stratigraphy surveys in order to assess the nature, extent and distributions of the hydrocarbons present. They were stored in wide-mouthed, Teflon-lined cap glasses (250 to 500 ml) to enable protection from light and to prevent chemical changes from occurring.

The numbers of samples and the reasoning behind the sampling strategies are presented in Table 3.3. The site surveys carried out at the three landslides showed little variability in terms of the structure and macrofossil content of the peats. Therefore, the investigation targeted the basal peats where failure occurred.

Table 3. 3.Samples taken at the Straduff Townland (ST) landslide, the Slieve Rushen (SR) landslide and Slieve Anierin (SA) landslide.

Test		Container (minimum dimensions	Number of samples /Readings			Reasoning (i.e. objective) behind the sampling strategies		
			ST	SR	SA	ST	Objective of sampling at SR	SA
a	Triaxial	Cylinders (0.5 × 0.3 m)	6	6	6	To assess of basal peats strengths and deformation properties under compression forces	Similar objective to ST	Similar to ST and SR
b	Permeability	Cylinders (0.53 × 0.51 m)	21	9	9	To assess the horizontal permeability of peats and variability with depth	Similar objective to ST	Similar to ST and SR
c	Direct shear strength	Block (0.03 × 0.1 × 0.1 m)	18	12	12	To assess shear (planar) strength and deformation properties of the peats and variability with depth	To assess shear (planar) strength and deformation properties of the basal peat where failure occurred. Based on the stratigraphy surveys, it was assumed that ST, SR and SA are not significantly different in terms of structure.	Similar to SR
d	Tensile strength	Block (0.05-0.2 × 0.1 × 0.1 m)	12	6	6	To assess deformation and tensile strength properties of peats and variability with depth	Assess the basal peat deformation and strength properties under tensile strength	Similar to SR
e	*In situ* vane	Not applicable	4/ (i.e. at 1.68- 1.71 m b.g.l.)	2/ (i.e. at 1.75-2 m b.g.l.)	2/ (i.e. at 1.5-1.7 m b.g.l.)	To assess the variability of *in situ* shear strength with depth (actual values of strength are over estimative)	Similar objective to ST	Similar to ST and SR
f	Macrofossil	Cubic (5×10^{-6} m^3)	Not analysed	7	Not analysed	To assess the spatial variability of macrofossil content across the landslide scar	The stratigraphy surveys revealed similar type of peats to ST therefore the spatial variability of macrofossil was not evaluated	Similar to SR
g	Macrofossil	Monoliths (0.73 m × 0.1 × 0.1 m^2)	3	3	3	To assess the variability of the original plant content with depth	Similar objective to ST	Similar to ST and SR
h	Hydrocarbons	Open mouth glasses and Teflon lined covers (250 -500 ml)	20	29	23	To assess the extent, nature and spatial distribution of hydrocarbons around the margins of the landslide scar	Similar objective to ST	Similar to ST and SR

Notes
b- Six samples taken at subsequent 0.05 m intervals from the base of the profile at all the sites
c- Three samples taken at 0.01 m b.g.l. for shear strength test at ST landslide
d- Three samples taken at 0.89 m and three at 0.01 m b.g.l. at the ST landslide
f- Samples for macrofossil analyses were taken at approximately 0.25 m intervals along the auger samples
g- Only the top 0.4 m, 0.1 m and 0.3 m were not sampled at ST, SR and SA landslides respectively. Two monoliths were taken at the bases and one at the top at each site
All other samples collected for permeability, shear and tensile strength, triaxial tests were taken at 0.00-0.01 m above the peat-mineral substrate interface.

This explains the sampling gaps in the surface peats shown in the results presented in Chapter 4. The numbers of samples collected do not always correspond with the number of discrete results obtained because (i) a single block sample taken for tensile strength measurement, for example, was used for up to three tests in some cases, and/or (ii) some of the samples taken may have been unsuitable for their planned analyses because they were disturbed

3.3- LABORATORY METHODS

Some physical properties of peat can give a rough indication of the state or condition of the peat (Hobbs, 1986). For the purpose of this research, it was necessary to determine the physical characteristics of the sampled peat that could then be related to the results of the geotechnical, physical and chemical analyses. Therefore, the water content, bulk density, loss on ignition and permeability of the peat from each monolith sampling site was determined using standard methods. As reported by Hobbs (1986), the proportion of intracellular and interparticle water depends upon the structure and morphology of the various plants present and on the degree of humification of peat. As such, the palaeoecological properties investigated were the macrofossil content and the degree of humification. Microfossils do not always represent the original *in situ* vegetation as explained in Chapter 2 (Section 2.4.1) therefore the analysis of pollen was not considered as part of this study. In an attempt to assess the influence of basal peat hydrocarbons content on peat instability, bitumen, Total Petroleum Hydrocarbons (TPHs) and Polycyclic Aromatic Hydrocarbons (PAHs) were also investigated.

3.3.1- Water content

The water content is the most important parameter because peat has a great capacity for taking up and holding water that have major influence on its structure. The water content (M_p) was determined according to Galvin (1976). Peat samples were oven-dried until constant mass was achieved (i.e. approximately for 24 h) at 105ºC. The water content was determined using Equation 3.1. The saturated water content was determined in the same manner using saturated samples that had been completely submerged in tap water (that better represents field conditions; Yang and Dykes, 2006) for at least 48 h. These saturated samples were also used for permeability, bulk density and shear strength measurements.

$$\boldsymbol{M_P = \left[\frac{W_w - W_d}{W_w}\right] \times 100} \qquad 3.1$$

Where:

M_p	=	Water content (%) of the peat sample (mass fraction or „gravimetric" water content)
w_w	=	Mass (g) of the wet peat sample (field-wet or saturated)
w_d	=	Mass (g) of the peat sample after drying at 105ºC until constant mass was achieved (i.e. for 24 h)

3.3.2- Loss on ignition

The organic content is an important geotechnical property because it affects the water holding capacity of peat (Hobbs, 1986) thus its physical and mechanical properties (MacFarlane, 1969). The peat samples were heated in a furnace at 550ºC for three hours as described by Landva *et al.* (1983). The loss on ignition (LoI) is the percentage difference in mass before and after combustion. It was calculated from the „ash" (inorganic) content using Equation 3.2. The „ash" content was calculated using the percentage of the mass of the peat (W_a) remaining after combustion divided by its initial dry mass (W_d) (Equation 3.3).

$$\boldsymbol{LoI = 100 - A_C} \qquad 3.2$$

Where:

LoI	=	Loss on ignition (%)
A_c	=	Ash content (%) of the peat sample

$$\boldsymbol{A_c = \left(\frac{W_a}{W_d}\right) \times 100} \qquad 3.3$$

Where:

A_c	=	Ash content (%) of the peat sample
w_a	=	Mass (g) of the peat residue after ignition at 550ºC for 3 h
w_d	=	Mass (g) of the peat sample after drying at 105ºC until constant mass was achieved (i.e. for 24 h)

3.3.3- Bulk density

Bulk density (γ) is an important intrinsic characteristic of peat because many other properties (e.g. degree of humification, void ratio) that might influence peat strength are closely related to it. The method adopted for the measurement of bulk density was that described by Galvin (1976). After each hydraulic conductivity test, the saturated bulk densities of the samples were calculated from the ratio of peat mass at saturation to the sample volume (Equation 3.4). The samples were then dried in an oven at 105ºC for 24 hours and the dry bulk density was calculated from the ratio of dry mass (W) to the initial volume (V_w) (Equation 3.4).

$$\boldsymbol{\gamma = \frac{W}{V_w}} \qquad 3.4$$

Where:

γ	=	Bulk density (g cm^{-3}) of peat sample
w	=	Mass (g) of saturated wet or dry peat sample at 105ºC until constant mass was achieved (i.e. for 24 h)
w_w	=	Total volume of wet (as received from the field) peat sample

3.3.4- The saturated hydraulic conductivity

The hydraulic conductivity k (m s^{-1}), is a key parameter used in wetland hydrological and landform development models since it influences the runoff characteristics of organic soils. The hydraulic conductivity of peat influences the physical structure and arrangement of the constituent particles in peat. These characteristics greatly influence the size and continuity of pores and/or capillaries in peat. The horizontal hydraulic conductivity was measured in this study in order to assess the rate at which water could flow horizontally within basal peat layer and induce its liquefaction.

The saturated hydraulic conductivity of the peat samples investigated was determined using a simple constant-head type apparatus as described by Galvin (1976) and Head (1994). Undisturbed core samples collected in thin-walled cylindrical tubes were trimmed to size and saturated by placing them in tap water under vacuum for 48 h. Each sample was then weighed and the unit weight calculated. The samples were mounted on the apparatus under a head of water of about 0.15m and the rate of vertical flow of tap water through the saturated peat was measured. A constant head of water was maintained at all times on the upper surface of the sample. The constant head hydraulic conductivity (k_{Ch}) was calculated using the equations 3.5 and 3.6. The hydraulic conductivity is derived from Darcy's Law (Charman, 2002) which expresses the proportional relationship between the instantaneous discharge rate through a porous medium, the viscosity of the fluid and the pressure drop over a given distance.

$$\boldsymbol{k_{Ch} = \frac{QL}{AtH}} \qquad 3.5$$

Where:

k_{Ch}	=	Permeability (m s^{-1}) at temperature T measured with constant head apparatus
L	=	Length (m) of peat specimen
t	=	Time (s) for discharge
Q	=	Volume (m^3) of discharge
A	=	Cross-sectional area (m^2) of cylinder containing the peat
H	=	Hydraulic head (mm) difference across length L

$$\boldsymbol{A = \frac{\pi}{4} D^2} \qquad 3.6$$

Where:

D	=	Inside diameter (mm) of the cylinder containing the peat

For comparative purposes, the falling head hydraulic conductivity (k_{Fh}) was also determined for some samples using methods described in Head (1994). The samples tested using the constant head apparatus were mounted on a falling head instrument arranged as specified in Head (1994) (Figure 3.5), with a permeability cell modified to suit the low permeability of peat and an immersion tank adapted to suit the dimensions of the cylinders containing the peat samples under investigation. Using the laboratory bench surface as a datum level, the manometer tube used for the test was calibrated and marked. Four reference points identified as 1, 3, 2 and 0 were marked from the top of the tube to the bench to facilitate the performance of the test. These points had heights above datum (γ) of 1220, 331, 520 and 135 mm respectively and heights above the outlet of 985, 616, 385 and 0 mm respectively. Water was allowed to flow in the manometer tube down through the sample. The times when the water level reached each reference point was recorded using a stopwatch and the hydraulic conductivity determined according to Head (1994). Samples with permeabilities that were too low to be reliably determined within 24 hours were further tested with closer reference points; i.e. for 1, 3, 2 and 0 using heights above datum of 800, 65, 60 and 0 mm respectively and heights above the outlet of 985, 885 934 and 135 mm respectively. Samples for which measurement could not be completed after 48 h were assumed to have the lowest coefficient of permeability (i.e. $\leq 10^{-11}$ m s^{-1}) reported in the literature. Three measurements were carried out on each sample and the permeability was calculated using equation 3.7. The viscosity of water increases with increasing temperature, so the permeability obtained was corrected to room temperature according to Head (1994).

$$k_{Fh} = 3.84 \times \frac{aL}{At} log_{10}\left(\frac{h_1}{h_2}\right) \times 10^{-5} \tag{3.7}$$

Where:

k_{Fh}	=	Permeability (m s^{-1}) measured with falling head apparatus
a	=	Area (m^2) of the burette
L	=	Length (m) of peat cylinder
A	=	Area (m^2) of the peat cylinder
h_1	=	Initial height (m) of water
h_2	=	Final height (mm) of water = h1 - Δh
t	=	Time (s) required to get head drop of Δh

3.3.5- Humification

The degree of humification of peat is a key property of peat as it influences the water holding capacity, pore sizes and size distribution, and fibre content of peat, all of which could have major influences on peat strength. The laboratory method used for determining humification followed a modified version of the Bahnson colorimetric method (Aaby and Tauber 1974; Blackford and Chambers 1993; Chambers *et al.* 1997). Subsamples taken contiguously at every 0.01 m from the monoliths, and the basal peat samples collected for hydrocarbon testing across the sites, were tested. The measurements were obtained using a Hatch 2500 spectrometer set up at 540 nm. Results are expressed as „raw" percentages of light transmission through the diluted peat solution. The more light passes through the peat solution, the less humified the sample.

3.3.6- Fibre content

The fibre content (*F*) is an important characteristic that influences peat stability (Long and Jennings, 2006) as it influences the peat structure and its strength properties. Therefore, in an attempt to create a new system (i.e. the modified fibre content (MFC)) that could quantitatively classify peat in terms of its fibres and amorphous fraction, the von Post „fine fibres" and „coarse fibres" categories have been modified as follows and further assessed. Citing Day (1968), Clymo (1983) defined a „fibre" as a fragment or piece of plant tissue that retains a recognizable cellular structure and is large enough to be retained on a mesh size of 0.15 mm. In order to assess the influence of the constituents of peat on stability, it was considered necessary to clearly define the different fractions. „Fine fibre" (Fm) has been redefined as a fragment or piece of plant tissue < 1 mm but > 0.15 mm in any dimension including length and diameter, and „coarse fibre" (Rm) as a fragment or piece of plant tissue > 1 mm in any dimension. In line with Day`s standard definition of fibre (ASTM, 1997), the „total fibre fraction" (Ft) has been defined as all fibres > 0.15 mm in any dimension. The humus fraction (Fh) was defined as all particles < 0.15 mm in any dimension. It was considered that (i) it is difficult to determine a specific shape of some fibres and (ii) depending on the orientation of the fibre, any dimension of a fibre or particle of a particular shape can prevent it passing through a hole in the sieve. Therefore fibre size distribution curves (i.e. using a program called Shape for example; Warburton, 2013 or a microspope) could be determined in future research to characterise similar peats and used for stability assessment. For monocotyledon peat for example, the fibres are elonguated therefore; the lengths and diameters are the dimensions that prevent them passing through a hole in the sieve. These are also the main influences on peat strength (Helenelund, 1976). It should be noted that even in mineral soils, which size distribution curves are often determined, it is difficult to determine the specific shape of individual particles and their orientations during the sieving process. Therefore, the specific dimension of each particle that prevents it from passing throught a hole on the sieve cannot be determined with accuracy.

As with the assessment of the organic content according to the von Post system, and to enable comparison with field measurements, fibre fractions were graded on a 5-point scale, i.e. 5 = fibre content greater than 95 %, 4 = fibre content between 95 and 80 %, 3 = fibre content between 80 and 60 %, 2 = fibre content between 60 and 40 % and 1 = fibre content between 40 and 0 %. Differentiating peat in this way should enable field estimates to be corrected with measurements obtained from laboratory tests. The 5-point scaling is simple and should also facilitate cluster analyses of the results to be carried out in a consistent way.

In this study, only the Fm and Rm fractions were estimated in the field. All of the fractions defined above were only determined in the laboratory. Monoliths were sub-sampled in the laboratory contiguously every 0.07 m with duplicate subsamples of known masses taken from each depth. In order to separate the peat into different fractions, the two duplicate subsamples from each depth were analysed differently.

The first sample was soaked in a dispersing agent (5% sodium hexametaphosphate) for approximately 15 hours. The peat was then washed through a 0.15 mm mesh size sieve by the application of a gentle flow of tap water. The fibrous material left on the sieve was washed through a further 1 mm mesh size sieve and the fine fraction that passed through was collected. The fibre remaining in the 1 mm sieve was the coarse fraction. Both fractions were oven-dried (at 105°C) until constant masses were achieved and these masses were recorded. The masses of fine and coarse fibres were combined to obtain the total mass of fibres. The mass of humus was obtained from the difference between the mass of total fibres and the initial dry mass of peat determined from the second sample. The second sample was dried at 105ºC for 24 h and the mass ratio of dry to wet peat determined. The ash content was also determined after loss of ignition test.

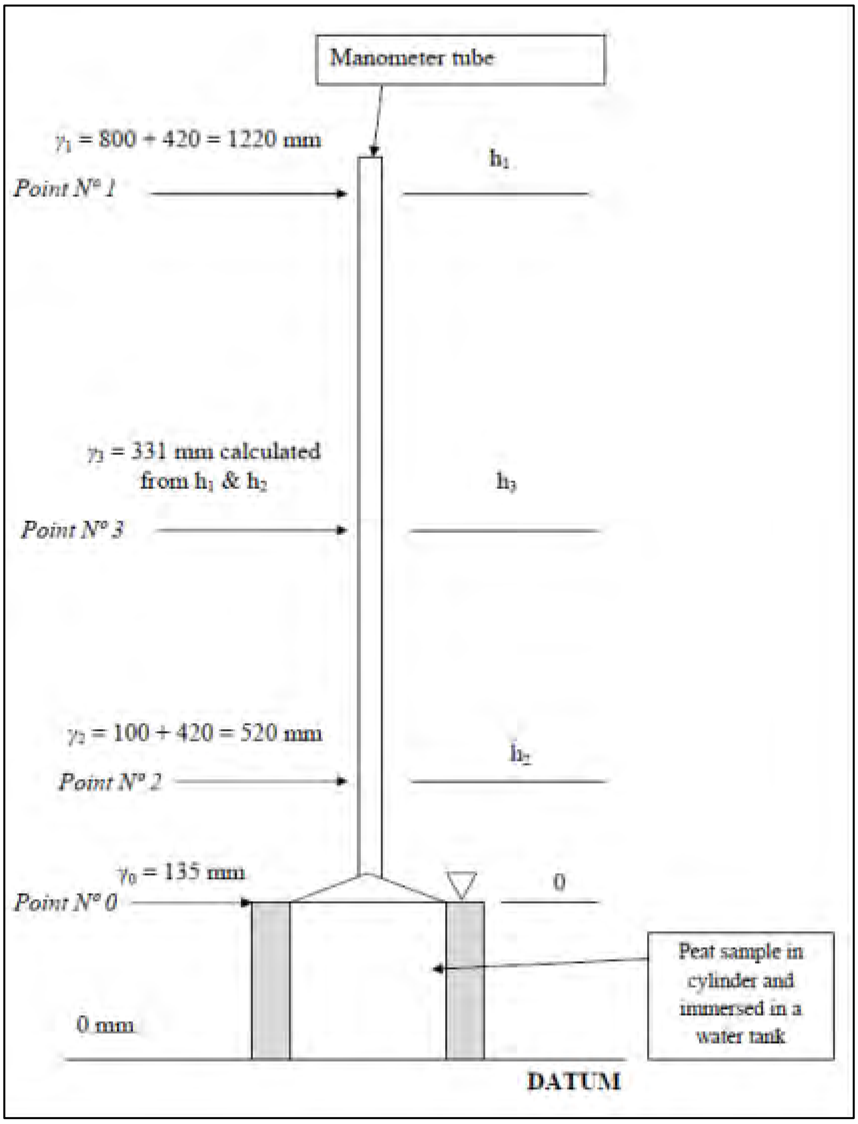


Figure 3.5. Falling head test arrangement (after Head, 1994).

The duplicate peat samples had slightly different masses and assuming that their respective mass ratios of dry to wet (as sampled in the field) peat were equal, the corresponding initial mass of the sample used for fibre content testing was established. The fibre (F_f)/humus (F_h) fractions without ash were then expressed as percentages of the initial dry mass (M_s) as shown on Equation 3.8.

It is anticipated that the humus fraction as defined in this document could be used as a potential indicator of the degree of peat humification and studies could be performed in different peatlands to study the variation of different fractions as defined in this study. The humus fraction could contain some proportion of plant tissues, therefore during detailed quantitative assessment this humus fraction could be further fractionated in order to determine the real humus acid content if necessary.

$$F_{f/h} = \left(\frac{M_{f/h}}{M_s}\right) \times 100 \quad 3.8$$

Where:

$F_{f/h}$	=	Fibre/Humus fraction (%)
$M_{f/h}$	=	Mass (g) of the peat fibre/humus fraction after drying at 105 ºC until constant mass was achieved (without ash)
M_s	=	Mass (g) of the initial peat sample after drying at 105 ºC until constant mass was achieved (without ash)

3.3.7- Macrofossil content

The heterogeneity of peat is due to the variability of factors that influence its initiation and development (Charman, 2002). In fact, the spatial variations in environmental gradients (e.g. climatic conditions, hydrology, land use, topography) determine the patterns of vegetation that accumulate to form peat and peatlands (Moore, 1984; Charman, 2002). The original plant composition of peat influences its structure and possibly its strength properties.

The monoliths obtained for investigating plant macrofossil content were subsampled (i.e. 5×10^{-6} m^3 subsamples) at 0.04 to 0.08 m intervals between samples. Basal material (i.e. > 0.05 m above peat-mineral interface) was sampled contiguously every 0.01 m. Analysis was undertaken using the „Quadrat and Leaf Count Macrofossil Analysis technique" (QLCMA) developed at the Southampton Palaeoecology Laboratory (Barber *et al.*, 1994). The method estimates the percentage coverage of all macrofossil types with the aid of a 10 × 10 grid graticule in the eyepiece of a stereomicroscope. Monocotyledon epidermis tissues and *Sphagnum* branch leaves were examined further at a magnification of ×400 under transmitted light. Daniels and Eddy (1990) (for *Sphagnum*), Smith (2004) (for other bryophytes), Grosse-Brauckmann (1968, 1972) and Katz *et al.* (1977) (for vascular plants) were used to identify the remains. The small cubic samples (5×10^{-6} m^3) obtained from the Slieve Rushen landslide site were further investigated using the method developed by Walker and Walker (1961). This method is very quick and easy to perform and it uses a scale of 0 to 5, 0 indicating absence and 5 indicating that the sample consisted largely of a particular macrofossil. This further investigation was carried out in order to confirm that peat at the monolith sampling points was representative of the entire blanket bog.

3.3.8- Strength properties

It is generally accepted in geotechnical engineering practice that peat exhibits shear strength and tensile strength owing to fibre reinforcement. Cohesive mineral soils exhibit both shear and tensile strengths: Following the conventional Mohr-Coulomb failure criterion, the shear strength is captured as a function of normal stress via the friction angle and the cohesion terms. The tensile strength is capture in terms of cohesion. However the application of the Mohr-Coulomb law to peat has been questioned (as explained in Chapter 2; Section 2.4.2). Furthermore, existing methods for measuring soil strength properties may be unsuitable for peat as explained by Long (2005), Dykes (2008b) and Boylan *et al.* (2008). A review of methods for measuring the shear strength of peat is presented by Long (2005). He suggested that the ring shear and direct shear were potentially the more appropriate methods for measuring peat strength. However, because the accuracy of a standard ring shear apparatus is limited at low loads (e.g. less than 5 kPa: Bromhead, 1979), the use of this instrument was not included in this study. Furthermore, trial tests were carried out on a few peat samples as part of this study using the current ring shear apparatus and results was very variable and not replicable. Different types of apparatus measure different stress paths, and the effects of fibres on the effective strength of peat depend on the apparatus used for measurement. For example, in the direct shear box, failure occurs in a predefined plane and the effect of fibres might be less significant because the direction of shearing is often parallel to the orientation of the fibres and, in this case, the peat matrix has more influence on the overall peat strength (Long, 2005). In a triaxial cell, peat fibres affect the geotechnical behaviour of peat by providing an internal lateral resistance to shear deformation (Landva and La Rochelle, 1983. Similarly, the lengths, thicknesses and strengths of fibres can strongly influence the tensile strength of peat (Helenelund, 1967). Helenelund (1967) suggested that the relationship between tensile strength and shear strength depends on the amount and type of fibres and the critical fibre length, and that the horizontal tensile strength is several magnitudes higher than the vertical tensile strength. Some more detailed explanations of the influence of fibres on the measurement of peat strength are explained by Landva and La Rochelle (1983) for the triaxial test, Helenelund (1967, 1975) for tensile strength, Long (2005) for direct shear and Landva (1980) for the vane test.

In this study, different instruments were used to measure peat strength in order: (1) to improve our understanding of peat behaviour under stress; (2) to identify potential improvements of current measurement or stability analysis techniques and (3) to facilitate correlation between peat physical and strength properties. Field measurement of shear strength was made using a shear vane. In the laboratory the shear strength of peat was measured under undrained and drained conditions using triaxial and direct shear tests respectively. Because of the low permeability of the peat and the difficulties in measuring the effective stress due to the presence of fibres, anisotropy and high compressibility properties of peat (Yamaguchi et *al,* 1985), no pore water pressure was measured. In fact, studies have revealed extremely low and sometimes negative effective stresses (Farrell *at al.*, 1998).

Soils are generally weak in tension and the determination of tensile strength encounters many experimental difficulties. Consequently, although numerous studies have been conducted to evaluate soil tensile strength by indirect means, tensile strength data for soils are rare (Ibarra *et al.*, 2005). Tensile strength measurements are used in desiccation cracking and slope stability which can influence geotechnical design. It has been reported that the presence of plant fibres, for example, increases the tensile strength of clay (Ziegler *et al.*, 1998). Examples of methods employed include centrifugal methods (Vomocil *et al.*, 1961) and indirect compression methods (Richards, 1953; Rogowski *et al.,* 1968; Frydman, 1964; Dexter, 1975; Snyder and Miller, 1985).

The lightweight aluminium tension box method suitable for tension tests both in the laboratory and in the field developed by Helenelund (1967) have been used for peat tensile strength measurement. The apparatus designed by Dykes (2008d) was used for this thesis. The experimental conditions, specifications and some advantages and limitations of the instruments used for the measurement of peat strength in this study are presented in the following sections.

***In situ* vane (shear) test:** The vane (shear) test is often used in the field to estimate the undrained shear strength of fully saturated clays without disturbance. Some limitations of the vanes on peat have been discussed by Helenelund (1967), Landva (1980) Long (2005) and Hanrahan (1994). In this study, it was considered that this method could be used as a means of assessing the variability of shear strength with depth at the failed blanket bog sites as also suggested by different authors (e.g. MacFarlane, 1969; Krik, 2001; Boylan *et al.*, 2008; Dykes, 2008b).

In the context of this study, small vane (i.e. 0.05 mm diameter (D) × 0.10 mm length) readings was made following standard procedures (BS 1377-9, 1990) at each blanket bog site in the undisturbed peat at approximately 1 m away from the sampling points. This location was intended to be close enough to the sampling point to enable comparison with strength properties measured in the laboratory to be made, but far enough for the peat not to have been affected by the excavation of the profile face. The undrained shear strength is calculated by equating the torque (M) to the moments corresponding to the total shear strength over the sides and the ends of the cylindrical shear failure surface (Equation 3.9). The undrained shear strength of peat (τ_f) (Equation 3.10) was considered proportional to the applied torque and the dimensions of the vane. As the ratio of length to width of the vane is 2 to 1, the value of K was simplified in terms of the diameter as shown in Equation 3.11 (BS 1377-9, 1990).

$$M = a + b \qquad 3.9$$

Where:

M	=	Torque (N m) used to shear the peat
a	=	Moment of shear resistance force (N m) on the side of the cylindrical failure surface
b	=	Moment of shear resistance force (N m) at the two ends of the cylindrical failure surface.

$$\boldsymbol{\tau_f = \frac{M}{K}} \qquad 3.10$$

Where:

τ_f	=	Undrained vane shear strength of the peat sample
M	=	Torque (N m) used to shear the peat
K	=	Constant (depend on dimensions and shape of the vane)

$$\boldsymbol{K = 3.66D^3 \times 10^{-6}} \qquad 3.11$$

Where: D = Diameter (m) of the vane

Direct shear test: This test is often performed to determine the consolidated-drained shear strength of soil. Although the mode of failure in a direct shear test may be applicable to that of peat landslide, i.e. failure along a plane (Long, 2005), some limitations exist, including: (1) conventional interpretations of the angle of internal friction from direct shear tests are considered incorrect and leads to underestimation of strength in peat (Long, 2005) as explained in Chapter 2; (2) reviewing the works of Wroth (1987), Airey and Wood (1987), Farrell *et al.* (1998), Jardine and Hight (1987) and Potts *et al.* (1987), Long (2005) concluded that the stress regime in the direct shear strength test is complicated and thus a simple interpretation of the results needs to be treated with caution. In particular, experience had shown that the effective strength parameters obtained from a direct shear test can be erroneous as they are derived from Mohr-Coulomb criteria that may not apply to peat.

In this study, a direct shear box with a square sample holder of 0.1 m length, 0.1 m width and 0.03 m thick was used to study the shear behaviour of the peat samples. All of the samples were sheared using experimentally very low normal stresses (i.e. 0.7, 1.2, 1.7, 2.2, 3.2, 4.2 and 5.6 kPa), in an attempt to replicate *in situ* conditions and obtain reproducible results. The actual mean effective stress in a peat mass *in situ* is very low (perhaps no more than 5 kPa based on the unit weight of peat that is very low). The peat samples were not consolidated before being sheared because peat failure occurred with negligible consolidation. Furthermore, and in view of the non-availability of specific data on peat failure rates and considering that triggering and/or preparatory factors could act gradually or suddenly to initiate slope failures, the samples were sheared at 1 mm min^{-1} to represent moderate failure (IUGS, 1995) with the associated likelihood of some undrained shearing effects.

Triaxial test: The conventional triaxial test is a common laboratory testing method widely used for obtaining shear strength parameters for a variety of soil types under drained or undrained conditions. Depending on the combination of loading and drainage condition, three main types of triaxial tests can be carried out. They are: (a) consolidated–drained; (b) consolidated–undrained; and (c) unconsolidated–undrained. Some limitations of the triaxial test which can influence the results of the test with respect to peat identified by Long (2005) then Long and Boylan (2012) include: (1) end platen roughness leading to large volume changes during consolidation, which can be eliminated by using special smooth end platens/silicon membrane inserts; (2) membrane stiffness effects and maintaining the verticality of the specimen during testing, which can be eliminated by accurate correction; and (3) consolidation stresses too high therefore difficult to control during consolidation. Even the most accurate pressure controlling device is only able to resolve to about ± 2 kPa. Long (2005) proposed the use of a differential pressure controller to ensure that the differential pressure between the cell and back pressure controlling devices is constant.

In the context of this study, the unconsolidated–undrained triaxial tests were carried out according to Head (1994). The following test procedure was adopted to replicate site specific conditions.

Samples were trimmed to 76 mm height and 38 mm diameter. Petroleum jelly was smeared on the periphery of the end platen in contact with the sample in order to minimise frictions that could occur between the sample and the end platen. In order to minimise the correction factor for membrane stiffness, thinner membranes of 0.0025 m thickness were used. Samples were not consolidated before testing. After full saturation, the lowest isotropic stresses (i.e. in line with the *in-situ* effective vertical stress) were applied to the sample. The lowest possible cell pressures of 50, 100 and 200 kN m^{-3} were used and samples were sheared at a rate of 1 mm min^{-1} as explained previously for the shear box. The rate of displacement and the strength were recorded every 20 seconds until shearing occurred. Shearing occurred when the measured strength remained constant for three consecutive readings. After each test was completed, the respective sample was visually inspected to assess the failure mechanism or sample deformation. The bi-linear correction of the deviator stress due to membrane stiffness was applied to the results. Stress-strain relationships and shear strength properties were determined to assess the behaviour of the tested peat samples under the applied stresses and to determine the undrained strengths.

Tensile strength test: Although previous tensile strength measurements obtained with the apparatus designed by Dykes (2008d) were reproducible and consistent as explained previously, some limitations exist. These limitations include (i) the fact that the current instrument does not allow a load to be placed on the sample to replicate the condition of the basal peat *in situ*, and (ii) sample disturbance may occur during installation. The methods used to prepare and install the peat samples in this testing apparatus are presented by Dykes (2008d). In this study and as described by Dykes (2008d), block samples of undisturbed peat obtained from excavated peat profiles in the margins of the source areas of selected landslides were cut to the appropriate shape and size. The fingers described by Dykes (2008d) were inserted manually into each peat sample before installation in the apparatus and a horizontal load was applied in increments of 100 g. The resulting tensile stress and the strain were recorded 30 seconds after each load increment was applied. This procedure was continued until the sample failed in tension. The tensile strength of a peat sample (T_p) was obtained by dividing the maximum tensile stress (F) by the cross-sectional area of intact peat, as described by equation 3.12.

$$\boldsymbol{T_p} = \frac{\boldsymbol{F}}{\boldsymbol{A - A_f}} \qquad 3.\ 12$$

Where:

T_p	=	Tensile strength (kPa) of the peat sample
F	=	Maximum tensile stress (N) prior to sample failure
A	=	Cross-sectional area (m^2) of the peat sample perpendicular to the direction of the applied tensile stress (i.e. 0.1 m × 0.1 m)
A_f	=	Cross-sectional area (m) of the sample occupied by the five steel fingers (i.e. 0.0050 m × 0.0125 m × 0.1000 m)

This residual area represents the area of the tensile crack where failure occurs. Stress-strain relationships and strength properties were determined in order to assess the behaviour of the tested peat samples under the applied stresses.

Once the peat properties were determined using the chosen methods described in the previous sections, stability analyses were performed not only to determine factors of safety corresponding with laboratory measurements of peat strength, but also to estimate field shear strengths from back-analyses of the failures (i.e. using FS = 1.0: Chandler, 1977, Bromhead, 1992).

Stability assessment: Several methods of slope stability analysis exist. The limit equilibrium methods, as reviewed by Duncan (1996), are routinely used in most practical cases because complicated geometric conditions and different geotechnical layers can be relatively easily analysed (Wright, 1969; Krahn, 2003; Duncan and Wright, 2005). Limit equilibrium methods require a continuous slip surface passing through the soil mass. This surface is essential in calculating the minimum factor of safety against sliding or shear failure.

SLOPE/W (GEO-SLOPE International, 2012) was used for this study. This commercial engineering software was applied successfully to a peat slide previously by Dykes and Kirk (2001) and also Dykes and Warburton (2008a). The SLOPE/W software incorporates several standard methods of stability analysis for solving two-dimensional slope problems. SLOPE/W can be used to analyse infinite slope problems using the Ordinary Method of Slices (Skempton and Hutchinson, 1969) or the more rigorous Morgenstern-Price Method (GEO-SLOPE, 1995; e.g. Dykes and Kirk, 2001). The SLOPE/W model is used for computing the factor of safety of earth and rock slopes based on site settings and the soil properties. By default, the model also produces a factor of safety from the application of Bishop"s and Janbu"s „simplified methods" to every problem analysed (Nash, 1987). An infinite slope analysis (Haefeli, 1948; Skempton and DeLory, 1957) conducted on the simplest configuration of the problem under investigation should yield a factor of safety that is within the range of values produced by the four methods in the SLOPE/W model, thus indicating the acceptability of the model results. SLOPE/W analyses problems with different soils layers. Some soil strength models featured in SLOPE/W include Mohr-Coulomb, „undrained" and „anisotropic strength".

Peat failures are considered to be shallow mass movements where sliding and seepage are taken as acting parallel to the slope faces; therefore they are comparable to infinite slope problems but can be analysed using the SLOPE/W software. A stability model representing each of the three failed peat slopes used for this study was therefore set up in SLOPE/W as presented in Figure 3.6.

For the analysis of the peat profile at each site, mean peat depths along the transects investigated in the field were used with peat stratification data. Field evidence suggested that at the study sites, failures occurred within the basal peat and not at the interface between the peat and the mineral substrate, and that peat profiles comprised different strata with different structures and textures and, thus, different engineering properties. The degree of peat humification increased with depth at the three sites. Based on the distribution of the degree of humication *in situ* throughout the profile, three different peat strata were considered. Stratum 1 (i.e. slightly to moderately humified peat) represented the surface (S) peat and included approximately the top 0.89 m of the peat profile throughout the site, Stratum 2, which was the middle peat (M) (i.e. moderately to strongly humified peat) was of variable thickness and Stratum 3 comprised the basal (B) peat (i.e. strongly to completely humified and/or greasy peat which was approximately 0.14 m thick) where failure occurred. Deformation of the peat occurred during auger sampling so the average depth of the basal peats (i.e. Stratum 3) used for the modelling process was determined from the cluster analyses of the results of physical properties investigated as presented in Chapter 4 (Sections 4.2-4.5). Data for the Straduff Towland were considered more reliable and used for modelling because the full depth of the profile was sampled and stratigraphy descriptions of peat at the three landslides showed that the structures of the peats were similar. This also explains why the mean depth of 0.14 m was used for all the basal peat at three sites as opposed to site specific data. Taking an average depth for the three landslides was used as a means of reducing the error due to (i) failure to sample the full depth at all the sites and failure to use a consistent sampling interval for all the parameters investigated.

It was further considered that using site specific data will not have major impacts on the result of the study as a whole. Stratum 4 represented the bedrock at each site.

As input parameters, the strength parameters and bulk densities of the peat strata investigated in the laboratory were used. Results from the literature show that peat strength varies with depth and with the equipment used for the analysis. Therefore, for a back analysis of slope stability, there should be starting values for each stratum‟s parameters that can then be modified to obtain Factor of Safety (FS) = 1.0 representing failure. For peat strata for which strength parameters were not measured as part of this study, minimum literature values were adopted as the basis for modelling as follows. These values were obtained from conventional testing methods or using peat samples from different type of peatlands. Therefore the result of the stability modelling should be treated with caution as the conditions modelled may not represent the conditions at the study sites. Minimum literature values of shear strength parameters (i.e. friction angle and cohesion terms) (Table 2.10) were used as input parameters for all three peat strata modelled for each site. For the undrained-unconsolidated triaxial strength, the minimum literature value (Table 2.10) was used as the input parameter for the surface peats and the site specific laboratory-measured values were used for the weak basal peats. With the assumption that the three landslides all failed in the similar way, site specific tensile strength data for the Straduff Townland landslide were used as input parameters for all the surface and middle peats at the three blanket bogs. As will be explained in Chapter 5 (Section 5.2), the tensile strength and cohesion of peat is thought to result from its fibres (Landva and La Rochelle, 1983). Therefore, the shear strength of fibrous peat may be estimated on the basis of the tensile strength (Helenelund, 1967).

For each landslide, a critical slip surface was drawn along the weak stratum. After inputting the strength parameters, the stability of each slope was analysed using the Mohr-Coulomb or the undrained strength models respectively. The validity of the literature and/or laboratory measured strength parameters were assessed by back-analysing the stability of the failed slopes. This was done in order to assess the suitability of each model and instrument for stability analyses. It was anticipated that the conclusions specified in Figure 3.6 could be drawn from the results of stability analyses. Marginal stable conditions prevail when the FS lies between 1 and 1.3, which suggest that transient changes in shear strength may be responsible for slope failure under the conditions modelled (Kirk, 2001).

A FS is really an index indicating the relative stability of a slope. It does not imply the actual risk level of the slope due to the variability of input parameters. Therefore, owing to the variability of *in situ* strength, it was considered necessary to further assess the probability of failure of the slope analysed based on the strength and bulk density ranges recorded in this study.

Slope/W can compute a probability distribution of the results of factors of safety (Geo-Slope, 2008). Slope/W includes an algorithm for probability analyses where all input parameters can be assigned a probabilistic distribution, and a Monte Carlo scheme is then used to compute a probability distribution of the results of factors (Geo-Slope, 2008). The probability of failure is determined once the probabilities of the safety factors are known. The probability of failure and the reliability index are two useful indices necessary to quantify the stability or the risk level of a slope using the probability analysis. The probability of failure is the probability of obtaining a FS less than 1.0 using the ranges of parameters obtained from the laboratory tests.

The reliability index is the normalised FS, defined in terms of the mean and the standard deviation of the factors of safety (Geo-Slope, 2008). It describes the stability in terms of the number of standard deviations separating the mean FS from its defined value of 1.0 (Geo-Slope, 2008) and can be considered as a way of normalising the FS with respect to its uncertainty. There is no direct relationship between the deterministic FS and the probability of failure (Geo-Slope, 2008). This means that a slope with a higher FS may not be more stable than a slope with a lower FS. For example, a slope with FS of 1.6 and a standard deviation of 0.7 has a higher probability of failure than a slope with FS of 1.1 and a standard deviation of 0.2.

Christian (1996) suggested that the reliability index (ß) provides a better indication of how close the slope is to failure than does the FS (FS). Slopes with large values of ß are less prone to failure than slopes with small values of ß, regardless of the value of the best estimate of the FS. If the form of the probability distribution of the FS is known, then it is possible to relate the reliability index ß to the probability of failure. Probabilistic modelling was used in this study in order to assess the stability conditions of the slopes at the three landslides under investigation. With the assumption that the FS was normally distributed, the models set up in Slope/W were simulated using the measured values of the tensile strengths (assumed to represent the cohesion between peat molecules: Helenelund, 1976) and bulk densities. The „Normal probability density function" was used to assess the spatial variability of peat strength *in situ*. During the analyses, the software samples the ranges of parameters values including the minimum, mean and maximum values and calculates the resulting FS during its Monte Carlo trials. In this case, 2000 trials were made.

Sensitivity analyses were carried out in Slope/W to find out the sensitivity of the slope stability to the parameters of the three modelled strata, i.e. the surface (S), the middle (M) and basal (B) peats.

Contrary to the probability analyses, during sensitivity analyses, the software selects the parameters by order and not randomly. For example, the strength parameter of a basal peat was held constant and the software computed a FS for each of the input parameters of the middle and surface strata. The trial was repeated for all the input parameters in turn and their corresponding FS were derived.

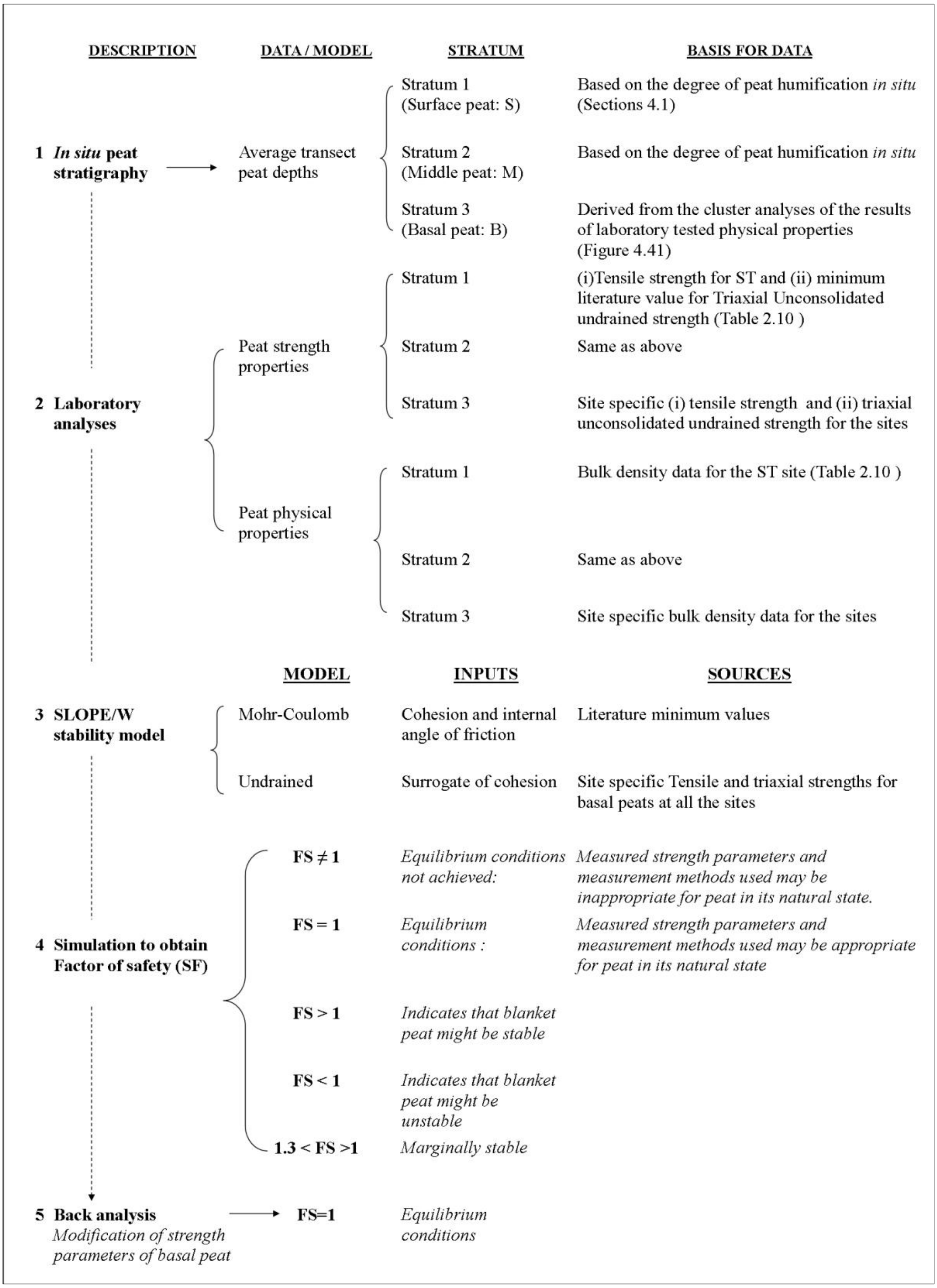


Figure 3. 6. Methodology for slope stability analyses using Slope/ W at the study sites.
ST= Straduff Townland

3.3.9- Chemical properties

Petroleum hydrocarbons were unexpectedly found at the base of the peat at the study landslide sites. As explained in Chapter 2 (Section 2.4), petroleum hydrocarbons are hydrophobic and viscous mixtures of molecules. They are temperature-sensitive and repelled from water within the peat. It is hypothesised that they could promote peat instability. The analytes of interest had to be separated from peat samples prior to their measurement according to the procedure described by Weisman (1998). The steps taken were as follows: (1) selection of the analytes of interest based on site evidence and the purpose of the study; (2) extraction of the analytes from the sample matrix then concentration of the extracts in order to enhance the detection ability of the equipment; and (3) quantitative measurement of concentration of the analytes. The peat samples that were collected were preserved according to the requirements specific to peat (which can undergo chemical changes) and to the analytes of interest (that are semi-volatiles).

Selection of the analytes: Sites that produce hydrocarbons are very difficult to assess owing to the variability of the compounds involved. Owing to the complexity of the peat matrix, the structure which is influenced by different factors that lead to different chemical and physical characteristics, three approaches were used to assess the indicator compounds for petroleum hydrocarbon and the carbon fractions that were present. The three approaches, which measure different petroleum hydrocarbons, were as follows:

(1) Measurement of „Total Petroleum Hydrocarbons" (TPHs) (API, 2001): A single number is generated from the measurement and represents the combined concentration of all petroleum hydrocarbons in a sample analysed with a particular laboratory measurement method. Total petroleum hydrocarbon is defined by the extraction procedure. In this thesis, TPHs is used to describe a broad family of several hundred of chemical compounds that could be present in the peat samples analysed. It is the area of all gas chromatographic peaks beginning with n-C_{10} and ending with n-C_{40} and it represents a mixture of chemicals made entirely from hydrogen and carbon. The bulk measurement of TPHs in an environmental sample has been used for human health risk assessment purposes because of different reasons including the variety of hydrocarbons involved. TPHs was measured because peat compounds are very variable, therefore the bulk TPHs could be used for an appraisal of the total hydrocarbons in the peat sample that could influence peat structure. The hydrocarbons were further fractionated into carbon numbers >C_{10}-C_{18}, >C_{18}-C_{36} and >C_{36}-C_{40} in order to have an idea of the „finger prints" of the hydrocarbons of peat samples from blanket bogs that are susceptible to bogflow types of failures.

(2) Measurement of „petroleum groups" (EA, 2005): different categories of hydrocarbons (e.g. saturates, aromatics) are separated and quantified, which may be useful for characterisation because different hydrocarbon sources can have characteristic levels of various petroleum groups.

In this study, percentages of bitumen and concentrations of split aliphatic and aromatic hydrocarbon fractions were assessed. After extraction of free bitumen (i.e. the bitumen randomly adhered or „sorbed" to sediment components, and extractable with organic solvents without previous chemical treatment of sediment (Rurka *et al.*, 2005)) using an appropriate solvent and determination of its percentage mass in dry peat, the petroleum fractions (i.e. aromatic and aliphatic carbon ranges $>C_{10}$-C_{18},$>C_{18}$-C_{36} and $>C_{36}$-C_{44+}) were further assessed in order to characterise the bitumen which may have influences on peat structure and strength properties. The bitumen was further fractionated to characterise the aliphatic fraction because it contains wax with high crystalline solids that are sensitive to temperature changes (Leahy and Birkinshaw, 1992) and may be relevant to peat instability during warm weather.

(3) Measurement of „individual petroleum hydrocarbon‟ (EA, 2005): concentrations of specific compounds that may be present in petroleum samples are quantified. In this study, the concentration of 15 common Polycyclic Aromatic Hydrocarbons (PAHs) included in the United States Environmental Protection Agency (USEPA) list of priority pollutants and of Benzo[e]pyrene and perylene were determined. These hydrocarbons have been found in peat and other burnt ecosystems (e.g. Zaccone *et al.*, 2009) and could also have evolved *in situ* from algae, spores/pollen and plant cell/wall material, promoted by the pyrolysis of organic materials at high temperatures during fires. PAHs can form chemical bonds and increase the strength of peat therefore, improving blanket peat stability. Prior to quantifying the selected analytes of interest, the peat samples were extracted as follows:

Extraction of the analytes: The peat samples for chemical analysis were stored at 4°C until analysis. They were dried at 50°C for 24 hours and then ground using an electric grinder. Approximately 3-5g of peat was extracted using a Soxhlet apparatus. Soxhlet extraction is a very efficient extraction process which is commonly used for semi-volatiles compounds analyses. Depending on the hydrocarbon of interest, an appropriate solvent was heated and refluxed through the peat samples continuously for one hour, until the drops of solvent from the peat samples were colourless. For TPHs and PAHs, n-pentane was used as solvent and the extract was concentrated to 10 ml before analysis. N-pentane was used in line with the Texas Natural Resource Conservation Committee (TNRCC) Method 1006 (TNRCC, 2012) and the EPA Method SW-846 3540 (USEPA, 2012). The extraction of free bitumen was carried out according to the standard International Humic Substances Society procedure (IHSS, 1983). The free bitumen was extracted with the azeotropic mixture of dichloromethane and methanol (boiling point 37.8ºC) and evaporated completely for percentage of dry mass determination. For further characterisation, fractionation of the bitumen into aliphatic and aromatic fractions was accomplished by solid phase separation of the extract using silica gel (similar to USEPA Method 3630C) (USEPA, 2012). The product was eluted with n-pentane to obtain an aliphatic fraction then eluted with a 1:1 mixture of acetone:ethylene chloride to obtain the aromatic fraction. The two separate fraction extracts were each re-concentrated to a final volume of 1 ml before analysis.

Methods for quantitative measurement of the analytes: Several methods exist to quantify hydrocarbons in environmental media. Weisman (1998) provided a critical overview of the analytical methods used for TPHs analysis. Gravimetric-based methods which are simple, quick and inexpensive are often used for very oily sludge and wastewaters, which will present analytical difficulties for other more sensitive methods. The gravimetric method was used to determine the percentage of total free bitumen which is a very complex mixture of compounds as mentioned previously.

Gas chromatography/mass spectrometry (GC/MS)-based methods were used for TPHs, PAHs and bitumen fractions measurements because they detect a broad range of hydrocarbons, they provide both sensitivity and selectivity, and they can be used for TPHs identification as well as quantification. Mass spectrometer systems are designed to ionize compounds and scan for ions of specific mass-to-charge ratios. Each compound breaks apart into a consistent, recognizable pattern of fragment ions. Coupling a gas chromatograph (GC) with a mass spectrometer (MS) allows one to separate a mixture into its constituents, ionize each constituent in turn, and identify the constituent compounds by their fragmentation patterns. GC/MS methods identify compounds by retention time and mass spectrum. The conditions specified in Table 3.4 were produced to assist in the qualitative determination of GC/MS elution patterns. A library of chromatograms (e.g. gasoline, diesel, crude oils) was generated to assist in the qualitative determination of possible petroleum hydrocarbons present in the peat samples. The chromatogram of the peat extract was closer to that of the diesel sample. The more volatile in the carbon range of nC_8 to nC_{10}, where gasoline samples eluted, were not present in the peat sample extract.

Typical GC/MS chromatograms are presented in Figures 3.7 to 3.11, showing a 2 mg l^{-1} diesel solution (Figures 3.7a), a 2 mg l^{-1} gasoline solution (Figure 3.7b), a peat extract (Figure 3.8), a commercially-prepared and certified 17 n-alkane compounds mixture in carbon disulfide (1000 mg l^{-1}) (Figures 3.9 and 3.10), a peat bitumen extract (Figure 3.11), and a PAH mixture (including Bis(2-ethylhexyl) adipate as internal standard compound) in cyclohexane (Figure 3.12). The analysis of the same solution using different GC/MS and conditions produced different outputs.

Retention times of the 17 n-alkane compounds (Table 3.5) in carbon disulfide were used to define and establish windows for the hydrocarbon ranges. Table 3.6 shows the n-alkane markers used. Commercially available diesel fuel solutions of up to 2mg l^{-1}were used as calibration standards to calculate the collective concentration of hydrocarbons within those hydrocarbon ranges in the peat samples. After every 10-20 samples had been analysed, the TPHs calibration standards, the standard solution for n-alkanes compounds and a blank sample were analysed as a check on the response of the gas chromatography. After integration of the resulting chromatograms, the concentrations of hydrocarbon ranges nC_{10}-C_{18} and >nC_{18}-C_{36} inclusive, then >nC_{36}-C_{40} for TPHs and >nC_{36}-C_{44+} for bitumen hydrocarbon fractions, were determined using the calibration factors produced. The summations of all hydrocarbon carbon ranges have been reported in the results presented in Chapter 4.

The amount of individual PAH was determined from replicate analyses and calculated from the calibration standard solutions prepared from the commercially available mixture. The PAHs standard mixture was used to (a) define the individual retention times of each of the PAH analytes listed in Table 3.7, and (b) determine average calibration curve regression equations that were, in turn, used to calculate the concentration of aromatic hydrocarbons in peat samples.

The Internal Standard (IS) compound of known concentration was added to every PAH calibration standard solution, blank solution and peat extract prior to analyses. An Internal Standard was used as the basis for quantification of the method"s target analytes and for quality assurance. The top standards with known concentrations and a blank solution were analysed after every 10-20 samples as a check on the response of the gas chromatography. Table 3.8 presents some calibration regression equations used for hydrocarbons calculations from the mean of two analyses for each peat extract.

Table 3.4. GC/MS conditions for hydrocarbon testing.

GC/MS Specifications	Condition 1	Condition 2	Condition 3	Condition 4
Instrument/Model Number	5975C	5975C	6890 GC -Agilent 19091S-433	6890 GC - Agilent 19091S-433
Oven temperature programme	50°C for 2 min then increase at 10°Cmin^{-1} to 320°C for 10 min	50°C for 2 min then increase at 10°Cmin^{-1} to 350°C for 10 min	50°C for 2 min then increase at 15°Cmin^{-1} to 160°C for 5 min, then increase at 10°Cmin^{-1} to 350°C for 10 min	50°C for 1 min then increase at 40°Cmin^{-1} to 295 °C, then increase at 5°Cmin^{-1} to 320°C for 5 min
Mode	Pulsed Splitless	Split	Pulsed Splitless	Pulsed Splitless
Column	30 m × 250 μm × 0.25 μm	30 m × 250 μm × 0.25 μm	HP-5MS, 0.25mm × 30m × 0.25μm	HP-5MS, 0.25mm × 30m × 0.25μm
Run Time	39 min	42 min	40.33 min	37.25 min
MS Acquisition Mode	Scan	Scan	Scan/SIM	SIM
Standard used	Diesel and 17 TPHs aliphatic mixture	Petrol and 17 TPHs aliphatic mixture	Diesel and 17 TPHs aliphatic mixture	17 PAHs mixture
Method Purpose	Assess Total n-C_{10}-C_{40} range and fractions for TPHs measurement	Assess Total n-C_8-C_{40} range for TPHs measurement	Assess total n-C_{10}-C_{44+} range and fractions for bitumen measurement	Assess PAHs and compounds

3.4- PRESENTATION AND ANALYSIS OF RESULTS

Results of peat descriptions and laboratory analyses of monoliths for palaeobotanical and physical properties were displayed using TILIA 1.4.9 software (Grimm, 2008). Numerical zonations were performed using the Constrained Incremental Sum of Squares (CONISS) and the least squares (Grimm, 1987). CONISS works by searching the dataset for the two most similar, stratigraphically-adjacent, samples, and combining them. The combination is then treated as a single sample, and the search repeated.This numerical procedure is fast and repeatable and reduces considerably the element of subjectivity. The dendrograms produced illustrate the hierarchical relationship between the clusters identified by the statistical analyses (Grimm, 1987). After examining these outputs, the clusters produced were used to identify potentially weak zones within the peat monoliths or profiles analysed. A zone represents a body of the peat profile or monolith which has similar properties and is thus differentiated from adjacent strata (Hedberg, 1972). Trends of parameters along the peat monoliths or profiles were interpreted using quantitative criteria which are the calculated mean values of the parameters investigated within each zone.

The Grubb (1969) test is a statistical test used to detect outliers in a univariable data set that follows an approximately normal distribution. To assess the occurrence of patches of hydrocarbons encountered during the monolith sampling, the concentrations of Total TPHs, bitumen and Total PAHs across the sites were assessed for outliers according to Grubb (1969) and areas of high concentration were identified.

Table 3.5. Retention times (RTs) for n-alkanes.

Carbon number	Compound	Molar mass (g mol^{-1})	Method	
			TPH (Condition 2)	Bitumen (Condition 3)
			RT(min)	RT(min)
6	n-Hexane	86	Not eluted	Not eluted
7	n-Heptane	100	3.90	Not eluted
8	n-Octane	114	5.61	4.02
9	n-Nonane	128	7.38	5.35
10	n-Decane	142	9.06	6.54
11	n-Undecane	156	10.62	7.61
12	n-Dodecane	170	13.45	8.80
14	n-Tetradecane	198	15.95	9.53
16	n-Hexadecane	226	18.20	11.99
18	n- Octadecane	255	20.24	16.23
20	n-Icosane	283	23.78	19.29
24	n- Tetracosane	339	26.80	23.33
28	n-Octacosane	395	29.43	26.39
32	n-Dotriacontane	451	32.92	29.04
36	n-Hexatriacontane	507	39.49	30.24
40	n-Tetracontane	563	40.43	31.50
44	n-Tetratetracontane	619	44.90	35.28

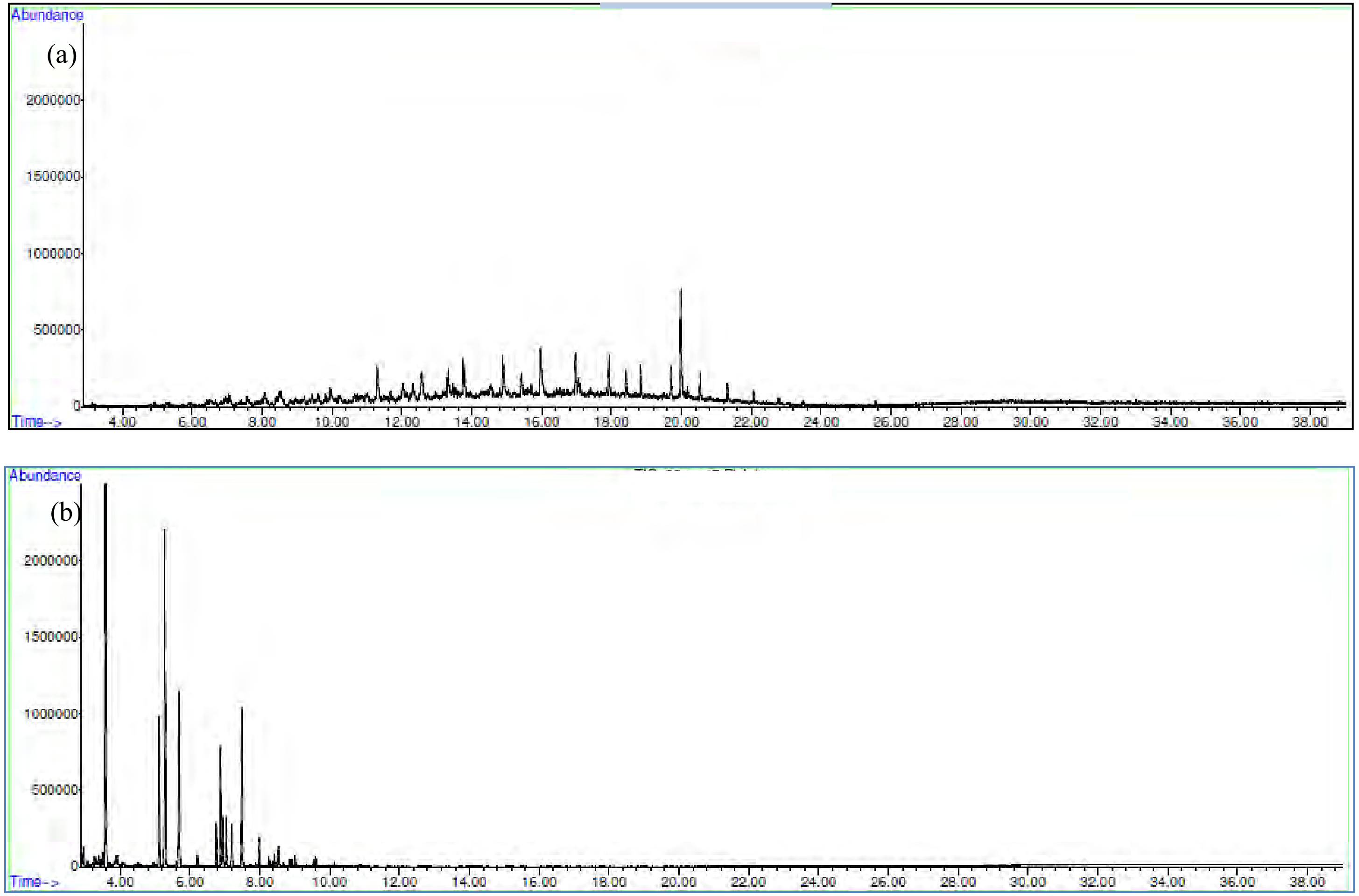


Figure 3.7. GC/MS chromatograms of (a) diesel and (b) gasoline standard solutions (2 mg l^{-1}) using conditions 1 and 2 respectively (Table 3.4). The time is in minutes.

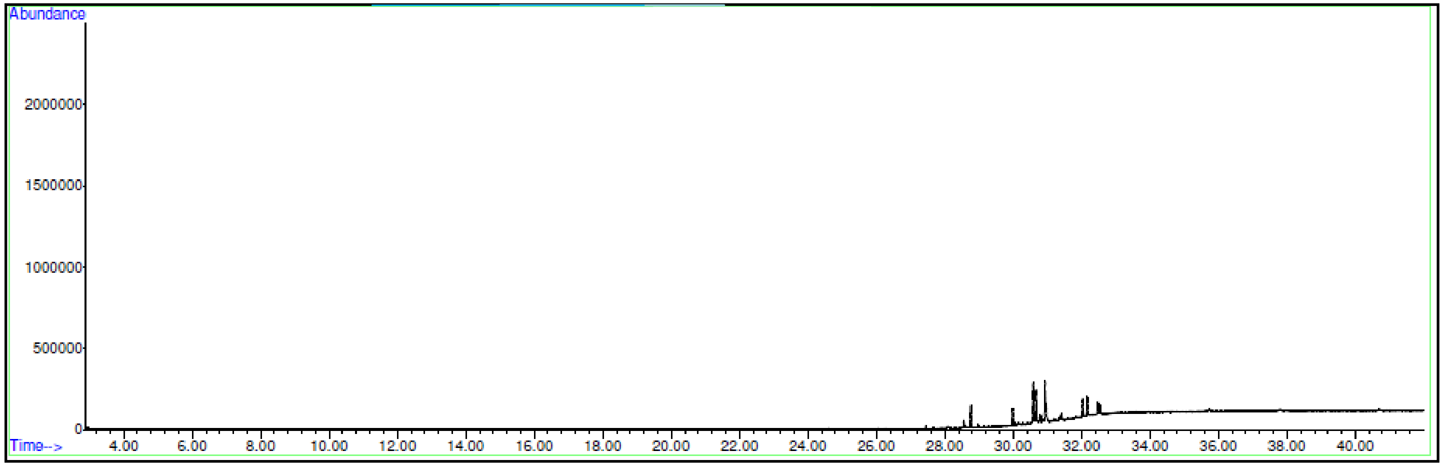


Figure 3.8.Example of GC/MS chromatogram of a peat sample using condition 1 (Table 3.4). The time is in minutes.

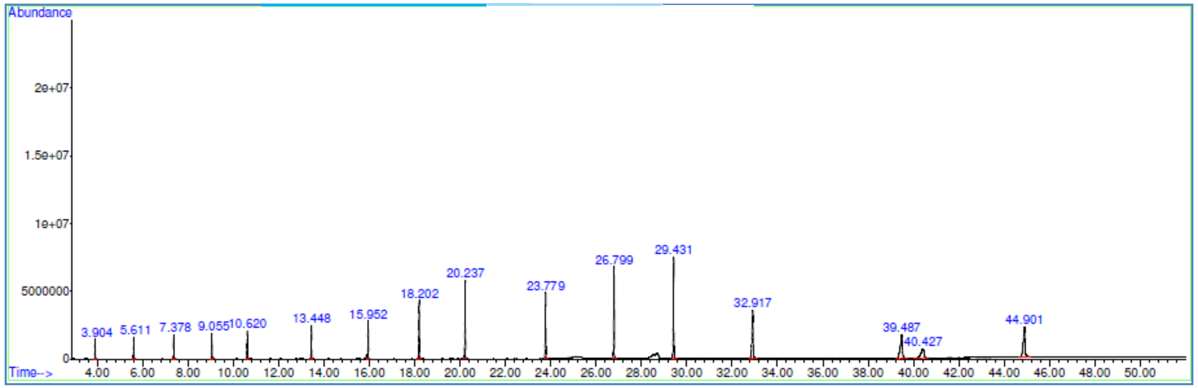


Figure 3.9.GC/MS chromatogram of 17n-alkanes mixture standard solution (1000 mg l^{-1}) (n-hexane is not represented) using condition 2 (Table 3.4). The time is in minutes.

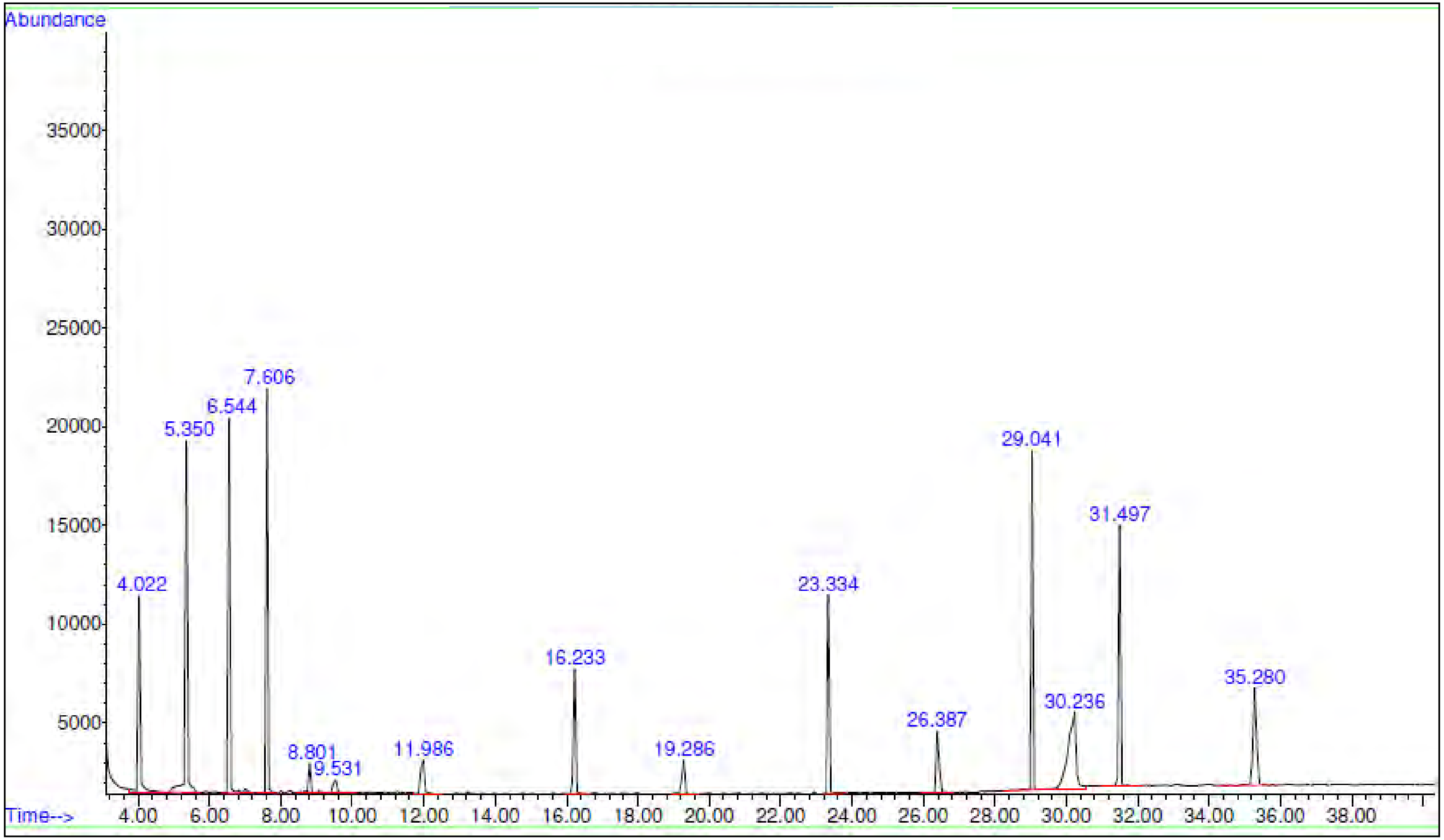


Figure 3.10.GC/MS chromatogram of 17n-alkanes mixture standard solution (1000 mg l^{-1}) (n-Hexane and n-Heptane are not represented) using condition 3 (Table 3.4). The time is in minutes.

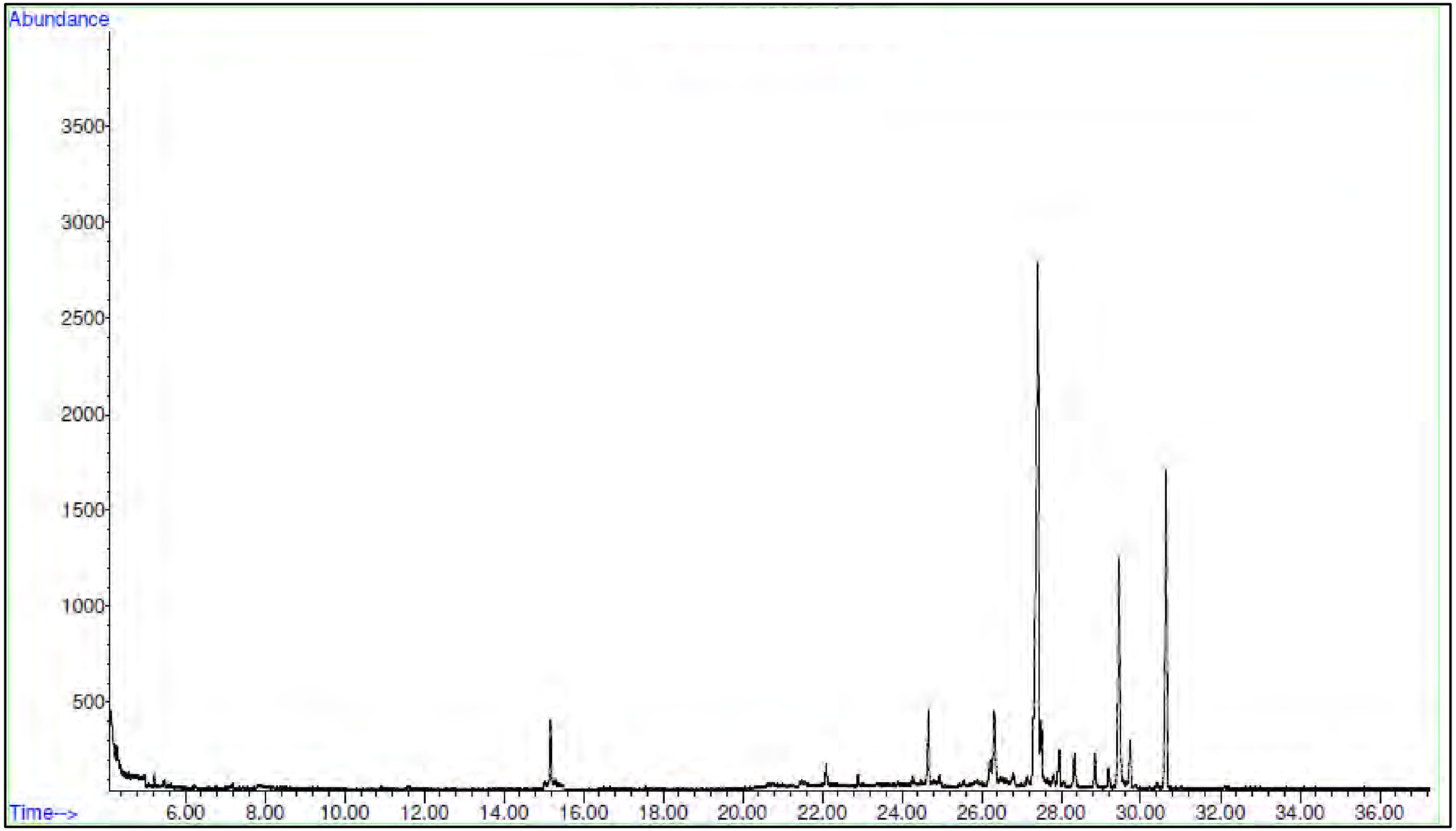


Figure 3.11. GC/MS chromatogram of bitumen extract using condition 4 (Table 3.4). The time is in minutes.

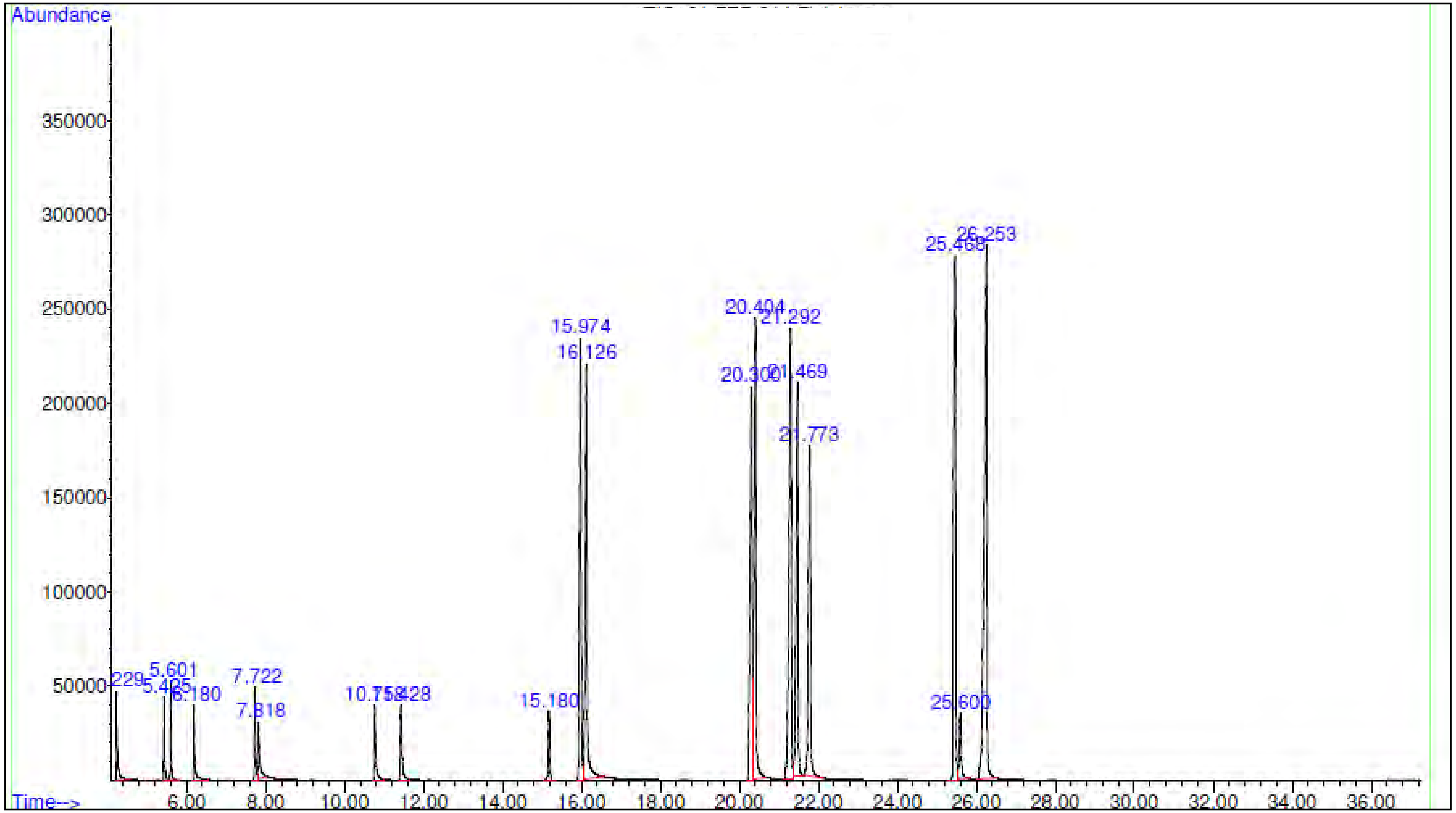


Figure 3.12. GC/MS chromatogram of 17 PAHs mixture standard solution including an Internal Standard compound using condition 4 (Table 3.4). The time is in minutes.

Table 3.6. Hydrocarbon fractions and n-alkanes markers.

Hydrocarbon fraction	**Beginning Marker**	**Ending Marker**
C_{10}-C_{18}	0.1 min before n-Decane	0.1 min after n-Octadecane
>C_{18}-C_{36}	0.1 min after n-Octadecane	0.1 min after n-Hexatriacontane
>C_{36}-$C_{40+/44+}$	0.1 min after n-Hexatriacontane	0.1 min after n-Tetratetracontane
Total (all fractions)	0.1 min before n-Decane	0.1 min after n-Tetratetracontane

Table 3.7. Retention times for Polycyclic Aromatic Hydrocarbons (PAHs).

Elution order	**Compound**	**Molar mass (g mol^{-1})**	**Retention Time (min)**
1	Naphthalene (Nap)	128	4.23
2	Acenaphthylene (Acen)	152	5.43
3	Acenaphthene (Ace)	154	5.60
4	Fluorene (Flu)	166	6.18
5	Phenanthrene (Phe)	178	7.72
6	Anthracene (An)	178	7.82
7	Fluoranthene (Fluor)	202	10.76
8	Pyrene (Pyr)	202	11.43
9	Internal standard	129	15.18
10	Benz[a]anthracene (B[a]a)	228	15.97
11	Chrysene (Chry)	228	16.13
12	Benzo[b]fluoranthene (B[b]f)	252	20.30
13	Benzo[k]fluoranthene (B[k]f)	252	20.40
14	Benzo[a]pyrene (B[a]p)	252	21.29
15	Benzo[e]pyrene (B[e]p)	252	21.47
16	Perylene (Per)	252	21.77
17	Indeno[1,2,3-cd]pyrene (I[1,2,3-cd]p)	276	25.47
18	Dibenz[a,h]anthracene (D[a,h]a)	276	25.60
19	Benzo[ghi]perylene (B[ghi]p)	276	26.25

<u>Note</u> Indeno [1, 2, 3-cd] Pyrene and Dibenzo [a, h] Anthracene co-eluted under the column and chromatographic conditions described in Table 3.4 for PAHs.

Table 3.8. Calibration curve regression equations used for hydrocarbons calculations.

Compounds assessed	**Equation *(3.n)***	**R Square**
Naphthalene	$y = 822447x - 57093$ ***(13)***	0.997
Acenaphthylene	$y = 452906x - 67584$ ***(14)***	0.997
Acenaphthene	$y = 801883x - 55496$ ***(15)***	0.995
Fluorene	$y = 636445x - 130053$ ***(16)***	0.997
Phenanthrene	$y = 636445x - 130053$ ***(17)***	0.994
Anthracene	$y = 626635x - 126259$ ***(18)***	0.993
Fluoranthene	$y = 671228x - 78614$ ***(19)***	0.997
Pyrene	$y = 695900x - 75250$ ***(20)***	0.997
Benz[a]anthracene	$y = 452736x - 816053$ ***(21)***	0.994
Chrysene	$y = 364881x - 541260$ ***(22)***	0.991
Benzo[b]fluoranthene	$y = 229139x - 319952$ ***(23)***	0.999
Benzo[k]fluoranthene	$y = 299918x - 449742$ ***(24)***	0.995
Benzo[a]pyrene	$y = 564419x - 984704$ ***(25)***	0.997
Benzo[e]pyrene	$y = 495798x - 1000000$ ***(26)***	0.995
Perylene	$y = 446333x - 855953$ ***(27)***	0.995
Indeno[1,2,3-cd]pyrene	$y = 393034x - 2000000$ ***(28)***	0.991
Dibenz[a,h]anthracene	$y = 21146x - 86387$ ***(29)***	0.994
Benzo[ghi]perylene	$y = 393942x - 2000000$ ***(30)***	0.993
Total petroleum(C_{10}-C_{40})	$y = 0.000000700x - 0.000002$ ***(31)***	0.993
Aliphatic/aromatic C_{10}-C_{18}	$y = 0.000000008x + 0.05810$ **(32)**	0.999
Aliphatic/aromatic >C_{18}-C_{36}	$y = 0.000000010x + 0.12180$ **(33)**	0.993
Aliphatic/aromatic >C_{36}-C_{44+}	$y = 0.000000020x + 0.12430$ **(34)**	0.993
Aliphatic/aromatic Total (C_{10}-C_{44+})	$y = 0.000000005x + 0.08220$ **(35)**	0.997

3.5- CONCLUSIONS

Figure 3.13 presents a summary of the framework of the research and how the components and information fit together to inform the objectives of the study. Like most studies and especially with peat that is very variable, errors and uncertainties may have occurred during sampling. Therefore sampling errors were measured in terms of the standard errors (i.e. the square root of the variance) of mean values of the physical properties. With the limited number of samples tested for some properties (e.g. one monolith per site for macrofossil analysis); caution must be applied to the finding of this study as peat is heterogonous and may have different properties within small distances and depths. These errors and uncertainties are however limitations that also apply to most geotechnical investigations and landslide studies in general and do not constitute a significant flaw in the interpretation of the results of this study.

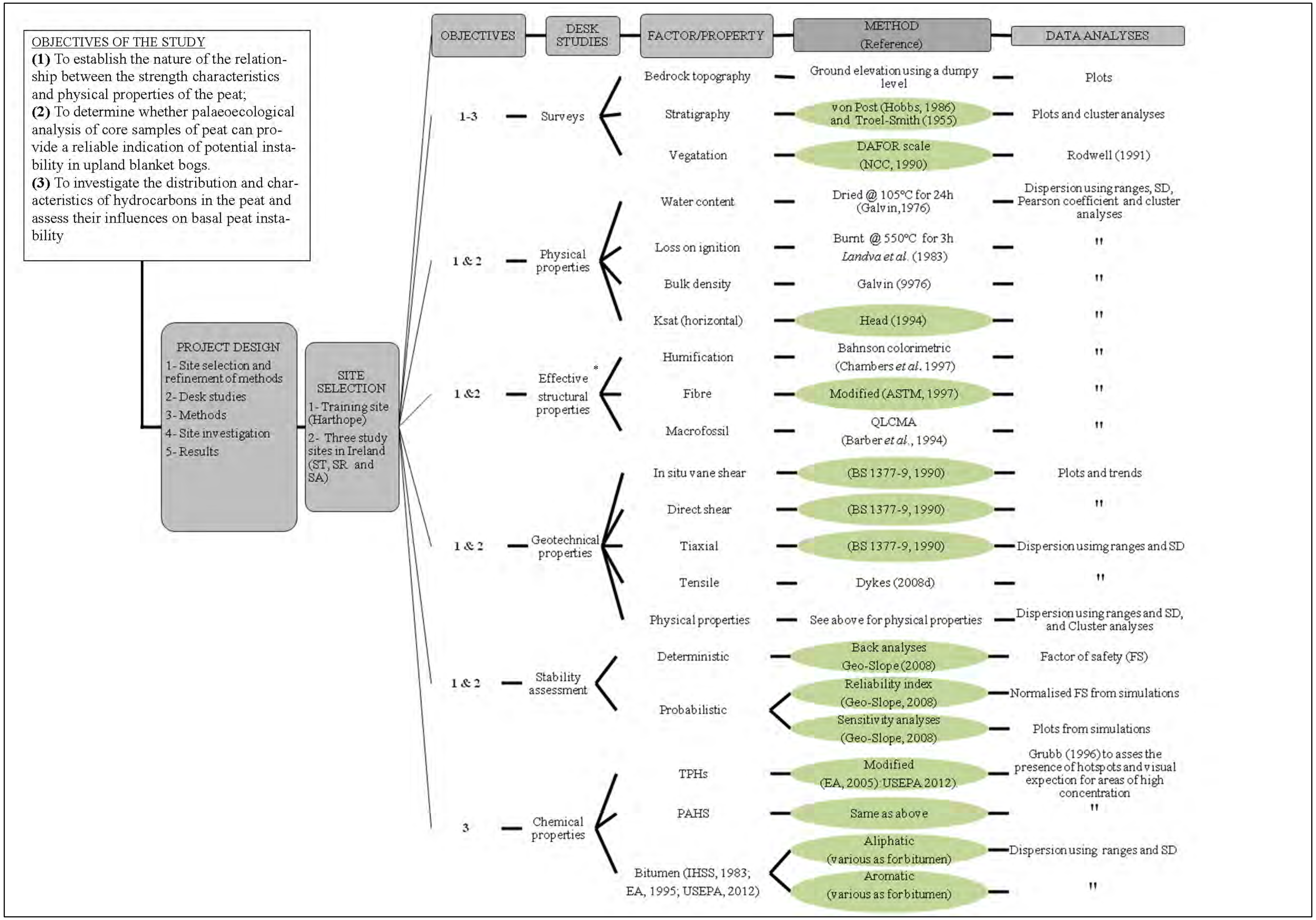


Figure 3.13. Summary of methods used in this study (the methods in the green boxes have been modified or adapted for this study). SD= Standard deviation. *„effective" structural properties (i.e. the humification expressed as „raw" percentage of light transmission, fibre content and macrofossil content) are properties which have not been investigated previously for peat instability purposes.

CHAPTER FOUR– SYNTHESIS OF RESULTS

This chapter aims to assess some common characteristics of the peat deposits at the sites investigated, i.e. the Straduff Townland, Slieve Rushen and Slieve Anierin landslides, for their potential uses as indicators of peat strength. The objectives of this chapter are: (i) to compare the results of the investigations carried out at the three study sites and (ii) to discuss the findings with reference to previous work on blanket bogs that failed as bogflows, and on other types of peat landslides or peatlands as appropriate.

4.1- COMPARISON OF THE ENVIRONMENTAL SETTINGS OF THE LANDSLIDES

The results of the desktop studies showed that the Straduff Townland , Slieve Rushen and Slieve Anierin landslides, which are all located in the Irish uplands, have slightly different environmental settings (Appendix A; Tables A1- A2). No fatalities were recorded at the three landslides investigated. As far as the ecological impacts are concerned, the areas are located within a Natural Heritage Area (NHA) and/or within a Special Area of Conservation (SAC). On-site and off-site ecosystems were significantly impacted (i.e. destruction of the bog landform system and adjacent woodland in the case of the Straduff Townland landslide) although no systematic evaluation of risk of the landslides to ecological and water features has been carried out.

A survey carried out in July 2011 at the Straduff Townland landslide revealed that the vegetation was composed of typical blanket bog species (Appendix A; Table A3), essentially the same as described on this site by Alexander *et al.* (1986). The vegetation assemblage present did not correspond to any plant community as defined by Rodwell (1991). The Slieve Rushen landslide was subjected to a fire between July 1010 and July 2011, therefore a vegetation survey was not carried out. However, remains of *Calluna vulgaris* and shoots of *Narthecium ossifragum* were abundant around the border of the source area. It should be noted that the fire appeared to have had little effect on the peat below the immediate surface (i.e. below about 0.01 m deep). A survey carried out in July 2011 showed that the vegetation on the Slieve Anierin landslide corresponded with the M20 *E. vaginatum* „raised and blanket mire community‟ (Rodwell, 1991) (Appendix A; Table A3).

4.1.1-Surface and subsurface hydrology and geology

Drainage features are not relevant to the landslide under investigation because there are none within 50 m (GSI, 2012) of the sites. The closest surface drainage was that found at the Slieve Anierin landslide, which was located within 50-100 m south from the Stony River (GSI, 2012), a tributary of Lough Allen. The degraded ditches (Figures 3.1) located to the north east of the eastern margin of the Straduff Townland were artificially constructed, and thus have no relation to natural drainage features. Although site inspection showed no direct pathway between these ditches and the landslide source area, the influence of the ditches or any pre-existing surface water features on the failure mechanism cannot be completely dismissed because the conditions of all the study sites prior to failure are unknown. In fact, preferential water flow pathways (e.g. pipes, cracks, surface drainage features) can contribute to the occurrence of peat failure by feeding storm runoff water into a susceptible part of the slope (e.g. Dykes and Kirk, 2001; Warburton *et al.,* 2004; Dykes and Kirk, 2006; Dykes, 2009). Geological faults can also cause the alteration of the drainage system by increasing flow from springs under the bog (Delap *et al.*, 1932). However, this latter factor is also not relevant to the study sites because, there are no known geological faults within 50 m of the sites and there is effectively no groundwater catchment that could produce springs so high up the respective slopes. Likewise the hydrogeology is not relevant because the sites are on a slope and there is little interaction between surface water and groundwater in their vicinities.

4.1.2- Characteristics of the slopes and their peat covers at the landslides

Figure 4.1 presents the outline geomorphological map of the three landslides showing: (a) the transects investigated, (b) sampling locations and (c) peat depths.The results of topography and stratigraphy surveys (Appendix A: Surveys) carried out at Transects AA‛‛ to HH‛‛ (Figures 4.1a (1-3)) of the three landslides showed convex bedrock forms at the Straduff Townland and Slieve Anierin landslides (Figure 4.2 and 4.4). The bedrock topography at the Slieve Rushen landslide (Figure 4.3) showed a slope from sampling points B1 to B5, and a planar bedrock surface from B5 to B10.

The literature review (Table 2.8) suggests that similar slope forms (i.e. with a break of slope at the heads) as that encountered at the study sites have occurred at other types of peat landslides (e.g. peat slides and peaty-debris slides: Dykes, 2008c). Although the results of surveys carried out at the study sites support the idea that bogflows may be common on convex slopes, some hydrological processes may occur on concave slopes and cause peat failure as explained in Chapter 2. It could be the case that convex bedrock or bog surface shapes are the more common shapes on Irish blanket bogs as also found by Hanna (1993) whose study was carried out in Counties Antrim and Donegal. A survey of the geometric configuration of slope and peat cover on more intact blanket bog slopes in the British Isles may enable an appropriate conclusion to be drawn on the influence of slope form on peat failure. As yet, very little such research has been done.

At the study sites, peat depths (Figure 4.1c (1-3)) varied from 0.8 m to 3.4 m (Appendix A; Figure A1) around the source areas of the landslides with the lowest depths having been recorded at the Slieve Rushen landslide. These finding are consistent with other blanket bogs that have been subjected to bogflow-type failures (Table 2.8).

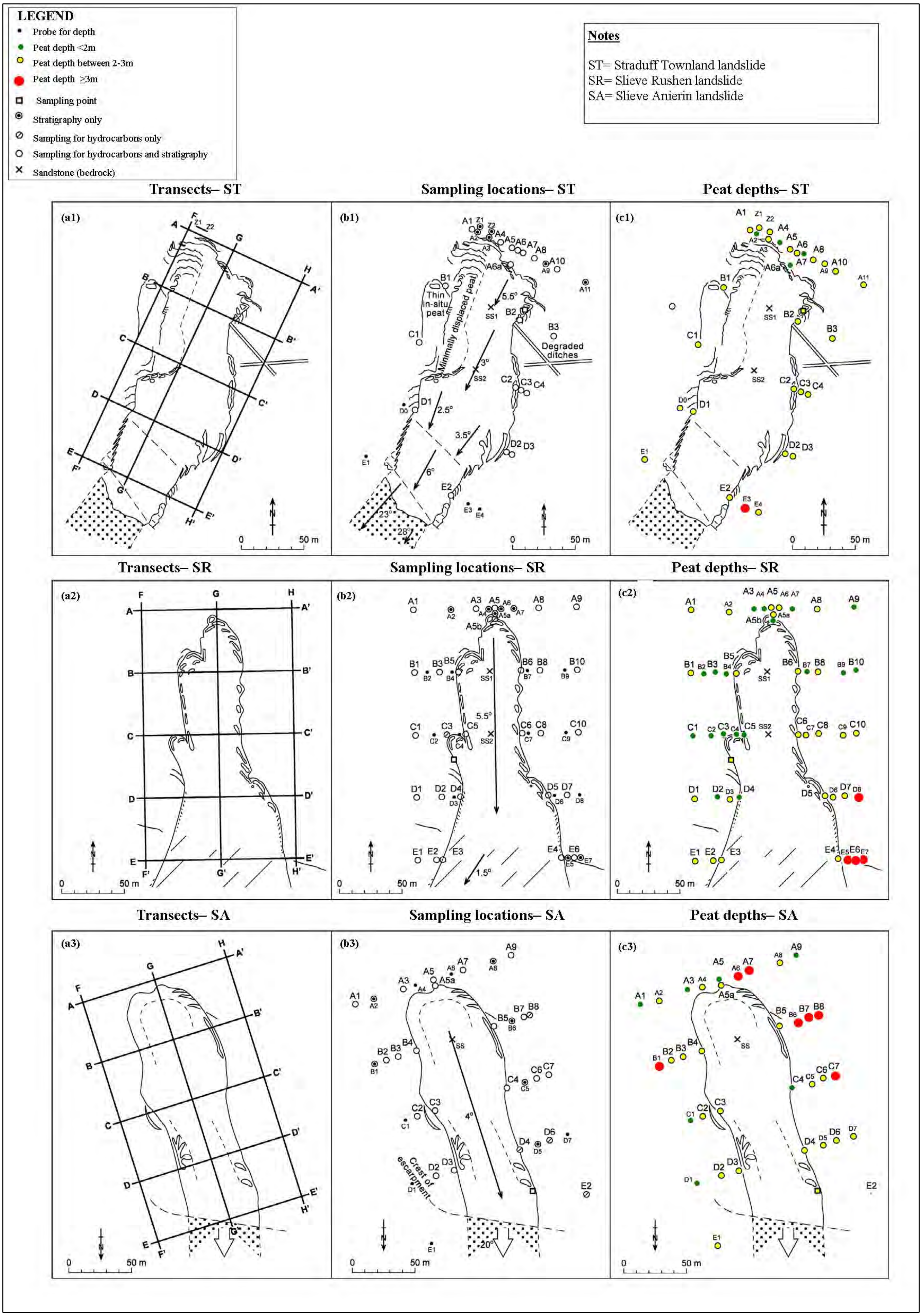


Figure 4. 1. Outline geomorphological map of the three landslides (Dykes, 2009) (i.e. the Straduff Townland (ST), Slieve Rushen (SR) and Slieve Anierin (SA)) showing: (a) the transect investigated, (b) sampling locations and (c) peat depths.

4.2- COMPARISON OF THE PEAT DESCRIPTIONS MADE IN THE FIELD

4.2.1- Description of peat at the monolith sampling points

The results of the site investigations (Appendix A; Table A4) show that at the monolith sampling sites, distinct units can be identified by describing the peat profiles according to the von Post (Hobbs, 1986), Troels-Smith (Troels-Smith, 1955) and the modified fibre content classification (MFC) schemes, as shown in Figure 4.5 and further examined in the following paragraphs. The peat deposits at the three landslides were underlain by pale and weathered sandstones in a clay matrix with low permeability.The most important factor from the detailed peat stratigraphy study in the field was that greasy, bituminous and highly humified, amorphous peats, sometimes also with pockets of sludge-like peat, were encountered at the bases of the profiles investigated at the three landslides. The presence of greasy and bituminous compounds suggests the occurrence of significant petroleum hydrocarbon compounds within these basal peats.

The peat descriptions using the Troels-Smith system showed that at all of the sites, the degrees of darkness and dryness of the peat were variable throughout the profiles. The peat was generally more stratified and elastic near to the ground surface and amorphous at the base. Thick boundaries (i.e. lim sup 2 - 10 mm), that could represent potential failure planes within the peat, were not found in the basal peat profiles investigated.

The thick upper boundary recorded at the ground surface of the Slieve Rushen peat profile was owing to the burnt surface layer which could be clearly distinguished from the underlying peat. The basal peats were amorphous with low fibre contents, which suggest low tensile strength.

Descriptions of the stratigraphy of blanket peats in the British Isles (e.g. in the Republic of Ireland by Hammond (1981) and Bowler and Bradshaw (1985), in the Southern Pennines by Conway (1954) and in South Wales by Chambers *et al.* (2007)) have revealed heterogeneous assemblages of plant remains in their profiles (i.e. with *Sphagnum* sp. dominated layers in all cases)). The stratigraphy of subantarctic islands peat, as summarised by Dykes and Selkirk-Bell (2010), showed higher plants.

The homogeneity of peat in terms of plant material at the study sites compared with the heterogeneity encountered at Hart Hope (Table 4.1) and elsewhere could suggests a potential link between bogflow-type failures and monocotyledon-dominated peats. Warburton *et al.* (2003) reported more diverse plant remains including mosses and tree roots at the peat base while this study found mainly the remains of herbaceous plants (Th) throughout the profiles. The values investigated using the Troels-Smith scheme at the peat slide studied by Warburton *et al.* (2003) and those obtained at the study bogflows were different and hence the structure of the sampled peat was also different. The stratigraphic description of a profile at the margin of the Carrowmaculla bogflow near Lisnaskea, Co. Fermanagh (Tomlinson, 1981) also showed a more diverse plant community (i.e. with *Calluna* and *Sphagnum* and drier peat at the base) than that encountered at the study sites. Tomlinson (1981) suggests that the stratigraphy of the failed area (that was not described) was, however, different from that of the peat at the margin. Furthermore, the blanket bog was a highland blanket bog as opposed to a mountain blanket bog as explained in Chapter 2 (Hanna, 1993) as at the study sites. This also poses a question of the suitability of the current peat failure classification method as defined by Dykes and Warburton (2007a) for all blanket bogs located at different altitudes. The vegetation type on lowland, highland and mountain blanket bogs could affect peat failure mechanism; therefore their failure type should be differentiated.

The von Post characteristics that generally decreased with depth are the fine fibre content (F) and the horizontal tensile strength (TH). The coarse fibre content (R), as defined by von Post, was low in the peats investigated at the three landslides. The results of a review of studies on different types of peat failures (e.g. Warburton *et al.*, 2003; Dykes and Kirk, 2001; Yang and Dykes, 2006; Dykes and Warburton, 2007b, 2008a, 2008b; Dykes, 2008b; Dykes, 2008d; Dykes and Jennings, 2011) showed that the values of the characteristics estimated in the field according to the von Post classification system were consistent with the ranges reported for failed Irish blanket bogs in general (Table 4.1), although wood and shrub remnants were absent in this study. Field descriptions of peat using the von Post classification system at Straduff Townland in this study and by Dykes and Jennings (2011) vary. This variability can be explained partly by the fact that field estimations of most characteristics are subjective and depend on different factors including the experience of the person undertaking the test and the time of year (as this may influence the chemical and physical characteristics of the acrotelm, e.g. Table 2.1) and partly by the heterogeneity of the peat itself. As noted by Helenelund (1967), an efficient geotechnical classification of peat should incorporate laboratory measurements. Furthermore, the current von Post classification was not designed for the purpose of assessing peat for stability because not all parameters are particularly useful for that purpose. No previous peat instability study has attempted to link characteristics including F, R, W and N, as defined by von Post, to peat instability. Only those characteristics directly relevant to peat stability should be identified (see Section 4.6.3) and used for stability assessment.

One of the issues that emerged from these findings is that the occurrence of greasy layers or hydrocarbons in fibrous peat can render the consistent application of the von Post system difficult because monocotyledon peat will tend to completely escape from the hand and look very homogenous when squeezed. Consequently, highly humified monocotyledon peat which seems apparently homogenous could reveal a high proportion of fibres when analysed in detail in the laboratory.

The definitions of the von Post fine fibre content (F) and coarse fibre content (R) were modified to include all the dimensions of the fibres which can be of different shapes as defined in Chapter 3 (Section 3.3.6). The results of this study indicate that the frequency of fibres and stems smaller than 1 mm increased with depth (i.e.Fm1-3) at all three landslides. Fibres and stems greater than 1 mm became less frequent with depth (i.e. Rm1-4) at all three landslides. The „modified fibre content" classification system, as defined in this thesis, gave similar results at the three landslides.

Table 4. 1. Classification of the basal peat at the three landslides compared to previous works.

System	Properties	This study	Dykes and Jennings (2011)	Hart Hope (Warburton *et al.*, 2003)	Literature for Irish landslides in general
Troels-Smith	Darkness (Nig.)	1-4	n/d	2-4	n/d
	Degree of dryness (Sicc.)	1-4	n/d	0-3	n/d
	Stratification (Strat.)	0-2	n/d	0-2	n/d
	Boundary strength (Lim sup.)	0-3	n/d	0-3	n/d
	Elasticity (Elas.)	0-2	n/d	0-3	n/d
	Peat constituents	Th1-4	n/d	n/d*	n/d
von Post	Degree of humification (H)	4-10	3-10	n/d	3-10 [a-g, i]
	Degree of wetness (B)	2-4	3-4	n/d	2-4 [c,e,i]
	Fine fibre (F)	1-3	1-3	n/d	0-3 [b-e, g-i]
	Coarse fibre (R)	0-2	0-1	n/d	0-3 [b-e, g-i]
	Horizontal tensile strength (TH)	0-2	n/d	n/d	n/d
	Wood (W)	0	0-2	n/d	0-3 [b-e, g-i]
	Shrub (N)	0	0-1	n/d	0-2 [b-e, g-i]

Notes
n/d =Not determined. *The core one was however dominantly *Turfa herbacea* and *Substantia humosa*, with shrub remants at the base of the profile.
[a]Dykes and Kirk (2001)
[b]Warburton *et al.*(2003)
[c]Yang and Dykes (2006)
[d]Dykes and Warburton (2007b)
[e]Dykes (2008b)
[f]Dykes (2008d)
[g]Dykes and Warburton (2008a)
[h]Dykes and Warburton (2008b)
[i]Dykes and Jennings (2011)

4.2.2- Comparison of zonations between sites

The cluster analyses of the data and subsequent zone delimitations based on the data from field descriptions of peat profiles, using all the classification systems, were undertaken in order to facilitate comparison between the zones and the sites. Table 4.2 presents the mean values and trends with depth at the three landslides. The study shows differences between the units described in the field and zones delimited by cluster analysis from the field data. This can be explained by the fact that the delimitation of units in the field is mostly based on few visible characteristics (e.g. the peat colour or the appearance) and not on all the parameters proposed in the classification system used (e.g. the peat structure, the composition of the sediment and the degree of humification).

The results of this study presented in Table 4.2 suggest that the mean values of the degrees of stratification and elasticity (Troels-Smith), the degree of humification (von Post), the modified fine and coarse fibre contents as defined in this thesis have similar trends with depth at the three landslides. The boundaries between basal peat layers at all the sites were either „diffuse" or „conspicuous".

It is anticipated that cluster analyses of the results of field characteristics using each of the classification systems used in this study should produce different clusters in the Tilia software because the parameters are estimated using different scales as presented in Figures 4.5. Cluster analysis in Tilia uses the sum square of the characteristics specified in the analysis; the character with the greatest abundance could have more impact on the output of the analysis. For example, the von Post humification and wetness had major influences on the results of the cluster analyses and subsequent zonations. As far as cluster analysis is concerned, for the purpose of stability assessment, the Troels-Smith system is the most appropriate system because all of the properties are described using an identical 5-point scale. Furthermore, the characteristics described in the classification system can be objectively assessed in the field. However, the system does not quantify fibres and does not consider all the dimensions of the fibres, which may have major influences on peat strength properties (Helenelund, 1975, 1976; Landva, 1980; Long, 2005). The system is also subjective because some results cannot be tested using laboratory measurements as explained in Chapter 2 (Section 2.3).

4.2.3- Description of *in situ* peat across the sites

Figures 4.2, 4.3, and 4.4 present the detailed stratigraphy of the peats at the transects investigated across the Straduff Townland, Slieve Rushen and Slieve Anierin landslides respectively. The results of the stratigraphy surveys (Appendix A; Surveys) undertaken at the three landslides were generally consistent and showed four major stratigraphic units (1-4) (Figures 4.2- 4.4; Legend). The minor differences were that (i) the eastern part of the Slieve Rushen site (i.e. located to the east of Transect A: Figure 4.3) extended into the source area of a former landslide (i.e. sampling points SRA7 to 9 where the peat was wetter than across the remainder of the site) and (ii) the burnt surface layer that were encountered across the remaining site, and (iii) greasy and clayey layers were found at different locations at the Straduff Townland and Slieve Anierin landslides and at the monolith sampling point at the Slieve Rushen landslide. From the surface to the bottom of the peat profile described at each site, the first unit was made of slightly humified peat, the second unit of moderately humified peat, the third unit of strongly humified peat and the fourth of highly humified and/or greasy peat (with bitumen or sludge like patches). The identifiable plant material in the peat was predominantly monocotyledon remains (*Turfa herbacea*) including undifferentiated roots, stems and leaves. An assessment of the greasiness of peat is not included in current peat classification systems.

The mineral substrates beneath all of the investigated peat profiles were consistent with those encountered at the monolith sampling points. The stratigraphic variations within the blanket bogs investigated therefore appear to be negligible. However, compaction of the peat occurred during auger sampling owing to the low density, the high water content and the generally weak nature of these peats. Consequently, the boundaries between different units described in the field using auger samples, as presented in this study, may not be correct indications of their real depths in the field and should be treated with caution.

Table 4. 2.Comparisons of the mean values of peat characteristics in the zones delimitated after cluster analyses of the data estimated *in situ* at the three landslides.

Classification system	Parameter	Straduff Townland	Slieve Rushen	Slieve Anierin	Trend of parameter with depth at the three landslides
		Z:5,4,3,2,1	*Z:4,3,2,1*	*Z:4,3,2,1*	
Troels-Smith (1955)	Darkness (Nig.) (0-4)	2,4,1,1,4	2,2,1,2	2,2,1,3	Variable (i.e. 1-4)
	Stratification (Strat.) (0-4)	2,0,0,0,0	1,2,0,0	1,0,0,0	Stratified near the top of the peat profile (i.e.0-2)
	Dryness (Sicc.) (0-4)	1,3,3,1,3	3,2,3,3	1,1,2,2	Variable (i.e. 1-3)
	Boundary strength (Lim sup.) (0-4) Mean (Maximum)	 0,0,0,0,0 (2,0,1,0,1)	 0,0,0,0 (3*,0,0,1)	 0,0,0,0 (1,0,0,1)	 „Diffused" (i.e. 0) Diffused to acute (i.e.0-3)
	Elasticity (Elas.) (0-4)	2,0,0,0,0	1,1,0,0	2,2,0,0	Slightly elastic near the top of the profile (i.e.0-2)
von Post (Hobbs, 1986)	Humification (H)(1-10)	6,7,8,9,10	5,6,6,7	6,7,8,9	Increased with depth (i.e. 5-10)
	Wetness (B)(1-5)	2,2,1,2,1	1,2,2,2	3,2,2,2	Variable (i.e. 1-3)
	Fine fibre (F)(0-3)	2,2,2,1,1	3,1,1,1	3,2,1,1	Variable (i.e. 1-3)
	Coarse fibre (R) (0-3)	0,0,0,0,0	0,0,0,0	1,0,0,0	Nil to very low(0-1)
	Horizontal tensile strength (TH) (0-3)	2,2,1,1,0	2,1,1,0	2,2,0,0	Decreased with depth (i.e. 0-2)
	Organic content (N)(1-5)	4,5,5,5,4	5,5,5,4	-,5,5,5	Variable (i.e. 4-5)
Modified fibre content method	Fine fibre (Fm) (1-5)	1,1,1,2,3	1,1,2,2	1,1,2,3	Increased with depth (i.e. 1-3)
	Coarse fibre (Rm) (1-5)	3,3,3,2,1	3,3,2,2	4,3,3,2	Decreased with depth (i.e. 1-4)
Potential weak zone depth (m)		*0.09*	*0.15*	*0.10*	*0.09-0.15*

Notes See Appendix A (Table A5, A13 and A21) for the raw data and the numbers of samples considered. The numbers in positions a, b, c, d and e correspond to mean values for Zones (Z)5,4,3,2 and 1 respectively (where „-"means no data available). *The high value of „3"represents the burnt layer at the ground surface.

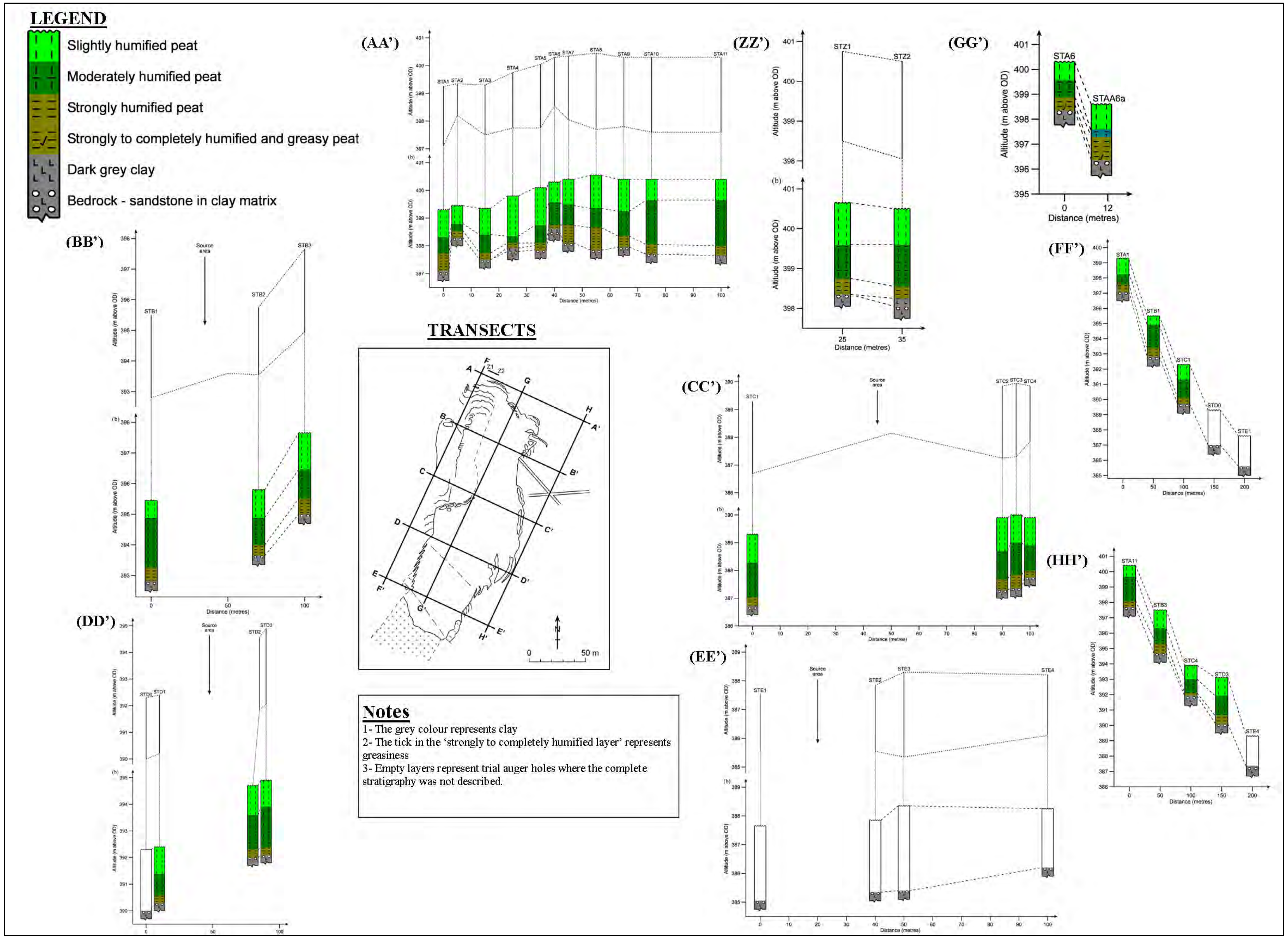


Figure 4. 2. Diagram showing (a) Surface and bedrock topography and (b) detailed stratigraphy of the Straduff Townland landslide and surroundings. The detailed description of the topography and stratigraphy has been presented in Appendix A (Surveys).

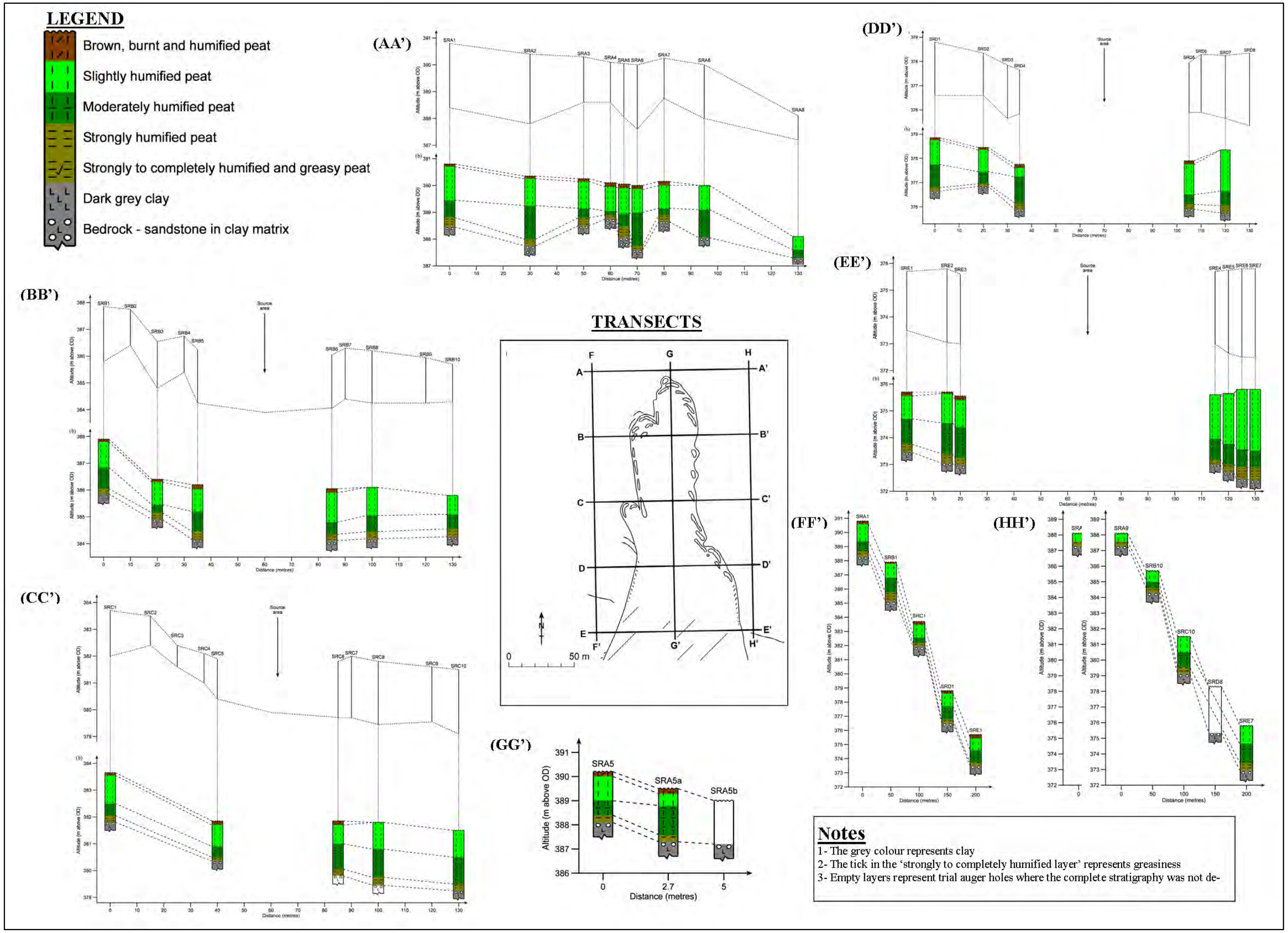


Figure 4. 3. Diagram showing (a) Surface and bedrock topography and (b) detailed stratigraphy of the Slieve Rushen landslide and surroundings. The detailed description of the topography and stratigraphy has been presented in Appendix A (Surveys).

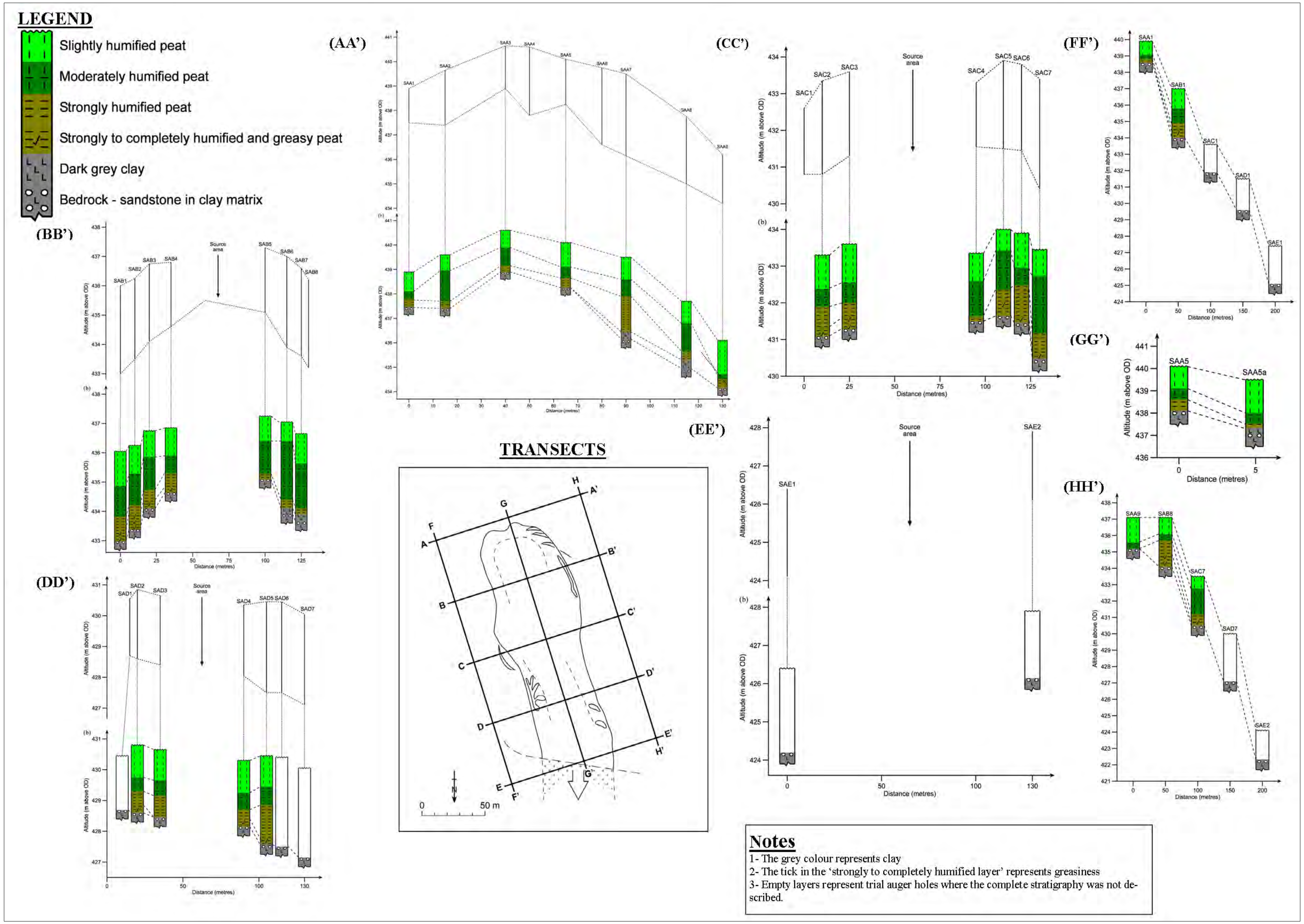


Figure 4. 4. Diagram showing (a) Surface and bedrock topography and (b) detailed stratigraphy of the Slieve Anierin landslide and surroundings. The detailed description of the topography and stratigraphy has been presented in Appendix A (Surveys).

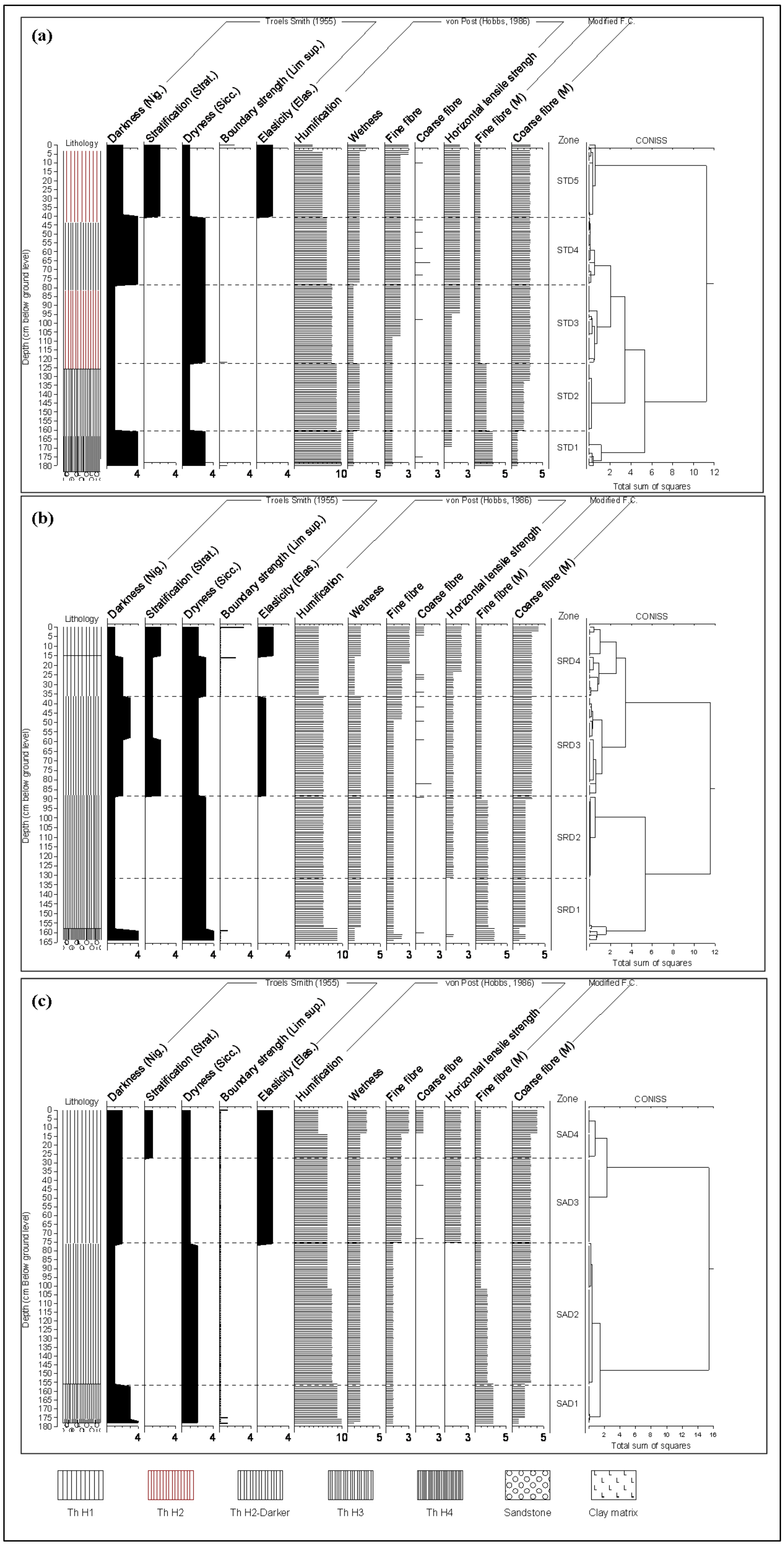


Figure 4. 5.*In situ* peat stratigraphy at the three landslides (i.e. (a) Straduff Townland, (b) Slieve Rushen and (c) Slieve Anierin) sampling locations showing, the dendrograms produced from unconstrained incremental sum square cluster analysis of the data in the Figures. Dashed lines separate clusters corresponding to zones in the diagrams. M = Modified. The vertical axes are in centimetres (cm) instead of metres (m) in accordance with previous palaeoecology literature work on peatlands.

4.3- SYNTHESIS OF LABORATORY RESULTS OF PEAT CHARACTERISTICS

The peat physical properties (i.e. water content, LoI, bulk densities and saturated hydraulic conductivity) presented in the following sections were determined to complement similar previous research carried out on failed blanket peats. These physical properties have been differentiated from „effective" structural properties (i.e. the humification expressed as „raw" percentage of light transmission, fibre content and macrofossil content) which have not been investigated previously for peat instability purposes. In the context of the results of this study, structural properties refer to both physical properties and effective structural properties.These latter parameters are directly relevant to peat instability because they may have significant influences on peat strength. The syntheses of the laboratory measurements of geotechnical and chemical properties, the updated peat classifications, the results of stability analyses of the three landslides and a proposed new classification, are presented in separate subsequent sections.

4.3.1-Physical properties

Water content : The results of this study indicate that field and saturated water contents of the peat monolith samples tested at the three landslides were generally variable within and between the sites, and consistent with (i) previous works on other bogflows (e.g. Dykes, 2008d), (ii) other types of peat failures (e.g. Dykes and Warburton, 2007b; Warburton *et al.*, 2003), and (iii) the studies of Tomlinson and Davidson (2000), Lewis *et al.* (2011) and Wellock *et al.* (2011) for other blanket bogs with similar peat depths (Figures 4.6 and 4.7). The general scatter of data with depth was expected for reasons presented by Hobbs (1986). The lack of general and consistent trends with depth suggests that variations of field water content may occur over small distances and intervals reflecting the varying proportions of different plant types and parts and the degree of humification (Clymo and Harwad, 1982).

This study shows that field water contents (Figure 4.6) were lower for subsamples taken from the surface to approximately 1 m below ground level at the Slieve Rushen and Slieve Anierin landslides compared with those taken from the monoliths from greater depths below the surface. These lower values could reflect (i) evaporative drying through tension cracks prior or post failure, (ii) surface drainage of peats following the landslides given that the samples were taken from the margins of the landslide source areas. Invasion of the sites by *Calluna vulgaris* following the landslides may have promoted further dying out of peat in the deeper layers.

Figure 4.8 represents the mean water contents of monolith samples and of field and saturated samples obtained from the three sites for geotechnical testing. The overlaps of the error bars showing the standard errors suggest that the Slieve Rushen and Slieve Anierin sites are similar in terms of their water contents. The Straduff Townland peat had higher field and saturated water contents than peat from the other two sites (Figures 4.8a, b). The error bars on the combined plot of saturated and field water contents overlap with the exception of the middle peat at the Straduff Townland landslide (Figure 4.8c) that had higher mean water content. All the mean values presented in Figures 4.8a,b,c are, however, consistent with literature values presented in Figures 4.6 and 4.7 and cited previously, suggesting that the peats had great quantities of water prior to failure and this factor may have influenced the peat failure mechanisms at the study sites.

Water is held in the main voids between the peat fibres (i.e. intercellular water) and in the fine voids (i.e. intracellular water) within the fibres (Berry, 1983). The proportions of these two classes of water critically affect the rate of peat consolidation (Berry, 1983) and also the liquid limit of peat. The degree of humification therefore influences the void ratio and the water content. In highly humified peat, the water content in the main voids between the peat fibres (i.e. free water) could give an indication of the consistency of peat and its flow rate in an event of a landslide. The greater the spaces between the fibres and the higher the water content, the higher the rate of flow during mass movements. A sudden addition of a small percentage of water in highly humified and colloidal peat may lead to a sudden disastrous increase of fluidity (Delap and Mitchell, 1939) because the space occupied by the voids within the fibres is reduced as result of plant decomposition. Any addition of water therefore accumulates between the fibres as free water that can readily flow.

Loss on Ignition: Loss on Ignition (LoI) values of the samples taken from the monoliths were variable within and between the sites investigated. There were generally no consistent trends of LoI with depth at the sites, which is in agreement with studies undertaken by Dykes (2008d) at the Maghera bog flow and others elsewhere (Figure 4.9). The results of this study are within the literature range of 91.7% to 99.5% (as at Dooncarton Mountain (Dykes and Warburton, 2007b) and Cuilcagh Mountain (Dykes, 2008d) respectively) for other failed blanket bog sites (Table 2.10). The variability of LoI throughout the monolith samples could reflect the differences in the degrees of peat mineralisation, the differences in the distribution of plant parts throughout the profiles and the history of the study sites. In fact, humification and mineralisation occur simultaneously in peat (Egglsmann *et al.*, 1993) and no peat deposit is free of mineral matter. For example, a distinction can be made between soil-derived quartz and plant-produced opaline silica (Clymo, 1983). Nutrients contribute to peat mineral content. In ombrotrophic peat, nutrients coming from precipitation, atmospheric dust (Charman, 2002) or from wind erosion are used by plants during photosynthesis and are released back to the peat when the plants die. Clymo (1983) and Hobbs (1986) suggested that grazing and the burning of bog over a period of time (Pearsall, 1950) can increase the peat mineral content. The high value at Slieve Rushen at 0.25 m depth could be due to difference in plant part or to low degree of humification.

Figure 4.10 shows the average values of LoI obtained from the monolith and geotechnical samples taken from the three sites. As shown by the error bars (plotted with standard errors) which overlap, the three sites cannot be distinguished. The basal peat from the Slieve Rushen landslide, however, had a higher organic content compared with the basal peat from the other two sites. This higher LoI could reflect localised different plant parts assemblages or different degrees of humification as these also affect the degrees of mineralisation.

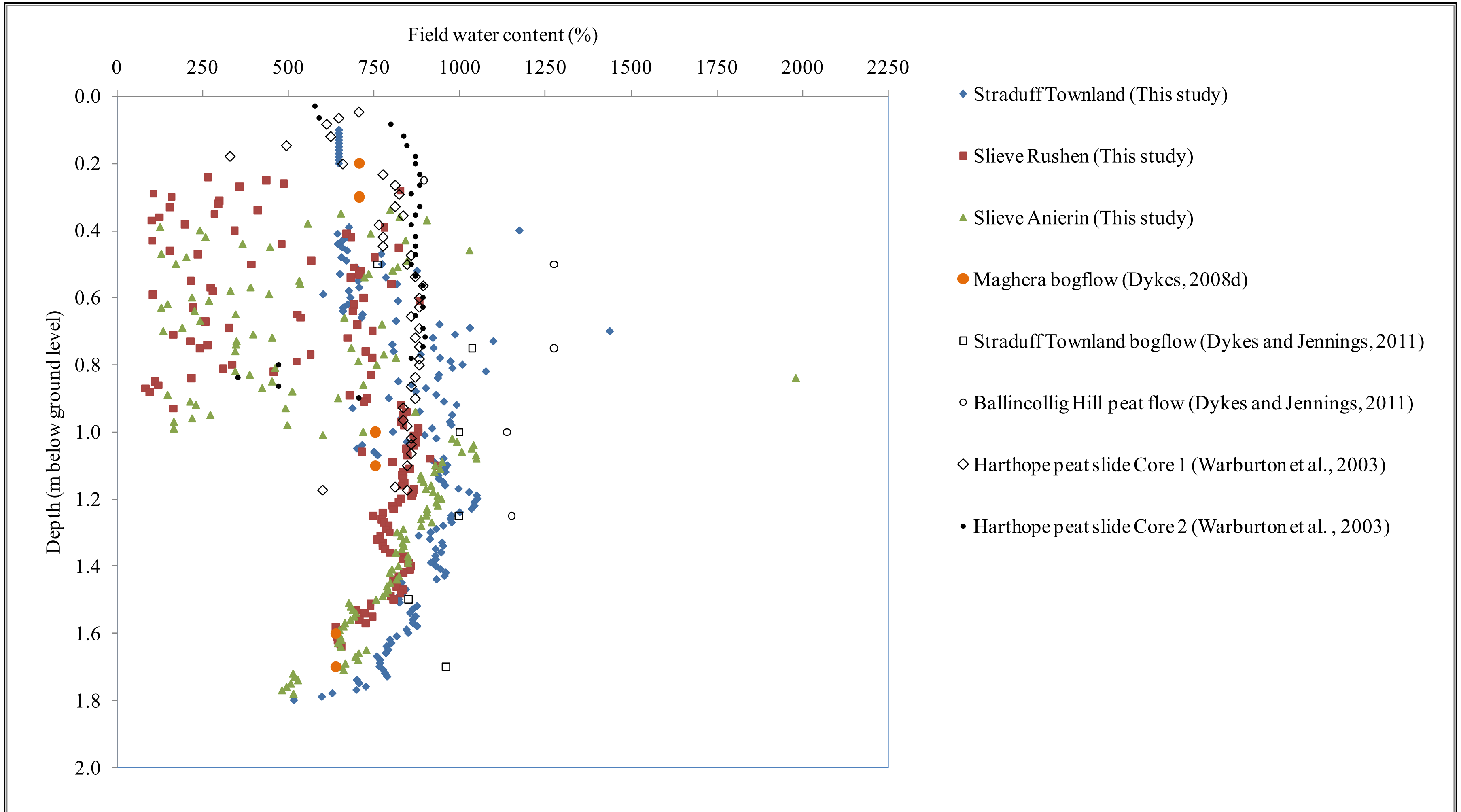


Figure 4. 6.Field water content (%) at the three landslides compared with selected literature data.

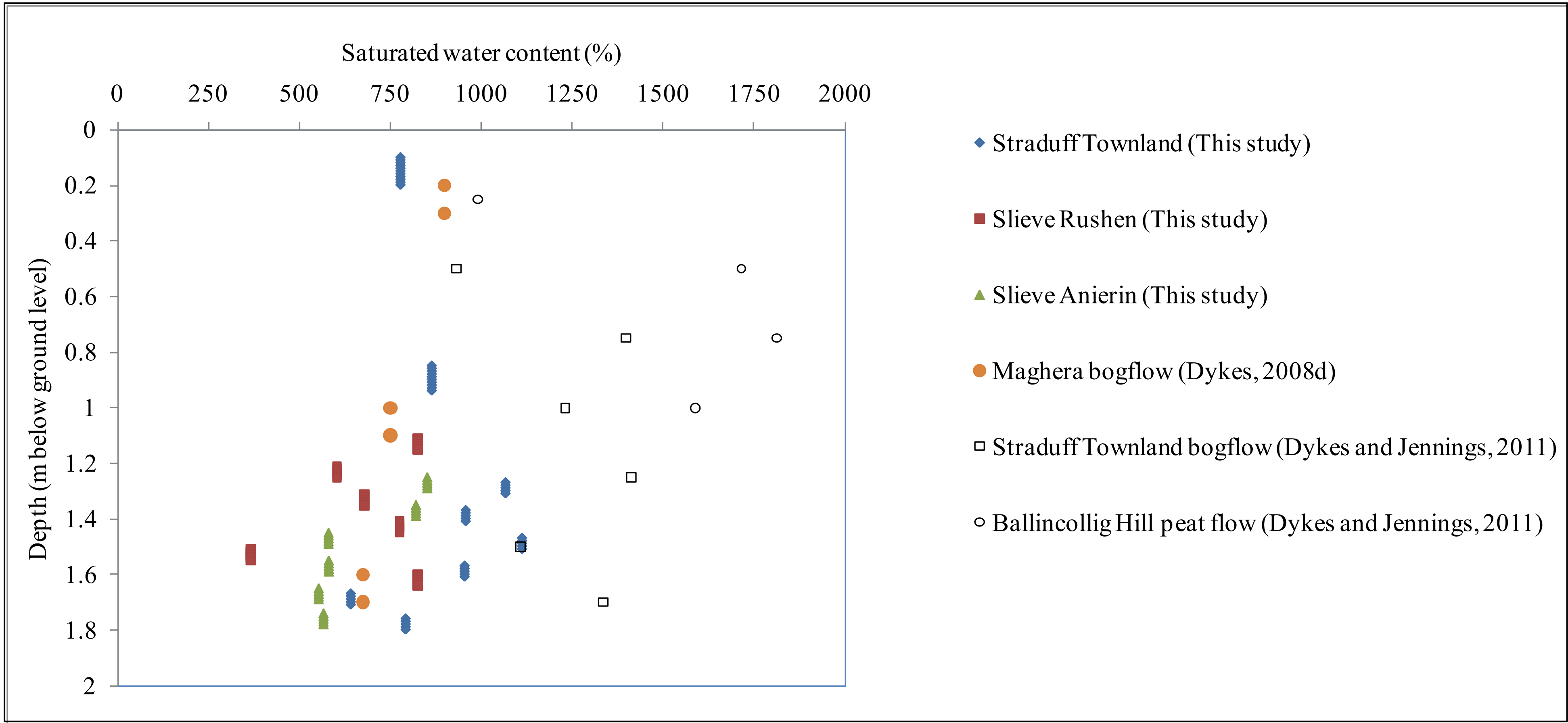


Figure 4. 7.Saturated water content (%) at the three landslides compared with selected literature data.

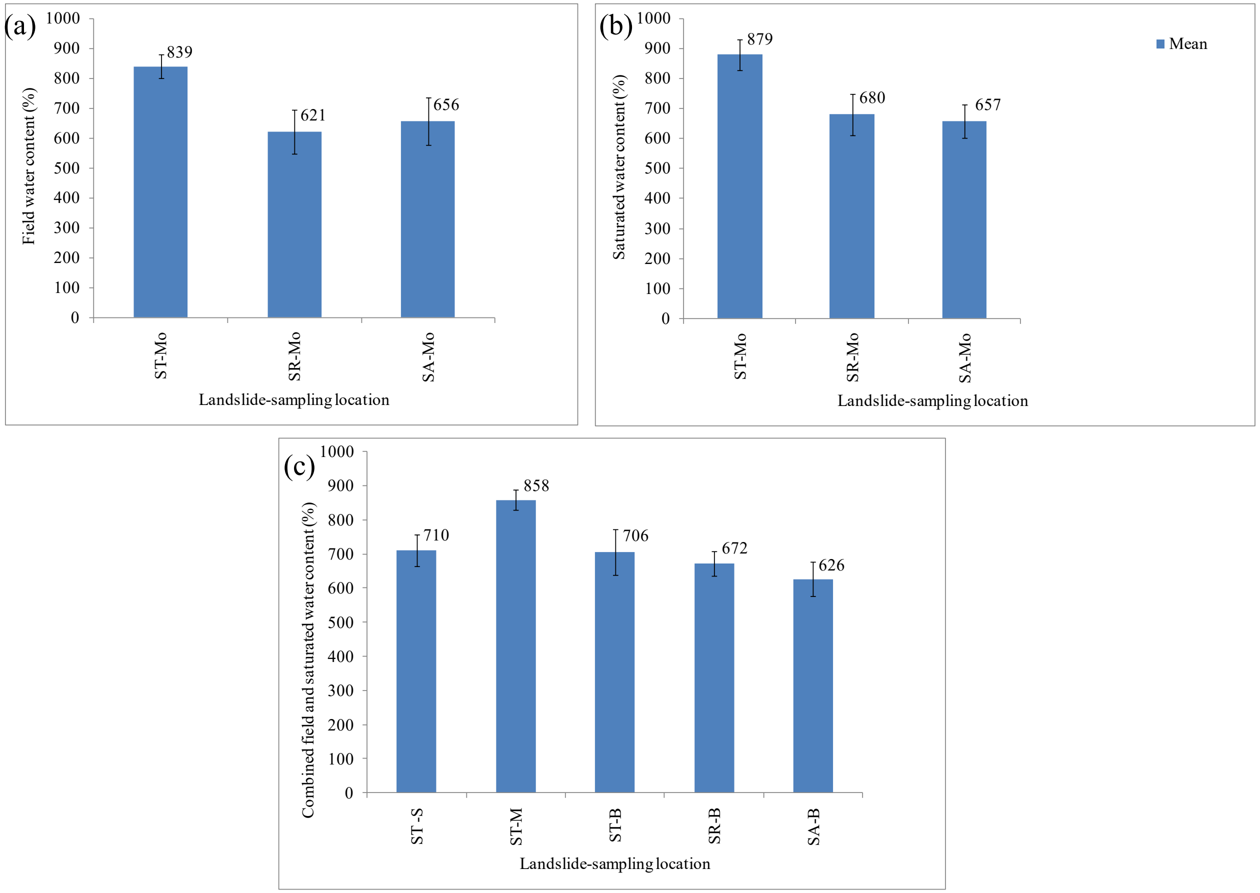


Figure 4. 8.Mean water content of multiple samples taken from the three sites (a) field, (b) saturated, and (c) combined field and saturated with error bars showing the standard errors. ST = Straduff Townland, SR = Slieve Rushen, SA = Slieve Anierin, Mo = Monolith, S = Surface peat, M = Middle peat, B = Basal peat. The number of samples are presented in brackets as follows; Field water content -Mo [ST (152), SR (142) and SA (145)]; Saturated water content- Mo [ST (30), SR (30) and SA (30)]; Combined field and saturated water contents- [S (25), M (7) and B (ST (105), SR (84) and SA (84))].The raw data are presented in Appendix A (Tables A29, A30 and A31).

The mean LoI of the basal peats and of the monoliths presented in this study is lower than the values presented in Table 2.14 (i.e. for the Straduff Townland and Slieve Anierin peat respectively). The higher LoI recorded at the study sites may be owing to their original plant materials, because peat mineral content depends on the density of the morphological features of the original plant species (Egglsmann *et al.*, 1993). Herbaceous plants (as recorded at the study sites: Section 4.1) such as sedges are denser than mosses and therefore have a much higher mineral contents and, thus, lower LoI (Clymo, 1983). Wein (1973) reported that *E. vaginatum* is rich in mineral nutrients. He suggested that *E. vaginatum* can concentrate mineral nutrients, especially phosphate, under ombrogenous conditions.

The organic content is an important geotechnical property because it affects the water holding capacity of the soil (Hobbs, 1986) and has a considerable effect on the physical and mechanical properties of peat (MacFarlane, 1969). However, the relationship is not a simple one since, as pointed out by Hobbs (1986), the water content and the manner in which the water is held is influenced by the state of the organic matter (i.e. the degree of decomposition).

Bulk density: The bulk density is an indicator of the degree of compaction of peat (Hobbs, 1986). Therefore it is an important physical property. The current study found that there is no consistent trend of bulk density with depth (Figures 4.11 and 4.12) as also reported by Alexander *et al.* (1986) for the 1984 Straduff Townland bogflow and for blanket bog in general by Marachi *et al.* (1982) and Lewis *et al.* (2011). The overlap of the error bars (showing the standard errors) in Figure 4.13 suggests that the mean saturated bulk densities of the peat monolith samples from the three landslides were not significantly different. All the mean saturated bulk densities were between 1.00 and 1.10 g cm^{-3}. Previous studies reported saturated bulk densities of 1.05 g cm^{-3} for the Slieve Anierin landslide (Dykes, 2008d) and 1.06 g cm^{-3} for the 1990/91 Straduff Townland landslide (Yang and Dykes, 2006) which are within the ranges of this study.

The mean dry bulk densities of the monolith peat samples from the Straduff Townland and Slieve Rushen landslides were not significantly different (Figure 4.14) as shown by the overlap of the error bars. The high mean dry bulk density of the monolith taken at the Slieve Anierin landslide could be due to differences in the degrees of humification and mineralisation as result of different plant parts. It could also be due to the incorporation of mineral matter from the site. All the mean dry bulk densities were however between 0.10 and 0.20 g cm^{-3}. Previous studies reported dry bulk densities of 0.13 g cm^{-3} for the 1990/91 Straduff Townland landslide (Yang and Dykes, 2006) and 0.15 g cm^{-3} for the Slieve Anierin landslide (Dykes, 2008d). Highly humified peats and herbaceous peats (e.g. with *E. vaginatum*) have shown higher dry bulk densities of about 0.12 to 0.22 g cm^{-3} (Clymo, 1983). Therefore, the mean bulk densities reported in this study are consistent with literature values for herbaceous peat in general.

Although the water contents and bulk densities obtained from this study do not reflect the conditions of the blanket bogs at the time that the landslides took place, they enabled estimates to be made of the mass of dry peat and water released in each case (Table 4.3).

Table 4. 3.Mass of peat and water released during the three landslide events.

Parameter	Straduff Townland	Slieve Rushen	Slieve Anierin
Total volume of material (m^3)	35,000[a]	20,000[b]	22,000[c]
Monolith mean dry bulk density ($g\ cm^{-3}$)	0.1	0.1	0.2
Dry mass of peat (tonnes)	3500	2000	4400
Mass of water (tonnes)	31,500	18,000	21,600

Notes
[a]Dykes (2009)
[b]Dykes (2008a)
[c]Yang and Dykes (2006)

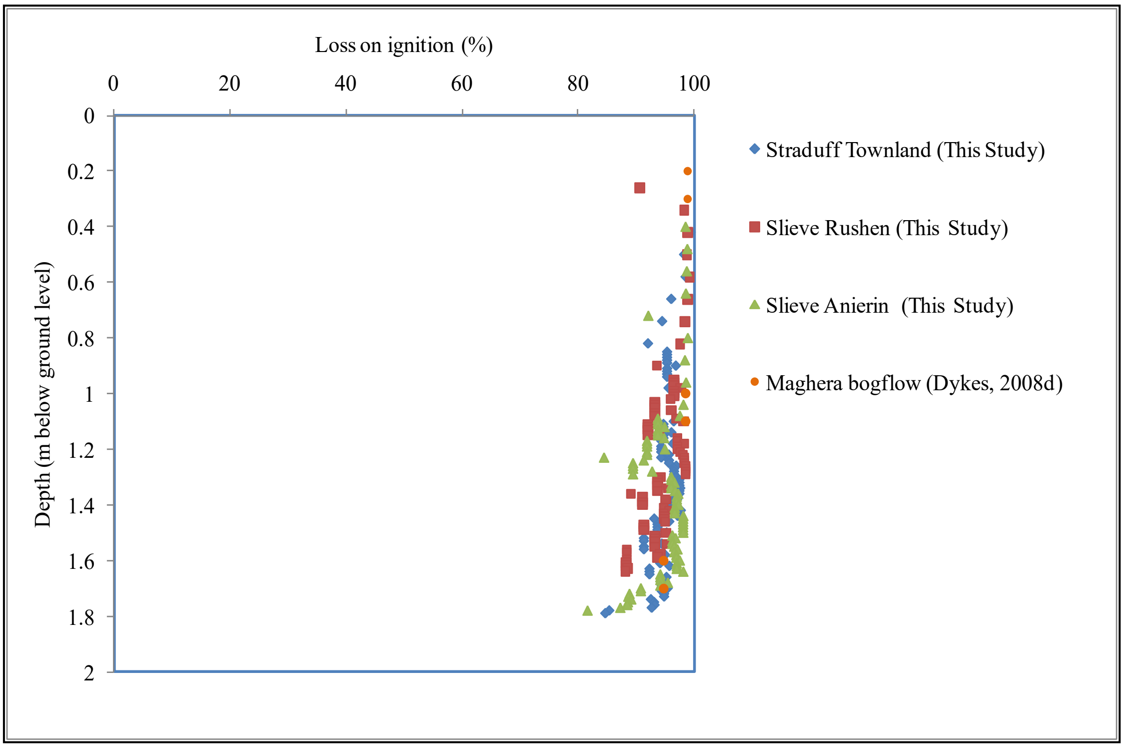


Figure 4. 9.Loss on Ignition (%) at the three landslides compared with selected previous work on Irish blanket bogs.

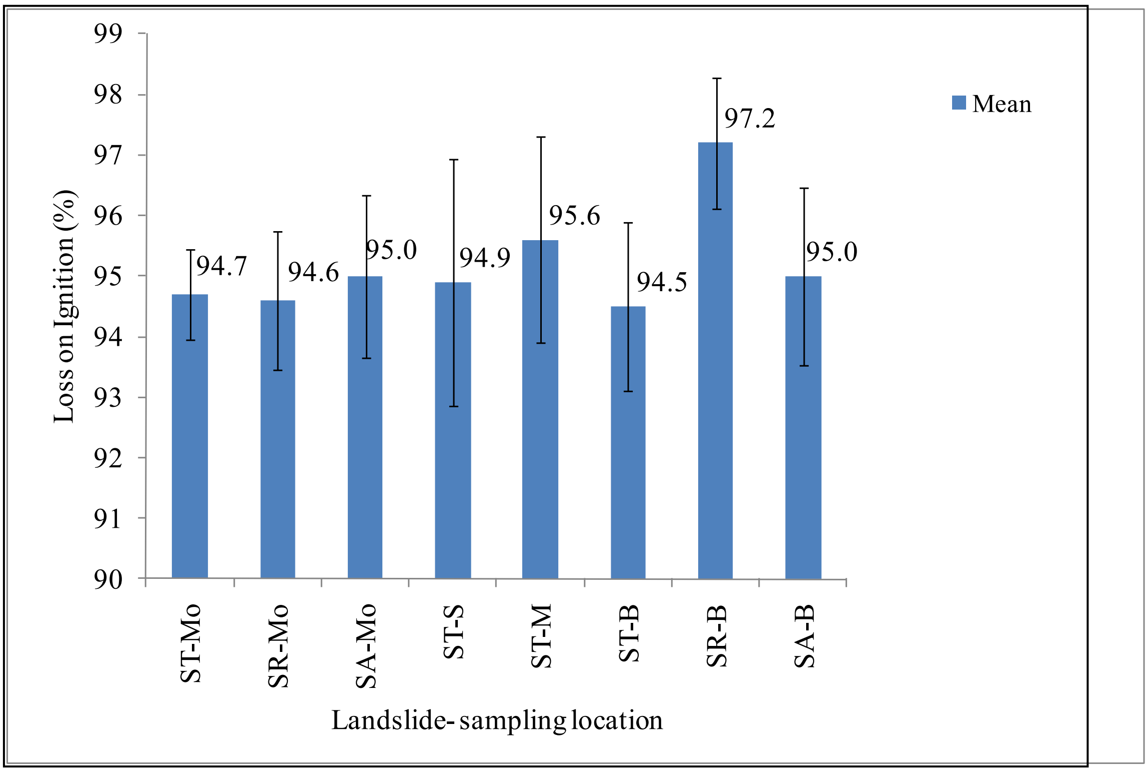


Figure 4.10. Mean Loss on Ignition (%) of peat monolith and samples from the three landslides with error bars showing the standard errors.ST = Straduff Townland, SR = Slieve Rushen, SA = Slieve Anierin, Mo = Monolith, S = Surface peat, M = Middle peat, B = Basal peat. The number of samples are presented in brackets as follows; Mo [ST (86), SR (79), and SA (80)]; S (15), M (11) and B [ST (84), SR (44) and SA (80)].The raw data are presented in Appendix A (Tables A29, A30 and A31).

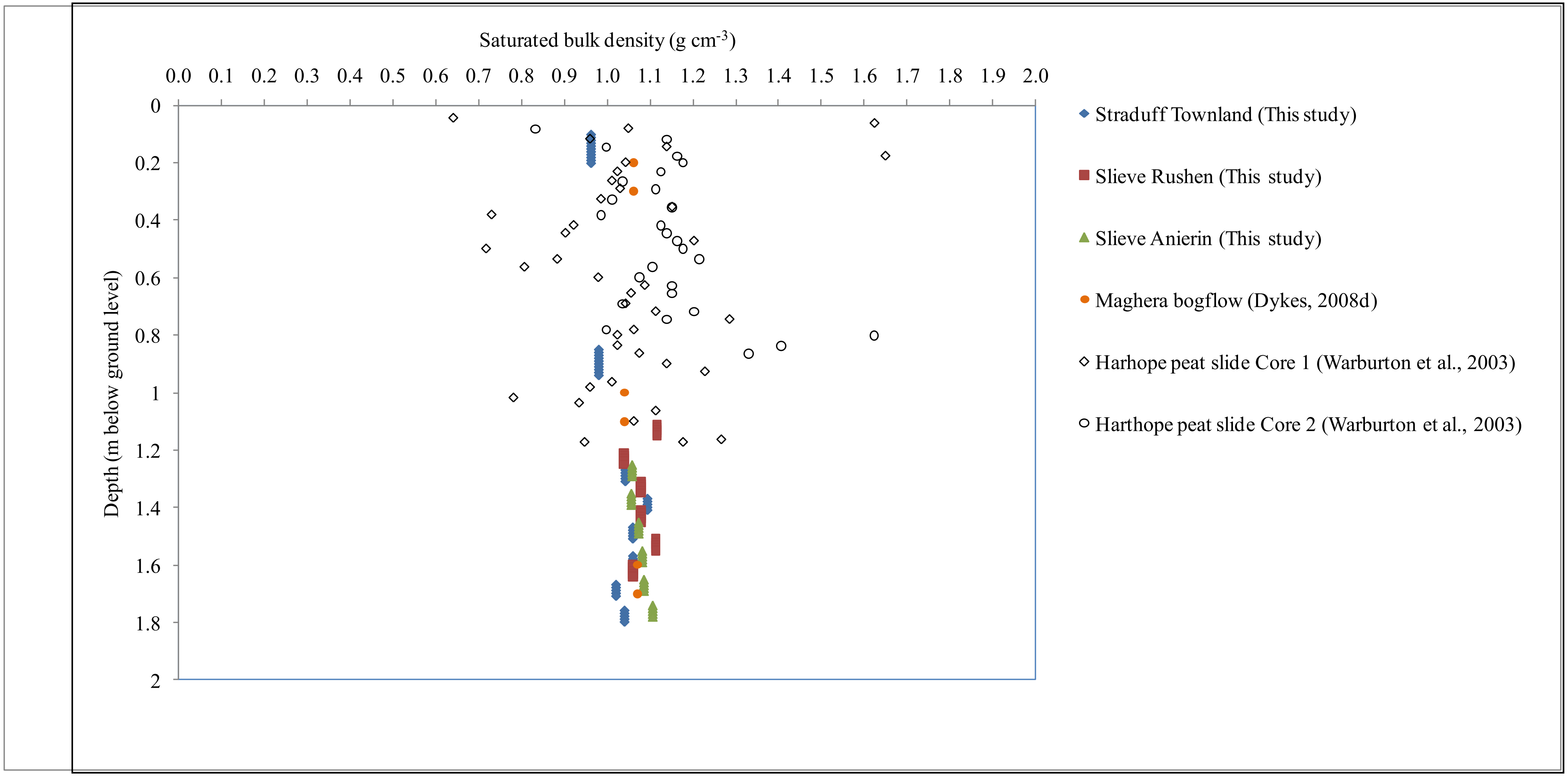


Figure 4. 11. Mean saturated bulk density (g cm^{-3}) at the three landslides compared with some literature data.

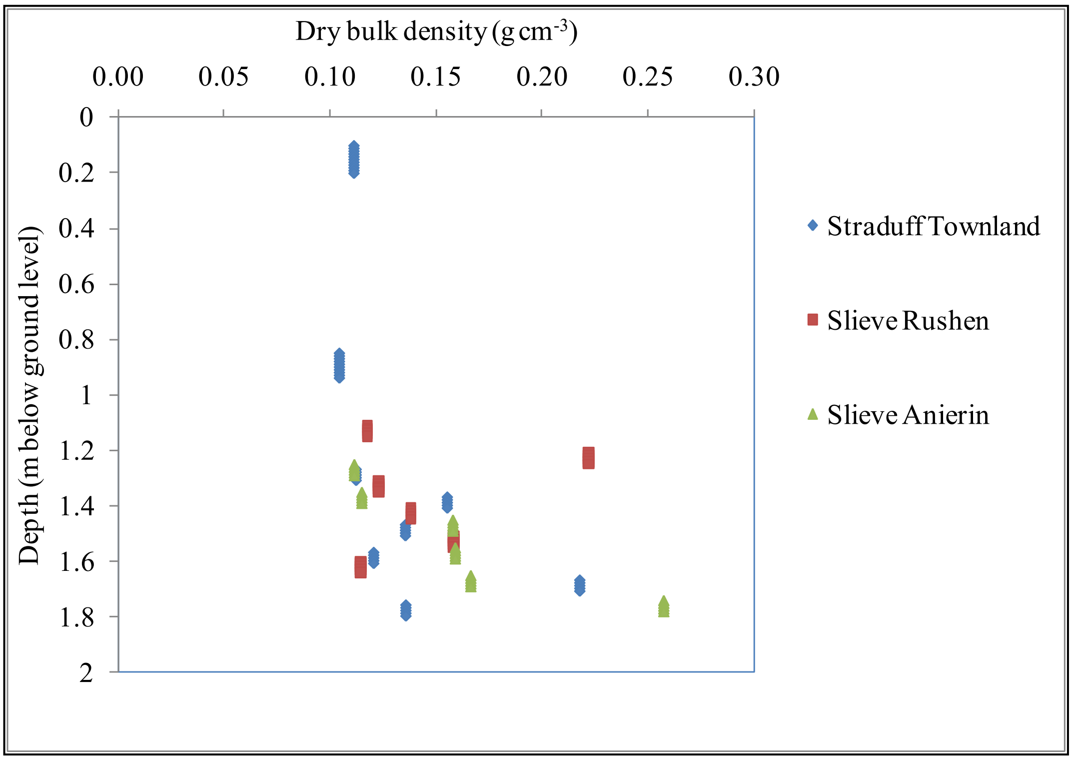


Figure 4. 12. Mean dry bulk density (g cm^{-3}) at the three landslides.

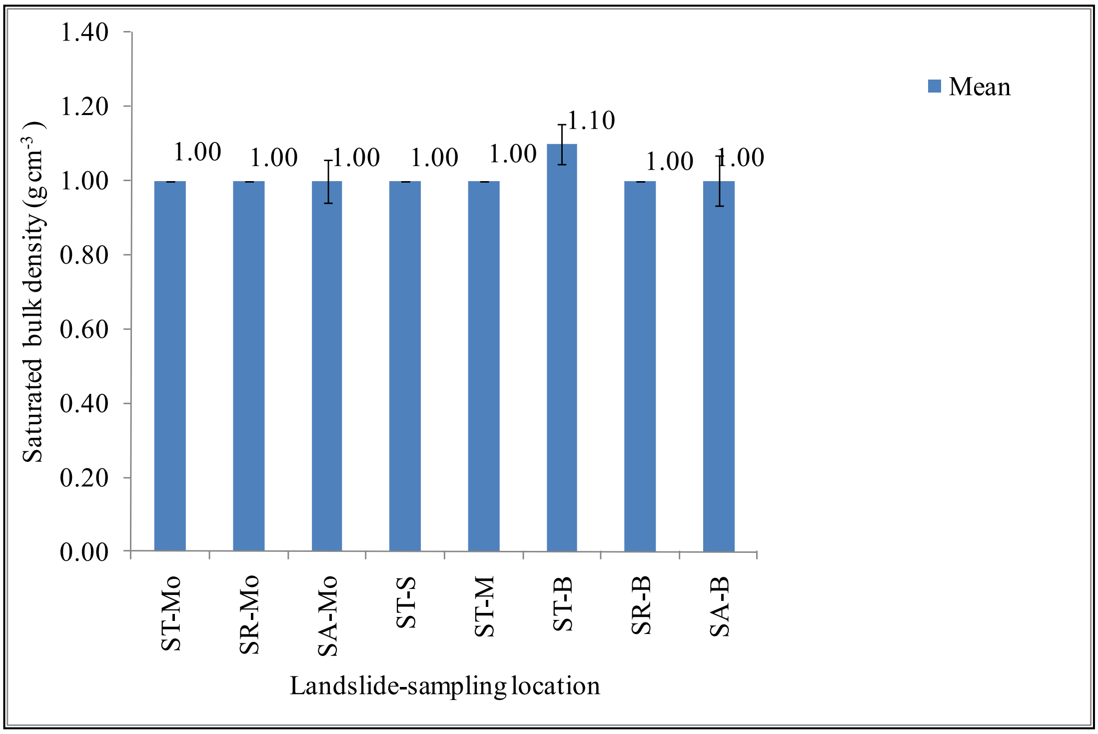


Figure 4. 13. Mean saturated bulk density (g cm^{-3}) of peat samples taken at the three landslides with error bars showing the standard errors. ST = Straduff Townland, SR = Slieve Rushen, SA= Slieve Anierin, Mo = Monolith, S = Surface peat, M = Middle peat, B = Basal peat. The number of samples are presented in brackets as follows; Mo (9 for all the sites), S and M (3 for all the sites); B [ST (11), SR (5), and SA (5)]. The raw data are presented in Appendix A (Tables A29, A30 and A31).

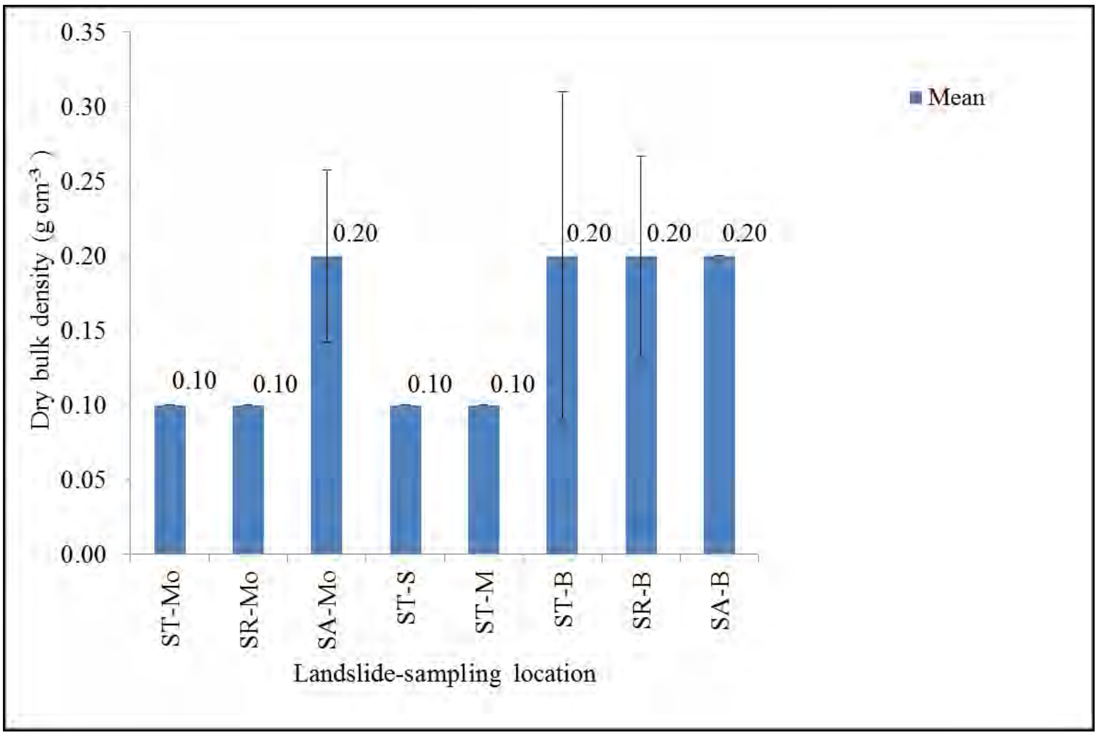


Figure 4. 14. Mean dry bulk density (g cm^{-3}) of peat samples taken at the three landslides with error bars showing the standard errors. ST = Straduff Townland, SR = Slieve Rushen, SA= Slieve Anierin, Mo = Monolith, S = Surface peat, M = Middle peat, B = Basal peat. The number of samples are represented in brackets as follows; Mo (9 for all the sites), S and M (3 for all the sites); B [ST (11), SR (5), and SA (5)]. The raw data are presented in Appendix A (Tables A29, A30 and A31).

Saturated hydraulic conductivity (horizontal): The results of this study show that there is no relationship between saturated hydraulic conductivity and peat depth at the three landslides (Figure 4.15), which is consistent with the results of peat samples taken in the acrotelm at the Maghera bogflow by Dykes (2008d) and measured using the constant head method. The finding is also consistent with previous work on other peatlands and types of peat failures (Chapter 2; Table 2.10). The mean constant head saturated hydraulic conductivities of monolith samples from the Slieve Rushen and Slieve Anierin landslides were similar while those of the Straduff Townland landslide were lower. The basal peat at Straduff Townland had a higher constant head saturated hydraulic conductivity compared with the middle and surface peats. These results are consistent with the ranges recorded at the 1990/91 Straduff Townland (Dykes, 2008d), Slieve Anierin (Yang and Dykes, 2006) and Maghera (Dykes, 2008d) bogflows. The saturated hydraulic conductivities of all the peat samples analysed using the two methods were consistent with the ranges reported in the literature (e.g. Rycroft *et al.*, 1975; Hobbs, 1986; Evans and Warburton, 2007; Dykes, 2008d).
Figure 4.15 represents the mean values of saturated hydraulic conductivities of monolith samples and multiple peat samples taken at the three sites. In this study, higher values for the saturated hydraulic conductivity were obtained using the falling head method. This could be explained by the entrapment of gas or air in the constant head instrument or within the peat. In fact, oxygenation of water may have occurred and subsequently caused further peat oxidation or gas entrapment within

its voids, leading to a reduction of the saturated hydraulic conductivity with time. It could also be the case that the constant head instrument, as presented in this study, is inappropriate for peat in terms of the dimensions (for example, the ratio $\frac{L}{AH}$: Equation 3.5 varies with sample dimensions). Theoretically, the longer the peat specimen (L) and the smaller the cross-sectional area of cylinder containing the peat (A) and the hydraulic head difference across length L (H), the higher the saturated hydraulic conductivity. However, larger than appropriate hydraulic gradients can cause finer peat particles to migrate downstream and clog the pores, therefore reducing the flow rate of water and the hydraulic conductivity. It follows from the above that there is a need to use a consistent and appropriate method for measuring peat hydraulic conductivity.

The vertical hydraulic conductivity could reflect the rates at which water infiltrates during rainfall from the surface peat (acrotelm) to the basal peat (catotelm) in a peatland with no preferential flow pathways (such as tension cracks and pipes). This study suggests that the actual vertical hydraulic conductivity at the study sites may be lower than the measured horizontal hydraulic conductivity, which is often higher than the vertical hydraulic conductivity (Beckwith *et al.,* 2003a) as discussed in Chapter 2 (Section 2.4.1).

This variability of hydraulic conductivity recorded in many studies could also be attributed to (1) the variability of methods and sample dimensions used for the respective analyses (Lewis *et al.*, 2011) and (2) the geometry of the sample, the distribution of water-filled pores in the sample and also on the characteristics of the fluid including the viscosity, the density, the polarity of fluid particles and the density of the electrical charge of the matrix surface and finally in the phase (i.e. whether is liquid or gaseous) (Eggelsmann *et al.*, 1993). It should also be noted that Darcy"s Law, which is used to calculate the saturated hydraulic conductivity, may not be applicable to highly humified peat. In particular, the accumulation of gas bubbles in peat below the water table can give rise to non-Darcian behaviour in peat (Baird, 1995) and critically affect the hydraulic conductivity.

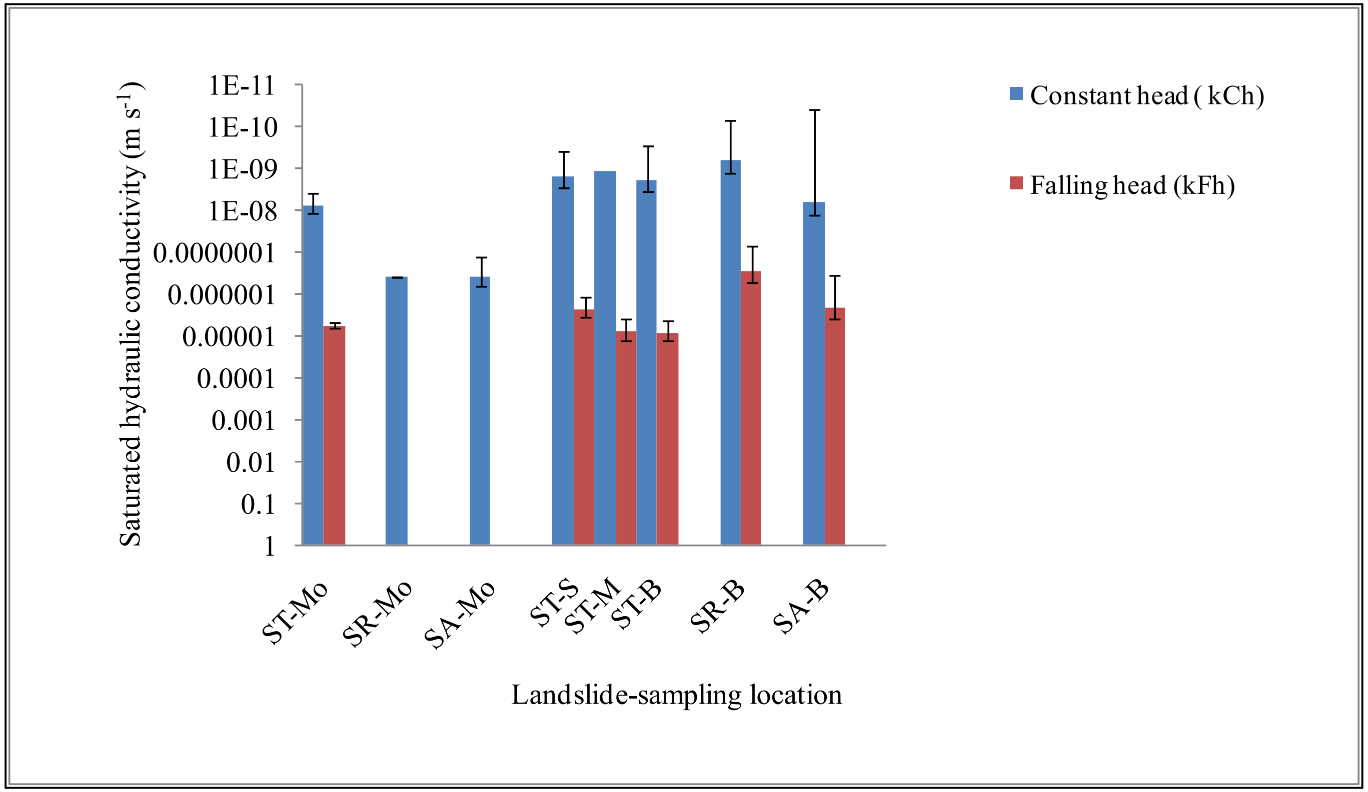


Figure 4. 15. Mean saturated hydraulic conductivity (m s^{-1}) of multiple peat samples taken from the three landslides with error bars showing the standard errors. ST = Straduff Townland, SR = Slieve Rushen, SA= Slieve Anierin, Mo = Monolith, S = Surface peat, M = Middle peat, B = Basal peat. The number of samples are presented in brackets as follows; for kCh, Mo (9 for all the sites), S and M (3 for all the sites); B [ST (11), SR (4) and SA (5)]. For kFh Mo (9) and B= 3 for all others). The raw data are presented in Appendix A (Tables A29, A30 and A31).

4.3.2- Effective structural properties

Humification and fibre content: Fibre content and degree of humification are important peat characteristics (Malterer *et al.,* 1992). The degree of humification is usually closely linked with the proportion of fibres, hence with the mechanical and hydraulic properties of peat (Clymo, 1983). The results of the current study indicate that the values of „raw‟ percentage of light transmission, as quantitative measures of the degree of humification, were generally variable and scattered at the three sites as shown in Figure 4.16. There was no general trend with depth at the Slieve Anierin landslide, but the values decreased with depth at the Straduff Townland landslide and seemed to increase down to 1.4 m below ground level at Slieve Rushen. The mean values of „raw‟ percentage of light transmission of the basal peat (Table 4.4) were low and in agreement with the higher degree of humification (von Post) observed in the field as discussed in Section 4.2.1. Figure 4.17 shows that the average „raw‟ percentages of light transmission of the monoliths and basal peat samples taken across the three sites, excluding the results from the monolith sampling points, cannot be differentiated as suggested by the overlap of the error bars showing the standard errors.

The low „raw‟ percentage of light transmission of the basal peats is consistent with the study of Blackford and Chambers (1995) for a blanket peat monolith sample from western Ireland. These results are also consistent with some works on other types of peatlands such as the intermediate raised-blanket mire at Coom Rigg Moss, Northumberland (Charman *et al.* 1999) and the Raeburn Flow raised bog (Mauquoy and Barber, 1999) with a more diverse original plant community as presented by Yeloff and Mauquoy (2006). The general variability of the results of „raw‟ percentage of transmission with depth are likely to reflect the varying influences of chemical, environmental and biological factors on the rate of plant types and plant parts decay with time as explained in Chapter 2 (Section 2.4.1). These findings suggest continuous peat decay in both the aerobic acrotelm and the anaerobic catotelm, and a possible decrease of basal peat strength with time. In general, shallow peat, owing to its more fibrous nature, is likely to have greater strength than more humified peat at depth (Kazemian *et al.*, 2011).

No previous studies have stratigraphically delimited the peat profile, based on the degree of humification measured in the laboratory as shown in Figure 7.18, for the purpose of investigating peat instability. The trend of „raw‟ percentage of light transmission at the study sites does not always reflect the von Post degree of humification or the laboratory measured humus fraction as defined in this study, both of which increase with depth. This could be owing to (1) the smaller sampling interval (0.01 m) used for „raw‟ percentages of light transmission compared to the other two methods, or (2) the fact that all of the methods are assessed differently. In any case, the degree of humification is an important peat characteristic (Malterer *et al.*, 1992) because it influences the structure of peat. In engineering practice, it is well known that the more fibrous the peat, the higher the tensile strength and shear strength, void ratio and water content (Bell, 2000). The type, the length and amount of fibres in peat influence its strength (Helenelund, 1967), and because of the influence of the fibres, peat has unusually high angles of internal friction (Hanrahan, 1954; Hanrahan *et al.*, 1967).

The results of this study indicate no general trends of different fibre fractions (as defined Section 3.3.6) with depth at the three study sites (Figure 4.19). The mean „total fibre fraction" (Ft) of the monolith samples was between 56.1% and 71.0% with the Slieve Rushen peat being more fibrous (Figure 4.20). However, the three sites cannot be distinguished in terms of total fibre contents as suggested by the overlap of the error bars plotted with the minimum and maximum values.

Table 4.5, which is derived from the cluster analyses of the fibre contents (Figure 4.21), shows that at all three sites the humus fraction (particles <0.15 mm) increased with depth. Coarse fibres (>1 mm) and the total fibre contents (i.e. fibres >0.15 mm) decreased with depth. The fine fibres did not show a consistent depth variation across the three sites.

Figures 4.22 and 4.23 show higher humus fractions at the base of the peat (Zone 1) at all three sites and a higher content of fibres >1 mm in Zone 2. Although the entire peat profile could not be fully analysed at any one site, it appears that the distributions of fine fibre fractions are erratic throughout the monoliths, but that the other fibre fractions yield consistent trends with depth across all three sites. In fact, the overlaps of the error bars plotted with the standard deviations show that the mean fibre contents of the zones delimited at the three sites cannot be distinguished.

Table 4. 4. Comparisons of mean „raw" percentages of light transmission for the different stratigraphic zones at the three landslides.

Parameter	**Straduff Townland**	**Slieve Rushen**	**Slieve Anierin**	**Trend of parameter with depth at the three landslides**
	Z:3,2,1	*Z:3,2,1*	*Z:3,2,1*	
Transmission (%)	70,39,23	29,36,18	35,42,16	Low at the base for all the sites
Potential weak zone depth (m)	*0.30*	*0.02*	*0.02*	*0.02-0.30*

Notes

See Tables A6, A14 and A22 for the raw data and Tables A7, A15 and A23 for the numbers of samples considered, in Appendix A. The numbers in positions a, b and c correspond with mean values for Zones (Z) 3, 2 and 1 respectively. The results of basal peats include the samples taken across the sites and presented in Figure 4.16.

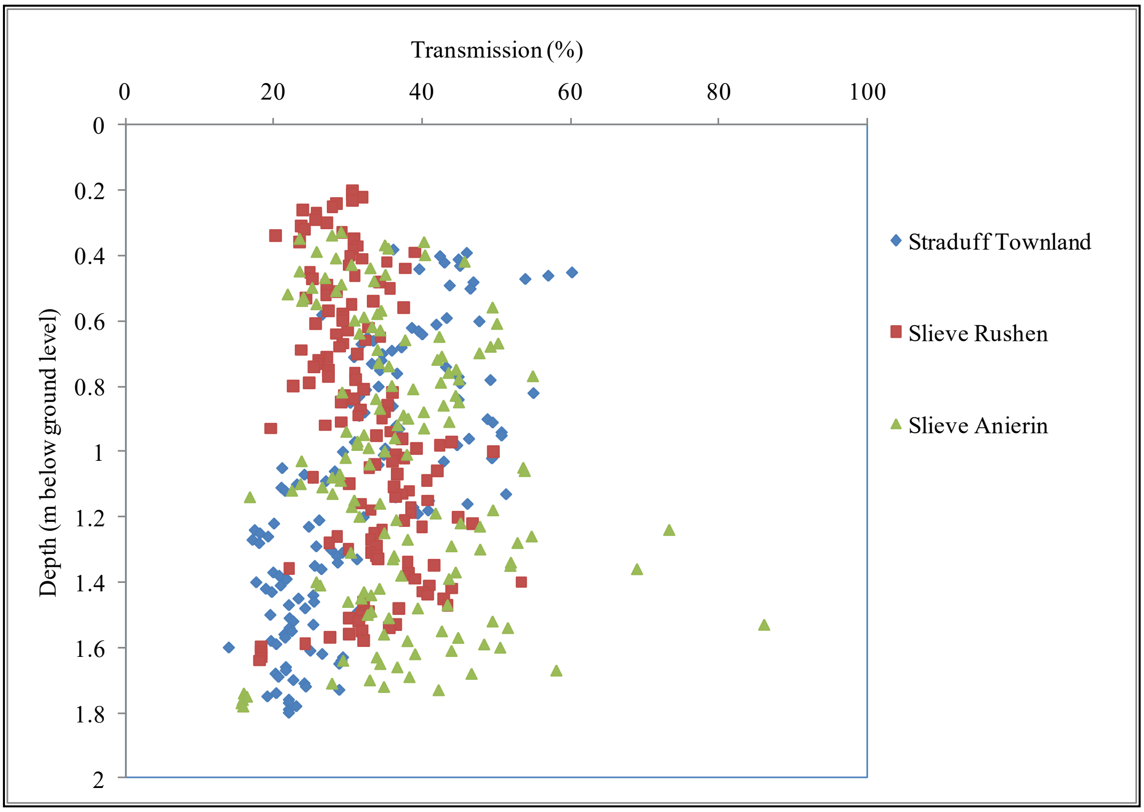


Figure 4. 16. „Raw" percentage of light transmission at the three landslides.

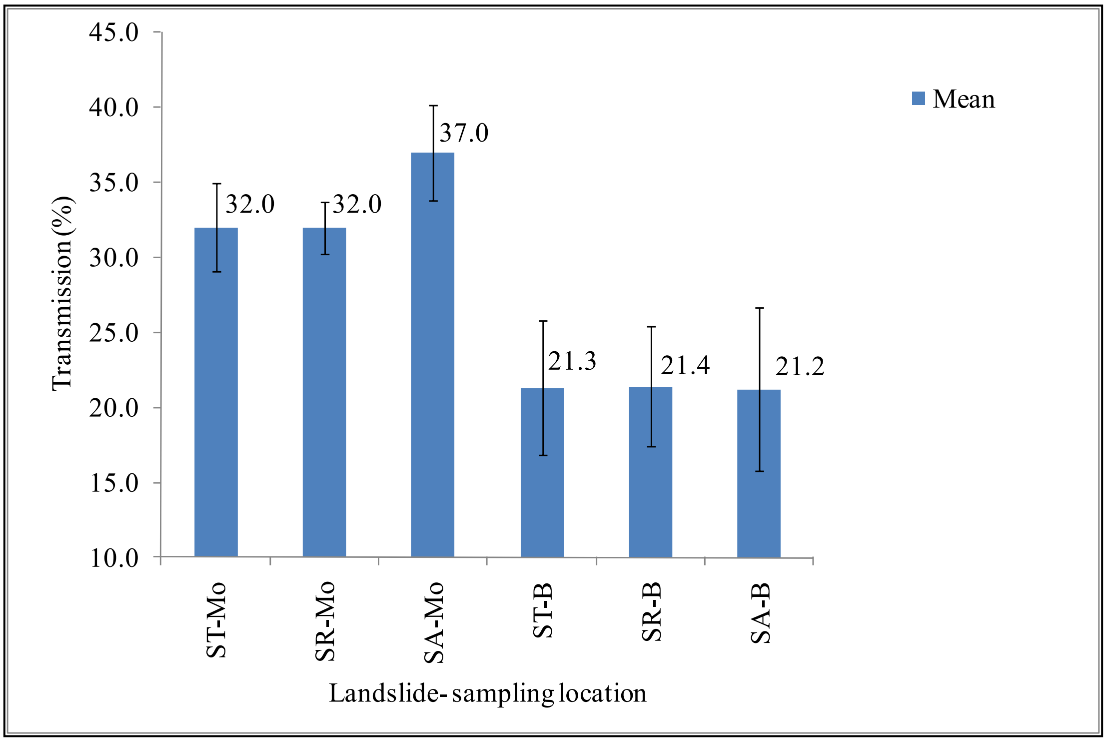


Figure 4. 17. Mean „raw" percentage of light transmission (%) of peat samples taken across the three landslides (excluding the sampling points) with error bars showing the standard errors. ST = Straduff Townland, SR = Slieve Rushen, SA = Slieve Anierin, Mo = Monolith. The number of samples are presented in the brackets as follows; Mo [ST (135), SR (144), and SA (146)]; B [ST (25), SR (35) and SA (28)]. The raw data are presented in Appendix A (Tables A29, A30 and A31).

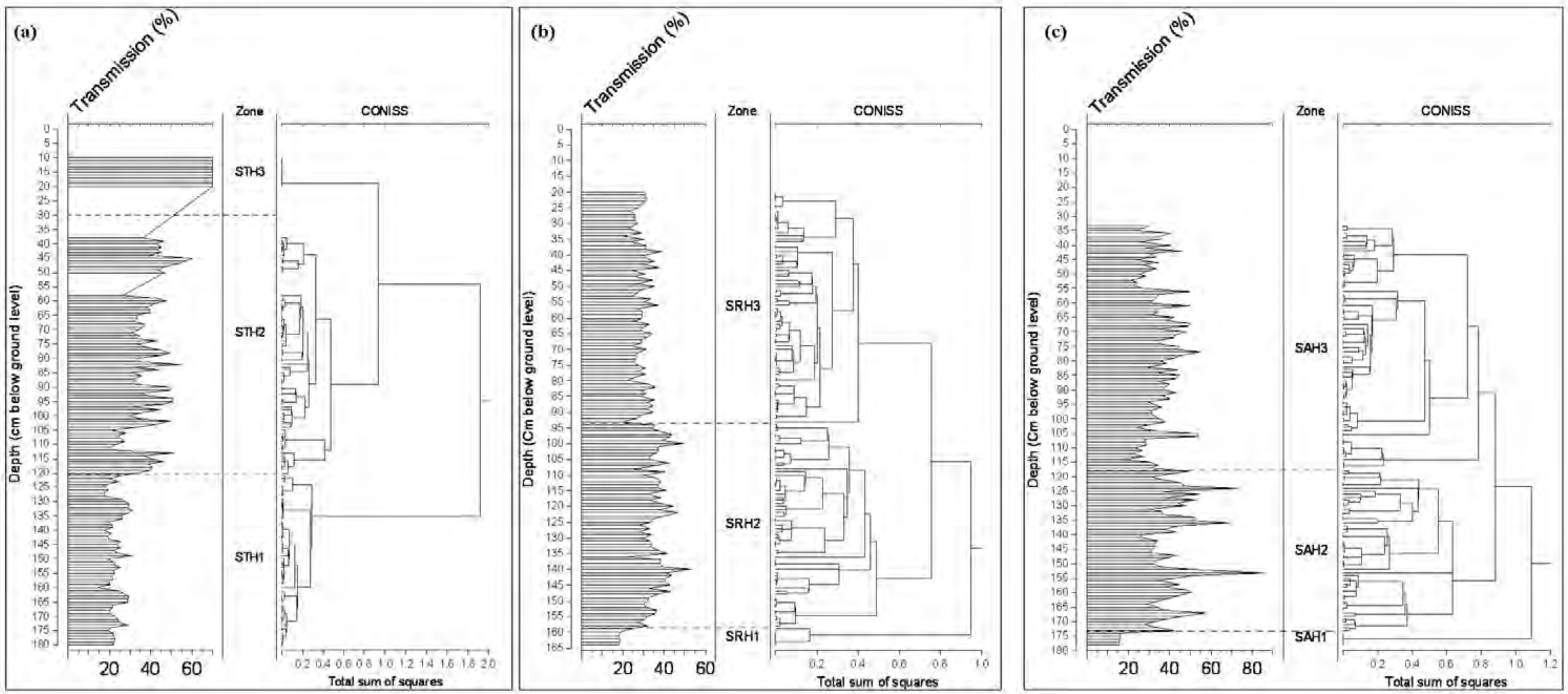


Figure 4. 18. Quantitative estimates of peat humification at three landslides. (a) Straduff Townland, (b) Slieve Rushen and (c) Slieve Anierin. Dashed lines separate clusters corresponding to zones in the diagram. Results from the basal peat represent mean values of multiple samples taken across the site (Figure 4.16). The vertical axes are in centimetres (cm) instead of metres (m) in accordance with previous palaeoecology literature work on peatlands.

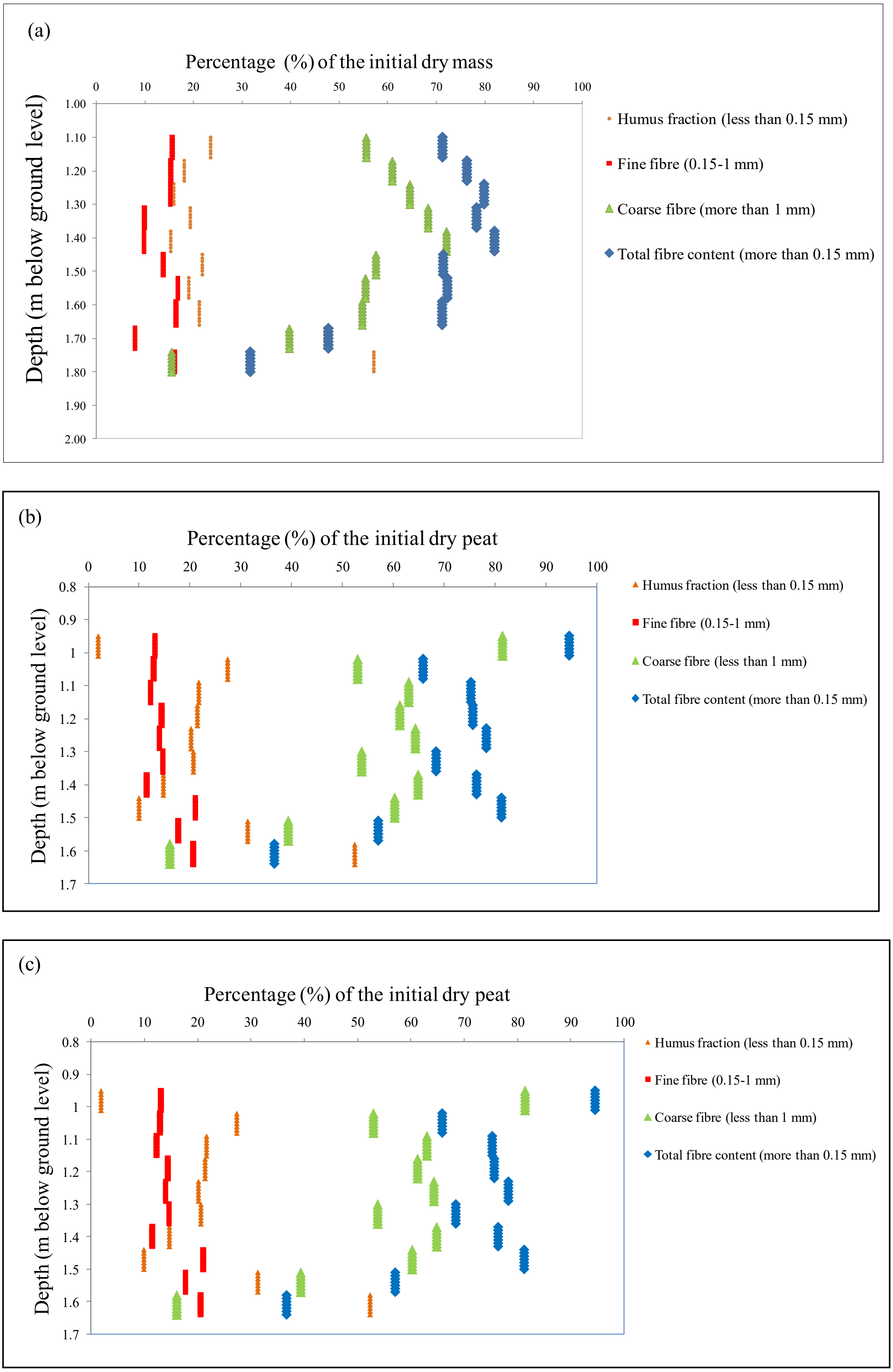


Figure 4. 19. Depth variations of peat fibre content at the three landslides: (a) Straduff Townland, (b) Slieve Rushen and (c) Slieve Anierin.

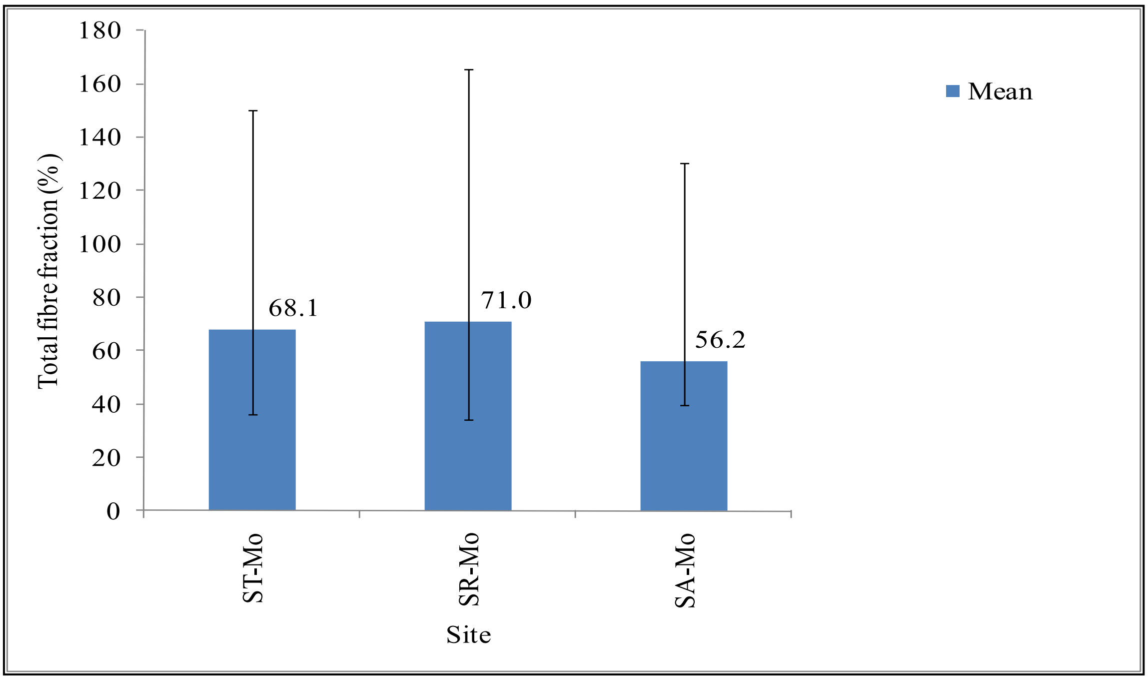


Figure 4. 20. Mean total fibre fraction (%) of peat samples from the three landslides with bars showing the minimum and maximum values. ST = Straduff Townland, SR = Slieve Rushen, SA= Slieve Anierin, Mo = Monolith. The analyses were done with 70 consecutive measurements per site. The raw data are presented in Appendix A (Tables A29, A30 and A31).

Table 4. 5. Comparisons of the mean fibre contents of the stratigraphic zones at the three landslides.

Parameter	**Straduff Townland**	**Slieve Rushen**	**Slieve Anierin**	**Trend of parameter with depth at the three landslides**
	Z:2,1	*Z:2,1*	*Z:2,1*	
Humus fraction (particles <0.15 mm)	19,52	17,42	31,59	increase with depth
Fine fibre (particles 0.15-1 mm)	14,12	14,19	14,14	variable with depth
Coarse fibre (particles <1 mm)	61,28	63,28	50,12	decrease with depth
Total fibre content (particles >0.15 mm)	75,40	77,47	64,27	decrease with depth
LoI	94,92	94,89	94,85	decrease with depth
Potential weak zone depth (m)	*0.70*	*0.06*	*0.11*	*0.06-0.11*

Notes See Appendix A (Table A8, A16 and A24) for the raw data and the numbers of samples considered. All values are in %. The first number is the mean value for Zone (Z) 1 and the second is the mean value for Zone 2.

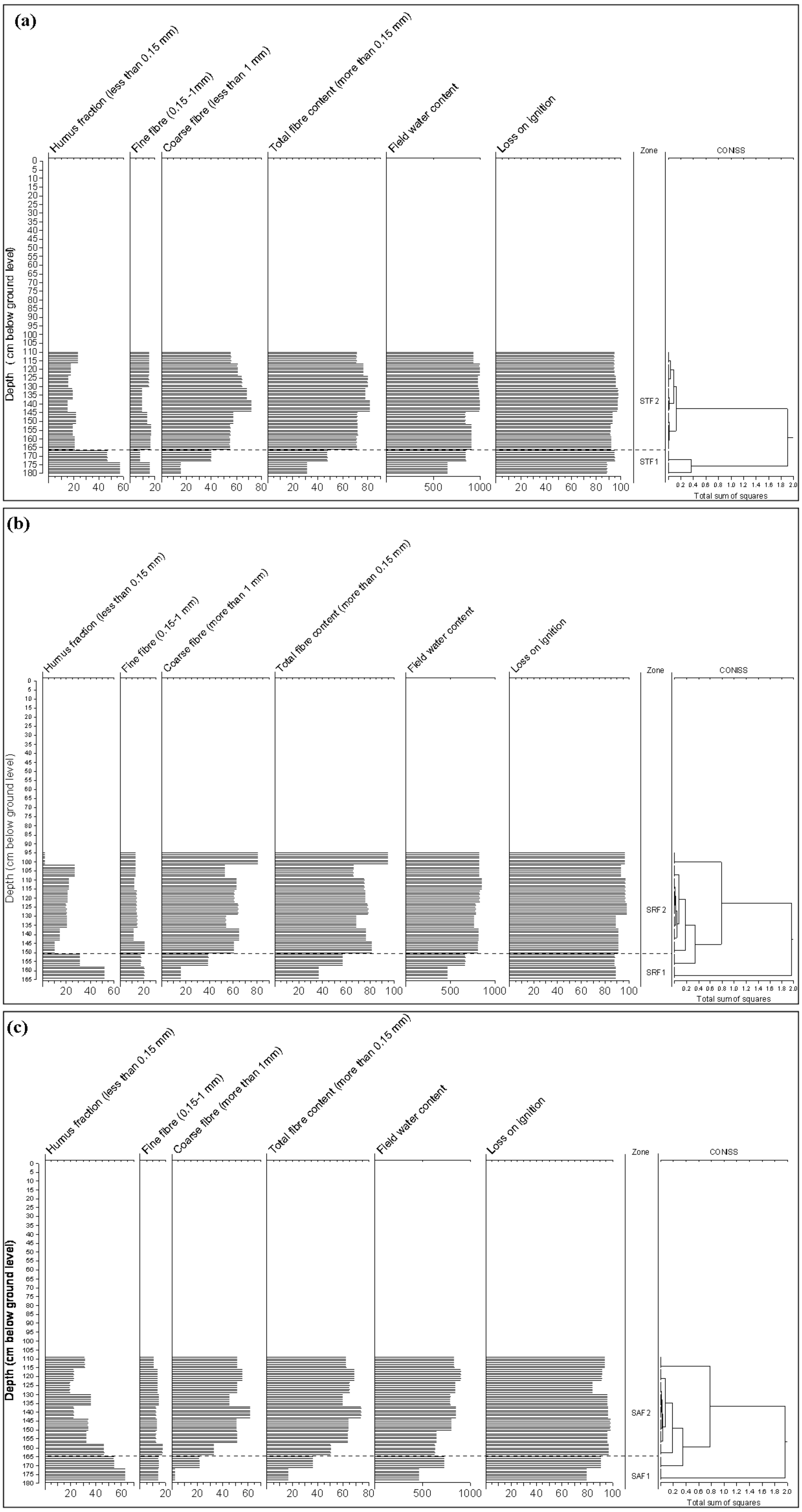


Figure 4. 21. Depth variations of peat fibre contents at the three landslides (a) Straduff Townland, (b) Slieve Rushen and (c) Slieve Anierin, showing the dendrogram produced from unconstrained incremental sum square cluster analysis of the strata investigated. Dashed lines separate clusters corresponding to zones in the diagram. All values are in %. The vertical axes are in centimetres (cm) instead of metres (m) in accordance with previous palaeoecology literature work on peatlands.

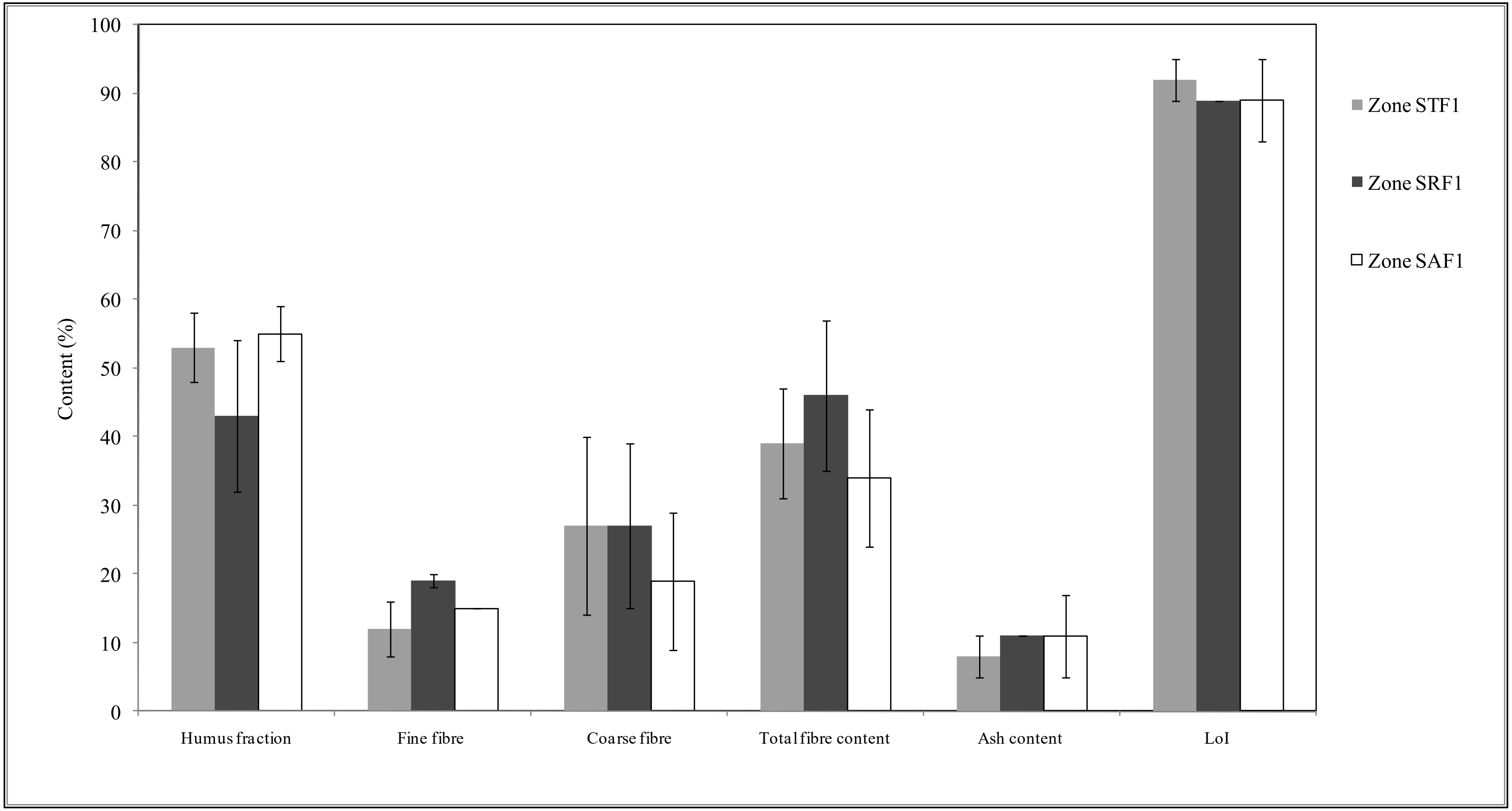


Figure 4. 22. Basal peat (Zone 1) fibre content at the three landslides with error bars showing the standard deviations. The statistical analyses were done using 14 measurements per site. ST = Straduff Townland, SR = Slieve Rushen and SA= Slieve Anierin.

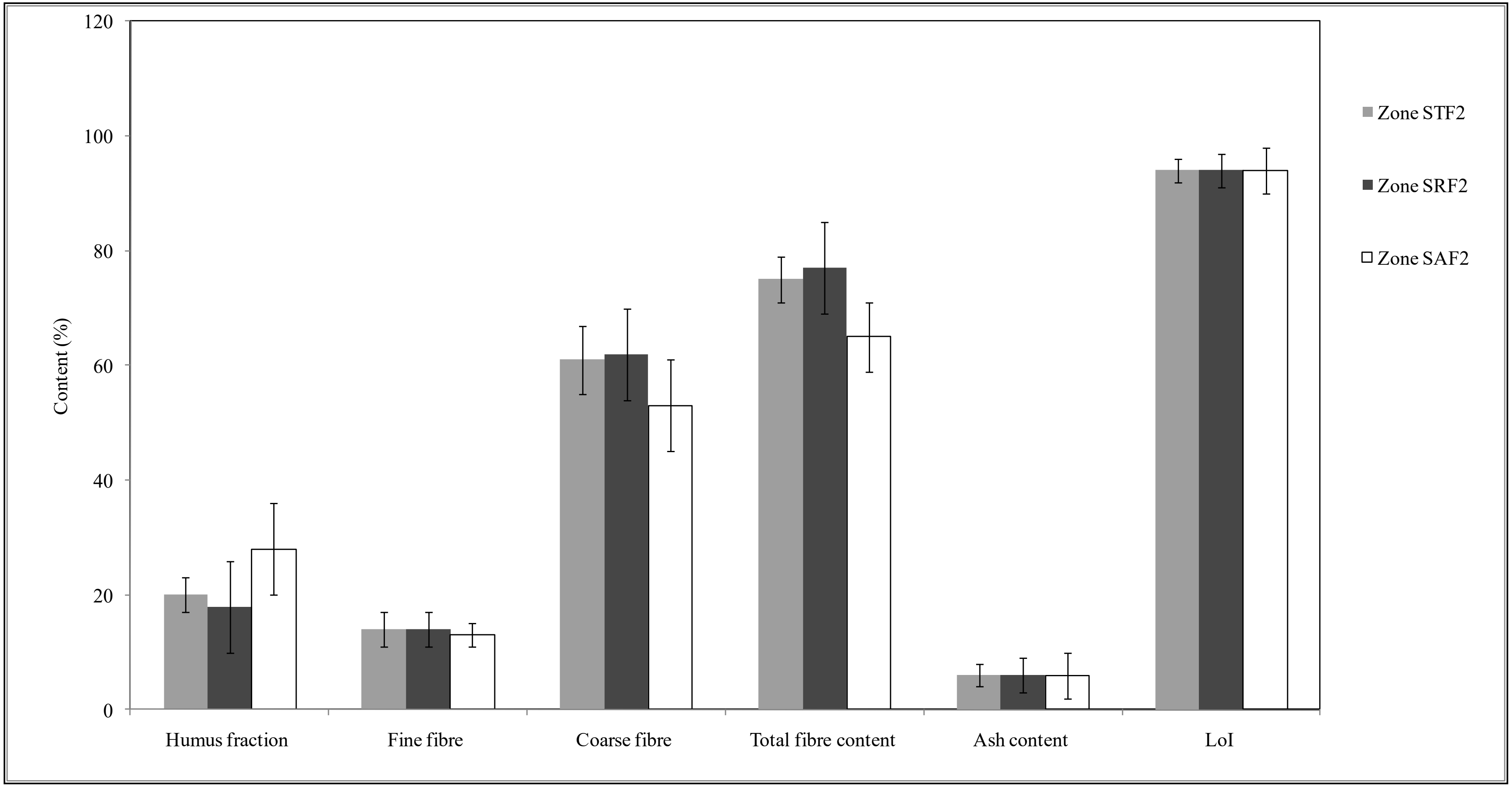


Figure 4. 23. Zone 2 fibre content at the three landslides with error bars showing the standard deviations. The statistical analyses were done using 56 measurements per site**.** ST = Straduff Townland, SR = Slieve Rushen and SA= Slieve Anierin.

Macrofossil content: The results of this study show that the blanket bog at all three sites comprised mainly the remains of monocotyledon plants (with abundant *E. vaginatum*) (Figure 4.24) (Appendix A; Figure A2). As shown in Table 4.6, monocotyledon contents were lowest in the basal peat zones (Zones 1 and 2 at Straduff Townland, Zone 1 at Slieve Rushen and Slieve Anierin) when compared with the upper zones. The Table also shows that root counts in each zone decreased with depth at all three blanket bogs. Ericales remains were low throughout the monolith samples from the three sites. *Sphagnum* sp remains were absent from the Straduff Townland and Slieve Anierin landslides but present in Zone 2 at the Slieve Rushen landslide. Unidentified organic matter increased with depth at the Straduff Townland and Slieve Anierin landslides. Unidentified organic matter was variable throughout the monolith at the Slieve Rushen landslide with the highest value recorded in the basal zone. Clymo (1983) suggested that different plants decay at different rates so it is not in general possible to reconstruct the vegetation history in detail.

It is difficult to ascertain whether the basal peats were monocotyledon-dominated because of the high proportions of unidentified organic matter content. Coulson and Butterfield (1978) suggested that the dominance of *Eriophorum* sp in peat could be owing to this plant being less attractive to soil fauna like earthworms that rework the plant material and therefore influence the degree of decomposition. This would imply that the original plant community was more variable than the findings of this study perhaps suggest. However, Clymo and Harwad (1982) showed that monocotyledons have higher rates of decomposition compared with other bog plants like *Sphagnum* sp. or Ericales. Therefore some remains of *Sphagnum* sp and Ericales would be expected to have persisted in the peat and to have been found as macrofossil remains if the bogs studied contained significant quantities of these plants during peat accumulation. The occurrence of significant proportion of *Sphagnum sp* and *Ericales* which have different physiology and morphological features may have influenced the strength properties of peat.

The results of this study show charcoal fragments in the peat from the three landslides (Figure 4.24). Counts of charcoal fragments of length 0.5-1 mm were variable and low throughout the monoliths. Analysis of charcoal in peat samples is the most comprehensive means of reconstructing fire events in peatlands. Such analyses enable an evaluation of the interaction between different biotic and anthropogenic factors including the vegetation, climatic and human disturbances (Patterson *et al.*, 1987). Macrofossils of 0.5 to 1 mm in size are generally assumed to be autochthonous because they are heavier and, therefore, less likely to have been transported to the site by wind. Charcoal fragments of less than 0.5 mm length were recorded throughout the monoliths from the study landslides. These could be either autochthonous or from other fires that occurred far away but were transported to the site by wind. The results therefore suggest that the study blanket bogs had been subjected to moorland fires at some point in their development. Charcoal can result from subsurface fires (Boyd, 1982; Moore, 1982). The restricted access of oxygen in the sub-surface layers does not represent an impediment to charcoal formation, with low oxygen availability preventing total combustion and therefore being a necessary condition for the production of charcoal (Clark and Russell, 1981). However, wood and some plant tussocks, for example, often survive such subsurface fires (Clark and Russell, 1981). In conclusion, although in most cases charcoal layers in peat are probably indicators of fire that occurred during the accumulation of the peat layer in which the charcoal occurs, the possibility of sub-surface fires must be borne in mind as discussed by Clark and Russell (1981). This suggests that charcoal fragments cannot be used a proxy of paleoevironment of a specific peat layer that influence its structure thus its strength properties.

Not all uplands in the British Isles have homogenous and monocotyledon (with *E. vaginatum*) dominated peats (Chambers *et al.*, 1997) like those at the study sites. Peat stratigraphy studies of blanket peat in England (e.g. Southern Pennine upland peat: Conway, 1954 and the Featherbed Moss peat; Tallis, 1965), in Scotland (e.g. Moine Mhor upland peat: Barker *et al.*, 2000) and in the Republic of Ireland (e.g. the upland peat at Slievenakilla Townland, Co. Leitrim: Hammond, 1981 and at Glenulra, County Mayo: Bragg and Tallis, 2001) have shown more variable macrofossil assemblages (i.e. including *Sphagnum* sp in all cases) throughout the profiles investigated. The results of this study further suggest that there could be a possible link between monocotyledons (especially with *E. vaginatum*) peat and bogflow-type failure.

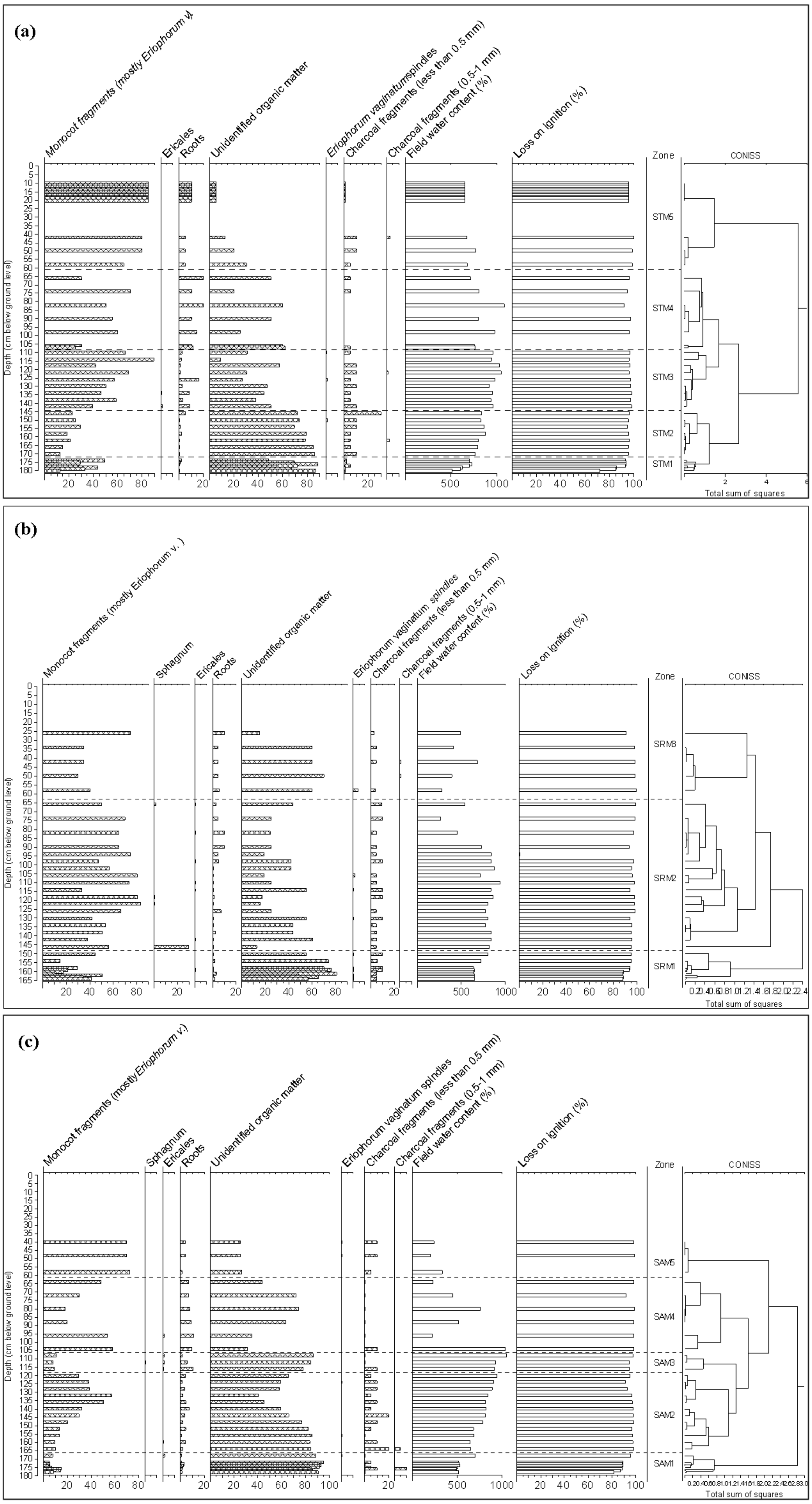


Figure 4. 24. Macrofossil content of the peat monolith from the three landslides: (a) Straduff Townland, (b) Slieveh Rushen, (c) Slieve Anierin. Parameter values are raw counts for charcoal and *E. vaginatum* spindles, otherwise percentages. The figure shows the dendrogram produced from unconstrained incremental sum square cluster analysis of strata analysed. Dashed lines separate clusters corresponding to zones in the diagram. The vertical axes are in centimetres (cm) instead of metres (m) in accordance with previous palaeoecology literature work on peatlands.

4.4- COMPARISON OF PEAT STRENGH PROPERTIES AND STABILITY ASSESSMENTS AT THE LANDSLIDES

Peat strength values not only depend on the peat structure as presented in the previous section but also on the method of its determination, as discussed in Chapter 2 (2.4.2). The following sections compare the results of peat strengths measured *in situ* and in the laboratory using different instruments as part of this study with previous research.

4.4.1- *In situ* vane test

Figure 4.25 shows measurements of peak shear strength obtained using the *in situ* vane test at the three landslides. The results of this study show that the undrained shear strengths decreased with depth, although the trend is less apparent in the results from the Slieve Anierin site. Measured shear strengths varied from 6.6 kPa at the Straduff Townland landslide to 14 kPa at the Slieve Rushen landslide. The values (4 to 14 kPa) obtained from this study are within the range of 2.0-37.3 kPa for the Maghera bogflow (Dykes, 2008d) but also within the ranges of other works on peat in general (e.g. Figure 4.25). The values obtained for the Straduff Townland landslide (i.e. 9.8 and 6.6 kPa) as part of this study were lower than those of Dykes and Jennings (2011) (15-27 kPa) for the same site. The higher strength recorded at Slieve Rushen could be explained by the reduction of moisture between plant particles in the peat owing to (i) pre- or post-failure evaporation through surface tension cracks, (ii) evapotranspiration through the root of *Calluna vulgaris* that was found to be dominant around the source area during the first visit in 2010 or (iii) owing to drainage of peat following the landslide as the samples were taken from the margin of the landslide. It should be noted that the influence of high temperature cannot be completely assessment because the specific date of the landslide is unknown.

The results obtained from this study confirmed that the vane test could be used to investigate depth variations of peat strength and assess potential weak zones. However, the investigation carried out by several authors (e.g. Dykes and Jennings, 2011) showed that undrained strength varies with depth and the data are scattered (Figure 4.25). For example the results of Marachi *et al.* (1982) on peat of 0.050 to 0.075 m deep revealed an undrained strength of 14.0-23.8 kPa. Piggot *et al.* (1992) reported a mean shear strength value of 5.5 kPa, ranging from approximately 3-39 kPa, for raised bog peat of 0.3-4.1 m depth.

In view of the single sample point per site in this study and the limited number of other studies on bogflows, it is difficult to ascertain whether there is a general reduction of the *in situ* shear strength of peat with depth at bogflow sites. The synthesis clearly shows that the undrained shear strength measured with the *in situ* vane varies with depth across most peatlands. This variability and inconsistency of vane test results on peat can be explained by the variability of the dimensions of the vanes used in different studies and the heterogeneity of the peat tested. Furthermore, the „undisturbed" peak undrained and remoulded undrained shear strengths obtained from the vane test follow the assumptions that: (1) penetration of the vane causes negligible disturbance, both in terms of changes in effective stress and shear distortion; (2) no drainage occurs before or during shear;

(3) the peat is isotropic and homogeneous; (4) the peat fails on a cylindrical shear surface; (5) the diameter of the shear surface is equal to the width of the vane blades; (6) at peak and remoulded strength there is a uniform shear stress distribution across the shear surface; and (7) there is no progressive failure, so that at maximum torque the shear stress at all points on the shear surface is equal to the undrained shear strength (Chandler, 1988). These assumptions are rarely, if ever, likely all to be valid, particularly with respect to peat material that is very complex and heterogeneous. In estimating the significance of the vane test results in a particular case, attention should be drawn to the shape of the stress-strain curve. This is not often reported with vane measurements and can have more than one peak value (Helenelund, 1967). In fact, vane rotation does not always cause shear failure along the periphery of the vane. Instead, the fibrous peat is bent outwards. If the peat is elastic enough it partly recovers its shape when the vane assumes an orientation equivalent to its original one (i.e. after rotation through an angle equal to that between two adjacent vane blades). The torque measured using an ordinary vane test may therefore not give reliable values for shear strength of fibrous peat.

The strength of fibrous peat depends mainly on the number and strength of fibres and root threads and on internal friction between the fibres (Helenelund, 1967). Landva (1980) demonstrated that smaller vanes give higher apparent strengths, as would be expected on account of the fibre action relative to the size of vane. However, the dimensions of vanes used for testing peat material are often missing from the vane measurements reported in the literature. The results of the investigation carried out by Landva (1980), as presented in Figure 4.25, are not applicable to truly fibrous sedge peat or any purely amorphous peat deposit such as is the focus of this study.

4.4.2- Direct shear test

Results from the experimental low-stress direct shear tests without pre-consolidation are shown in Figure 4.26. As noted by Foteu *et al.* (2012), the interpretation of these results is highly problematic although the general trend of shear stress to increase with applied load can be noted. The failure envelopes for most soils are curved towards zero strength at zero normal stress (Atkinson, 1993). These curves show that the strength appears to be increasingly frictional as the normal stress reduces, probably due to the resistance of fibres to applied stresses (Hanrahan, 1954; Hanrahan *et al.*, 1967) when the test is carried out using low normal load as used in this study. In fact, the results of the fibre content analysis showed that although the basal peats at the study sites were highly humified, they contained 27 to 47% of „total fibres‟ (Table 4.5). It is possible that during the tests, the compression of the fibres produces a resistance to shearing that increases to a critical point at which failure occurs. The higher the normal load, the quicker the fibres aligned themselves to the direction of shearing and the smaller the effect of fibre reinforcement. Conversely, smaller normal stresses could induce more progressive peat compression therefore increasing resistance to shearing, leading to increasing frictional strength but lower strength.

Table 4. 6. Comparisons of the mean macrofossil contents of the stratigraphic zones at the three landslides.

Parameter	Straduff Townland	Slieve Rushen	Slieve Anierin	Trend of parameter with depth at the three landslides
	Z:5,4,3,2,1	*Z:3,2,1*	*Z:5,4,3,2,1*	
Charcoal fragments (less than 0.5 mm) (count)	3,4,7,8,2	3,6,6	8,2,4,9,4	Variable (i.e. 2-9)
Charcoal fragments (0.5-1 mm) (count)	0,0,0,0,0	0,0,0	0,0,0,0,2	None (rare i.e. 0-2)
E. vaginatum spindles (count)	0,0,0,0,0	0,0,0	1,0,0,0,0	None (rare i.e. 0-1)
Field water content (%)	700,886,962,820,670	437,693,700	505,535,938,790,579	Variable (i.e. 503-962)
LoI (%)	96,95,96,94,84	97,95,91	99,98,94,96,90	Variable (i.e. 84-98)
Saturated water content (%)	779,864,1011,896,793	-,721,597	-,-,-,693,560	Variable (i.e. 560-1011)
Transmission (%)	53,37,27,23,22	29,34,27	32,39,29,42,30	Low at the base; Zone 1 at all sites
Monocot fragments (mostly *E. vaginatum*) (%)	83,48,56,23,29	52,59,27	65,36,14,30,9	Low at the base; Zone 1 at all sites
Roots (%)	9,12,5,1,0	6,3,1	4,9,5,3,1	Decrease with depth (i.e. 0-9)
Unidentified organic matter (%)	8,45,38,75,70	53,34,68	26,55,78,66,89	Increase at ST and SA and high at the base, i.e. Zone 1 at SR
Sphagnum (%)	Not detected	0,2,0	0,0,0,0,0	None (rare i.e. 0-2)
Ericales (%)	Not detected	0,0,0	0,0,1,0,0	None (rare i.e. 0-1)
Potential weak zone depth (m)	0.06	0.07	0.05	*0.05-0.07*

<u>Notes</u> See Appendix A (Tables A9, A17 and A25) for the raw data and Appendix A (TablesA10, A18 and A26) for the numbers of samples considered. The numbers in positions a, b, c, d and e correspond to mean values for Zones (Z)5,4,3,2 and 1 respectively (where „-" means no data available)

Research on peat strength using the experimental conditions presented in this thesis is rare and none has previously been carried out on bogflow-type failures. Most direct shear tests carried out on samples of peat from bogflows or other failed sites (as summarised by Dykes, 2008b) used standard experimental conditions. For example, Dykes (2008d) tested peat samples from the Maghera bogflow using normal stresses of 5.0-30.0 kPa and a shearing rate of 5 mm min^{-1} which gave cohesions of 5.2 and 16.4 kPa and angle of internal frictions of 33.4 and 0º respectively. However, the Maghera bogflow block samples of peat were taken from 1.1 and 1.6 m deep and not at the base as is the case at the study sites for this thesis. The only work presented in the literature that used similar experimental conditions is that of Dykes (2008b) carried out with peat samples from the Cuilcagh Mountain bogslide (Dykes and Kirk, 2006). Results from this study are consistent with those obtained by Dykes (2008b) as can be seen in Figure 4.26. The low strengths obtained for the peat samples taken at the study landslides are consistent with their physical properties (e.g. degree of humification) analysed in the laboratory and also with the evidence from the field work carried out at the sites.

Figure 4.27a shows some stress-displacement plots from tests in which the shear stress clearly attained a maximum value, indicating the probable formation of a failure plane within the respective samples. However, many of the samples did not develop failure planes associated with maximum shear stresses, probably because the maximum test displacement of 11 mm was insufficient. Therefore, the maximum shear stresses registered may be underestimates. The plots of force versus displacement presented in Figure 4.27a also show smooth curves that do not always represent the behaviour of heterogeneous fibrous peat under an applied load. These results suggest that the fibres may have less influence on the direct shear test than the peat matrix. It should be noted that the structure of peat matrix is more uniform across all of the peat samples tested, has a greater effect on the overall strength (as explained by Long, 2005).

4.4.3- Triaxial test

This study presents very low strengths when measured with the triaxial apparatus, suggesting very low fibre contents and highly humified peat providing little resistance to the applied compressive stresses. The low strengths obtained using this method are consistent with field studies and also with the results obtained using the vane and direct shear tests. The results indicate that the unconsolidated undrained shear strength of peat samples taken from the three landslides are around 2 to 3 kPa (Figure 4.28) with the lowest values recorded at the Straduff Townland landslide. The slight variations in the Mohr‟s circle diameters (Figure 4.29) are owing to the heterogeneity of the peat structure, as also observed by Hanharan (1954) for peat samples from a raised bog. This could also reflect the presence of gas in the peat which may lead to variations in pore water pressures within the samples.

The unconsolidated undrained triaxial shear strength of peat samples from a peat failure site has not been determined previously using the conditions presented in this thesis. Most studies have been carried out on peatlands in general and for different purposes. Figure 4.29 shows that the values obtained from this study are much lower than those presented by Hanrahan (1954) from raised bog, thus reflecting different structural and strength properties. Long (2005) suggested that for highly fibrous peats, the effect of fibres is expected to be more dominant in triaxial measurements and could lead to the peat not failing under compression or load while with more humified peat, failure could occur. Elastic or spongy peat will not fail and will compress and then rebound back after the compressive stress has been removed. In fact, as discussed by MacFarlane (1969), the spongy nature of peat means that large deformations occur as the peat develops its inherent resistance to an applied load. Examples of stress–strain plots for the peat samples from the study landslides are shown in Figure 4.27b. The graphs show different deformation properties under stress. Modes of peat failure were neither brittle nor non-brittle. Owing to the elasticity of samples tested, peat deformed without failing and bounced back after applied stresses were removed. However, several tests did show the shear stress apparently attaining a maximum value. This can be explained by the effect of fibres. In fact the distribution of fibre contents and sizes throughout the peat profile is variable and can lead to different peat deformation properties as explained in Section 5.1.

In the great majority of practical situations, values are required for parameters that will reflect the change in shear strength with variations in the stress environment and loading history of the peat. Quantifying the effects of the physical parameters (e.g. the water content, the rate of strain and fibre content) on peat triaxial measurements could improve understanding of peat strength for stability assessments. Quantitatively, it has been suggested that the shear strength of peat often varies inversely with its water content and directly with its ash content and degree of deformation in compression (Wyld, 1956). MacFarlane and Allen (1964) also suggested that in general, the greater the organic content, the greater the water content, void ratio and compressibility of the peat. Peat fibres affect the geotechnical behaviour of peat by providing an internal lateral resistance to shear deformation in the triaxial mode of shear (Landva and La Rochelle, 1983). As explained by these authors, pore pressures reduce this resistance, so loading of the peat under drained conditions, i.e. with no excess pore pressure, provides better stability through lateral resistance. These authors also suggested that the internal resistance of peat through fibre reinforcement is a function of the friction between the fibres (or between the fibres and the matrix) and the strength of the fibres. The lateral resistance induced by the fibres cannot be measured directly in peat. However, if the results of triaxial tests are plotted as a Mohr diagram, the fibre resistance can be deduced if the shear strength without any influence from fibres is known. A ring shear instrument that can produce good results with low applied loads (e.g. less than 5 kPa: Bromhead, 1979) as encountered *in situ* would be virtually unaffected by fibre reinforcement and produce more consistent results for the peat matrix. The effect of fibres is negligible in the ring shear test because the fibres tend to align themselves at right angles to the direction of the applied stress (Landva and La Rochelle, 1983). The relationships between peat‟s physical properties and peat‟s strength discussed by Wyld, (1956), MacFarlane and Allen (1964) and Landva and La Rochelle (1983) have not been proven on failed blanket peat.

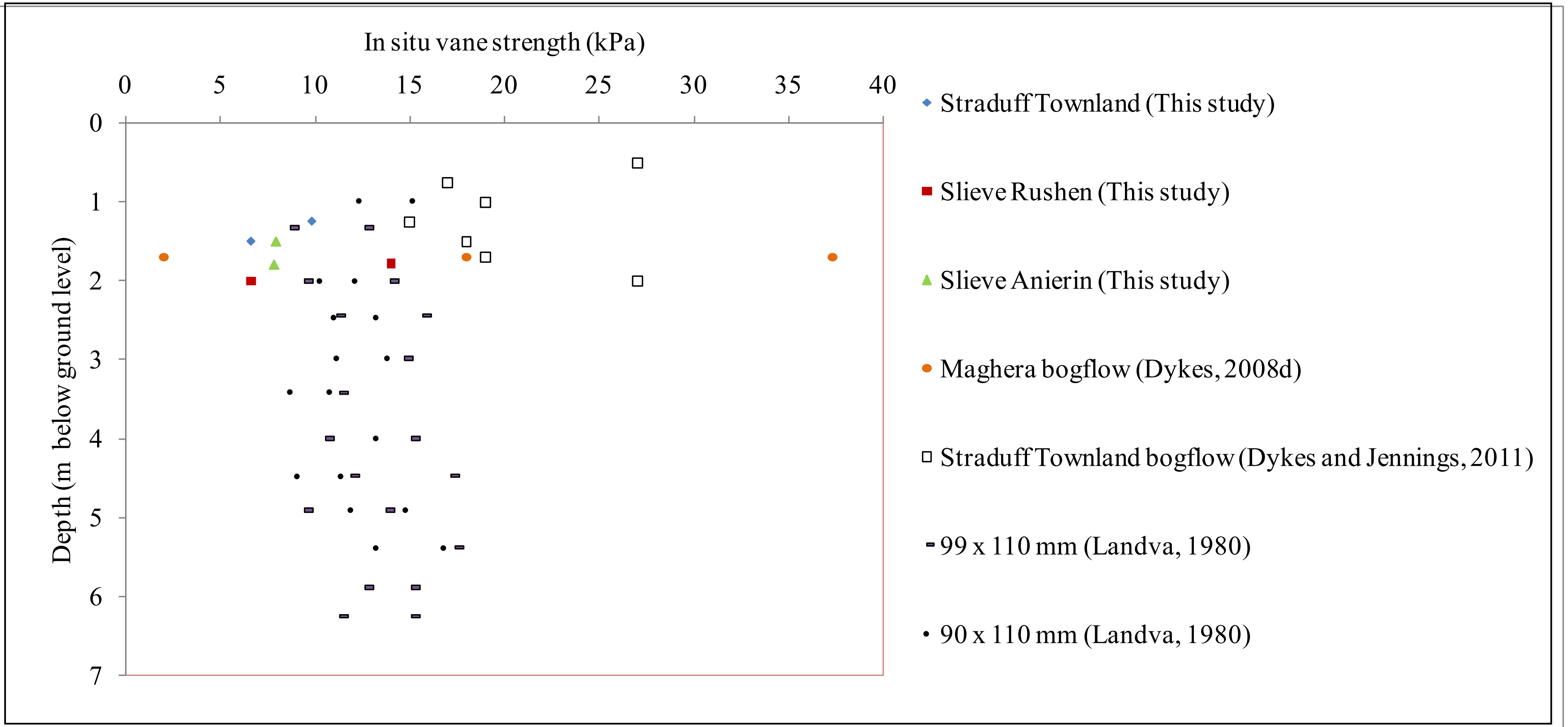


Figure 4. 25. Comparison of *in situ* vane strengths of peat at the three landslides with selected values obtained from other blanket bogs and peatlands.

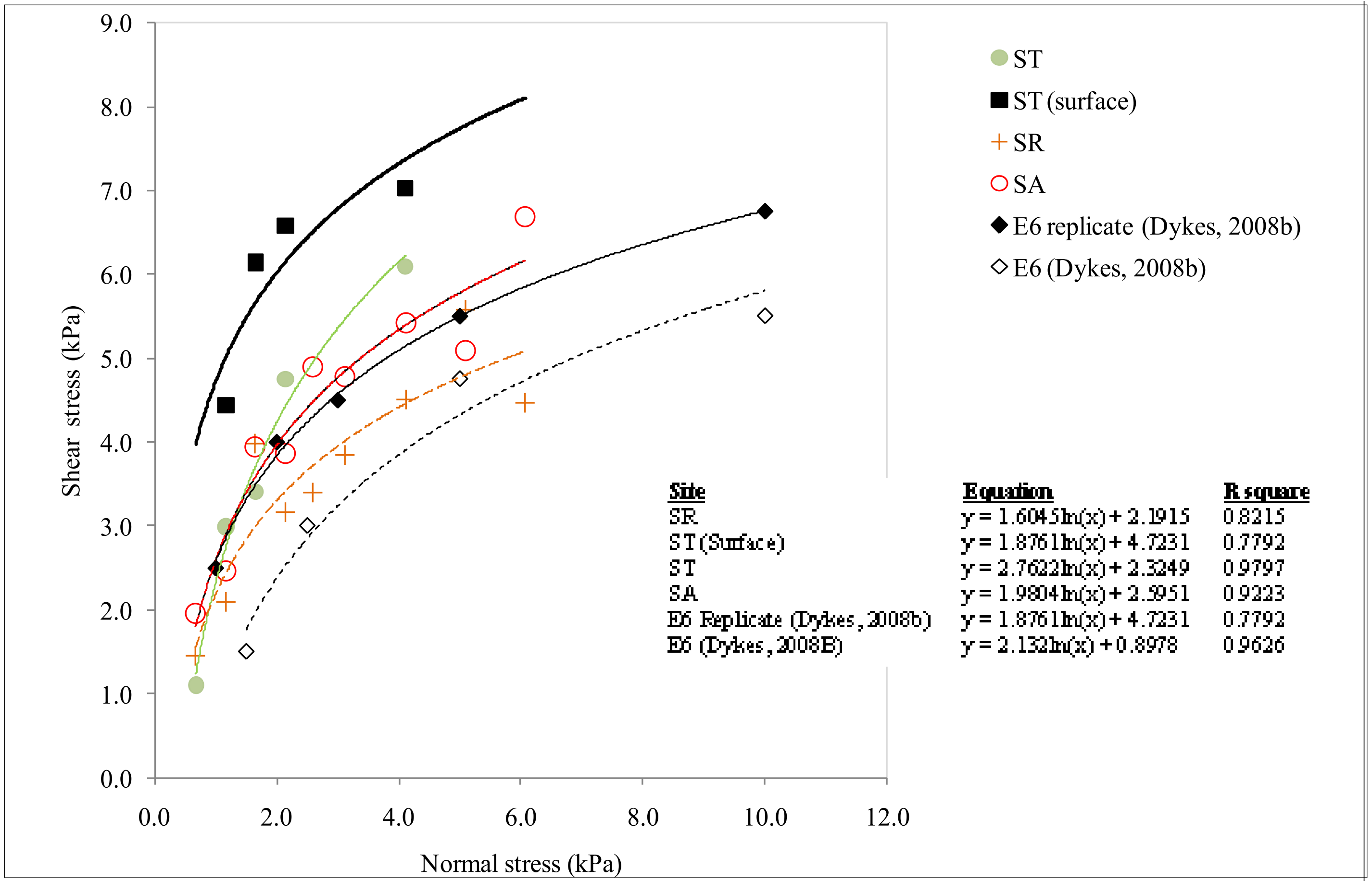


Figure 4. 26. Experimental low-stress shear strength results obtained from direct shear tests of samples of basal peat from the three sites (and from 0.01 m depth at Straduff Townland) compared with previous works. At least two samples were tested for each normal load investigated.

4.4.4- Tensile strength

Figure 4.30 presents a comparison of tensile strength results obtained from the three sites, using the laboratory apparatus described by Dykes (2008d), with literature values. Examples of stress-strain plots for tensile strength tests on peat samples taken from the three landslides are shown in Figure 4.27c. Stress-strain curves also show the erratic behaviour of peat material when subjected to tension stresses. The low average basal peat tensile strengths obtained in this study are also consistent with the results obtained at the Straduff Townland bogflow and the Ballincollig Hill peat flow (Dykes and Jennings, 2011) suggesting that the tensile strength (kPa) may be an indicator of peat strength (Helenelund, 1967; Dykes, 2008d) and should be given further consideration. The low tensile strength of the basal peat appears consistent with the condition of the peat encountered during sampling at each site, i.e. highly humified and less fibrous, and the general strength reduction with depth is also indicated at the Straduff Townland bogflow (Dykes and Jennings, 2011). Dykes and Jennings (2011) showed that the tensile strength reduced sharply with depth throughout the bogflow peat profile, e.g. 15 kPa at 0.25 m depth to less than around 4 kPa below 0.75 m depth at that site.

The tensile strength may not always decrease with depth, as shown at the Ballincollig Hill landslide (Dykes and Jennings, 2011) where the results were very low and varied only slightly with depth, and at one of the Dooncarton Mountain landslides (Dykes and Warburton, 2008b) where results were low at the base but varied throughout the profile (Figure 4.30). The tensile strength results obtained by Helenelund (1976) from *Sphagnum* bog peat are within the lowest ranges of results presented in this study, showing that monocotyledon peats have higher tensile strengths than *Sphagnum* bog peat. In sedges or monocotyledons peat, fibres are remains of vascular bundles formed from the root systems that grow perpendicularly to the ground surface. The resulting tensile strength will therefore be related to the resisting force produced by the fibres – the content of which decreases with depth and is inversely proportional to the degree of humification – in each test sample. This could also explain the low strength obtained for *Sphagnum* peat (Helenelund, 1967) which has a low fibre content compared with monocotyledon peat. In fact, Helenelund (1967) suggested that the fibre contents, types and orientations – which depend on the morphology and the mode of growth of the original plant assemblage that formed the peat – may have major influences on the tensile strength. The macrofossil analyses of peats from the study sites revealed remains of sedges, the degrees of humification of which increased with depth. In fact, owing to the effect of compression during the accumulation of the peats, some fibres that were originally distributed vertically through the peat are squashed progressively to a horizontal position as pressure increases. The degree of inclination of these fibres toward the horizontal plane will therefore increase with depth.

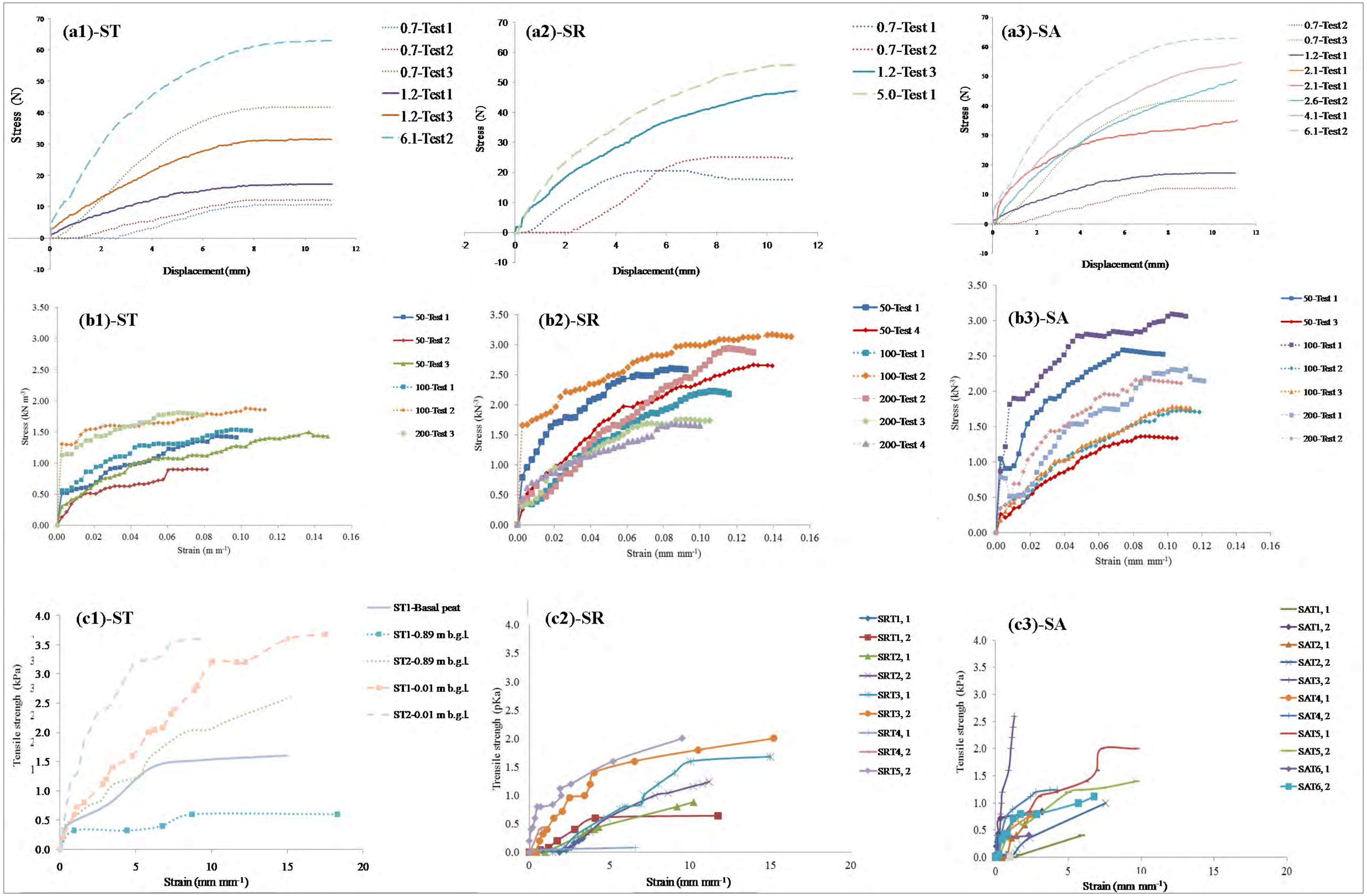


Figure 4. 27. Stress–strain plots for (a) direct shear, (b) triaxial and (c) tensile tests on peat samples from the three landslides showing the variability of maximum forces and the unpredictable behaviour of stress paths. „0.7-Test1" means sample 1 tested with an applied normal stress of 0.7 kPa. 50, 100 and 200 represent applied stresses (in kN m $^{-3}$) used for testing. (m b.g.l. represents metres below ground level). (1) Straduff Townland, (2) Slieve Rushen and (3) Slieve Anierin.

The tensile strength values (Appendix B; Table B1) presented in this thesis were measured in a horizontal plane. The directions of peats shearing in tension were therefore almost perpendicular to the orientation of the fibres. This resulted in higher surface tensile strengths and lower tensile strengths in the basal peats which fibres were assumed to be parallel to the shearing plane.

4.4.5- Comparison of undrained strengths of peat samples from the three landslides

This study has shown that the highest values of peat strength were obtained from vane tests (undrained shear strength) and the lowest values were obtained from tensile strength tests, which are considered to be comparable to the cohesion (Figure 4.31). These results do not match the study by Long (2005). He reported that strength values obtained from triaxial tests are too high and overestimate peat strength. The discrepancies of the results are owing to the fact that the data reported by Long (2005) were obtained under conventional experimental conditions as opposed to the low stresses in this study. The findings of this work confirm that the vane test overestimates the shear strength of peat (Hanrahan, 1994) and is not reliable in fibrous peat (Helenelund, 1967). However, the vane test can be used in peat to evaluate the variability of strength with depth, and the presence and positions of hard or soft layers (Hanrahan, 1994). The higher shear vane values in Figure 4.31 could be explained by the fact that the rotation of the vane blade in a monocotyledon peat could lead to the entanglement of fibres, producing more resistance to failure and therefore higher values of shear strength. All mean measured basal peat tensile strengths at the three landslides were ≤ 2 kPa and the triaxial undrained shear strengths were in the range 1.5-2.5 kPa.

It appears that measurements of the tensile strength of basal peat may be used as indicators of potential peat instability. The results of basal peat tensile strength obtained from blanket bogs that experienced bogflows are consistent with the low shear strengths obtained from basal peat samples in triaxial tests and with field observations as presented in Section 4.2.3.

4.4.6- Comparison of quantitative descriptions of peat following laboratory measurement of physical and strength properties

The results of this study show that the measured characteristics of peat after cluster analyses (Figure 4.32) were consistent across all three sites (Table 4.7) with the exception of the von Post degree of wetness. The degree of wetness was lower in the upper zone of the peat profile at the Slieve Rushen landslide; this may be due to prior or post-failure evaporation through tension cracks, due to the evasion of the site by *Calluna vulgaris* or drainage because the conditions of the site prior to failure are unknown. The humus fraction (i.e. particles <0.15 mm) increased with depth and the fine fibre content (0.15-1 mm) was the same across all of the zones and sites, recorded as „1" (i.e. fibre content between 40% and 0%). Coarse fibre (i.e. >1 mm) and total fibre (i.e. >0.15 mm) contents decreased with depth and were recorded as „1" in the basal zones. The results of the fibre fractions as defined in this study were therefore consistent at all three sites. This implies that some characteristics described using the „Modified Fibre content" (MFC) method in this study could occur at potential bogflow sites and may contribute to a new method for assessing the stability of blanket peat. In fact, the coarse fibre and humus fractions are the main influences on peat variability because the fine fibre fractions were constant throughout the monoliths investigated. Tensile strengths are also constant throughout the upper profile (i.e. 2 on the scale: Table 4.7) at the Straduff Townland site. The lack of variability of tensile strength with depth in the surface peat which does not correspond with the degree of humification increasing with depth, is owing to: (i) the outlier that was included in the calculation of the mean; and (ii) the classification of tensile strength in the von Post scheme not being appropriate for the variability or ranges of tensile strengths encountered *in situ* and measured for the purpose of stability assessment. The third interval in the von Post classification (i.e. 2-10 kPa) of tensile strength may be too large and should be reduced as proposed in Section 4.6.3.

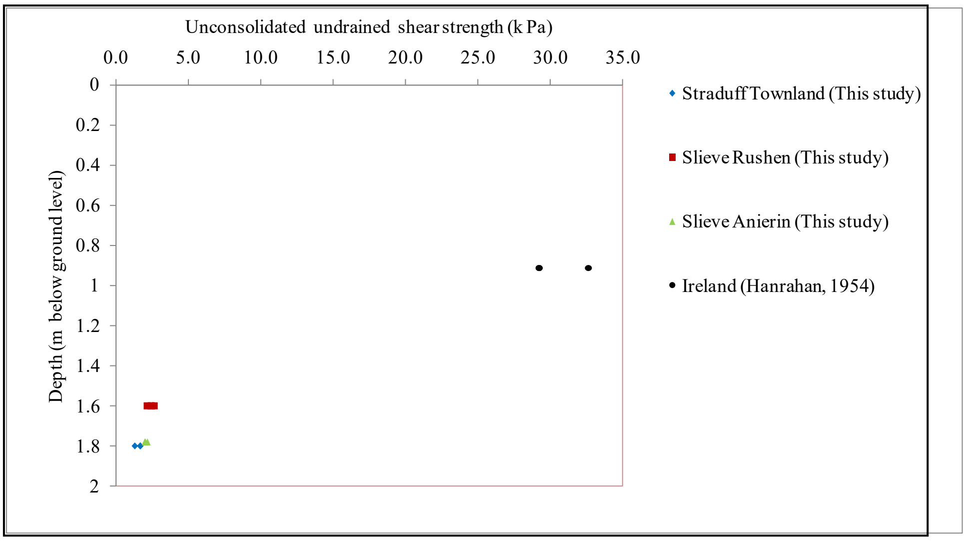


Figure 4. 28. Comparison of unconsolidated undrained shear strengths, obtained from triaxial tests of peat samples obtained from the study sites, with selected literature values.

Table 4. 7. Comparisons of the mean quantitative fibre contents of the stratigraphic zones at the three landslides.

Parameter	**Straduff Townland**	**Slieve Rushen**	**Slieve Anierin**	**Trend of parameter values with depth at the three landslides**
	Z:4,3,2,1	*Z:3,2,1*	*Z:3,2,1*	
Dryness (Sicc.)	2,2,2,2	3,2,2	2,2,2	Variable (i.e. 2-3)
Wetness (B)	3,3,3,3	2,3,3	3,3,3	Variable (i.e. 2-3)
Horizontal tensile strength (TH)	2,2,1	-,-,1	-,-,2[1]	1 or 2 at the base
Humus fraction (Fh) (< 0.15 mm)	-,-,1,3	-,1,2	-,1,2	Increase with depth
Fine fibre (Fm) (0.15-1 mm)	-,-,1,1	-,1,1	-,1,1	Similar at the three sites (i.e. 1)
Coarse fibre (Rm) (> 1 mm)	-,-,2,1	-,3,1	-,2,1	Decrease with depth
Total fibre content (Ft) (> 0.15 mm)	-,-,3,2	-,3,2	-,3,2	Decrease with depth
Potential weak zone depth (m)	*0.1*	*0.06*	*0.1*	*0.06-0.10*

Notes See Appendix A (Tables A11, A19 and A27) for the raw data and Appendix A (Tables A12, A20 and A28) for the numbers of samples considered. The numbers in positions a, b, c, d correspond to mean values for Zones (Z) 4,3,2,1 respectively („-" means no data).

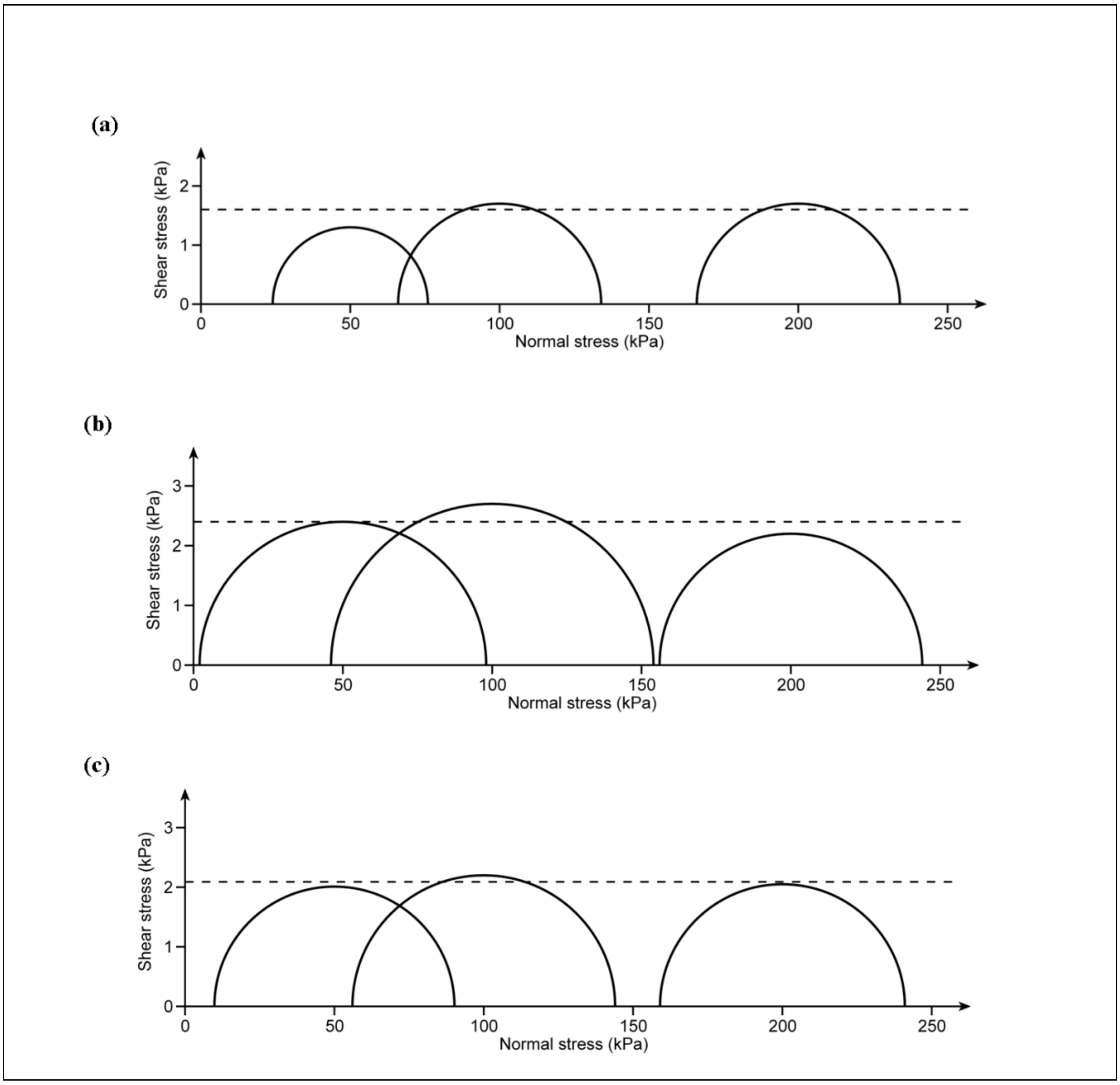


Figure 4. 29. Mohr Circle plots for unconsolidated-undrained triaxial tests on peat samples from the three landslides: (a) Straduff Townland, (b) Slieve Rushen and (c) Slieve Anierin, showing a small variability of shear stress with applied normal stress.

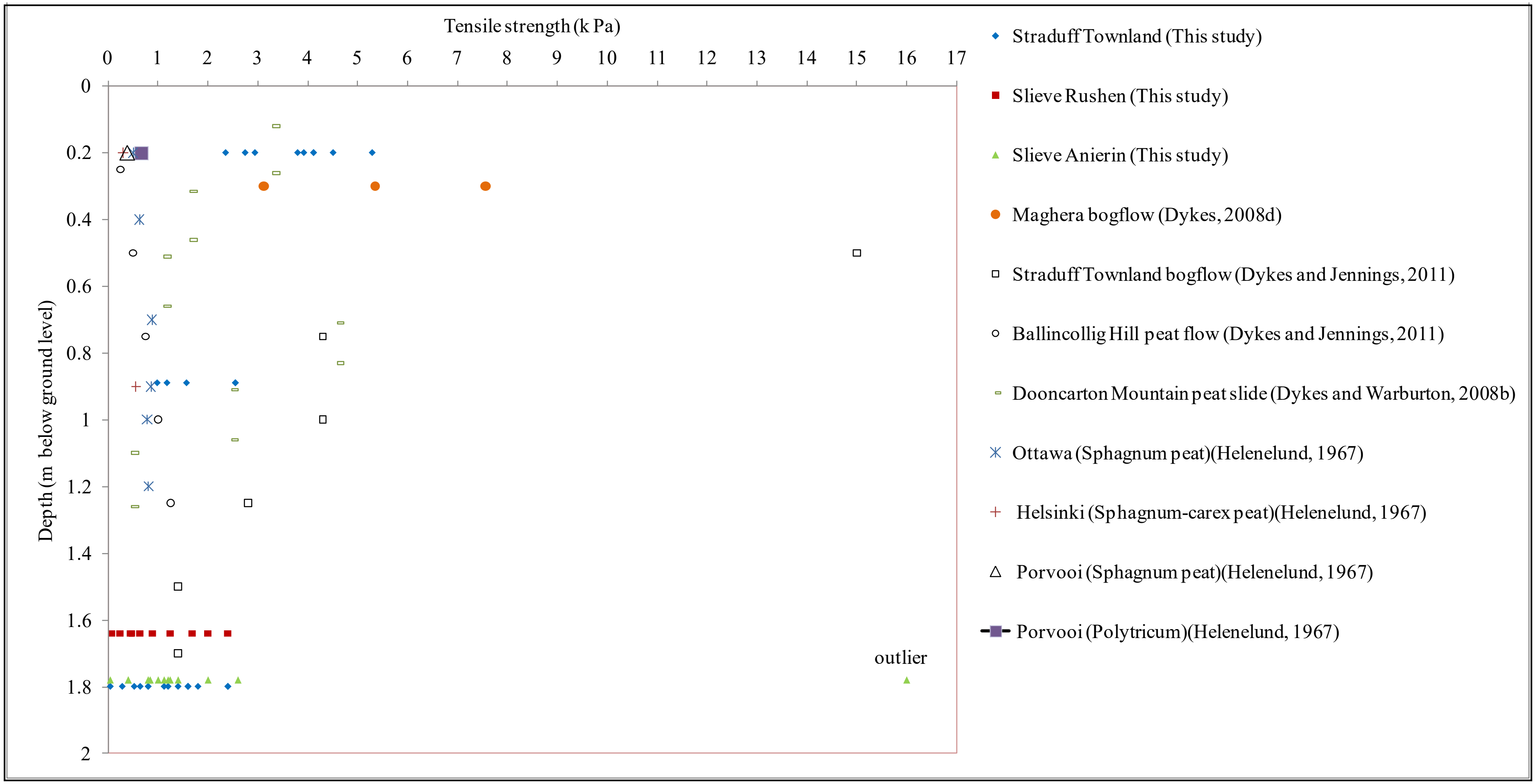


Figure 4. 30. Tensile strength measurements of peat samples from the study sites compared with previous studies. All literature tensile strengths represent mean values as presented in the respective sources.

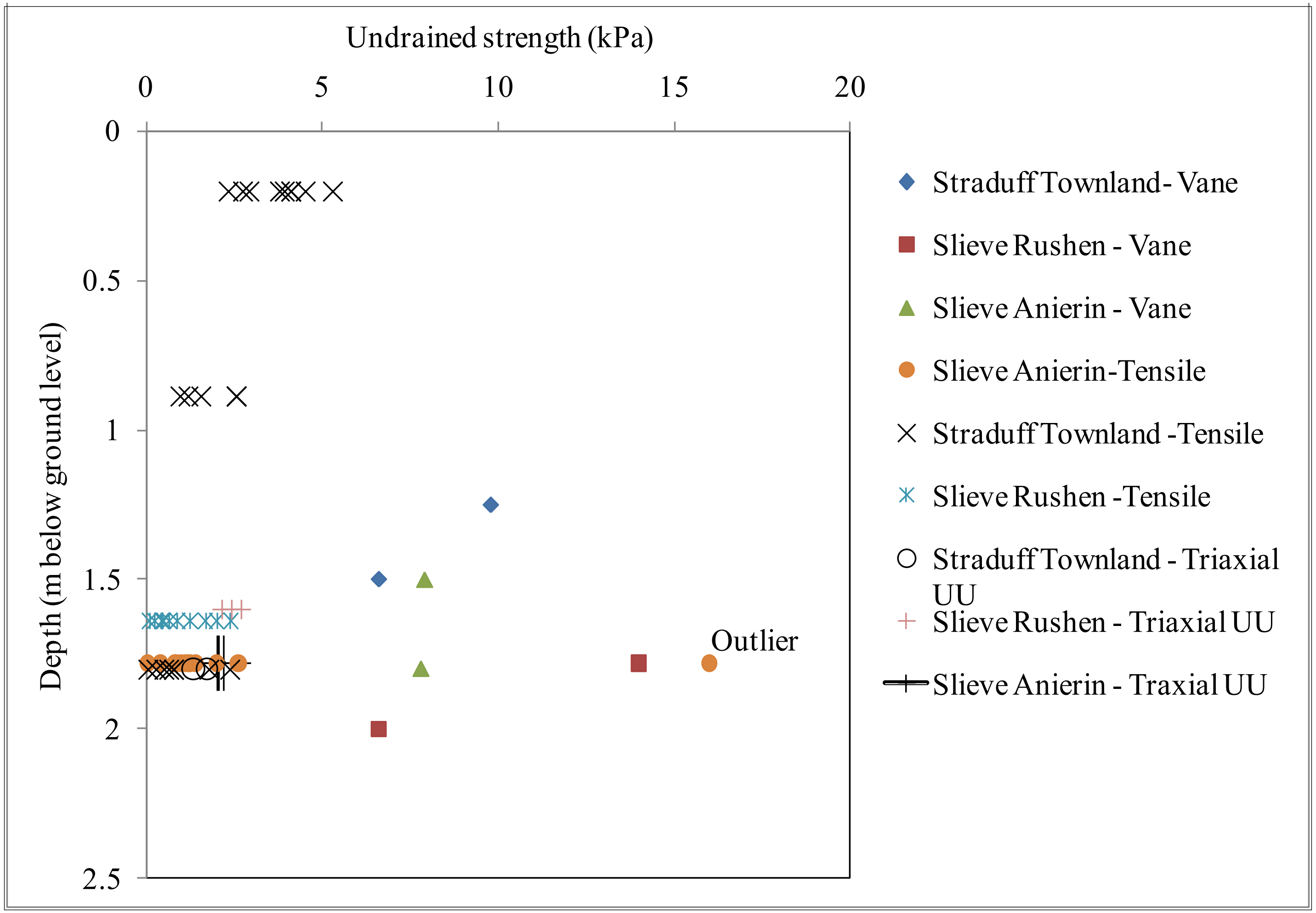


Figure 4. 31. Variations of the undrained strength of peat samples from the three landslides with instruments used for testing. UU = Undrained Unconsolidated.

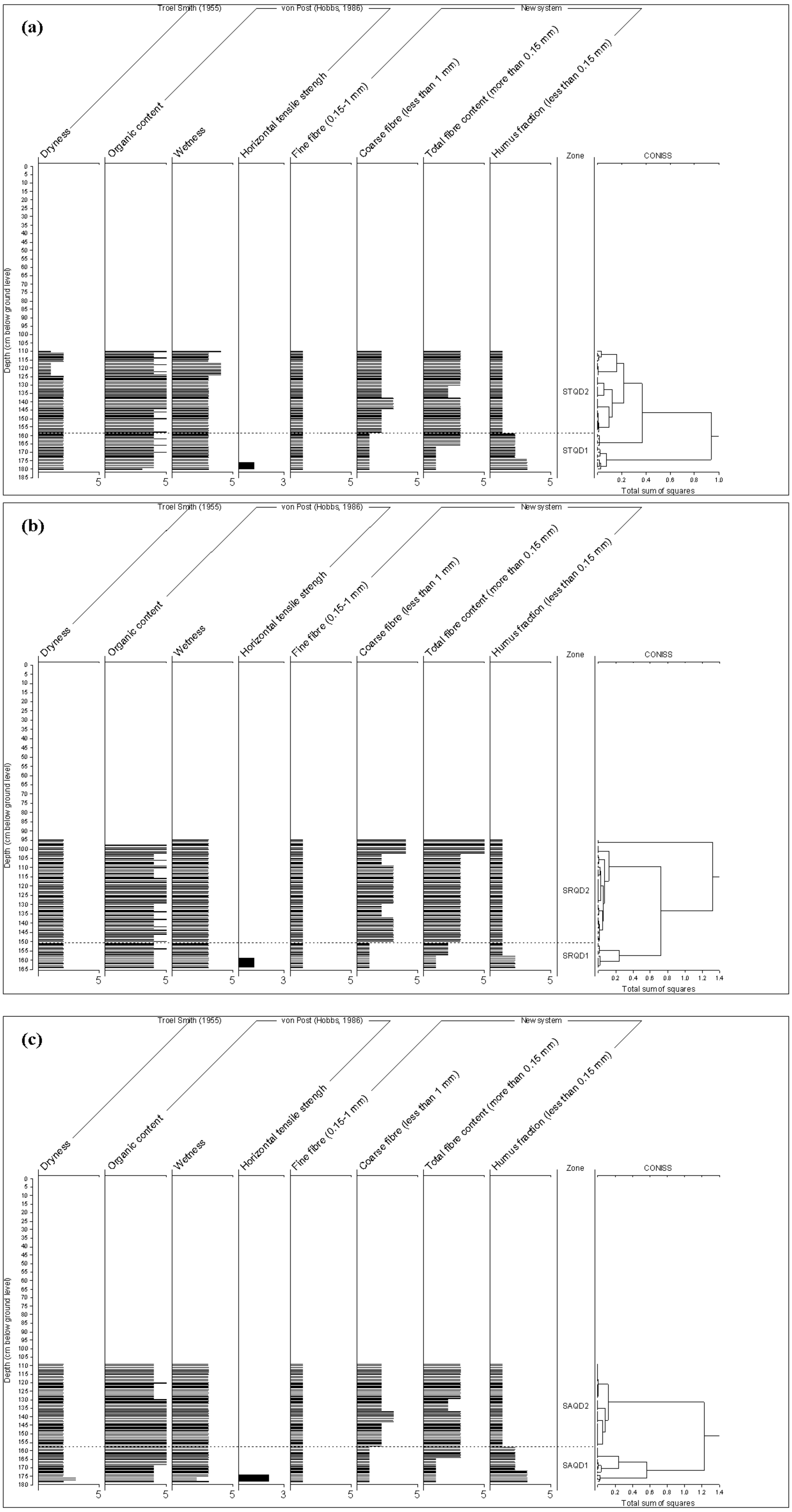


Figure 4. 32. Quantitative determination of peat physical properties from the three landslides: (a) Straduff Townland, (b) Slieve Rushen and (c) Slieve Anierin.The vertical axes are in centimetres (cm) instead of metres (m) in accordance with previous palaeoecology literature work on peatlands. Due to lack of data for the fibre contents for the surface peats, all other parameters investigated using the surface pears have been excluded from the analyses.

4.5- COMPARISON OF CHEMICAL PROPERTIES OF THE BASAL PEATS

Figure 4.33 summarises the hydrocarbon contents of the peat samples (Appendix B; Figure B1 and Table B3) from the three landslides. The overlaps of the error bars showing the standard errors indicate that the concentrations of total free bitumen and petroleum hydrocarbons cannot be distinguished between the three sites. This Figure shows no relationships (i.e. low coefficients of determination (r^2): Table 4.10) between concentrations of different hydrocarbon types.

Mean concentrations of TPHs were similar at the three sites but the statistical analyses of the data according to Grubb (1969) showed some „hotspots" (Figures 4.34). These hotspots are consistent with the patches of oily and bitumen-like compounds encountered in the basal peats at the three landslides during the fieldwork. The residual fibres in the basal peats, i.e. those that are readily compressible because they are broken remains of lignified tissues with no discernable water holding capacities, may have piled up and undergone the different stages of petroleum hydrocarbon formation. This process involves plant material deposition in an aquatic environment, compression under the influence of pressure and temperature then formation of hydrocarbons and production of bitumens. It can be speculated that the shape of the bedrock at the study sites may have influenced the accumulation of such substances. Hydrocarbon spots could occur on convex bedrock shapes as a result of pressure of the upper less permeable peat layers upon the lower basal peat layers, containing fibres with high molecular weight hydrocarbon compounds like cellulose and lignins that resist decomposition. They could also migrate and accumulate in localised concave or depressive areas or pockets. Although the pressure in peat is very low as result of low unit weight compared to other mineral soils, the compressions of plant materials should require very little normal forces. The formation of such hydrocarbon spots in the basal peat warrant further research.

The fractionation of the TPHs data revealed that petroleum hydrocarbon of carbon ranges C_{21}-C_{36} was predominant in the peat samples from all the sites. No previous study of peat instability has reported TPHs. It should be noted that TPHs is defined by the analytical method that is used to measure it. As reported by the API (2001), TPHs concentrations have been measured in many plant parts or other items that can be found throughout nature, including grass (14 mg g^{-1}), pine needles (16 mg g^{-1}) and oak leaves (18 mg g^{-1}). It has also been measured in household petroleum jelly at concentrations of 749 mg g^{-1}. Mean concentrations of 10.5 to 16.1 mg g^{-1} in dry peat, as recorded in this study (Figure 4.33), are well below the ranges reported by the API (2001) (i.e. 14 to 18 mg g^{-1}) for plant parts.

The overlap of the error bars in Figure 4.33 shows that the concentrations of poly aromatic hydrocarbons (Appendix B; Table B3) cannot be distinguished at the three landslides investigated. The ranges of PAHs concentrations at all the sites are however lower than the ranges of 84.1 to 1,250 ng g^{-1} reported for a Swiss ombrotrophic bog (Zaccone *et al.*, 2009). The values are within the ranges of 38.7 to 136.2 ng g^{-1} found in Chinese wetland sediments (Wang, 2012). The ratios of parent PAHs of the molecular masses 178, 202, 228 and 276 (e.g. phenanthrene/anthracene and fluoranthene/pyrene) are often used to distinguish between natural and anthropogenic sources (Lee *et al.*, 1982; Budzinski *et al.*, 1997; Yunker *et al.*, 2002). As reported by Wang (2012), different PAH sources can generate PAH isomers in certain ratios, and these ratios are often relatively constant during the dispersion from the source into the environment due to the similar thermostability of isomer pairs (Yunker *et al.*, 2002). Table 4.8 presents a comparison of the ratios of different polyaromatic hydrocarbons from this study with literature values presented by Yunker *et al.* (2002). This Table shows that the PAHs originated predominantly from incomplete combustion with the ratio of Anthracene to Anthracene-and-Phenanthrene clearly exceeding the 0.1 threshold that indicates combustion activities.

Figure 4.35 also shows that the concentrations of individual poly aromatic hydrocarbons (Appendix B; Tables B5-7) were not significantly different at the three landslides with the exception of Benzo[b]fluoranthene and Benzo[ghi]perylene whose concentrations were higher in the peat sample from Slieve Rushen landslide. It should be noted that links between these two compounds and plant types are unknown. Figure 4.35 shows that higher molecular weight PAHs predominate in all of the peat samples from the three landslides. Citing Bucheli *et al.* (2004), Pontevedra-Pombal *et al.* (2012) suggested that concentrations and distributions of PAH in soil not only depend on the increasing impacts of industry, traffic and domestic heating, but also on the proximity of the pollution source, the molecular weight of the compound and the form in which it is transported in the atmosphere. In view of the remote location of the landslides from industrial and even urban areas and the occurrence of higher concentrations of PAHs of higher molecular in the samples, it can be inferred that the PAHs originated *in situ* from peat combustion as reflected by the presence of charcoal in the macrofossil analyses. Citing Qiao *et al.* (2006), Zaccone *et al.* (2009) reported that in general, PAHs of petrogenic origin consist predominantly of PAHs of lower molecular weights (2 to 3 aromatic rings) whereas PAHs of pyrogenic origin show higher molecular weights (4 to 6 aromatic rings). The latter types were observed in this study. The ratio of IP/IP + Bghi did, however, reveal contributions from urban or industrial sources. In fact, as explained by Pontevedra-Pombal *et al.*(2012), PAHs can be transported over long distances in the atmosphere in gaseous form or bound to aerosol particles (Halsall *et al.*, 2001) and accumulate on peat or other soils by wet and dry deposition (Baek *et al.,* 1991). Therefore, it would be unwise to completely ignore contributions from human activity. It should be noted, however, that blanket peat accumulation started approximately 7000 years B.P. (Chambers, 1983) which is very remote in time from the industrialisation that occurred much later.

Figure 4.33 shows that the percentages of bitumen cannot be distinguished at the three landslides as suggested by the overlap of the errors bars showing standard errors. Klavina *et al.* (2011) studied the composition of the hydrocarbons found in peat bitumen using cores from raised bogs in Latvia. Following extraction of dry peat samples in a Soxhlet apparatus for 6 hours using dichloromethane, Klavina *et al.*(2011) found that the total amount of bitumen in the studied bogs ranged from 1% to 8% and was higher in peat with a higher degree of decomposition. Klavina *et al.* (2011) reported values which are within the ranges presented in the literature (e.g. Fuschman, 1980). Leahy and Birkinshaw (1991) also studied Irish peats and their results showed 9% of bitumen in dry weight of peat. The bitumen was recovered following extraction at 90°C for 3 hours using a Shell solvent called Special Boiling Point (SBP) 11. In this study, bitumen was extracted for 1 hour only (to avoid extraction of associated bitumens (Rurka *et al.*, 2005) which may not influence peat instability), which contrasts with the previous studies. All of these studies used different solvents with different degrees of polarity. Klavina *et al.* (2011) emphasized the importance of further studies of peat bitumen hydrocarbons, knowledge of which currently remain very rudimentary.

Figure 4.36 shows that the mean concentration of aliphatic hydrocarbon of carbon ranges >C_{18}-C_{36} is the highest, followed by carbon ranges >C_{36}-C_{44+} and C_{10}-C_{44+} in all of the peat samples taken from the three sites investigated (Appendix B; Table B4). With the exception of the hydrocarbon banding >C_{18}-C_{36}, concentrations of all aliphatic fractions are higher than those of their corresponding aromatic fractions. Figure 4.36 also shows that the Straduff Townland and Slieve Anierin landslides appear to be significantly different in terms of aliphatic hydrocarbons fractions C_{10}-C_{18}, >C_{36}-C_{44} and aromatic fraction C_{18}-C_{36}. This could be due to the varying degree of transformation of peat compounds to hydrocarbons compounds. It should also be noted that the error bars showing the standard errors are based on small sample sizes, which limits the statistical power of the analyses.

Klavina (2011) also found that aliphatic hydrocarbons were more concentrated in peat bitumen than aromatics. She also reported the presence of a wide range of both aromatics and aliphatics of carbon ranges C_{12} to C_{27}. This study revealed hydrocarbon banding of up to C_{44+}. These are heavier and are interpreted as having been derived *in situ*, being too heavy to have been brought on site by other deposition processes.

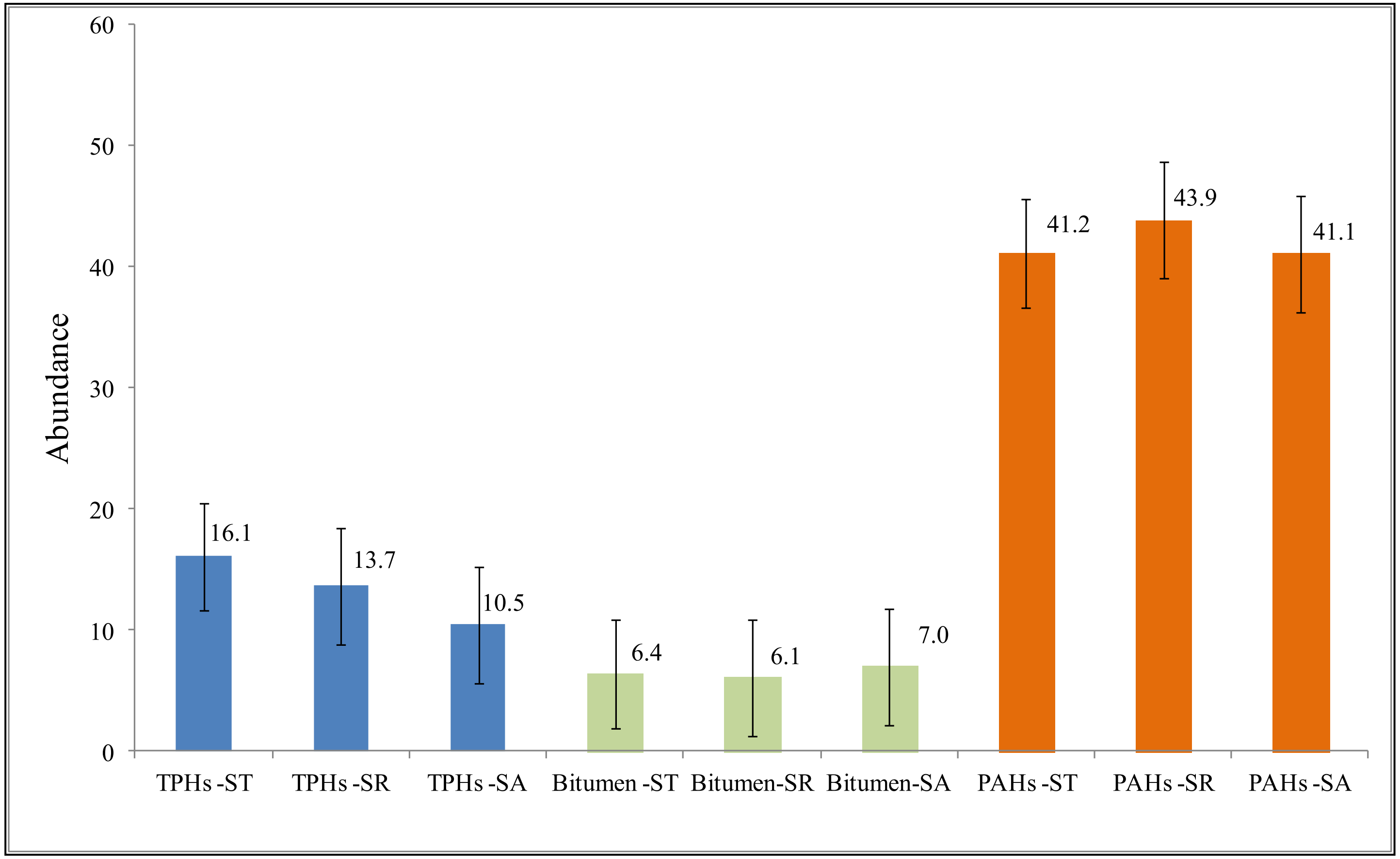


Figure 4. 33. Mean total hydrocarbon contents (dry peat) at the three landslides. PAHs expressed in ng g^{-1}, TPHs in mg g^{-1} and bitumen in %, with error bars showing the standard errors. The numbers of samples are shown in brackets as follows; ST (20), SR (23) and SA (23). ST = Straduff Townland, ... etc.

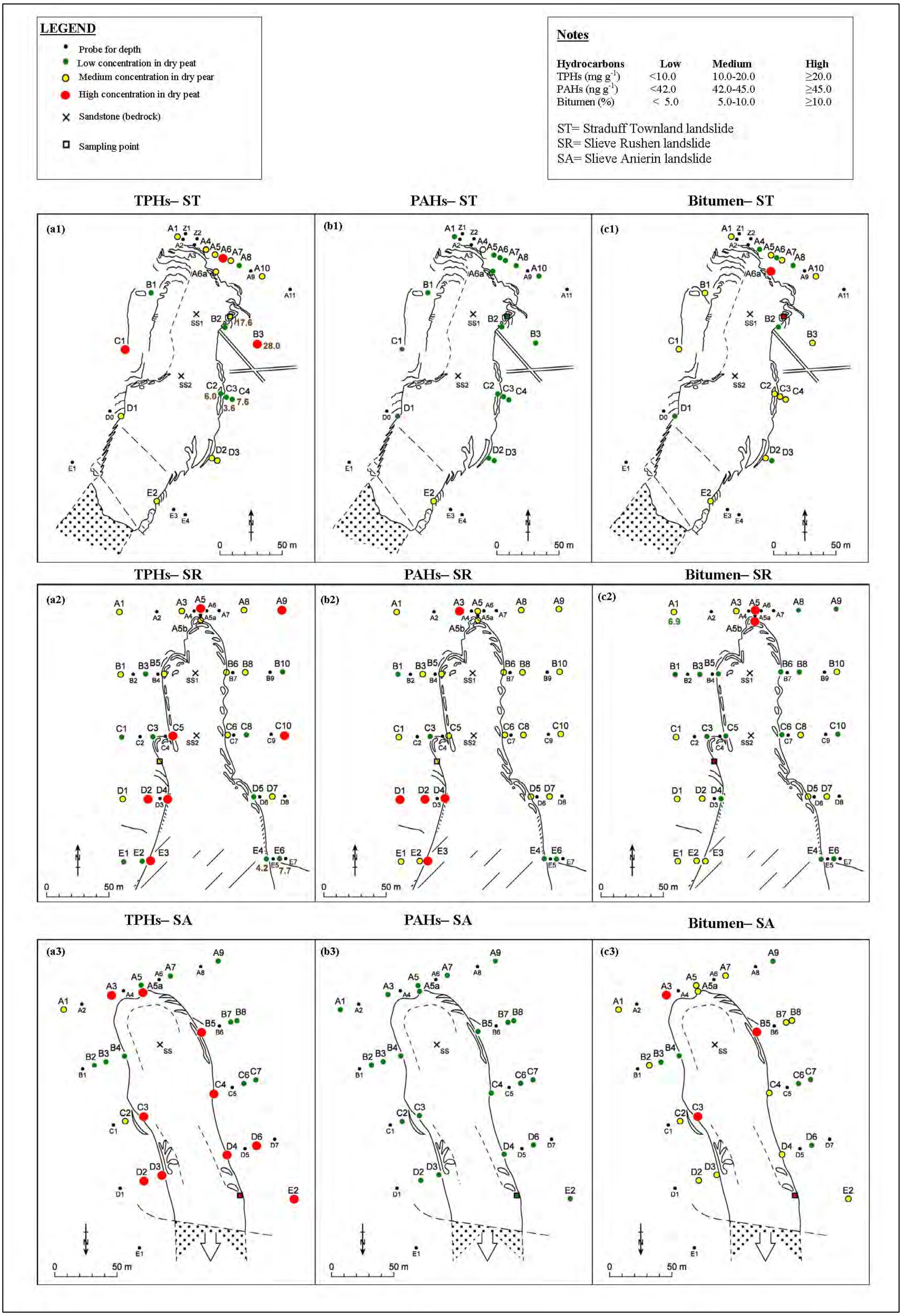


Figure 4. 34. Spatial distribution of hydrocarbons in the basal peat at the three landslides (map from Dykes, 2009): (a) TPHs contents (brown numbers, mg g^{-1} dry peat); (b) PAHs contents (purple numbers, ng g^{-1} dry peat); and (c) bitumen contents (green numbers, % dry peat). In all three maps, potential hotspot areas are indicated by red spots. ST = Straduff Townland, ... etc.

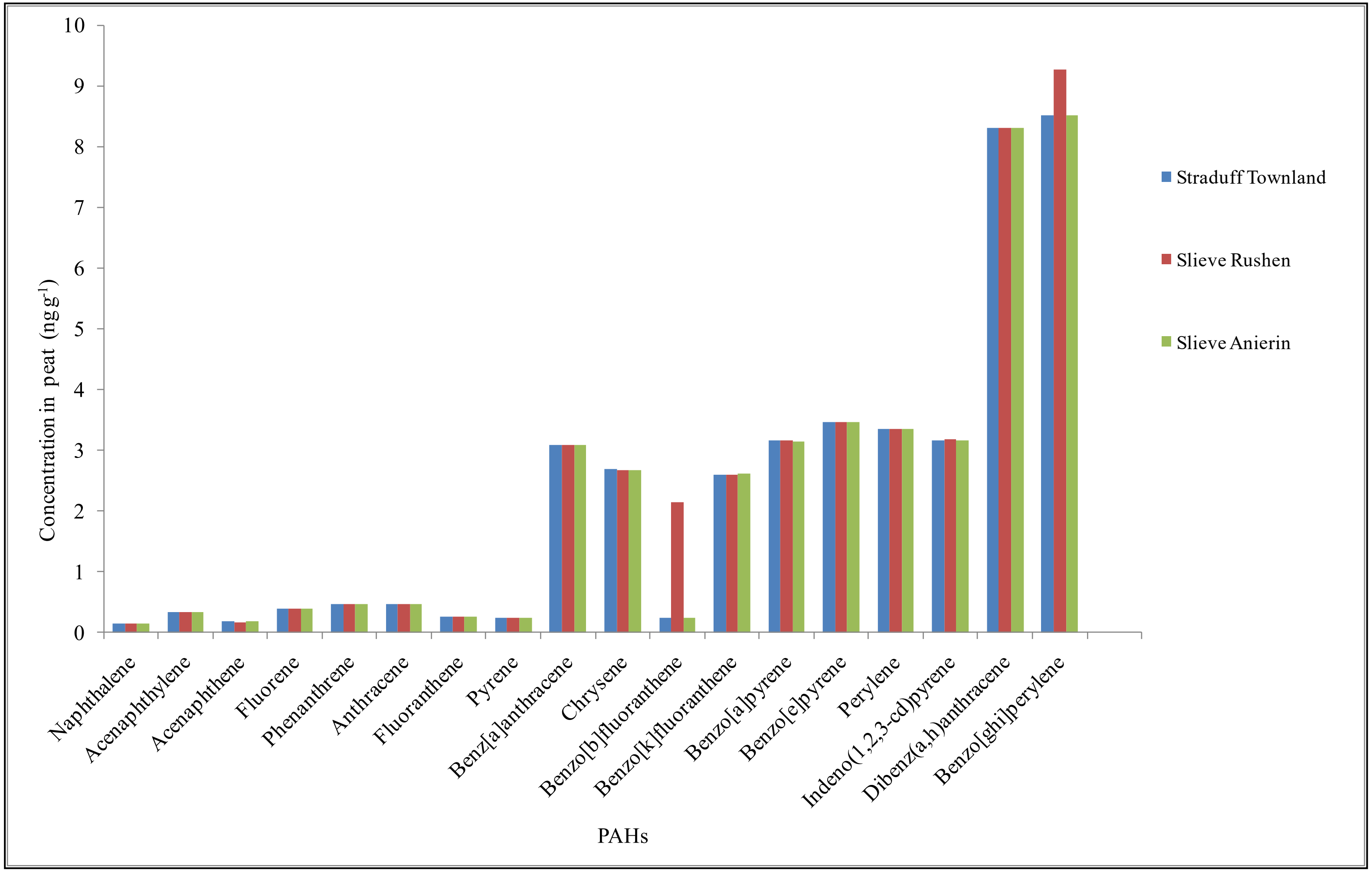


Figure 4. 35. Mean concentration of PAHs in dry peat at the three landslides. See Appendix A (Table B3) for number of samples tested.

Table 4. 8. PAHs ratio in peat samples from the three landslides compared with literature values for combustion and environmental samples.

Ratio[1]	**Landslide**			**Combustion (after Yunker *et al.*, 2002)**				**Environmental samples (after Yunker *et al.*, 2002)**		**Budzinski *et al.* (1997)**	
	ST	SR	SA	Diesel oil	Coal	Asphalt	Grasses	Bush fire	Savanna fire	Combustion	Petroleum
An/178	0.003	0.003	0.003	0.030-0.170	**0.000-0.410**		0.130-0.230				
Fl/Fl+Pyr	0.532	0.525	0.525	0.010-0.470			**0.530-0.630**	0.610	0.580-0.600		
BaA/228	0.014	0.014	0.014	0.120-0.710		0.500	0.440-0.490	0.230			
IP/IP+Bghi[2]	0.271	0.255	**0.271**	**0.250-0.650**		0.520-0.540	0.520-0.690	0.700	0.310-0.440		
An/An + Phe	0.500	0.500	0.500							>0.100	<0.100

Notes

[1] A Anthracene, Fl = Fluorenthene, Pyr = Pyrene, BaA = Benzo[a]anthracene, IP =Indeno [1, 2, 3-cd] pyrene, ghi = Benzo[ghi]perylene, Ph = Phenanthrene

[2] could also have originated from urban air, truck and vehicles, or fuel oil (Yunker *et al.*, 2002).

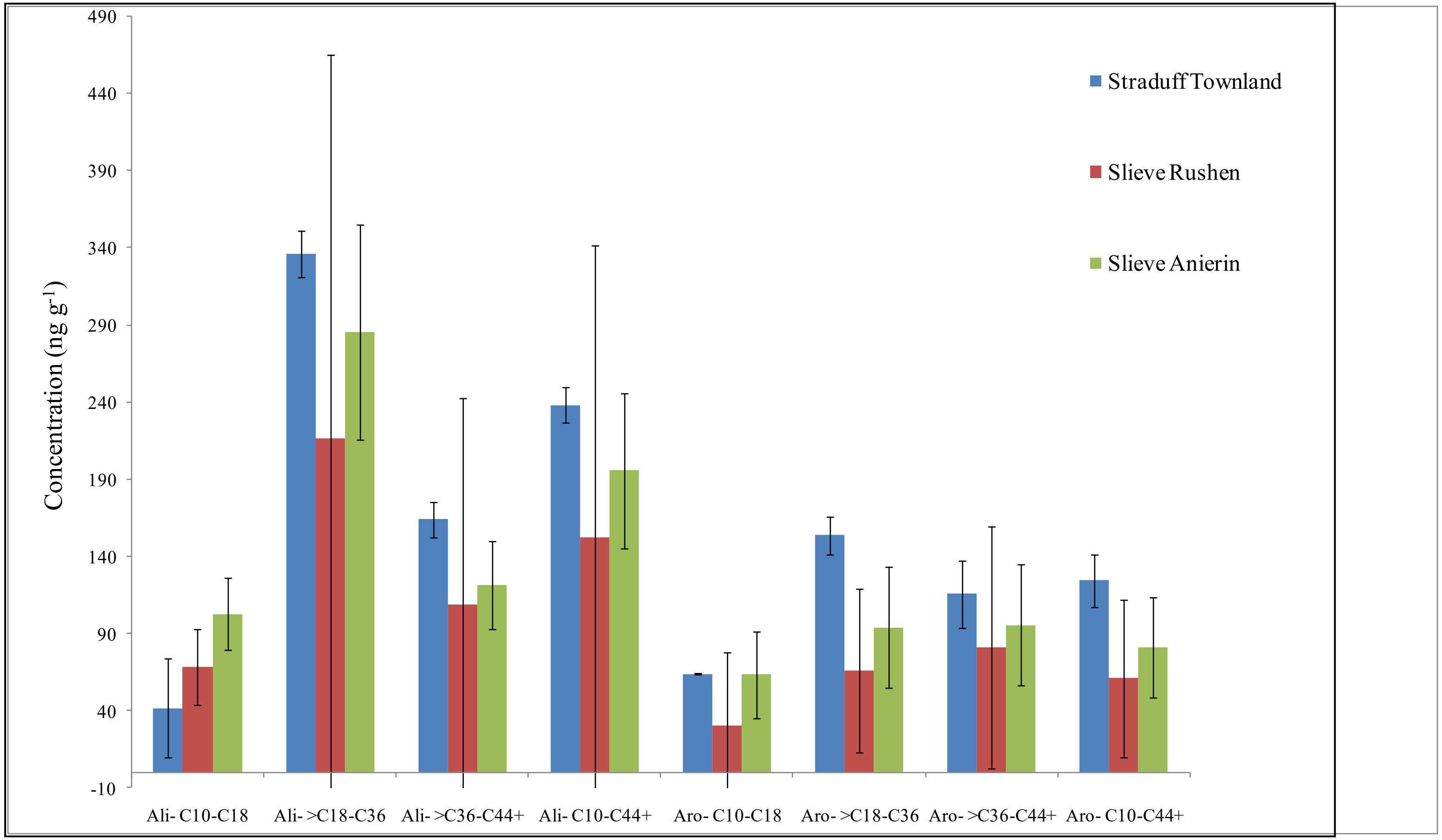


Figure 4. 36. Mean bitumen aliphatic (Ali-) and aromatic (Aro-) hydrocarbon fractions at the three landslides with error bars showing the standard errors. The number of samples are in the following brackets; ST (8), SR (5) and SA (6).

4.6- ANALYSIS OF PEAT DATA

Analyses of the data obtained in this study are presented in the following sections in order to assess their significance and potential uses for peat instability assessment.

4.6.1- Peat structural and chemical properties

The structural properties of peat may be interrelated so that the knowledge of one or a few of them enables the prediction of many others with considerable success (Clymo, 1983). Therefore, any relationship between the properties investigated as part of this study may help reduce the number of parameters that are often needed for blanket peat characterisation for the purpose of stability assessment.

The correlation coefficient (Pearson's r) is a statistical test which measures the linear association between two quantitative variables. Table 4.9 shows the correlation coefficients (significant and not significant at P value <0.05, i.e. 95% confidence level) between the physical and effective structural properties (Sections 4.3.1 and 4.3.2) and Table 4.10 shows those of the chemical properties measured/estimated *in situ* as part of this study. The statistically significant associations were indicated by a wide range of correlation coefficients, the absolute values of which were occasionally lower than 0.3. In this study, only parameters with $|r|$> 0.7 and consistent at the three landslides were interpreted as having a causal relationship because the study was based on a single monolith per study site. Furthermore, the full depth of the peat at each site was not analysed for most of the parameters investigated.

Some correlation coefficients were not significant at the 95% confidence level and are shaded in grey. This finding means that there were no relationships between those respective parameters. These include, for example, the constant head hydraulic conductivities vs. the falling head hydraulic conductivities, and all of the hydraulic conductivities vs. most physical properties.

Values of the coefficient near to unity (e.g. 0.85 or 0.90) indicate a high degree of correlation and values near to zero (e.g. 0.15 or 0.20) indicate an absence of correlation except when the coefficient has been calculated from a large number of pairs of values of the bivariate distribution (Loveday, 1971). With larger samples sizes, a low strength of correlation (e.g. $|r|$< 0.3: the % of „raw" transmission vs coarse fibre content at the Slieve Anierin landslide, which was plotted with 70 samples) can be statistically significant. However, the correlations between two variables do not always define or explain any causal association between the variables.

These results show that the trends of some correlations are not consistent at the three landslides (e.g. LoI vs. saturated bulk density or LoI vs. dry bulk density), therefore they cannot be interpreted with confidence. The trends of some relationships were consistent at the three landslides (e.g. LoI vs. coarse fibre content and LoI vs. total fibre content) but the $|r|$were all < 0.7.

Table 4.9 shows that the strongest and consistent associations (i.e.$|r|$> 0.7) between the structural properties at the three landslides were between (a) von Post degree of humification and coarse fibre content, (b) von Post degree of humification and total fibre content, (c) total fibre content and coarse fibre content (Figure 4.37), (d) humus fraction and total fibre content (Figure 4.37), (e) field water content and total fibre content(Figure 4.37), and (f) LoI and total fibre content (Figure 4.37).

The very strong association (i.e. $|r|$> 0.9) between the coarse fibre content and total fibre content and the humus fraction content at the three landslides mean that only one of these fractions may be needed to investigate the „effective" structural properties of peat. These properties influence peat structure and strength and can be used for stability assessment because their contents at the study sites were consistent and showed good (i.e. $|r|$> 0.9) correlation with other properties at the study sites.

The very strong association (i.e. $|r|$> 0.9) between the coarse fibre content and total fibre content and the humus fraction content at the three landslides can be explained by the fact that with increasing plant decomposition, the size and amount of organic particles decrease, resulting in low fibre contents as shown in Figure 4.37 a-b. When the fibre content decreases, the water content also decreases (Figure 4.37c) because the voids within the fibres which contain the largest amount of water (MacFarlane and Radforth, 1968) also decrease. With increasing fibre content (total or coarse), the LoI increases as shown on Figure 4.37d, especially for the Straduff Townland and Slieve Rushen data, as result of decreasing mineralisation. Boelter (1968) showed that there was a relationship between the degree of decomposition and peat bulk density. One would expect that with increasing plant decomposition, the size of organic particles would decrease, resulting in smaller pores and more dry material per unit volume as shown in Figure 4.37e for the Straduff Townland and Slieve Anierin landslides. However, the results of this study do not completely corroborate these findings. The trendlines between LoI and coarse fibre content at the three landslides shown in Figure 4.37f were not consistent. This finding implies that the relationship between fibre content and LoI may not be as simple as one would expect with blanket peat.

With the exception the von Post degree of humification and the percentage of unidentified matter (with P-values < 0.05 (5.7×10^{-15}, 1×10^{-3} and 5.5×10^{-6} for the Straduff Townland, Slieve Rushen and Slieve Anierin data respectively), there were no consistently high correlations between the macrofossils data and the physical properties of peat as shown in Figure 4.38. This could be owing to the fact that the QLCMA method used for macrofossil analyses may be more appropriate for *Spagnum* peat with small leaves which can be easily counted, compared with monocotyledons peat with bigger original plant fragments.

The general lack of strong or consistent correlations between the physical properties (i.e. LoI, bulk density, hydraulic conductivity) and other effective structural peat properties at the three landslides (Table 4.9) suggests that these physical properties cannot be used as indicators of peat structure and, thus, of peat instability. However, the MFC method can be used to investigate relationships between the structural properties of failed Irish blanket peat in order to classify peat for stability assessment.

With regards to chemical properties, Table 4.10 shows that the significant, consistent and strongest correlations (i.e. $|r|$> 0.9) at the three landsides were between the aliphatic and aromatic hydrocarbon fractions C_{10}-C_{44+} and C_{10}-C_{18}. The similarities of the results of bitumen, TPHs and PAHs across the three landslides as presented in Figure 4.33 suggested that peat from other susceptible Irish blanket bogs may have similar hydrocarbon contents. The strong and consistent correlations between the hydrocarbons fractions specified also suggest that either fraction can be used for stability assessment. It would be interesting to analyse other peats to test the hypothesis that the correlation between these hydrocarbons could be simply due to the chemical nature of the peat material and have no significant influence on peat instability. There were no consistently high correlations between the hydrocarbons compounds, fractions analysed and the „raw" percentage of light transmission of the peat samples from the three landslides.

4.6.2- Geotechnical properties

The macrofossil analyses at the three landslides showed that the original plant assemblage was predominantly monocotyledons with *Eriophorum v.* as discussed in Section 4.2. Therefore, the undrained strengths obtained at the three landslides were plotted against the physical properties in order to investigate any possible relationship that may exist. The statistical analyses showed that none of correlation coefficients was significant (i.e. all P-values < 0.05). It is inconceivable that peat strength would reduce with increasing fibre content as shown in Figure 4.39; therefore, the trends shown on the graphs may be an artefact of the limited data.

According to Long (2005), upland peats fail along a plane and therefore they fail in shear. Their failure mechanism should be theoretically modelled using shear strength values. The shear strength, tensile strength and even compressive strength are all related to some fundamental characteristic strength (Atkinson, 1993). The link between these different strengths is the maximum shear stress (i.e. Mohr circle of stress) that a material can sustain under specific experimental conditions. For example, the ratios between the maximum stresses investigated using different instruments can be used to assess peat deformation behaviour under different experimental conditions for potential use for peat instability assessment.

The tensile strength is often considered more than the shear strength in most materials (i.e. with the ratio of tensile strength to shear strength equal to 0.5: Kelly and Tyson, 1965; Helenelund, 1976). Helenelund (1976) implied that a general relationship could exist between tensile strength and shear strength for fibrous materials like peat. Citing Kelly and Tyson (1965), he suggested that peat behaves in a different way from mineral soils and so the relationship found for mineral soils cannot be applied to fibrous peat.

Table 4.11 shows the ratios of the measured direct shear and tensile strengths to undrained shear strengths of the basal peat at the study sites. As shown in this table, the ratios are different at each site. All ratios of tensile strength/*in situ* vane strengths, excluding the tensile strength outlier of 16 kPa at the Slieve Anierin landslide, are low and between 0.1 and 0.2. Helenelund"s (1976) measurements of *Sphagnum* peat gave a ratio between average tensile strength and *in situ* vane shear strength of about 0.5.

Table 4. 9. Pearson correlation coefficients of the physical parameters at the three landslides.

	Physical parameter	H	R	F	Rm	Ft	Fh	S. γ	D. γ	kCh	kFh	LoI	F. Mp	S. Mp	T	N
STRADUFF TOWNLAND	H, Von post Humification (E)	1.00														181
	R,Von post Fine fibre (E)	-0.84	1.00													181
	F, Fine fibre(D)	-0.21	n/d	1.00												70
	Rm, Coarse fibre (D)	-0.57	n/d	-0.20	1.00											70
	Ft, Total fibre content (D)	-0.62	n/d	-0.01	**(0.98)**	1.00										70
	Fh, Humus fraction (D)	0.62	n/d	-0.12	**(-0.95)**	**(-0.99)**	1.00									70
	S. y, Saturated bulk density (g cm^{-3})	0.82	-0.90	0.39	-0.21	-0.15	0.10	1.00								51
	D.y, Dry bulk densit (g cm^{-3})	0.68	-0.64	-0.50	-0.70	-0.80	0.85	0.58	1.00							51
	kCh, Hydraulic conductivity (m s^{-1})	0.42	-0.50	0.16	0.02	0.04	-0.10	0.31	0.23	1.00						51
	kFh, Hydraulic conductivity (m s^{-1})	0.89	-0.44	n/d	n/d	n/d	n/d	0.59	0.33	-0.29	1.00					26
	LoI (%)	-0.29	0.16	-0.34	0.66	0.61	-0.55	-0.34	-0.44	-0.02	-0.31	1.00				99
	F.Mp, Field water content (%)	0.18	-0.25	-0.03	0.82	0.83	-0.79	0.26	-0.21	0.11	0.54	0.38	1.00			153
	S.Mp, Saturated water content (%)	0.17	-0.38	0.42	0.67	0.76	-0.81	0.42	-0.39	0.19	0.75	0.23	0.33	1.00		52
	T, Transmission (%)	-0.67	0.70	0.10	0.11	0.13	-0.13	-0.71	-0.50	-0.37	-0.77	0.13	-0.06	-0.30	1.00	136
SLIEVE RUSHEN	H, Von post Humification (E)	1.00														165
	R,Von post Fine fibre (E)	-0.46	1.00													165
	F, Fine fibre(D)	0.56	0.35	1.00												70
	Rm, Coarse fibre (D)	-0.80	-0.51	-0.65	1.00											70
	Ft, Total fibre content (D)	-0.77	-0.49	-0.51	**(0.99)**	1.00										70
	Fh, Humus fraction (D)	0.79	0.50	0.44	**(-0.95)**	**(-0.98)**	1.00									70
	S. y, Saturated bulk density (g cm^{-3})	-0.33	-0.25	-0.17	0.08	0.05	-0.11	1.00								30
	D.y, Dry bulk densit (g cm^{-3})	-0.37	-0.28	-0.17	0.35	0.38	-0.30	-0.51	1.00							30
	kCh, Hydraulic conductivity (m s^{-1})	-0.17	-0.13	-0.17	-0.01	-0.05	0.11	0.85	-0.26	1.00						30
	LoI (%)	-0.46	-0.23	-0.44	0.62	0.61	-0.51	-0.25	0.78	-0.26	n/d	1.00				79
	F.Mp, Field water content (%)	0.15	-0.41	-0.66	0.82	0.78	-0.75	0.24	0.17	0.13	n/d	-0.08	1.00			141
	S.Mp, Saturated water content (%)	0.41	0.30	-0.11	0.03	0.01	0.06	-0.18	-0.53	-0.18	n/d	-0.41	0.13	1.00		30
	T, Transmission (%)	-0.22	-0.33	-0.49	0.70	0.68	-0.69	0.16	0.34	0.00	n/d	0.35	0.45	-0.14	1.00	145
SLIEVE ANIERIN	H, Von post Humification (E)	1.00														179
	R,Von post Fine fibre (E)	0.85	1.00													179
	F, Fine fibre(D)	0.51	0.59	1.00												70
	Rm, Coarse fibre (D)	-0.87	-0.84	-0.48	1.00											70
	Ft, Total fibre content (D)	-0.86	-0.81	-0.40	**(1.00)**	1.00										70
	Fh, Humus fraction (D)	0.85	0.85	0.46	**(-0.95)**	**(-0.95)**	1.00									70
	S. y, Saturated bulk density (g cm^{-3})	-0.59	-0.35	-0.06	0.71	0.73	-0.56	1.00								30
	D.y, Dry bulk densit (g cm^{-3})	0.81	0.68	0.15	-0.85	-0.87	-0.84	-0.80	1.00							30
	kCh, Hydraulic conductivity (m s^{-1})	0.13	0.24	0.30	0.07	0.09	0.02	0.21	-0.04	1.00						25
	LoI (%)	-0.47	0.37	0.01	0.50	0.53	-0.25	0.76	-0.54	0.25	n/d	1.00				80
	F.Mp, Field water content (%)	0.30	0.34	-0.45	0.82	0.81	-0.86	0.69	0.92	-0.57	n/d	-0.05	1.00			145
	S.Mp, Saturated water content (%)	-0.63	-0.69	-0.22	0.59	0.59	-0.77	0.17	-0.70	-0.32	n/d	-0.04	0.75	1.00		30
	T, Transmission (%)	-0.03	0.02	0.17	0.27	0.30	-0.28	0.73	-0.80	0.03	n/d	0.18	0.06	0.47	1.00	146

Note: Grey cells = not- significant value, bold, shaded in green and in parentheses = High (absolute value (| |)of r> 0.9) and consistent correlation at the three landslides.

Table 4. 10. Pearson correlation coefficients for the chemical parameters at the three landslides.

LANDSLIDE	**Chemical parameters**	% Bitumen	TPHs (mg g $^{-1}$)	PAHs (µg g-^{1})	Ali-C10-C18 (mg g^{-1})	Ali->C18-C35 (mg g $^{-1}$)	Ali->C35-C44+(mg g^{-1})	Ali-C10-C44+(mg g^{-1})	Aro-C10-C18(mg g^{-1})	Aro ->C18-C35(mg g^{-1})	Aro->C35-C44+(mg g^{-1})	Aro-C10-C44+(mg g^{-1})	% Transmission	Number of samples
STRADUFF TOWLAND	% Bitumen	**1.00**												20
	TPHs (mg g $^{-1}$)	0.20	**1.00**											20
	PAHs (µg g^{-1})	-0.34	0.03	**1.00**										20
	Ali-C10-C18 (mg g^{-1})	-0.26	-0.09	n/d	**1.00**									8
	Ali->C18-C35 (mg g $^{-1}$)	-0.30	-0.01	n/d	-0.27	**1.00**								8
	Ali->C35-C44+(mg g-1)	-0.22	-0.12	n/d	**(0.99)**	-0.22	**1.00**							8
	Ali-C10-C44+(mg g^{-1})	-0.31	-0.02	n/d	**(0.98)**	-0.38	**0.95**	**1.00**						8
	Aro-C10-C18(mg g^{-1})	**0.68**	0.05	n/d	-0.05	-0.17	-0.02	-0.11	**1.00**					8
	Aro->C18-C35(mg g^{-1})	-0.17	0.00	n/d	-0.36	0.32	-0.39	-0.30	-0.51	**1.00**				8
	Aro->C35-C44+(mg g^{-1})	0.48	0.06	n/d	-0.58	-0.06	-0.60	-0.52	0.27	0.63	**1.00**			8
	Aro-C10-C44+(mg g^{-1})	0.53	0.03	n/d	0.16	-0.16	0.20	0.08	**(0.94)**	-0.76	-0.09	**1.00**		8
	% Transmission	0.43	0.06	-0.51	0.00	0.44	0.08	-0.15	-0.08	-0.20	-0.39	0.06	**1.00**	19
SLIEVE RUSHEN	% Bitumen	**1.00**												29
	TPHs (mg g $^{-1}$)	0.47	**1.00**											29
	PAHs (µg g^{-1})	0.09	0.26	**1.00**										29
	Ali-C10-C18 (mg g-^{1})	**0.88**	0.30	**0.85**	**1.00**									5
	Ali->C18-C35 (mg g $^{-1}$)	0.08	0.08	0.20	0.21	**1.00**								5
	Ali->C35-C44+(mg g-^{1})	**0.73**	0.64	**0.90**	**(0.89)**	0.19	**1.00**							5
	Ali-C10-C44+(mg g^{-1})	**0.74**	-0.28	0.43	**(0.72)**	-0.19	0.38	**1.00**						5
	Aro-C10-C18(mg g^{-1})	-0.11	0.27	-0.12	-0.55	-0.37	-0.46	-0.34	**1.00**					5
	Aro->C18-C35(mg g-^{1})	0.20	-0.34	0.01	0.08	**0.72**	-0.21	0.18	-0.05	**1.00**				5
	Aro->C35-C44+(mg g-^{1})	-0.09	0.24	-0.12	-0.54	-0.37	-0.47	-0.31	**1.00**	-0.02	**1.00**			5
	Aro-C10-C44+(mg g^{-1})	-0.12	0.28	-0.12	-0.55	-0.38	-0.45	-0.36	**(1.00)**	-0.07	**1.00**	**1.00**		5
	% Transmission	0.11	0.06	0.09	0.24	-0.13	0.45	-0.07	**0.58**	-0.21	**0.57**	**0.59**	**1.00**	29
SLIEVE ANERIN	% Bitumen	**1.00**												23
	TPHs (mg g^{-1})	0.36	**1.00**											23
	PAHs (µg g-^{1})	-0.15	0.22	**1.00**										23
	Ali-C10-C18 (mg g^{-1})	0.22	0.11	-0.08	**1.00**									6
	Ali->C18-C35 (mg g $^{-1}$)	0.60	0.09	-0.47	**0.90**	**1.00**								6
	Ali->C35-C44+(mg g-^{1})	0.28	0.13	-0.14	**(1.00)**	**0.92**	**1.00**							6
	Ali-C10-C44+(mg g^{-1})	0.04	0.07	0.10	**(0.98)**	**0.80**	**0.97**	**1.00**						6
	Aro-C10-C18(mg g-^{1})	0.23	-0.46	0.02	-0.08	0.05	-0.07	-0.12	**1.00**					6
	Aro->C18-C35(mg g^{-1})	0.29	-0.92	-0.03	0.10	0.24	0.10	0.08	0.50	**1.00**				6
	Aro->C35-C44+(mg g^{-1})	0.17	-0.94	0.10	-0.09	0.03	-0.10	-0.10	**0.70**	**0.95**	**1.00**			6
	Aro-C10-C44+(mg g^{-1})	0.13	0.32	-0.06	-0.03	0.01	-0.01	-0.08	**(0.68)**	-0.28	-0.04	**1.00**		6
	% Transmission	0.39	-0.15	-0.28	0.21	0.53	0.26	0.05	0.01	0.20	0.05	-0.04	**1.00**	23

Notes Grey cells = not- significant value (i.e. at P < 0.05: 95 % confidence limit), bold, shaded in green and in parentheses = High (absolute value of r > 0.9) and consistent correlation at the three landslides. Ali = Aliphatic and Aro = Aromatic.

Table 4. 11. Ratios of measured tensile, direct shear strengths/undrained shear strengths of the basal peats from the three landslides.

Landslides	Ratio of direct shear stress / undrained shear strength		Ratio of tensile strength / undrained shear strength	
	In situ vane	Triaxial	*In situ* vane	Triaxial
Straduff Townland	0.9	3.8	0.2	0.8
Slieve Rushen	0.7	1.9	0.2	0.4
Slieve Anierin	0.9	3.2	0.5	1.9
Slieve Anierin *	Na	Na	0.1	0.5

* excluding the outlier (i.e. 16 kPa), Na= Not applicable

It is clear from the results of this study that the ratios of tensile strength to undrained shear strength of basal peats, measured at different sites and with different instruments varies. This lack of consistency suggests that there is no significant relationship between the direct shear, tensile strengths and shear strength measured with the experimental conditions used in this study. Therefore, neither of the measurements carried out using different instruments can be used to predict the other. This is due to the fact that the influence of fibres varies with the instrument used for measurements as discussed earlier in Section 3.3.8. The effects of fibre reinforcement on the measurements made with the shear vane, direct shear and triaxial instruments have not been quantified, modelled or validated. Furthermore, the vane test overestimates the undrained shear strength of peat as reported by several authors (e.g. Landva and La Rochelle, 1980; Landva, 1980) and shown by the results of this study. The results of the tensile strength measurements obtained from this study and by Dykes and Jennings (2011) were consistent, suggesting that the tensile strength may constitute a reliable indicator of peat strength. If the influences of physical properties on tensile strength measurements are quantified, the tensile strength of peat could be predicted using these properties. This can enable the stability assessment of blanket bogs to be carried out without the need for significant intrusive site investigations as explained in Chapter 5 (Section 5.4), thus considerably reducing the cost and time that is often required.

4.6.3- Proposed peat classification for stability assessment

The strength of peat depends on its „effective" structural features including the fibre types, lengths and contents, and the degree of humification as described and tested in this study. The following should be considered to classify upland peat for stability assessment:

1- **Peat constituents:** It is proposed that blanket bog peat be assessed with its principal (structural) constituents using a 5-point scale. The 5 points are described quantitatively as presented in Table 4.12 and qualitatively as 1 = very low (VL), 2 = low (L), 3 = medium (M), 4 = high (H) and 5 = very high (VH) presence of the character. A field assessment of peat constituents using this 5- points scale should provide a more simple and consistent way of describing peat for stability assessment. This should facilitate cluster analysis of the data using parameters of the same weighing, to determine potential weak zones within any peat profile for stability assessment.

The constituents of peat should be investigated *in situ* and corrected with laboratory tests. The statistical analysis showed a high correlation (i.e. $|r|> 0.9$) (Table 4.9) between total fibre (Ft), coarse fibre (Rm) and humus (Fh) fractions. Therefore it should be sufficient to describe only one of these fractions in the field using the criteria presented.

The results of the analyses of the fibre contents showed that the von Post system does not always work because highly humified monocotyledon peat can still contain a considerable amount of fibres. As a consequence, the categories for estimating humus and total fibre contents in the field have been modified as shown in Table 4.12. The humus fraction, which cannot be objectively assessed with the naked eye, should be assessed in the laboratory.

The greasiness (Gr) of the peat should be further investigated using the 5-point scale presented in Table 4.12. This is pending future laboratory experimental trials to determine the classes of the concentration of hydrocarbons throughout upland peat profiles.

The basal peat should be described at consecutive intervals (i.e. at a maximum interval of 0.14 m but preferably 0.1 m) representing the mean depth of weak basal layers as identified in Section 4.7. The laboratory measurements should be carried out according to the methods described in this thesis. Testing consecutive subsamples of the same known volume (e.g. 0.1 m^3 or less) from peat monoliths should enable the identification of weak and „sludge-like" layers or pockets throughout the profile.

The proportion of monocotyledons should be investigated using the 5-point scale as modified from Walker and Walker (1961) (Table 4.12). After treatment of cores in the laboratory according to Walker and Walker (1961), an assessment should be carried using a microscope. Detailed macrofossil analyses should only be carried out if there is apparent variability in the plant macrofossil assemblage. For monocotyledon peat, which can have various fragment sizes, a macrofossil size distribution curve should be produced in order to characterise the deposit. The influence of parameters such as wood and shrub remains on peat strength measurement is currently difficult to assess (Helenelund, 1976). They are rare in such peat anyway, and a note of their occurrence in peat samples should be made after strength measurements and during macrofossil analyses.

A peat profile should be delimited into zones after cluster analysis of the quantitative peat description data in order to identify potential weak zones within the peat profile. Parameters for the determination of principal structural features of the peat are given equal maximum weighting (i.e. 1-5) to avoid bias during the cluster analysis.

2- **The stratigraphy of the peat in the field:** The appearance of the peat should be determined *in situ* using the secondary characteristics as presented in Table 4.12. Secondary characteristics should include the degree of darkness, stratification, peat elasticity and boundary strength as described by Troels-Smith (1955) (Table 4.12).

This new semi-quantitative classification system is based on the characteristics of the peat in terms of its different constituents. It requires the peat to be analysed for its constituents, including microscopic examination for its palaoeobotanical content. The results of the new fibre content test should enable the characterisation of all peat fibres in terms of their diameters and lengths, which may strongly influence the strength of fibrous peat in particular (Helenelund, 1976). The assessment of the degree of humification using the humus fraction as defined in this thesis could overestimate the humus acid content, which could potentially include some dissolved organic matter and particulate organic matter (Krull *et al.*, 2004). However, this method provides a quick, simple, cost effective, consistent and universal way of quantifying the degree of plant degradation as result of humification that influence peat structure and strength that has major impact on peat instability. The method requires no sophisticated equipment. Detailed quantitative assessment should be carried out to investigate the actual humus acid distribution throughout the profile if necessary.

4.7- SLOPE STABILITY ANALYSIS AND MODELLING

The Slope/W software was used for slope stability analysis and modelling (Appendix B; Table B2 and Figure 4.40). Due to the fact that compression of peats occurred during sampling as discussed in Section 4.1, it was necessary to define the thickness of the basal peat according to the results of the study carried out at the three landslides. Figure 4.41 presents the thickness of the weak basal peat at each site as identified by cluster analyses of the results of the field descriptions, „raw" percentages of light transmission, fibre contents, macrofossil contents and quantitative fibre contents. The results from the Straduff Townland landslide show a thicker weak basal layer compared with the other two landslides. With the assumption that the sites failed in a similar way, the mean thickness of 0.14 m (i.e. 0.25, 0.07 and 0.07 m for the Straduff Townland, Slieve Rushen and Slieve Anierin landslides respectively) above the peat-mineral interface was used for modelling the weak basal peat layer at all three sites as explained in Chaper 3 (Section 3.3.8)

During the fieldwork, some geotechnical samples were obtained from depths more than 0.14 m above the peat interface with possibly slightly less humified, and therefore stronger, peat than the basal material. As a result, the actual *in situ* strength of the weak basal peat at the study sites may be slightly lower than this study suggests. These particularly weak peats may be so close to the base that they could not be feasibly sampled for testing using current methods. A consistent and suitable sampling and testing method for investigating physical and geotechnical properties of peat for stability assessment should improve blanket peat stability assessment methods, as proposed in Section 4.6.3.

The analyses of the slopes using measured or published values as the basis for strata parameters (Appendix B; Table B2) produced the strength values presented in Figure 4.42 for the three landslides.

The higher mean measured tensile strength for the Slieve Anierin landslide is owing to the outlier of 16 kPa that was not removed from the data. Although Dykes (2008d) and Dykes and Jennings (2011) used different modelling approaches for the Maghera and Straduff Townland bogflows, the reported values of cohesion (i.e. < 2 kPa) for the basal peat are consistent with the findings of this study.

The resulting probabilities of failure are presented in Table 4.13 (Appendix B; Figure B2). They indicate that the Straduff Townland slope apparently had no chance of failing under the experimental conditions indicated in the model. This finding suggested that other sites factors (e.g. the presence of the escarpment) may have significantly influenced the peat failure.

The effect of water pressure on the stability of the slopes was assessed by increasing the water level and including tension cracks in the bog surfaces, through which water could enter the catotelm peat if there was rainfall. In fact, most peat landslides have been triggered by heavy precipitation. However, the excess load provided by excessive precipitation is relatively small because although an additional 2 mm depth of water is equivalent to 0.02 kPa, this is negligible on a bog over approximately 3 m thick (Bishopp and Mitchell, 1946). This implies, for example, that 90 mm of rain brought an increase of about 0.9 kPa in the head of water at Dooncarton Mountain and 200 mm brought about 1.9 kPa of increase of the hydraulic head in the Shetland blanket peat prior to failure in September 2003. In fact, increasing the hydraulic heads up to 0.2 m showed no effect on the FS for the Straduff Townland and the Slieve Anierin blanket bogs. A slight decrease in the probability of failure (Table 4.13) was observed at the Slieve Rushen blanket bog.

These findings confirmed that during significant rainfall events (i) in the presence of tension cracks in the peat, (ii) in the absence of preferential flow pathways such as pipes that cannot be fully represented using Slope/W and (iii) due to the negligible permeability of peat that gives rise to undrained conditions, hydrological loading has less influence on the failure mechanism on some slopes. This finding rejects the hypothesis that loading of peat as result of rainfall or standing water can induce failure. The following possible explanations are proposed about the influence of rainfall on peat instability: (1) further saturation may occur within the peat and critically reduce the basal peat strength by decreasing capillary forces and undrained strength, or (2) rainfall may enter the cracks and infiltrate into the peat, therefore decreasing the cohesion between hydrophobic hydrocarbon areas or layers in the lower catotelm and its wet surrounding peat material, leading to peat failure.

Some limitations of the modelling include: (i) Slope/W does not simulate rainfall and does not take into account the reduction of peat strength with time due to increase water content (especially in the highly humified lower catotelm); and (ii) the influences of hydrocarbon compounds in the basal peats, which may reduce the cohesion between peat layers or molecules, cannot be assessed using Slope/W. If the influence of these hydrocarbons could be quantified, an appropriate reduction factor could perhaps be applied to the strength parameters.

Sensitivity analyses

Sensitivity analyses were carried out in Slope/W to find out the sensitivity of the slope stability to the parameters of the three modelled strata, i.e. the surface (S), the middle (M) and basal (B) peats. Contrary to the probability analyses, during sensitivity analyses, the software selects the parameters by order and not randomly. For example, the strength parameter of a basal peat was held constant and the software computed a FS for each of the input parameters of the middle and surface strata. The trial was repeated for all the input parameters in turn and their corresponding FS were derived. Sensitivity analyses of the tensile strengths and bulk densities using Slope/W (Figure 4.43) showed that the stability of the Slieve Rushen and Slieve Anierin slopes was influenced by the cohesion of their basal peats. At the Straduff Townland landslide, the strength of the middle peat has more influence on the stability of its slope. These findings could indicate different influences on the failure mechanism at the Straduff Townland blanket peat because the results of the water content also showed that this middle peat was different from the surface and basal peats in having higher water contents. The cohesion is more important than the unit weight in this case. In fact, the modelled blanket bogs that flowed are located on slope with low slope angles (e.g. slope angle at the head of the source areas < 6º as presented in Table 2.8). It is considered that with low and almost negligible unit weights as revealed by the results of laboratory analyses of peats from this study sites (e.g. low saturated bulk density; Figure 4.13 and 4.14); the main influence on the peat mass movement is the cohesion resulting from the bonds between peat chemical compounds.

Given the inherent variability and uncertainty of actual field conditions and the fact that model outputs should realistically be regarded as indicative rather than definitive (Dykes and Kirk, 2000), the results of the modelling presented in this Section, which suggest that under the experimental conditions the probability of these slopes failing was <20%, should be treated with caution.

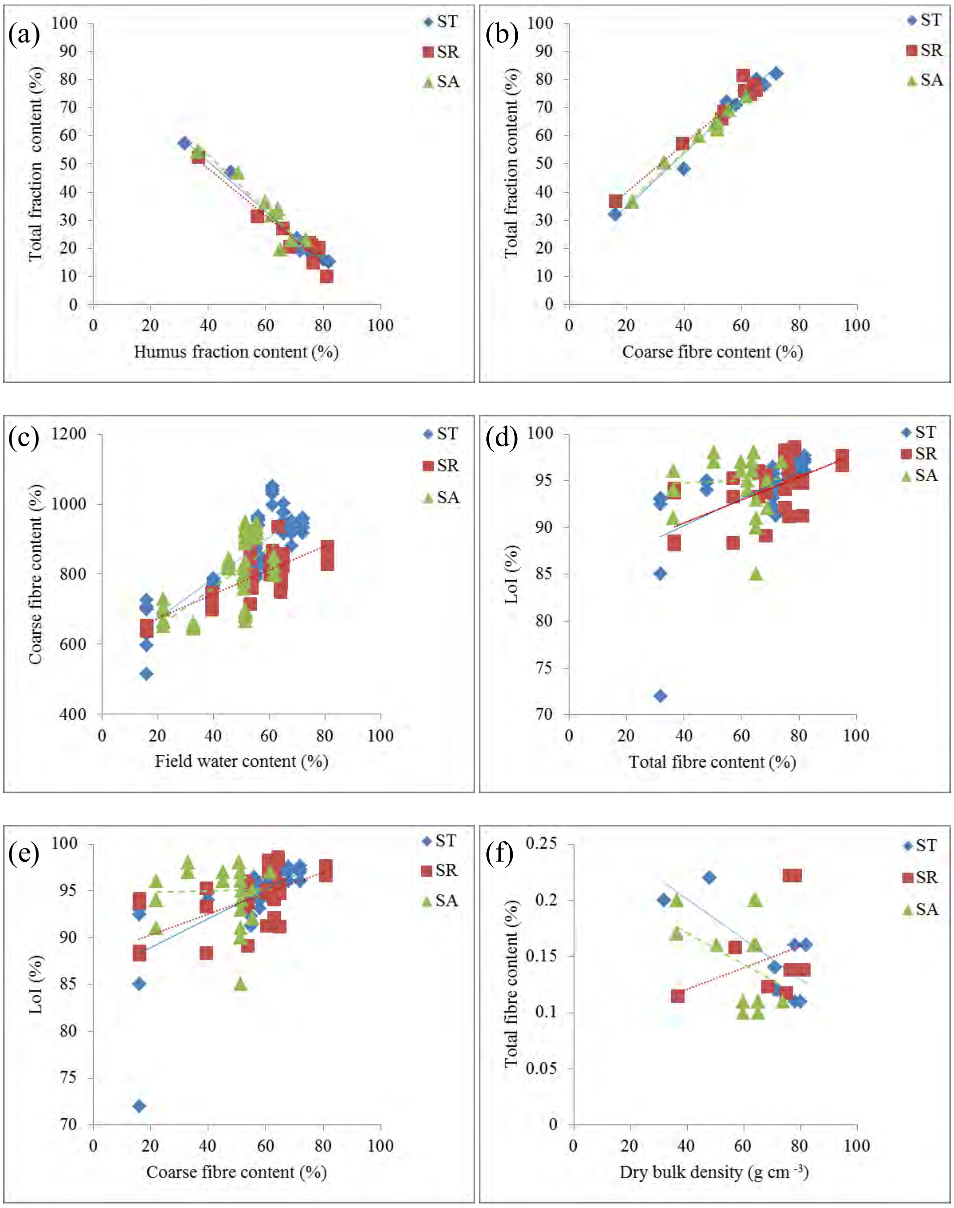


Figure 4. 37. Linear regression plots: (a) total fibre content vs. coarse fibre content, (b) humus fraction vs. total fibre content, (c) field water content vs. total fibre content, (d) LoI vs. total fibre content, (e) LoI vs. coarse fibre content and (f) total fibre content vs. dry bulk density. All the points presented in the graphs represent multiple sampling points as presented in Table 4.9.

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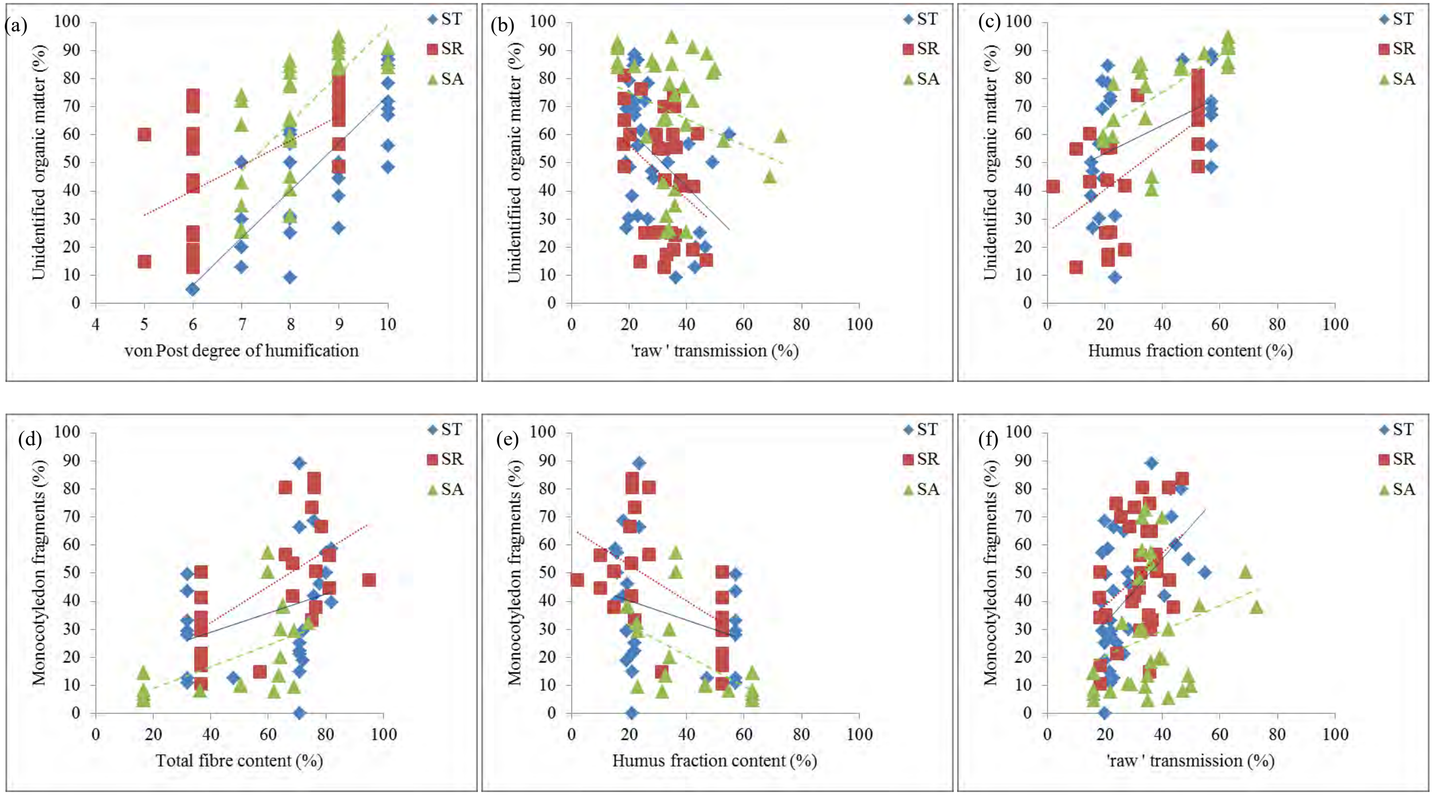

Figure 4. 38. Linear regression plots: (a) von Post degree of humification vs. unidentified organic matter (UOM), (b) UOM vs. „raw‟ percentage light transmission, (c) UOM vs. humus fraction content, (d) monocotyledons fragments vs. total fibre content, (e) monocotyledons fragments vs. humusfraction content and (f) monocotyledons fragments vs. . „raw‟ percentage light transmission.

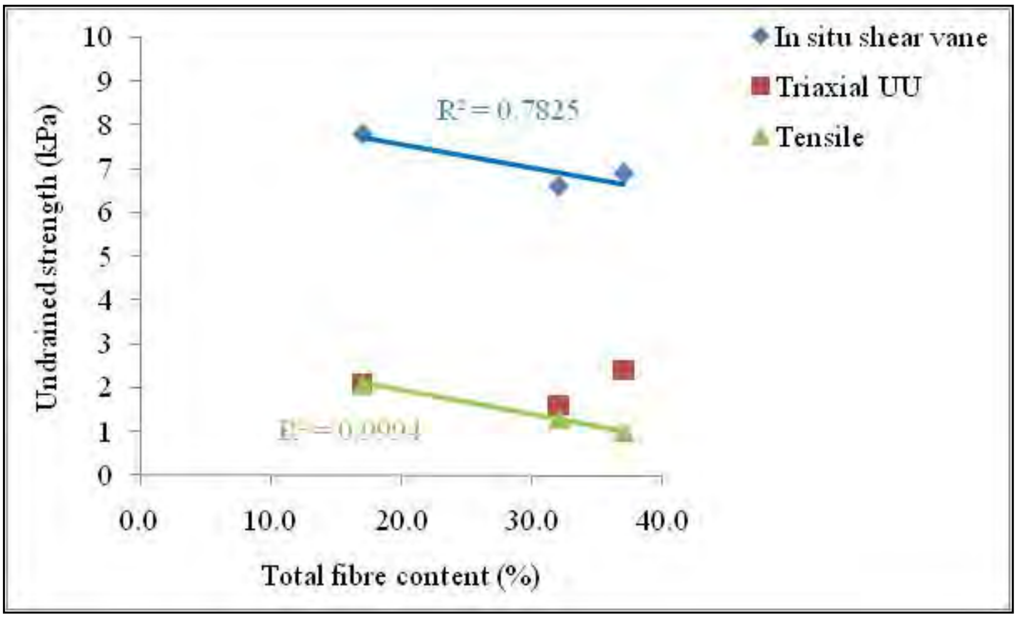

Figure 4. 39. Graphs of the undrained strength plotted against total fibre content at the three landslides investigated.

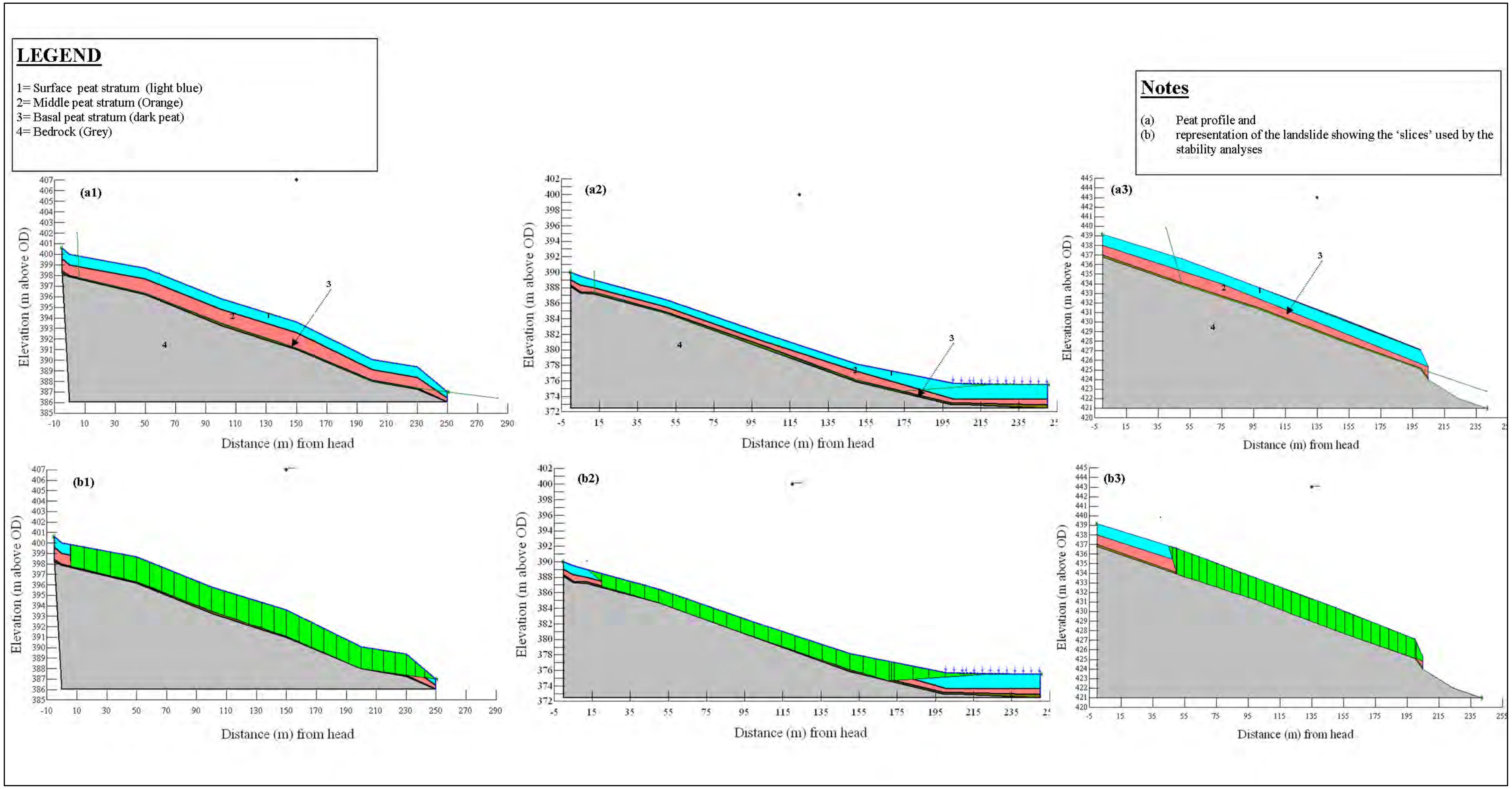

Figure 4. 40. Stability model of the three landslides: (1) Straduff Townland, (2) Slieve Rushen, (3) Slieve Anierin, showing (a) peat profile and (b) representation of the landslide showing the „slices" used by the stability analyses. Layers 1-3 are peat strata and 4 is the bedrock.

Table 4. 12. Proposed parameter scales for quantitative peat descriptions.

Type	Properties	Scale						Assessment method
		0	1	2	3	4	5	
Principal [a]	Humus fraction (Fh) (<0.15 mm) (%)	N/d N/d	20-40 & (H1-3)[b]	40-60 & (H4-7)[b]	60-80 & (H8-10)[b]	80-95 & (H8-10)[b]	>95 & (H8-10)[b]	Field/Laboratory
Principal [a]	Fine fibre (Fm) (0.15-1 mm) (%)	N/d	20-40	40-60	60-80	80-95	>95	Laboratory
Principal [a]	Coarse fibre (Rm) (>1 mm) (%)	N/d N/d	20-40 & (H8-10)[b]	40-60 & (H8-10)[b]	60-80 & (H8-10)[b]	80-95 & (H4-7)[b]	> 95 & (H1-3)[b]	Field/Laboratory
Principal [a]	Total fibre content (Ft) (>0.15 mm) (%)	N/d	20-40	40-60	60-80	80-95	>95	Laboratory
Principal [b]	Organic content (N) = LoI (%)	N/d	20-40	40-60	60-80	80-95	>95	Laboratory
Principal [b]	Wetness (B) (%)	N/d	0	< 500	500-1000	1000-2000	> 2000	Field/Laboratory
Principal [a,c]	Monocotyledons (Mt) (%)	N/d	0-20	20-40	40-60	60-80	80-10	Field/Laboratory
Principal [a]	Tensile strength (H or V) (kPa)	N/d	0-2	2-4	4-6	6-8	>8	Field/Laboratory
Principal [a]	Greasiness/oiliness (Gr)	N/d	no visible greasiness	slightly greasy	moderately greasy	very greasy	bituminous	Field/Laboratory
Secondary [f]	Darkness (Nig.)	0-1/8 - absence to slight presence of	1/4- minor presence of	2/4- medium presence of	3/4- major presence of	4/4 – maximum- or sole- presence of	N/d	Field
Secondary [f]	Stratification (Strat.)	"	"	"	"	"	N/d	Field
Secondary [f]	Boundary strength (Lim sup.)	"	"	"	"	"	N/d	Field
Secondary [f]	Elasticity (Elas.)	"	"	"	"	"	N/d	Field

<u>Notes</u>

[a] New

[b]von Post (Hobbs, 1986)

[c]After Walker and Walker (1961)

[f]Troels-Smith (1955)

H=Horizontal and V=vertical

Table 4. 13. Reliability index and probability of failure at the modelled blanket bogs.

Blanket bog	Mean FS	Reliability Index (ß)	P[b] (Failure) (%)	Standard Deviation	Minimum FS[c]	Maximum FS	Number of Trials
Straduff Townland	1.8	2.2	0.0	0.4	1.0	2.6	2000
Straduff Townland [a]	1.8	2.2	0.0	0.4	1.0	2.6	2000
Slieve Rushen	1.6	1.5	5.9	0.4	0.7	2.6	2000
Slieve Rushen [a]	1.6	1.5	5.5	0.4	0.7	2.7	2000
Slieve Anierin	2.6	0.9	19.4	1.7	0.1	8.8	2000
Slieve Anierin [a]	2.6	0.9	19.4	1.7	0.1	8.8	2000

Note
[a] Plus 0.2 m hydraulic head
[b] P = Probability
[c] FS= Factor of Safety

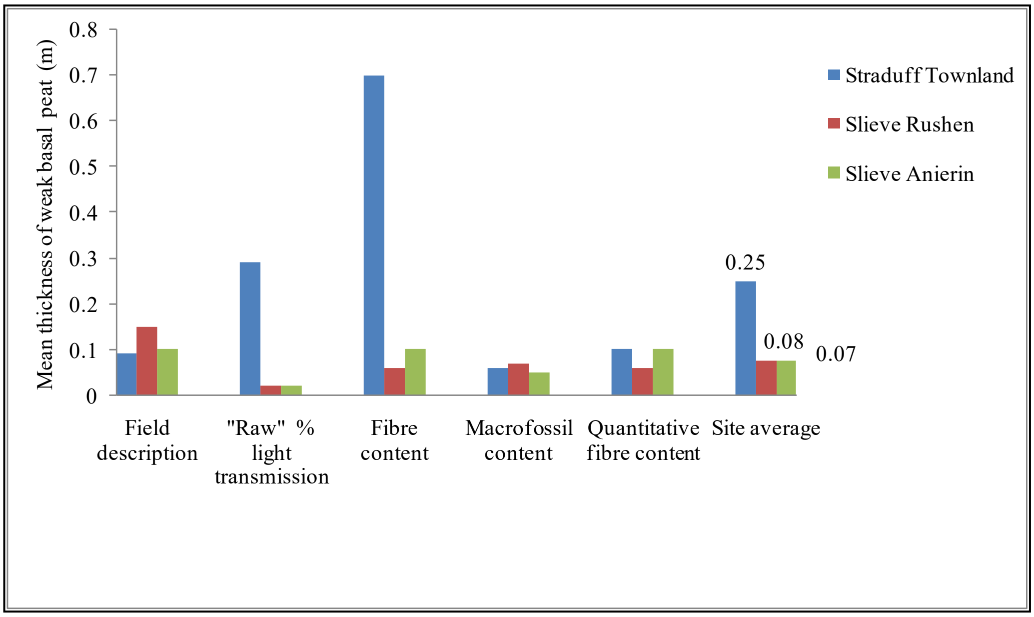

Figure 4. 41. Variation of mean thickness of basal peat depths according to specific physical properties at all three landslides.

4.8- SOME MAJOR CONCLUSIONS OF THE SYNTHESIS OF RESULTS

The synthesis carried out in this chapter indicated that the major influences on peat undrained strength and instability are the degree of humification, the fibre content and the macrofossil content, the results of which were consistent between the study landslides. The statistical analyses showed a correlation between fibre fractions as defined in this thesis, suggesting their possible uses for blanket bog stability assessment. The MFC classification adopted in this study showed reproducible results at the three landslides investigated, which may suggest similar structural properties.

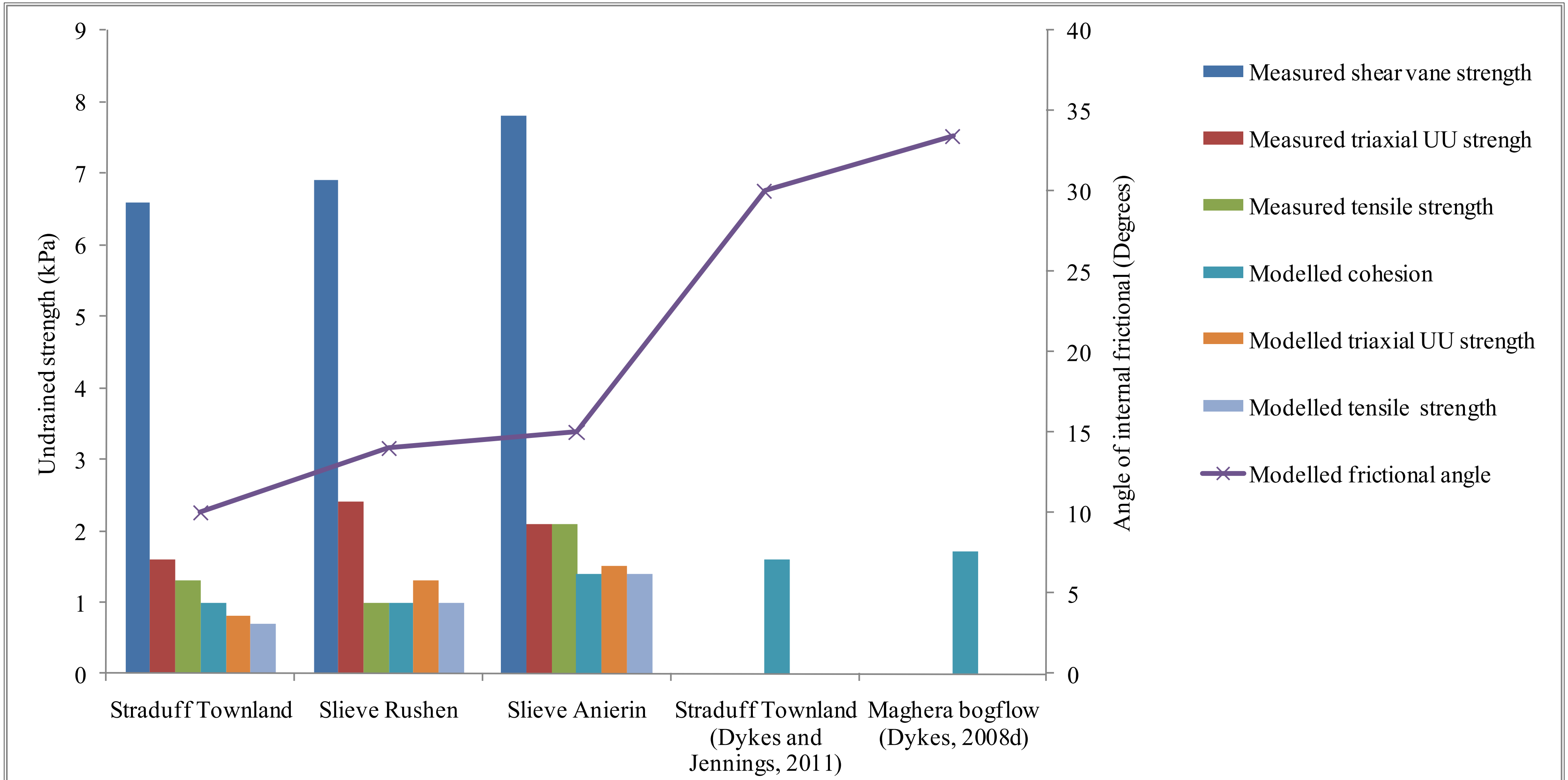

Figure 4. 42. Basal peat strength parameters measured and modelled. UU = Unconsolidated undrained. The modelled triaxial and tensile strengths refer to their surrogates for cohesion.

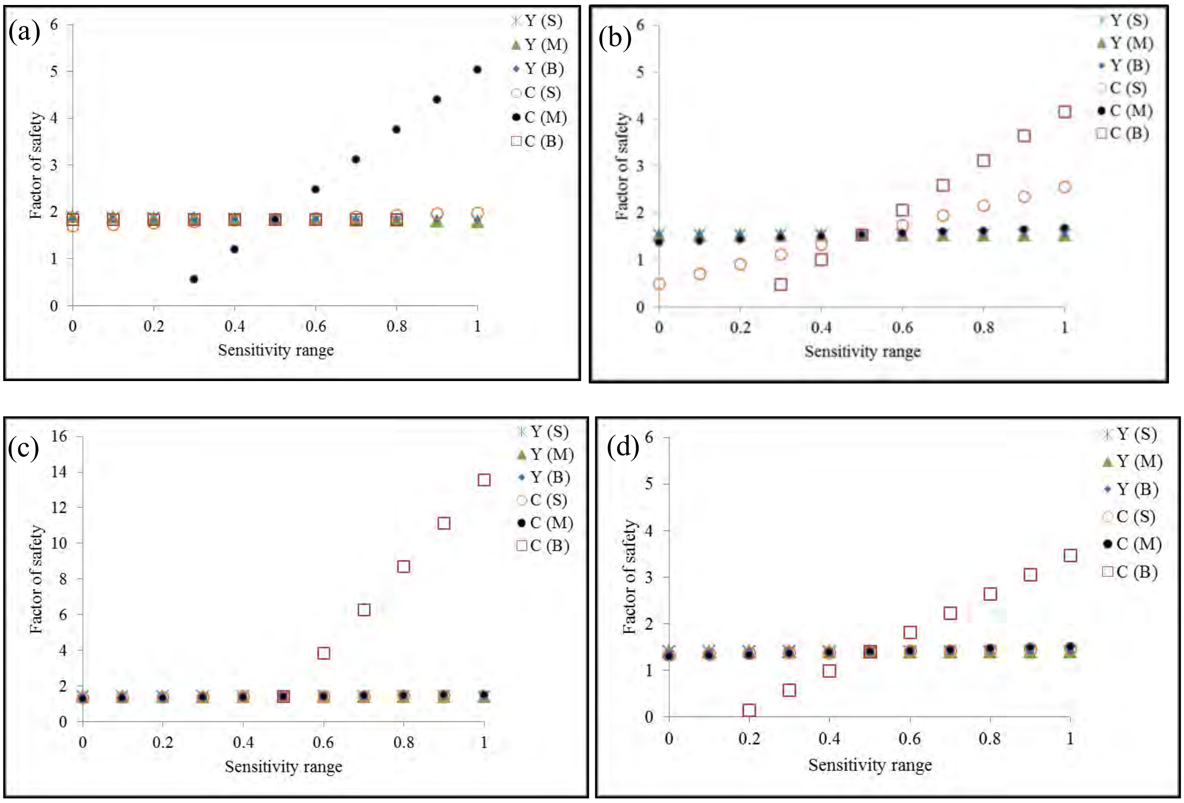

Figure 4.43. Plots of slope stability sensitivity analyses at: (a) Straduff Townland, (b) Slieve Rushen, (c) Slieve Anierin including the outlier (i.e. cohesion 16 kPa) and (d) Slieve Anierin excluding the outlier. S = surface, M = middle, B = basal peats. C = Cohesion (i.e. surrogate of tensile strength), y = Unit weight. On each graph, the point where the sensitivity curves cross each other is the deterministic factor of safety at the mid-point of the range for each of the strength parameters specified.

The LoI, the water content, the bulk density and the hydraulic conductivity measurements accord with results from other types of peat landslides. However, these parameters influence peat instability but cannot be used as indicators of peat failure mechanisms. The correlation coefficients between these parameters were either not very strong (e.g. $|r| < 0.7$), not statistically significant or significant but not consistent at the three landslides (e.g. LoI vs. wet saturated bulk density with low negative correlation for Straduff Townland and Slieve Rushen and high positive correlation for Slieve Anierin).

The results of this study indicate that the undrained strengths of the basal peats, measured with very low experimental conditions using different instruments, were generally low and accord with site evidence and previous research carried out using similar experimental conditions. Further analyses of the geotechnical results suggested no consistent relationships between undrained strength measured with different instruments at the study sites. The analyses confirm a relationship between the von Post degree of humification and peat strength. However, the method has some limitations that need to be taken into account during blanket bog characterisation.

Hotspots of hydrocarbons were found to occur in the basal peats at the three landslides and may have promoted the bogflows. The results of bitumen, TPHs and PAHs could not be differentiated and there was a strong relationship (i.e. $r > 0.9$) between some hydrocarbon fractions at the study sites.

CHAPTER FIVE – DISCUSSION

This chapter addresses the research question by examining the influences of peat properties on upland blanket peat instability. The specific objectives are: (i) to discuss the influences of the peat properties on the occurrences of the landslides and (ii) to assess the implications for upland peat stability assessment.

5.1- INFLUENCES OF PEAT STRUCTURAL PROPERTIES ON PEAT INSTABILITY

Based on plant physiology and the principles of organic chemistry, it can be suggested that the strength of peat depends on its chemical properties (e.g. the nature, strength and proportion of chemical bonds between its molecules and macromolecules) which in turn depend on the cytology, histology and anatomic characteristics of the original plants (and animals) as presented in Figure 5.1. The „effective" structural and chemical properties analysed have been differentiated from other properties that have been considered to have less influences on peat strength (Section 4.6). Some factors studied as parts of this work and presented in this Figure are discussed in the following sections.

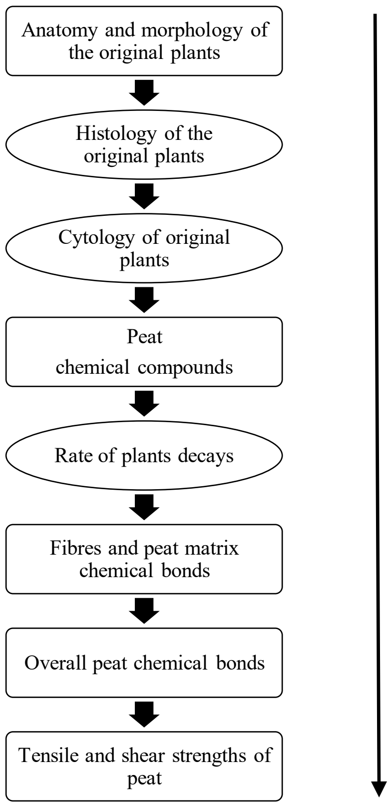

Figure 5. 1. Possible relationships between peat physical, chemical and geotechnical (specifically strength) properties. The items in rectangular boxes have been discussed in this study.

5.1.1- 'Effective' structural and chemical properties of peat

The strength of peat is mostly determined by its macrofossil content and type, which influence the proportion of fibres, peat matrix and the chemical characteristics of peat molecules and macromolecules that have major influences on peat strength.

Macrofossil content: Relatively little palaeoecological work has been carried out on failed blanket peat for stability assessment purposes, using published methods (e.g. Birks and Birks, 1980) or otherwise.The results of macrofossil analyses (Figures 4.24) suggested that the original plant assemblages throughout the monoliths were homogeneous with monocotyledons (with *Eriophorum vaginatum*) and contained high proportions of unidentified organic matter at the bases. Monocotyledons have distinctive characteristics that may promote peat instability. These include their parallel major leaf venation, elongated leaves and roots (Landva and Pheeney, 1980) that could promote flow and/or slippage and that differentiate them from other blanket bog plants. Furthermore, sedge peat does not have any discernible water-holding cells and so the resistance of the cells to applied loads may arise only from the resistance of the cell walls and possibly any additive deposited during fossilization (MacFarlane and Radforth, 1968).

The absence or rarity of *Sphagnum* sp. in the samples analysed suggests that the peats accumulated under relatively dry conditions (Evans and Warburton, 2007) compared with conditions where *Sphagnum* sp. often grows. *Eriophorum* spp. (especially *E. vaginatum*) has very deep rooting habits compared with *Sphagnum* sp. and is therefore a primary species for eroded peats (Evans and Warburton, 2007). This implies that the study sites may have been eroded at some point. In fact, processes such as erosion or burning of peat over a short period of time that led to a reduction in the vegetation cover (e.g. Colhoun *et al.*, 1965), may lead to drying out and possibly shrinkage cracking of the surface peat. During a drought episode, the surface layers of peat dry out, shrink, crack and the continuous colloidal structure of a peat mass is destroyed. With prolonged desiccation, during exceptionally dry summers, the cracks penetrate progressively deeper into the peat mass, creating vertical fissures which can then persist as long-lived features because of the inability of the dried out peat to absorb water and coalesce again on subsequent re-wetting (Tallis, 2001). If a drought period occurred at the study sites during the accumulation of peat, tension cracks may have developed within the peat masses. Subsequent rainfall could have moved rapidly down to the lower peat layers (e.g. Bowes, 1960; Colhoun *et al.*, 1965; Alexander *et al.*, 1986). The transmission of water through to bedrock could be prevented by any existing impermeable (or hydrophobic) plane at the bases of the profiles or around hydrophobic localised spots (i.e. bitumen spots: Rennie, 1810) within the basal peats. Owing to the low densities of the peats (Figures 4.11-4.14), this may have caused buoyancy effects (i.e. generation of artesian pressures) and peat failure (Warburton *et al.*, 2004).

The mean percentages of monocotyledon fragments were low (i.e. <29%) for the basal peats collected at the three landslides, which may suggest lower *in situ* strengths compared with the upper peats that had higher percentages of monocotyledons fragments (Table 4.6). Most or all of the constituents of sedge plants (*E. vaginatum)* in the basal peats are small, partly or completely broken or torn as a result of humification, therefore the intra-particle water would escape as readily as would the inter-particle water when peat is compressed due to loading by the peat mass above or by water (Warburton *et al.*, 2004). This could explain the large quantities of water released during the bogflows as presented in Table 4.3.

The analysis of peat samples for their macrofossil contents (Table 4.6) also showed that all the peats contained low counts of charcoal fragments, which meant that the blanket bogs at the study sites were subjected to fires at some point in time. The incomplete combustion of surface or sub-surface plants/peat may have influenced the structure of the peat in the burnt areas by increasing its overall PAHs content therefore the chemical bonding within the chemical compounds in peat and peat strength as explained in the following sections.

The high proportion of unidentified organic matter encountered in the basal peats from the study sites suggested high degrees of humification. Figures 4.38a-c show that peat humification increases with an increasing percentage of unidentified organic matter and that this trend is consistent at the three landslides.

Humification and fibre content: The results of this study confirm that the degree of humification is highly related to the fibre content as shown in Figures 4.37b and discussed in Section 4.6. The descriptions of the basal peat at the three landslides using the von Post and the MFC systems (Tables 4.1, 4.2 and 4.7) showed high degrees of humification as also confirmed by the low means of „raw" percentages of light transmission (i.e. < 23%; Figures 4.17-4.18, Table 4.4). These findings suggest highly humified peat and lower strengths compared with the surface peat samples with less humified peats. Periods favouring low plant decomposition have been associated with wetter and/or cooler climatic conditions (Caseldine and Gearey, 2005). The higher degrees of humification at the base of the peats are consistent with previous works (e.g. Blackford and Chambers, 1995) as discussed in Chapter 4 (Section 4.3). Furthermore, they could imply drier conditions compared with the upper less humified layers if the rate of plant decomposition was exclusively due to the fluctuation of water table level during the formation of the peat. In view of the results of the macrofossil analyses which show monocotyledons dominating the peat at all three landslides, it can be hypothesised that the degree of peat humification as a result of negligible fluctuation of water table is more likely to increase with depth if the original plant assemblage throughout the profile is homogenous with the same plant species. In fact, Figures 4.38d-f show that the percentage of monocotyledons as analysed in the laboratory decrease with increasing humus fraction and also with decreasing „raw" percentage of light transmission at the three landslides. In such cases where peat macrofossil contents are homogenous, the rate of peat humification is principally due to the activity of microorganisms over time and the degree of decomposition throughout the peat profile depends on the characteristics of the principal plant species present. The chemical characterisation of the molecules and macromolecules of such peats can be used as a proxy to determine their paleohydrology (Kuder and Kruge, 1998) and thus their paleoecology.

The original plant species assemblage (Figure 5.1) influences the degree of humification (e.g. Coulson and Butterfield, 1978; Clymo and Harwad, 1982; Clymo, 1983; Hughes *et al.,* 2012; this study). Theoretically, the more humified the basal peat, the lower its bearing capacity and strength and the less stable the blanket peat. Citing Boelter (1969) and Hobbs (1986), Dykes and Kirk (2006) commented that high humification corresponds with lower water contents and lower liquid limits. Dykes and Kirk (2006) implied that the lower porosity and liquid limit may cause the highly humified basal catotelm to be susceptible to failure because it would take a smaller increase in water content to bring about significantly higher water pressures or even a change of state. On the other hand, any contrast in shear strengths between layers could control the occurrence and position of shear failure above the base of the peat profile (Delap and Mitchell, 1939).

Most studies of peat landslides have used the von Post degree of humification as discussed in Section 4.1 but this cannot be quantitatively determined in the laboratory. The laboratory colorimetric (i.e. alkali) method used in this study extracts a complex mixture of different compounds (including humins) which are often assumed to be humic and fulvic acids (Caseldine *et al.*, 2000; Morgan *et al.*, 2005; Hughes *et al.*, 2012). This constitutes a limitation in the interpretation of the humification data expressed as „raw" percentage of light transmission because it is unclear what has actually been measured or quantified.This limitation can also explain why this measure of the degree of humification does not consistently increase with depth as it often does according to the von Post scheme.

The analysis of the fibre contents of the peat samples showed that although the basal peat at the three study landslides was very highly humified, it comprised 27-47% of total fibres (Figures 4.19 and 4.20, Table 4.5). The occurrence of significant fibres at the base of the peats was unexpected in view of the smooth and homogenous texture of the basal peats *in situ* and may suggest that the fibre content throughout a peat profile may not be the only factor that influences peat strength. Distributions of fibre lengths and thicknesses may also be important. Peat fibres contribute to peat strength (e.g. Helenelund, 1976; Landva, 1980). The high fibre contents of the peat encountered at the study sites therefore accord with the results of macrofossil analysis that showed monocotyledon remains which have elongated and lignified strong leaves and stem tissues that resist microbial degradation. Another interesting implication from this finding is that the residual fibres in the basal peats, i.e. those that are readily compressible because they are broken remains of lignified tissues with no discernible water holding capacities, may have accumulated, compressed and undergone the different stages of petroleum hydrocarbon formation.

Chemical properties of peat: The results of this study showed that at all of the study sites, the concentrations of solvent extractable hydrocarbons and free bitumen were high in some spots (Figure 4.33). These findings accord with the field observations and the results of peat classifications according to the MFC method that showed very greasy and bituminous basal peat (i.e. Gr 4-5) at the sampling points at the three landslides. These findings also support previous observations (e.g. Alexander *et al.*, 1986; Creighton, 2006) from peat failure sites and other peatlands (Rennie, 1810).

Peat 'effective' structural properties, influences on peat overall chemical bonds, strength and instability

An understanding of peat stability and the influences of peat"s physical properties should begin with the understanding of the nature, distribution and strength of the bonds that hold its ions, atoms, molecules and macromolecules together to form peat as a substance. In any material, chemical bonds may be of different types which give specific strength and physical properties to the material (Table 5.1). In mineral soils, Mitchell *et al.* (1969) postulated that the effective normal and shear stresses are transmitted via the interparticle contacts. They suggested that physical-chemical forces of interaction act mainly to influence the initial fabric during formation of the soil structure and to modify the interparticle contact forces. The interparticle contact zone is considered to be solid in nature, and to involve the development of interatomic bonds of strength of the same order of magnitude as primary valence bonds (Mitchell *et al.*, 1969). Furthermore, any interparticle contact in mineral soils may contain many interparticle bonds, each of which is of approximately the same strength with the actual number being proportional to the normal force transmitted at the contact (Mitchell *et al.*, 1969).

Figure 5.2 (adapted from Charman, 2002) shows that the overall strength of peat depends on the overall chemical bonds provided by its chemical compounds. Different plant types and parts have different tissues and chemical compounds thus different chemical bond strengths. Humic and fulvic acids are stable molecules and provide the smallest number of chemical bonds compared with humins. The strongest chemical bonds are provided by sclerenchyma tissues which can bond with cellulose, hemicellulose and pectin to form vascular tissues which are complex tissues. Fibres and scleroid are dead tissues of sclerenchyma complex tissues which are mostly made of lignin, i.e. a very complex polymer of phenol (Schellekens *et al.*, 2012). The tensile strength of fibres of woody plants has been estimated to be 15-20 kPa, which is equivalent to that of a steel wire of the same diameter and is due to both lignin and extensin (i.e. glycoprotein attached to cellulose in plants cell walls; Taiz and Zeiger, 1991). Unlike polymers of cellulose, the units of lignin are not linked in an organised, repeating way. Each lignin molecule may be unique and species dependent (Taiz and Zeiger, 1991). Such thermosetting polymers have extensive cross-linking which render the molecule difficult to rupture. Furthermore, phenol compounds such as lignin are microbiological refractory compounds and they are inhibitors of plant decomposition in peat (Freeman *et al.*, 2004; Charman, 2002). The refractory property of phenol compounds is due to the fact that oxygen constraints upon the activity of phenol oxidase promote conditions that inhibit decomposition (Freeman *et al.*, 2004). The strength of bonds in phenol compounds contributes a great deal to peat strength because these compounds have high energy that stabilises their carbon-carbon bonds in their aromatic rings (Freeman *et al.*, 2004).

The remains of the cell walls of the leaves and stems found in peat are therefore mostly the remains of elongated parallel scherenchyma tissues that resist microbial decomposition and influence peat strength.

Table 5. 1. Various types of chemical structures and bonds and their occurrence in peat (after Otter, 2008).

N	Types of bond	Types of particles	Chemical bonding mechanism	Compounds	Hardness	Melting or boiling points	Solubility in water	Examples in peat (Charman, 2002)	Frequency in peat
1	Ionic[1]	Ions	Strong ionic bonds: attraction between oppositely charged ions	Metals-non-metals	Hard but brittle	High/Intermediate strength e.g.Sodium Chloride,800ºC; Magnesium oxide, MgO, 2800ºC	Often soluble	Sodium Chloride: NaCl; Calcium Oxide, CaO	Rare (Frequent in minerals)
2	Covalent networks[2]	Atoms	Strong covalent bonds; attraction of atoms"nucleii for shared electrons	Some elements of Group 4 of the periodic table and their compound	Very hard (if three dimensional) / High	Very high e.g. Silica, SiO_2" 1600 °C	Insoluble	Silica, SiO_2	Low (Frequent in mineral solid)
3	Metallic[1]	Positive ions surrounded by delocalised electrons	Strong metallic bonds; attraction of atoms"nucleii for delocalised electrons	Metals	Very hard but malleable	Generally high e.g. Cast iron, 1200°C	Insoluble (but react)	Sodium, Na; Iron: Fe	Low (Frequent in mineral solid)
4	Covalent simple molecules[3]	Small molecules	Weak intermolecular bonds between molecules; strong covalent bonds between the atoms within molecules	Some non-metal elements and compounds	Soft	Low e.g. α-D-glucose: 146°C; Fluvic acid, 246°C	Usually insoluble, unless molecules contain groups which can hydrogen-bond with water	Glucose, humicacids, fluvic acid	Very frequent and decrease with peat humification
5	Covalent macromolecules[4]	Long-chain molecules	Weak intermolecular bonds between molecules; strong covalent bonds between the atoms within molecules	polymers	Variable: many are often flexible	Moderate – often decompose on heating e.g.Tetracontane,524°C; celluloses, 500°C	Usually insoluble	Vascular plant peat: lignin, celluloses; Non-vascular plant peat: Paraphenic macromolecules,	Very frequent and decrease with peat humifaction

Note[1-2] Giant lattice, [3-4] Covalent molecular bonds

A study of the lignin content of peat showed that the lignin composition varies strongly between plant species, plant parts and elements of plant cells, and its resistant to decay may show similar differences (Schellekens *et al.*, 2012). Schellekens *et al.* also showed that non-lignin phenolic compounds (e.g. Suberin) and non-lignified polysaccharides are degraded during the first stage of peat humification in the acrotelm. Pure lignin is degraded later in anaerobic conditions by specific organisms, which are mostly fungi (Kuder and Kruge, 1998). It should be noted that lower plants (e.g. *Spagnum* sp.) do not have complex tissues; simple tissues perform all the physiological functions. These plants have non-lignin phenolic compounds (Schellekens *et al.*, 2012) and they form peat that is likely to have fewer fibres and lower strength compared with monocotyledon peat at the same degree of humification. Figure 5.2 shows that the chemical properties of peat determine the rate of plant decomposition and the amount and dimensions of fibres in peat. These properties influence peat strength.

The number of covalent bonds that contribute to peat strength is also determined by the sizes of the original plant parts. In general, the longer and larger the chains of molecules or monomers, the stronger the polymer formed. Therefore, the longer a fibre, the longer its macromolecules and the higher the energy that is required to (1) break up its inter- and intra-molecular bonds or (2) extrude the fibre from the peat matrix. Furthermore, the greater the number of strong chemical bonds per unit surface area, the greater the difference in energy that is required to break up the material. These chemical principles suggest that a thick layer of fibres should be stronger than a single or small fibre with the same degree of humification and macrofossil type. For example, Table 5.2 compares the approximate dimensions of two different plant parts as presented in the literature and shows that vascular plants have larger components than mosses. Considering that different plant parts also have different chemical compounds and different rates of decomposition, Table 5.2 suggests that the sample size that is required to investigate peat physical parameters may vary depending on the anatomy of the original plant material. For example, small sample sizes (10 mm × 10 mm × 5 mm: Barber *et al.*, 1994) may give an indication of plant cells, tissues and chemical compounds that critically affect its properties, but may not be appropriate to investigate some properties of monocotyledon peat that may contain larger/longer macrofossil parts.

It also follows from the preceding explanations that peat fibres have more strength than the amorphous matrix because peat strength reduces with decreasing fibre sizes and frequency; the matrix has smaller particles sizes and fewer chemical bonds. In highly humified peat, the overall peat strength results only from the chemical bonds provided by its humic compounds. Monocotyledon peats appear to be more humified and weak at the base, as indicated by the recorded high percentage of unidentified organic matter. Monocotyledon peat will have higher tensile strength than *Sphagnum* peat owing to the higher strength provide by its persistent fibres.

It can be also postulated that if the original plant assemblage at a blanket bog is homogenous and the chemical composition of its tissues is known, the distribution of the remains of plant tissues throughout the peat profile can give an indication of: (i) the molecules, macromolecules and the number of chemical bonds and energy present, and (ii) the strength properties of the peat. For example, the distribution and type of lignin throughout a peat profile can give an indication of original plant type (s) and the degree of decomposition. The analyses of macrofossil contents and fibre length distributions in these basal peats are therefore necessary for upland site investigations undertaken for the purpose of peat stability assessment. Research on peat fibre distributions could improve our understanding of the influence of fibre dimensions on peat instability. As yet, very little such research has been done.

Table 5. 2. Comparison of the dimensions of plant parts and tissues of a vascular plant and a non - vascular plant.

Plant name	Plant parts	Location of part	Dimension (mm)
Sphagnum capillifolium (Daniels and Eddy, 1990; Watson, 1968)	Branches leaves	Above ground	15
	Capsules	Above ground	0.024-0.228
	Fascicles	Thallus[1]	5.9-15
	Hyaline cells	Thallus[1]	1.4-1.8; 0.160 × 0.025
	Pending branches	Above ground	<15
	Reproductive cell	Above ground	4.4
	Stems thickness	Above ground	0.7
*E. vaginatum*L. (Sell and Murell, 1996; Wein, 1973)	Anthers	Above ground	2.5-3.0
	Flowers stalks	Above ground	100
	Glumes	Above ground	6-7
	Leave length	Above ground	500
	Leave thickness	Above ground	1
	Nuts	Below ground	2-3
	Perianth bristles	Above ground	20-30
	Rhizomes	Below ground	1520
	Stems	Above ground	15-80
	Tussock diameter	Above ground	300
	Tussocks length	Above ground	20-40

Note [1]The thallus could be up to 120 mm in some mosses (Watson, 1986).

Chemical properties, influences on peat overall chemical bonds, strength and instability

A simplistic schematic representation of the genesis of hydrocarbons in peat discussed in the previous section and hydrocarbon influences on peat instability is presented in Figure 5.3. The bitumen aliphatic hydrocarbons of carbon ranges $>C_{18}$-C_{36} and $>C_{36}$-C_{44+} with high molecular weights (Figure 4.36) were higher than hydrocarbon banding (i.e. C_{10}-C_{18}) with lower molecular weights in all of the peat samples tested. Haynes and Mokolobate (2001) suggested that the most important organic carbon groups in complexation reactions (i.e. chemical reactions that take place between metal ions and molecular or ionic entities known as ligands, containing at least one atom with an unshared pair of electrons) were soluble humic molecules and low molecular weight aliphatic organic acids. The presence of higher molecular weight hydrocarbons in the basal peat therefore suggests low complexation and adsorption reactions and, therefore, the formation of fewer chemical bonds with the surrounding wet peat molecules. This would imply less cohesion between peat compounds and particles.

The laboratory analyses of peat samples for PAHs confirm that concentrations of PAHs (Figures 4.33 and 4.35) which could contribute to chemical bonding and, thus, overall peat strength, were low in the basal peat at all the sites. Krull *et al.* (2004) suggested that high sorption affinities have been demonstrated for PAHs, which are associated with soot, char and other carbonaceous particles. Charcoal is one of the strongest sorbing forms of soil organic carbon (Krull *et al.*, 2004). As explained by Krull *et al.* (2004), the number and position of acidic groups attached to aromatic molecules were shown to control the effectiveness of sorption. PAHs contribute to the formation of chemical bonds because the electrophilic substitution provides ways of introducing different functional groups (i.e. groups of atoms responsible for the characteristic reactions of compounds) into the benzene ring present in their structure (Otter, 2008). The groups may then be modified further to build up more complex molecules. However, owing to the low content of charcoal fragments (Table 4.6) and PAHs (Figures 4.33 and 4.35) encountered at the study sites, influences on peat strength and stability were considered negligible.

It is considered that saturating peat with different and known concentrations of hydrocarbons and testing for their strength properties using appropriate instrument (i.e. instrument that also takes into account factors such as topography and physical properties of peat) could give an indication of the influences of hydrocarbons on the cohesion and friction between peat particles.

5.1.2- Physical properties of peat

The physical properties discussed in the following sections cannot be used as indicators of peat failure because their values are not unique to bogflow-type landslides. The analyses of the results of these physical properties showed no consistent correlations at the study sites. This could be owing to the methods used that can be improved by using appropriate sample sizes, for example, as discussed in Section 5.1.1. These properties do, however, influence peat instability as discussed in the following sections.

Water content: The water contents (Figures 4.6-4.8) of the peat samples taken at the three landslides indicated that the margins of the source areas were still very moist at the time of sampling (i.e. several years after the events occurred) with water contents >600%. The ranges of the basal peat water contents recorded at the study sites are, however, not significantly different from those encountered at other peat landslides. These results are consistent with previous work on other bogflows (e.g. Dykes, 2008d) and on other types of peat failures (e.g. Dykes and Warburton, 2007b; Warburton *et al.*, 2003), and by Tomlinson and Davidson (2000), Lewis *et al.* (2011) and Wellock *et al.* (2011) for other blanket bogs with similar depths of peat.

Selby (1993) suggested that cohesion, which critically affects soil strength and thus its stability, is derived not only from chemical bonds within soil particles but also from water molecules which are polar and contain functional groups (OH) that can form chemical bonds with other soil polar molecules.

The understanding of the influence of water on peat landslides begins with an understanding of the manner in which water is held in its liquid phase within the peat matrix (Table 5.3). This is particularly important for peat which is mainly made of water and the failure of which has been known to be triggered by high rainfall. Like most shallow landslides induced by rainfall, peat failures can be caused not only by the increase of positive pore water pressure in saturated peat owing to the groundwater table rise, but also by the loss of unsaturated shear strength owing to the dissipation of matric suction or capillary forces (Tsai, 2010).

Although peat in the catotelm is often considered permanently saturated, it may contain some gas as result of the processes of metagenesis (i.e. the last stage of maturation and conversion of organic matter to hydrocarbons) that produce gases such as CH_4 or H_2S. Indeed, measurements of pore pressure have been found problematic because of the presence of gas in peat (Long and Boylan, 2012) which influences its strength properties.

Citing Wilson (1972), Warburton *et al.* (2004) suggested that high pore-water pressures may damage cell structures within plant remains, releasing more water into voids, which can lead to a reduction in the shearing resistance of peat and eventually to failure (N6, Table 5.3). As theoretically demonstrated in Table 5.3, for example, monocotyledon dominated peat is more likely to flow than *Sphagnum* sp dominated peat with similar water contents and degrees of humification because a greater quantity of its water is free and it can readily flow. In fact, Figure 4.37c shows increasing water contents with increasing fibre contents at the three landslides, suggesting that intracellular water (i.e. the capillary water) may make a major contribution to the peat water content (Table 5.3).

The lower peats within the source areas would probably have been in even wetter conditions than shown by the results of this study prior to the flows. The samples analysed were obtained from the margins of the source areas. A significant quantity of water may have evaporated through post-failure cracks and drainage lines after the peat failure and reduced the water content to the values presented in this study.

In the absence of preferential flow pathways, Bishopp and Mitchell (1946) suggested that some process analogous to (i) a reversal of phase, (ii) disturbance of peat by tremors induced by wind pressure for example, (iii) a sudden fall in barometric pressure, which may release gases being generated in or dissolved in the bogs and (iv) infiltration of salted water or water with electrolytes, may have caused the liquefaction of the basal peats prior or post rupture of the peats walls. In fact, the peats sampled were relatively firm but water saturated when *in situ* although they may also have become liquefied when disturbed (e.g. Bishopp and Mitchell, 1946) owing to the high proportion of free water encountered in monocotyledon peat (Table 5.3).

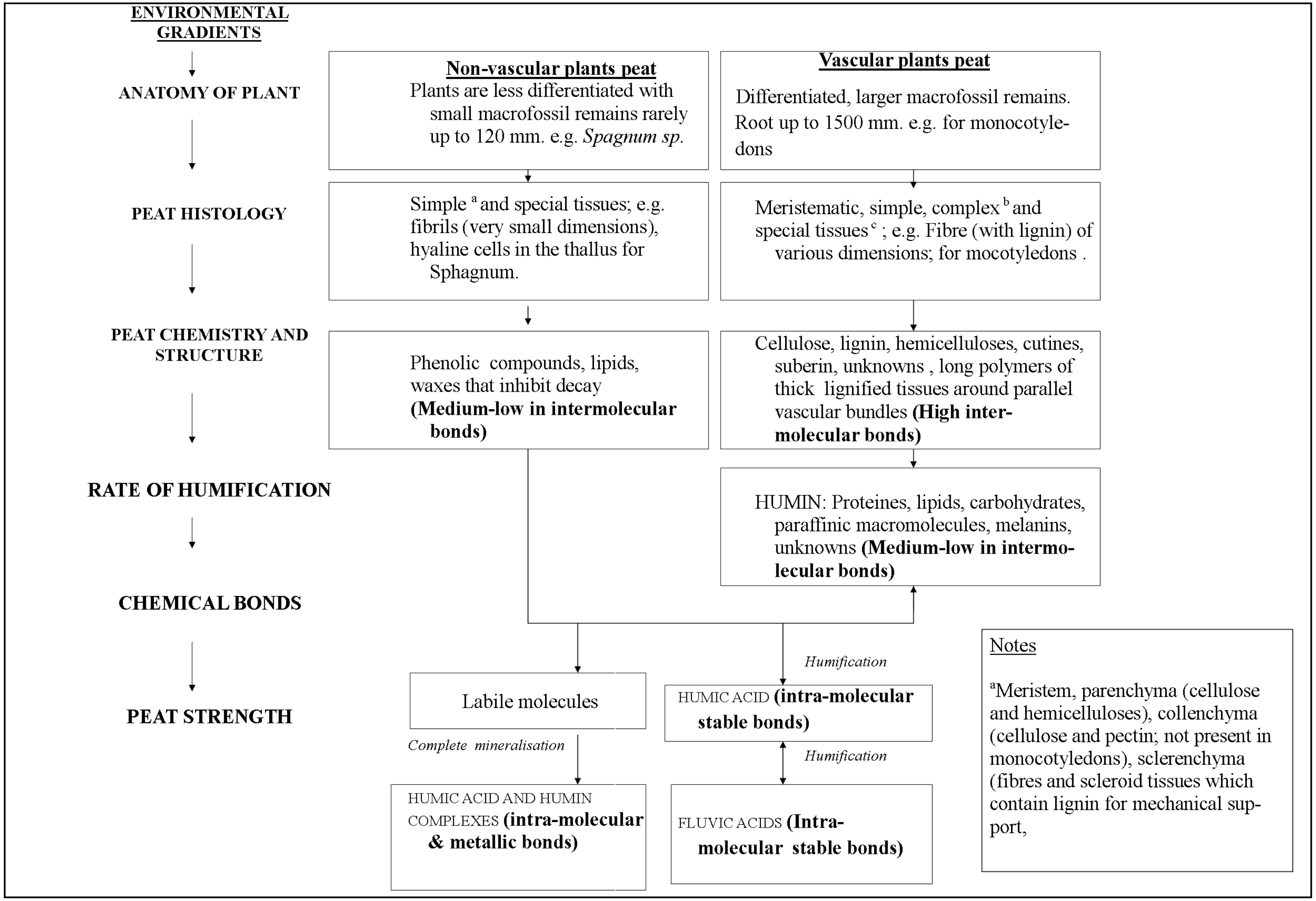

Figure 5. 2. Influence of environmental gradients and plant anatomy on the physical, chemical and strength properties of peat.

If this had occurred at the site as a secondary process, then the sudden loss of stability and dramatic release of large quantities of water could perhaps be explained as suggested by Colhoun *et al.* (1965). Following heavy and persistent rainfall, water could have penetrated the peat profile via shrinkage cracks or other macropore structures, increase the free water content, which induced the liquefaction of the basal which gradually began to flow. The high water content observed in the middle of the monolith sampled at the Straduff Townland landslide (Figure 4.8) could also mean that this middle peat swelled and destabilised the blanket peat, causing its failure. An increase of water content in the middle peat could increase the overall pressure on the basal peat, therefore causing its outflow.

In either case, (1) the peat at the study sites may have had greater quantities of free water compared with peats at other landslide sites where failure mechanisms were different, or (2) the pockets of slurry found at the sites, which contain more than 1000% water content as suggested by Dykes and Kirk (2006) at similar sites, may have contributed to the flows because significant quantities of water (Section 4.3) were involved. Investigating the different proportions (Table 5.3) of water at previous landslide sites by using appropriate temperature ranges (e.g. below 105ºC) could help explain the influences of different fractions on peat instability and their relationships with other peat physical properties. It should be noted that the temperature of 105ºC used in this study removes all water phases in peat (Hobbs, 1986) which may not have the same influences on peat instability. The sludge-like pockets, considered as free water, may have formed *in situ* as result of peat liquefaction (Bishopp and Mitchell, 1946) or from seeping surface water that filled the voids left by continue decay of plant material or pipes within the peat. It can also be hypothesised that the three dimensional distributions and the volumes of these pockets within the lower catotelm may be significantly higher for blanket peats that flow than for other blanket bogs that have been subjected to other types of failures or not failed at all. The investigation of the distribution and volumes of these pockets using remote sensing or geophysics, for example, could improve our understanding of their influences on peat instability. Standard sample collection techniques tend to avoid obvious weaknesses in the *in situ* peat mass, which are typically of a greater extent than the size of each sample (Dykes, 2008b) or in liquid phase. The test results presented in this study may therefore underestimate the real *in situ* water contents of the basal peats.

Loss on ignition and bulk density: Figures 4.9 and 4.10 show that the peat samples taken from the three landslides had high organic contents (i.e. > 95 %) and low bulk densities/unit weights compared with mineral soils. The ranges of LoI values at the study sites is in agreement with studies undertaken by Dykes (2008d) at the Maghera bog flow and others such as Skempton and Petley (1970) elsewhere. These high organic contents accord with low bulk densities encountered at the study sites (Figures 4.11-4.14). The low bulk densities encountered at the study sites, i.e. <1.10 g cm^{-3} for mean saturated bulk density and <0.20 g cm^{-3} for mean dry bulk density, accord with the data presented by Alexander *et al.* (1986) for the 1984 Straduff Townland bogflow and for blanket bog in general by Skempton and Petley (1970), Marachi *et al.* (1982) and Lewis *et al.* (2011). The high measured organic contents and bulk densities could potentially promote failure by favouring the buoyancy effect as explained by Warburton *et al.* (2004). In fact, Pigott *et al.* (1992) suggested that in its naturally saturated condition, peat can sometimes float because of gases that reduce its field bulk density to slightly less than that of water (e.g. Hobbs 1986; Dykes and Warburton 2007a). The similarity of bulk densities of water and peat samples implies that both vertical and horizontal *in-situ* effective stresses are near zero. When the water table is near to the surface, a condition of near-flotation may exist. Pigott *et al.* (1992) also suggested that actual flotation may be resisted only by the temporary and very low adhesion of the peat to the underlying inorganic strata. Discontinuities can also increase this buoyancy effect leading to peat failure.

In the absence of the sludge-like structures and preferential water storage features in peat (e.g. pipes or „sink or swallow-holes": Tallis, 2001), the combination of two other factors generally results in high water content in peat and affects its stability. These are the fibrous structure of the peat which results in large voids, and the high cation exchange capacity (CEC) of organic matter which increases the attraction of water molecules (Table 5.3). The LoI, which relates to the organic matter (Skempton and Petley, 1970), is often used as an alternative indicator of the susceptibility of the peat, but this is unreliable as the liquid limit and water content vary with humification (and usually depth) and with type of peat (Yang and Dykes, 2006; Dykes, 2008d). In fact, the ability of organic soils to hold „unfree" water (i.e. N2-6: Table 5.3) is dependent not upon the organic content of the soils but upon the stage of decomposition and nature of the original plants (MacFarlane, 1970). Dykes (2008d) showed that the analysis and interpretation of natural failures in blanket bogs should be primarily based on data obtained from site-specific peat samples as discussed in Chapter 2 (Section 2.2.4). However, Figures 4.37d-e show a possible relationship between the fibre content and the LoI, as discussed in Section 4.6, that should be investigated further.

Saturated hydraulic conductivity: Figure 4.15 shows that all mean saturated hydraulic conductivities of the peat samples from the study sites were $<10^{-5}$ ms^{-1}. These low mean saturated hydraulic conductivities are consistent with the ranges recorded at the 1990/91 Straduff Townland (Dykes, 2008d), Slieve Anierin (Yang and Dykes, 2006) and Maghera (Dykes, 2008d) bogflows. This could be because many of the small pores are thought to be dead end or closed pores, filled in with the remains of plant cells, and so contribute little to the flow (Lewis *et al.*, 2011). Furthermore, the decline in the size and number of pores in well-humified peat corresponds to a decline in hydraulic conductivity, as suction increases (Boelter, 1968). This is explained by the fact that the scale of the voids are similar to the scale of the water molecules, so that electrostatic attraction between water molecules and the surfaces of the solid (colloidal) particles (i.e. „adhesion") dominates over any gravitational or hydraulic force that may otherwise drive flow. Water held in an amorphous-granular element (e.g. cellulose gels, humus gels, humic acid gels and possibly pectin) is very difficult to expel under pressure and it is this colloidal condition which so drastically affects the permeability of amorphous-granular peats (MacFarlane, 1968).

The saturated hydraulic conductivity is involved in drainage and seepage and has a controlling influence on the strength properties of peats, on their responses to stress, and hence on stability conditions (MacFarlane, 1968). MacFarlane (1968) also suggested that the physical-chemical nature of the peat is of primary importance in this control of peat hydraulic conductivity. The hydraulic conductivity of acrotelm peat greatly influences the ground water table and peat water content and, thus the cohesion between hihly humified basal peat particles and its strength. The probability of any buoyancy effect occurring in any blanket peat also depends on the saturated hydraulic conductivity of the peat as this influences the rate at which water can reach the basal catotelm during rainfall events, for example.

The low permeability of the peat samples from the study sites suggests that vertical and horizontal flows within the peat mass must be limited. This implies that during rainfall, water could cause failure of blanket bogs only when there are preferential flow pathways through which water can reach the catotelm or the mineral substrate underneath the peat. Where there are no preferential flow pathways, excessive rainfall will tend to flow downhill as overland flow. The results of stability analyses using the probability function as presented in Section 4.7 show no significant change in the Factor of Safety with an increase of hydraulic head at the modelled Straduff Townland and Slieve Anierin blanket peats with escarpments. It can be postulated that failure at these sites may have been promoted by the low hydraulic conductivity of the peats that led to high volumes of overland water flow during significant rainfall events, which ruptured the escarpments that acted as dams giving free pathway for the basal peats to flow downhill.

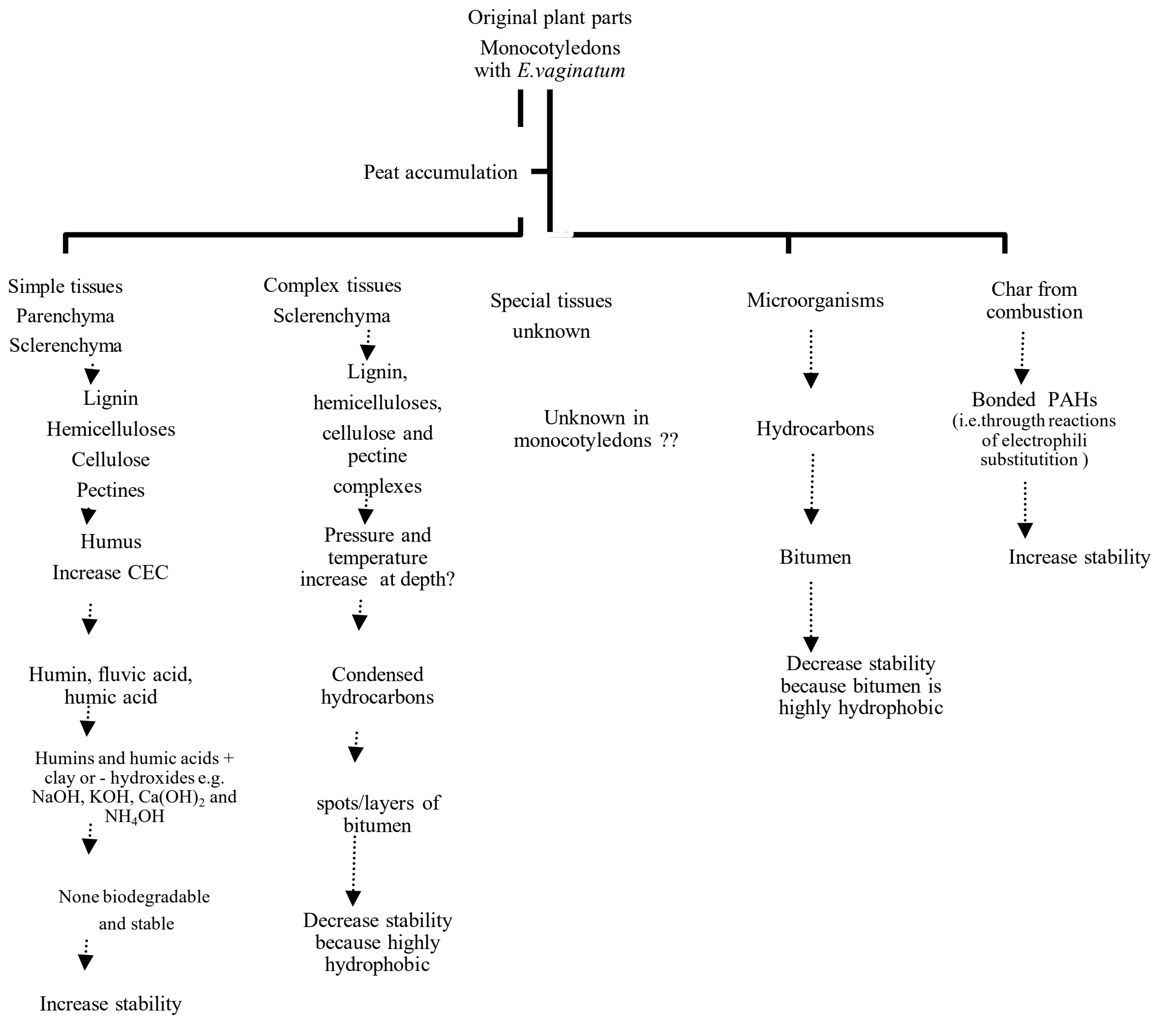

Figure 5. 3. Simplified relation between histology of plant tissues, hydrocarbon genesis in peat and influences on peat instability.

Table 5. 3. Distribution of water in different peats and theoretical influences of different water categories on peat strength and instability.

N	Water category (MacFarlane and Radforth, 1968)	Description (MacFarlane and Radforth, 1968)	Influence on peat strength	Influence on peat landslide	Comparison of water contents of vascular and non-vascular plants dominated peats	
					Monocotyledon	***Sphagnum***
1	Free water (easily removed by displacement, remoulding of peat and disturbance of peat structure):	Cavities between fibres that adhere together: This fraction may be expelled by consolidation and it influences drainage and flow	Reduces cohesion in highly humified peat	Promotes bogflow	**Higher** (Tubular open ended interlinked fibres and larger void space)	**Lower** (More compact, reduced void space)
2	Capillary water (most abundant: held by capillary forces which are physical-mechanical bonds);	Present in narrower concave and convex cavities of peat fibres and tissues: This fraction may be expelled by consolidation	Increases matric suction and unsaturated strength	Increases stability of slope	**Higher** (Hollow fibres with larger surface areas)	**Lower** (Small surface areas of fibres although all *Sphagnum* remains are hydrophilic)
3	Physically bound water (adsorbed water: held by tremendous forces of tension)	Water molecules bordering the solid phase	Increases peat strength	Increases stability of slope	**Higher** (Fibres with larger surface areas)	**Lower** (Small surface areas of fibres although all *Sphagnum* remains are hydrophilic)
4	Chemically bound water (chemical association with the peat material: difficult to rupture by temperature < 150°C	Water of hydration	Increases peat strength	Increases stability of slope	**Lower (**Lower CEC)	**Higher** (Higher CEC)
5	Colloidally bound water (difficult to rupture)	Water present in the gels (e.g. cellulose, pectines, humus and humic acid gels)	Increases peat strength	Increases stability of slope	**Higher** (Higher percentage of hydrophilic compounds)	**Lower** (Lower percentage of hydrophilic compounds)
6	Osmotically bound water in leaves (second largest after N2): mechanically removable by pressures)	Osmosis is a stage in the swelling of the colloidal substances that proceeds without liberation of heat involving intracellular compounds	Increases turgor pressure and strength	Increases stability but could promote burst when cell membrane ruptures	**Lower** (Broken remains of fibres with no discernible water holding capacity)	**Higher** (Presence of hyaline cells with high water holding capacity)

Notes Oven drying of peat at 105ºC removes water types N 1-6 and water types N 4-6 constitute absorbed water and depends on the physical chemical and botanical characteristics of peat (Hobbs, 1986).

5.2- INFLUENCES OF PEAT GEOTECHNICAL PROPERTIES ON PEAT INSTABILITY

This section discusses: (1) the strength properties of the peat, (2) relationships between the structural properties and geotechnical properties of peat, and (3) the implications of these relationships for stability assessment.

5.2.1- Strength properties of peat

Under the experimental conditions used in this study, all of the mean undrained strengths (Figure 4.31) of the basal peats were <3 kPa. These results of strength measurements therefore confirmed that basal peats at the study sites were characterised by small strengths and were weak compared with the upper peats.

The modelled angles of internal friction were also lower (i.e. 14-21º) than the literature values (i.e. 21-33º; Figure 4.42). Figure 4.26 indicates that the shear strengths of peat at other blanket bogs that could be subjected to bogflows or bog slides may be outside the range of normal analyses using the direct shear box (e.g. using the maximum displacement of 11 mm or the stress conditions used in this study). It can also be suggested that undrained test conditions owing to the extremely low measured saturated hydraulic conductivities of the peat samples analysed (Figure 4.15) were not achieved because equilibrium conditions were not reached in some cases, but it is unclear whether they could ever be attained given the fundamental differences between the properties of the organic particles in peat compared with, for example, an over-consolidated clay (Foteu *et al.*, 2012). The strength and stiffness of over consolidated clay is uniform (Atkinson, 1993), therefore during undrained test for example, the volume of the voids come to equilibrium leading to non-asyrnptotical conditions. Furthermore, water may have migrated out of the shear zone and into the rest of the sample, or vice versa, during shear. The overall change in average water content of the sample would have been negligible.

The tensile strength results were consistent with the study carried out by Dykes and Jennings (2011) (Figure 4.30) and also with other work carried out elsewhere (e.g. Dykes and Warburton, 2008b; Helenelund, 1976). The low basal peat strengths shown by the results of this study do, however, corroborate the ideas of Dykes and Warburton (2008b) and Dykes (2008b) who suggested that the basal peats at failed blanket bog sites had very little *in situ* strength in their undisturbed states. In fact the modelled cohesions were also <2.0 kPa, which is in agreement with previous work on Irish landslides (Figure 4.42: Dykes and Jennings, 2011; Dykes, 2008d).

This factor is not particular to bogflows because peat samples from other types of Irish peat landslides (e.g. the Dooncarton Mountain peat slides) and other peatlands (e.g. Helenelund, 1967) have shown similarly low undrained strengths as presented in Figure 4.30. The trend of undrained strength to decrease with depth may be an important factor for bogflows.

The *in situ* shear vane (Figure 4.25) overestimates peat strength, and in contrast to earlier findings on other Irish bogflows and peatlands elsewhere (e.g. Landva, 1980) (Figure 4.25:

Dykes, 2008d; Dykes and Jennings, 2011; Landva, 1980), the results show a general reduction of undrained strength with depth. This trend is also consistent with the results of tensile strength tests carried out on peat samples from the Straduff Townland landslide (Figure 4.25) and from the same study site by Dykes and Jennings (2011). This may further suggest that mean undrained tensile strength of Irish blanket peat subjected to bogflows often decreases with depth because this trend is not apparent in the results from other types of peat failure sites as shown on Figure 4.25. It should be noted that this conclusion is based on two datasets only. This general trend of peat strength to reduce with depth reflects the structural features of peat (MacFarlane and Radforth, 1968) including the macrofossil content, the degree of humification and the fibre content which critically reflects the strength of chemical bonds between its chemical compounds. Based on site evidence, Dykes and Warburton (2008b) suggested that the Shetland peat slides in 2003 may have had high tensile strengths throughout their peat profiles. The study of peat properties for this thesis suggests that there may be a relationship between peat strength and its physical properties although not apparently shown on the graphs on Figure 4.39, owing to the limited number of samples analysed. The relationship between physical and geotechnical properties should be used for slope stability assessment as explained in the following section.

5.2.2- Peat properties and stability assessment

The investigation of the physical properties shows that the basal peats contained significant hydrocarbon areas, pockets of slurry and low fibre contents of monocotyledon remains with high degrees of humification at the three study landslides. These peat strengths were low and consistent at the three sites as discussed in the previous section. Therefore, there is a relationship between some peat botanical, physical and geotechnical properties that may provide a new basis for blanket peat stability assessments. These results imply: (1) that peat strength can be estimated from measuring its effective structural properties as distinct from its geotechnical properties, as explained in the previous Section; and (2) that the effect of physical properties on peat strength can be quantified and used to develop a suitable model for peat stability assessment.

5.2.3- Implications of the relationship between peat properties for peat strength modelling and slope stability assessment

Peat mass movements often occur under the influence of a specific external trigger event acting on the slope (Dykes and Kirk, 2006). Peat material has very low permeability (e.g. Section 4.3.1), therefore „drained conditions" probably rarely occur during failure. During undrained loading of soil in general, the stress is applied so quickly that there is not time for any drainage to occur and so the void between particles does not change because the volume remains constant. When the loading is isotropic with no distortion or volume change, the effective stress remains constant (Atkinson, 1993). The *in situ* basal blanket peats are considered to be in undrained and unconsolidated conditions prior to failure. No pre-consolidation or dissipation of excess pore pressure occurs. The undrained peat strength, which is measured in terms of total strength, is independent of any changes in the total normal stress. To replicate *in situ* conditions of peat during failure, the tensile strength tests should be performed very quickly with no pre-consolidation. In peat, the tensile strength is related to cohesion owing to the bonds formed between peat matrix particles and the bond in the fibre molecules as shown by strength modelling (Figure 4.42). Helenelund (1967) and Landva and La Rochelle (1983) suggested that because the cohesion component of shear strength is thought to result from peat fibres, the shear strength of fibrous peat may be estimated on the basis of the tensile strength. The results of this study seem in agreement with this observation. Therefore it seems reasonable also to assume that the tensile strengths (which are more consistent across the sites investigated and with previous findings) approximate the values of the cohesion for the purposes of interpreting natural failures (Dykes, 2008b).

Different loading and drainage conditions are often used for tensile strength measurements. Axial tensile strength tests (direct tension test) were carried out as part of this study with measurement of displacement. Most problems with the axial tensile strength test are related to the uniform distribution of tensile stresses in the test section of the specimen. This limitation is also often overcome with the application of different types of connections between the sample and the tensile instrument (e.g. using nails: Helenelund, 1976; freezing: Haefeli, 1951).The „fingers" on the tensile instrument used in this study (Section 3.3.8) have equal dimensions to ensure that stresses are uniformly distributed in the sample. Another limitation is that not all *in situ* stresses can be modelled. The impact of this limitation is negligible in tension tests on peat (Helenelund, 1976).

Helenelund (1976) modelled the tensile strength of peat based on the characteristics of its fibres and matrix and on the principles used to model the tensile properties of fibre-reinforced metals presented by Kelly and Tyson (1965). With the assumption that metals have plastic flow patterns, i.e. that they behave as Newtonian fluids only if stresses exceed a certain threshold, the model was based on the idea that shear stresses at the fibre/matrix interface are limited by flow stress of the matrix or by the shear strength of the interface. Helenelund (1976) explained that during tensile strength tests, some fibres are pulled out of the peat. Therefore, in addition to the tensile stress, shear stresses are developed between these fibres and the surrounding matrix. He proposed that the maximum tensile force (σ_t) that can be applied to an individual fibre and the maximum shear force ($\boldsymbol{\tau_t}$) developed when the fibre is pulled out of the surrounding matrix should be calculated using Equations 5.1 and 5.2 respectively. Helenelund also considered that fibres embedded in a composite must exceed a certain critical length if they are to be stressed to facture during deformation. It should be noted that for upland basal peat analysed in this study, fibres are mostly pulled out of the opposing matrix during tensile test.

$$\sigma_t = \pi r^2 \sigma_f \qquad 5.1$$

$$\boldsymbol{\tau_t = \pi r l \tau_m} \qquad 5.2$$

where:

σ_t = Maximum tensile force
r = The fibre radius
σ_f = The ultimate tensile strength of the fibre material
τ_t = Maximum shear force
l = The fibre length
τ_m = The shear strength of the matrix

He then assumed that the distance between the failure plane and the end of the fibre was half the fibre length and he calculated the critical fibre length (***l***), at which the tensile force is equal to the shear force, from Equation 5.3. He further suggested that the critical fibre length ($\boldsymbol{l_c}$) was proportional to the ratio of the fibre tensile strength to the shear strength of the peat matrix.

$$l_c = \frac{r\sigma_f}{\tau_m} \qquad 5.3$$

where, l_c = The critical fibre length, *l*, at which the tensile force is equal to the shear force

By using Equation 5.4 to determine the relative matrix area, the ultimate tensile strength ($\boldsymbol{\sigma_t}$) of the fibrous material was then given by Equation 5.5. Assuming that the tensile strength of the matrix ($\boldsymbol{\sigma_m}$) was double the shear strength of the matrix ($\boldsymbol{\tau_m}$), he obtained the ratio presented in Equation 5.6 (Kelly and Tyson, 1965).

$$\boldsymbol{A_m = 1 - A_f} \qquad 5.4$$

$$\sigma_t = A_f\sigma_f + A_m\sigma_m = \frac{A_f l_c \tau_m}{r + A_m \sigma_m} 8.5$$

$$\frac{\sigma_t}{\tau_m} = \frac{A_f l_c}{r} + 2(1 - A_f) \qquad 5.6$$

where:

σ_m = The tensile strength of the matrix
A_f = The relative fibre area
A_m = The relative matrix area

A suitable method for modelling peat strength that takes into account all of the peat properties and the forces involved must be developed using the above relationship, the physical properties of peat and its strength properties. If some input parameters can be determined by laboratory analysis of peat samples under a microscope, for example, then Henelelund‟s theoretical relationship can be used as a basis to predict the ultimate tensile strength. The ratio of tensile strength to shear strength of peat is not constant but its value depends on the amount and type of fibres and on the critical fibre length (Helenelund, 1976). Peats with similar amounts, types and orientations of fibres should show the same ratios of tensile strength to shear strength measured with the same experimental conditions. The ratio $\frac{\sigma_t}{\tau_m}$ or $\frac{\tau_m}{\sigma_t}$ (with $\frac{\sigma_t}{\tau_m} > \frac{\tau_m}{\sigma_t}$ for fibrous peat: Helenelund, 1976) must also be similar for peat samples with the same physical properties and the same degree of humification. The ratio $\frac{\sigma_t}{\tau_m}$, for example, should be determined from experimental trials for different peat types with different physical properties. The relationship represented by Equation 5.6 should be tested and calibrated with laboratory measurements using suitable instruments. An appropriate model-fitting method (e.g. Monte Carlo methods) should enable the estimation of the unknown parameters.

The peat matrix shear strength (τ_m) should be measured using a ring shear test that can measure strengths of less than 5 kPa and would be unaffected by the effects of fibres (Long, 2005).

The dimensions of individual fibres (e.g. l) of various types at different degrees of decomposition and from different peat types should be measured in the laboratory using an appropriate microscope. The relative fibre (A_f) area and the relative matrix area(A_m) should be estimated following volumetric analysis of the total fibre content (Ft) and the humus fraction (Fh) respectively as defined in this study (Chapter 3; Section 3.3).

The proposed tensile strength model should use physical parameters of peat to predict its undrained strength. It best represents peat behaviour during failure and should facilitate stability assessment on peatlands. The creation of a suitable tensile strength apparatus may significantly contribute to the future development of the tensile strength model by providing a more robust means of investigating the influences of peat structural properties on its tensile strength.

Proposed modifications to the tensile strength model

The (ultimate) tensile strength of peat presented by Helenelund (1967) is based on several assumptions used by Kelly and Tyson (1965) to model the tensile properties of fibre-reinforced metals. Some of these assumptions can be modified to suit the organic nature of peat. For example, the assumption that the tensile strength of the matrix is half the shear strength of the matrix (Helenelund, 1976) can be modelled using a chemical approach. Peat is a substance of which the structure is the result of the activity of microorganisms and the chemical processes that take place within its matrix. Highly humified peat contains complex colloidal compounds that should be considered during peat strength modelling (Kovalenko and Anisimov, 1977). Like mudslides, bogflows are considered to have colloidal and complex flow properties. A blanket bog flow mechanism is intermediate between the behaviour of a solid and a liquid as described by Bouquet *et al.* (2009). At rest, a peat bog behaves like an elastic solid, but flows like a liquid when disturbed.

With the advances in chemistry of recent years and the understanding of the nature of inter-atomic, ionic, metallic and molecular bonds, a simple and more suitable model that incorporates all of the forces brought about by the fibres and the peat matrix is proposed as shown in Figure 5.4. This figure shows other factors that theoretically influences peat strength. The cohesion between the particles in the peat matrix is owing to (i) the chemical bonds between the atoms, ions and molecules in the humus, and (ii) the forces that arise from capillary and other pore-scale force mechanisms because peat typically contains some gas (Hobbs, 1986) and is rarely, if ever, fully saturated (MacFarlane, 1986). The theoretical basis of atomic elasticity, based on Coulomb"sLaw of electrostatic attraction and van der Waals forces, should be used to model the strength of the chemical bonds within the peat. Coulomb"s law holds within the atoms and describes the force between the positively charged nucleus and each of the negatively charged electrons in an atom. It also accounts for the forces that bind atoms together to form molecules and for the forces that bind atoms and molecules together to form solids and liquids.

Engineering assessments of slope stability typically assume that soils are either fully saturated or completely dry, in order to calculate stress, strength and deformation parameters and corresponding system responses (Goulding, 2006). However,owing to the presence of gas, the peat may not be fully saturated in its natural state. Peat typically contains 1-7% gas by volume (Ivanov, 1981) as a result of metagenis during peat maturity. Modelling of capillary forces owing to fluctuations of the water content within the peat should be carried out in order to assess or quantify the effect of these forces on peat strength. The inter-fibre forces arising from capillary and other pore-scale force mechanisms could increase both the shear and tensile strengths of peat through matric suction (Goulding, 2006). The general behaviour of these pore-scale forces, their roles in macroscopic stress, strength and deformation behaviour, and the changes that occur in the field under natural or imposed changes in water content, must be investigated because their possible roles in peat failure remain uncertain. Future research should focus on the determination or understanding of the effects of capillary-induced inter-fibre forces in partially saturated peat on macroscopic shear strength, tensile strength and deformation behaviour. This is particularly relevant for engineering work on peatlands as gas has a significant influence on initial consolidation, rate of consolidation, pore pressure under load and permeability (Bell, 2004).

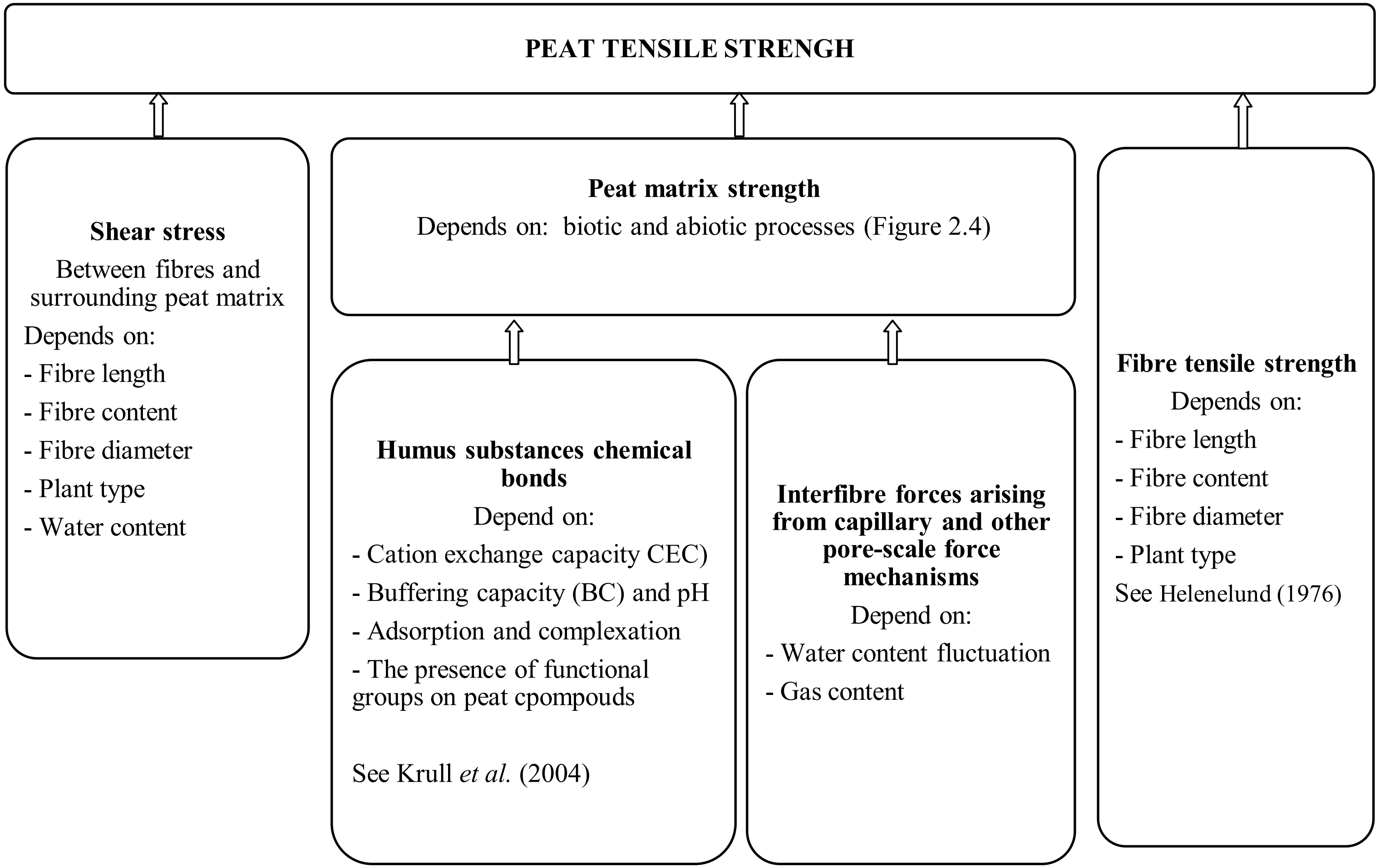

Figure 5. 4. Proposed conceptual model for the tensile strength of peat.

5.3- INFLUENCES OF SITE FACTORS ON PEAT INSTABILITY

The three study sites shared several site characteristics in common with earlier blanket peat failures, as explained in Chapter 4 (Section 4.1). However, the initial states of the blanket bogs prior to failure are unknown. Therefore, although the possible influences of site and anthropogenic factors on the failure mechanisms at the study sites may not be significant, they cannot be ignored. These influences have been discussed in detail elsewhere as briefly explained and referenced in Table 5.4.

A combination of contributory causal and/or trigger factors could occur at the same site and render the determination of the primary cause of a landslide challenging. For example, Table 5.5 shows four hypothetical peat failure scenarios. In the case of Failure 1, the collapse of the dried peat overlying the escarpment (e.g. the Straduff Townland: Alexander *et al.*, 1986) induced the failure of the system. In the case of Failure 2, owing to the impervious nature of the bedrock (e.g. peat slides: Warburton *et al.*, 2004), artesian water pressure was generated below the peat and caused the landslide. In Failure 3, peat growth with an increase in peat mass was the primary causal factor (see Section 4.1) and in Failure 4, the basal peat became highly liquefied and flowed downhill (e.g. at the study sites).

With the exception of Slieve Rushen where there is no escarpment, all of these scenarios may have applied to the study sites. The shapes of the heads of the landslides (Figure 3.1) and the appearance of the debris in the field, which suggests that the movement of the flow was rather turbulent in manner, showed that rupture occurred in the basal peat. In fact, site evidence showed that the acrotelm of the peat at the three landslides was intact in each case, i.e. fairly firm and bound together by the roots of existing vegetation but the lower catotelm was highly humified and weak (Section 4.2). Several hypotheses have previously been suggested for the initiation of landslides such as those investigated for this thesis.

Hypothesis 1: The peat along the crest of the escarpment (e.g. Failure 1), where present, may have given way as result of a significant rainfall event, for example, and the first rushing of the basal semi-liquid peat carried the firmer crust along in the form of rafts to be dumped on the flatter slope below (e.g. Mitchell, 1935). The downhill movement of the lower peat could have produced enough stress to rupture the fibrous peat above (e.g. Colhoun *et al.,* 1965). After this initial rupture the upper peat was separated into blocks and carried away as rafts on the lower peat. In this respect, several other peat failures (e.g. Colhoun *et al.*, 1965 Sollas *et al.*, 1897; Delap *et al.*, 1932, Mitchell, 1935; Bishopp and Mitchell, 1946) failed in the same manner, some of which are classified as bog slides by Dykes and Warburton (2007a).

Hypothesis 2: An initial shear failure on a discrete sliding surface may have occurred prior to the flow, as suggested by Boylan *et al.* (2008), and destabilised the whole system causing the flow of the liquefied basal peat that dragged the upper fibrous peat downhill. They hypothesised that all types of peat failure begin with this type of basal shearing while Dykes (2009) suggested *in situ* collapse of peat structure, catastrophic loss of strength and outflow of basal peat.

This study gives rise to a further hypothesis, as follows.

Hypothesis 3: Based on this study, it is suggested that specific homogenous peats in terms of macrofossil content (e.g. monocotyledons with *E. vaginatum*) may fail as a result of progressive weakening of the lower catotelm. This weakening may be owing to increasing humification, liquefaction (as explained previously) and chemical repulsion between localised areas in the catotelm. This progressive weakening of the basal peat may decrease its strength to a critical point at which the slope fails. Any additional factors speed up the process. For example, at the study sites, excessive heat may have melted the hydrocarbons present in the basal peat causing a bog flow. If the lowest layer was attached to the underlying mineral surface but had a greasy plane which was suitable for the flow to pass over (e.g. Mitchell, 1935), the overlying surface peat would have slid over it and moved downslope as a bog slide. Intense rainfall on blanket peat with or without tension cracks could also trigger the failure.

Despite the uncertainty about the factors that initiated the three landslides, the hypothesised liquid states of the basal peats that depend on their physical properties promoted the flows. The assessment of the properties of the basal peat is therefore required for assessing the potential for failure of blanket peat. The assessment of the influence of human activity (Delap and Mitchell, 1939; Bowes, 1960; Colhoun *et al.* 1965; Tomlinson, 1981; Alexander *et al.*, 1986), hydrological factors (Warburton *et al.*, 2004; Dykes, 2008c) and slope topography (Mitchell, 1938; Bishopp and Mitchell, 1946; Calhoun *et al.*, 1965; Tomlinson and Gardiner, 1982; Alexander *et al.*, 1986) is also necessary.

5.4- A MODEL PROCEDURE FOR BLANKET PEAT STABILITY ASSESSMENT

Table 5.6 presents some indicators of peat weakness and further influences on bogflows and bog slides revealed by this study. Although further studies are needed in order to explain the influences of these chemical and biological properties on peat strength, this work has increased our knowledge of bogflow controlling factors (Section 5.1).

This study suggests that there may be a means of initially assessing peat properties for stability analysis without the need for significant intrusive excavations. In fact, the basal peat at the three sites could be classified as shown in Tables 4.7 and 5.6 and the results were consistent across the three sites. Hydrocarbon analyses of the basal peats showed aliphatic hydrocarbons of higher molecular weights. The stratigraphy surveys and macrofossil analyses showed negligible variability with regards to macrofossil contents across the study sites. All of the monolith samples showed monocotyledon peats (with *E. vaginatum*) with the degree of humification increasing with depth below the surface. The similarity of the „effective" structural properties at the bogflow sites may explain why the blanket bogs are unstable. These findings suggest that other upland blanket peats with similar characteristics to those presented in this study may be potentially unstable. This also implies that: (i) an auger designed to sample peat with minimal disturbances can be used to assess the peat for visible signs of weakness (Table 5.6) as presented in the proposed new classification (Section 4.6.3); and (ii) basal peat monoliths sampled with a purpose-designed tool (e.g. a 100 mm

× 100 mm version of the Swedish Geotechnical Institute (SGI) peat sampler: Long and Jennings, 2006) can be used to obtain samples for a detailed assessment in the laboratory. The sampler should have a sharp opening that is inserted into the peat to cut it without significant disturbance. One side of the proposed plastic sampler (e.g. Long and Jennings, 2006) could be made of soft plastic that is easily cut to enable the extraction of samples with minimum disturbance. The square shape should facilitate sample installation on a tensile strength sample box and/or the shear box apparatus that have the same dimensions.

The findings of this study may have significant implications for peat slope stability assessment. Construction projects on upland peatlands require the identification of potential instability and the design of appropriate mitigation measures to overcome them. Current guidelines for electricity generation developments, for example, recommend the use of the vane test to determine the undrained strength, and the use of Troels-Smith and von Post systems to classify the peat material (Scottish Executive, 2006). The limitations of these methods to assess peat failure have been discussed in Section 3.3.8. The development of an appropriate model to assess peat instability that uses its physical properties as input parameters can help to minimise (i) the environmental impacts of intrusive site investigations and (ii) the time and cost required for such works. While waiting for such models to be designed, this study can be used to improve stability assessment methods on upland blanket peat.

Based on this study, a systematic approach to peat stability and landslide risk assessment to complement current guidance (e.g. DoEHLG, 2007; Scottish Executive, 2006) is proposed (Figure 5.5). This proposed method should enable: (i) an assessment of the bedrock topography to allow the influences of some hydrological process to be assessed, (ii) an assessment of the peat based on its structural and chemical properties, (iii) a less subjective and consistent assessment of upland peat properties, (iv) the dimension of fibres that have major influences on peat strength to be considered, (v) the identification of weak zones within the peat profile based on a quantitative and less subjective method (i.e. cluster analysis), (vi) fewer parameters to be investigated that have influences on peat structure and strength and (vii) stability assessment to be carried out in a consistent way without the need for very intrusive site investigations. This procedure should improve stability assessment of upland peat during construction works. The shapes of the upland peat fibres should be characterised during future work and fibre distribution curves produced for stability assessment. In addition to macrofossil analyses, microfossil analyses should be considered to assess the spatial variability of plant species and possible structural variability of the peat, throughout the area of interest, as discussed by Radforth (1952).

Table 5. 4. Influence of different site factors on peat instability.

Factors	Influence on peat instability	Some Section references in the thesis
Temperature	Evaporative drying of the peat surface leading to contraction crack formation. The effect is uncertain at the study sites.	2.2
Rain	Hydrostatic loading or liquefaction of peat. Rain affected the Straduff Townland landslide but the effect is unknown at the other two study sites.	2.2
Acrotelm	The acrotelm is more fibrous therefore increases peat stability. This factor is relevant for the study landslides.	2.1
Catotelm	May fail if weak. This factor is relevant for the study landslides.	2.1
Clay rich drift	Possible shear plane for peat slides. This factor is not relevant for the study landslides.	2.2
Tension cracks	Preferential flow pathways for water to reach the basal peats. Where there is no significant gradient change, the conditions of the lower peat upslope and downslope of the line of fracture are different (i.e. water seep from the former area and increase pressure on the latter area; Colhoun *et al.*, 1965).	2.2
Hydrocarbon deposits	Hydrophobic areas and planes reduce the cohesion or friction between peat particles or layers. Hydrophobic areas are relevant for the study landslides.	1.1 , 3.2, 3.3 and 4.5
Slurry pockets	Unusually high water contents in localised areas therefore increasing the overall basal peat water content therefore weaken it. They promote bogflows. This factor is relevant for the study landslides.	5.1
Gas/air	Gas may influence the liquefaction of the basal peat and may also increase peat strength through matrix suction. The effect is unknown at the study sites because the gas content of the peat has not been quantified.	5.1 and 5.2
Fibres	Increase peat strength and help stabilise the bog. The effect of fibre reinforcement is relevant at the three study sites.	2.2 and 4.3
Dried peat layers on the escarpment	Support the peat upslope therefore contributing to stability of the slope. This factor was absent at the Slieve Rushen landslide. It should be noted the peat bank may be considered as an unsupported steeper toe-slope, i.e. an inherently less stable topographic configuration.	2.2
Snow	Hydrostatic loading of peat. The effect is unknown at the study sites.	2.2
Bedrock	May influence the system if it contains fractures or faults allowing groundwater ingress to the base of the peat. This factor is not relevant to the study sites.	2.2
Escarpment	Promote overland flow therefore influence the peat drainage system. This factor was absent at the Slieve Rushen landslide.	2.2

Table 5. 5. Hypothetical scenarios for upland peat failures.

Hypothetical peat failure scenario	Triggering factor	Site factor	Mechanism	Condition of the peat	Likely type of failure
1	Precipitation (Snow, rain)	No preferential flow pathways on the bog but presence of escarpment	Overland flow of water and weakening of the dried peat on the escarpment and loss of support for peat upslope	(a) Basal peat liquefied	Bogflow
				(b) Presence of failure plane within the peat	Bog slide
				(c) Mineral subtract involved	Other types
2	Precipitation, hot summer with high temperatures	Presence of preferential flow pathways on the bog and impermeable layers in or below the peat	Generation of artesian water pressures and uplifting of peat	(a) Basal peat liquefied	Bogflow
				(b) Presence of failure plane within the peat	Bog slide
				(c) Mineral subtrate involved	Other types
3	Peat loading	Peat growth (i.e.type of failure depend on the original plants types, growths and species)	Increasing loading by peat mass: Threshold of stability reached and failure occurs independently of peat properties	(a) Homogenous peat, presence of hydrocarbons and hot weather	Bogflow
				(b) Homogenous greasy basal peat in cold weather	Bog slide
				(c) Heterogeneous	Other types
4	Any factor could trigger the landslide	Specific peat types: any other site factors promote the failure	Low bearing capacity of basal peat due to; (1) Liquefaction (i.e. due to (i) reverse phase, (ii) wind pressure, (iii) fall in barometer pressure, (iv) chemical reactions with salt or electrolytes) (2) Chemical repulsion between particles or hydrophobic spots (3) Increasing humification	Liquefied and low strength of basal peat due to its properties including low fibres, high humus fraction, presence of hydrocarbons spots such as bitumen or/and of pockets of sludge and high water content	Bogflow

Note e.g. Failure 1: Alexander *et al.,* 1986; Failure 2: Warburton *et al.*, 2004; Failure 3: hypothesis (Section 2.2)

Additional objectives to complement current guidance

PHASE 1

Desk study

(i) Identification of potential receptors at risk from peat failure

Reconnaissance survey

1- **Stratigraphy survey:** Peat description according to the MFC method (this study)

(1a) Establish the peat depth and topography of the mineral interface around the chosen area

(1b) Establish the spatial extent and stratigraphic distribution of hydrocarbons

(1c) Assess of potentially weak and/or more humified strata extent and distribution

2- **Peat sampling**: Drill tube of 100 mm × 100 mm and extrude to obtain the undisturbed peat samples

(2a) Quantitative peat description and macrofossil analysis of peat samples (Table 4.12)

(2b) Determination of potentially weak and/or more humified strata by cluster analysis of the data.

<u>CONCLUSION PHASE 1</u>

If the results are similar to that presented in Table 5.6

Results different from that presented in Section Table 5.6 suggest low risk from bogflow

PHASE 2

Stability assessment

(i) Identify potential weak zone thickness for the blanket bog conceptual model design

(ii) Stability assessment using undrained strength of 2.0 kPa for basal peat and the results of ST for the surface and middle peats as defaults for site specific data. because (no other work on bogflow is currently available)

<u>CONCLUSION PHASE 2</u>

FS < 1 may suggest potential instability (i.e. that failure is highly likely if not already under way)

FS >1 may suggest low risk (but the larger the FS value the lower the risk of failure)

Figure 5. 5. Procedures for blanket bog stability assessment.

Table 5. 6. Indicators of weak peat and factors contributing to peat failure (partly after Selby, 1993).

Factors/property		**Description**
Laboratory/*in situ* measured basal peat Undrained strength (This study)	(i)	Low tensile strength (i.e. <3kPa ; MFC TH < 2)
	(ii)	Low triaxial shear strength (i.e.<3kPa)
	(iii)	Low shear vane strength (i.e.<8kPa)
	(iv)	Low modelled (undrained) cohesion (i.e. <2kPa)
Composition and texture (This study)	(i)	Weak and sludge-like pockets
	(ii)	Loosely packed highly humified peat particles
	(iii)	Presence of hydrophobic substances at the base (i.e. hydrocarbons and bitumen)
Composition and texture- fibre (This study)	(i)	Smooth and uniform fibre shapes and sizes
	(ii)	Monocotyledon peat with *E. vaginatum* (Monocotyledons (Mt), <2 at the base)
	(iii)	Low total fibre content (Ft) (i.e. <2)
	(iv)	High humus fraction (Fh) (i.e. 2-3), high von Post H (i.e. >7) and Transmission (<25%).
	(v)	Decreasing fibre dimensions with depth
	(vi)	High greasiness/oiliness (Gr) (i.e. >4)
Micro-biological factors (This study)	(i)	High activity of thermophilic fungi in the basal peat (chemical analysis)
	(ii)	Occurrence of micro-organisms at the basal peat like the aphids that produce hydrophobic substances
Relict structures (This study)	(i)	Planes of weakness
	(ii)	Highly impermeable basal peat layers
Physico-chemical reactions (This study)	(i)	High cation (base) exchange capacity
	(ii)	Low polymer compounds
	(iii)	Low and weak chemical bonds
	(iv)	Low PAHs
	(v)	Presence of TPHs with aliphatic hydrocarbons of high molecule weight
Factors		**Factors contributing to peat weakness (after Selby, 1993)**
Overloading	(i)	Weight of rain or snow
	(ii)	Fill, structures
Climate	(i)	Persistent and intense rainfall, high temperature
Removal of underlying support	(i)	Undercutting by running water
	(ii)	Sub-aerial weathering, wetting and drying, frost action
	(iii)	Subterranean erosion, squeezing out of underlying peat soils
	(iv)	Mining activities near the site
Effects of pore water	(i)	Buoyancy effect
	(ii)	Reduction of capillary tension
	(iii)	Viscous drag of moving water on peat, drainage features, piping and spontaneous liquefaction
Increase of slope angle (This study)	(i)	Bedrock angle >2°
	(ii)	Peat depth >0.8 m
Geometry of the slope (This study)	(i)	Break of slope at the head or toe (e.g. convex or concave bedrock shapes)
Transitory stresses	(i)	Earthquakes – ground motion near the peat
	(ii)	Vibration from human activity – blasting, traffic, and heavy machinery near the site

CHAPTER SIX –CONCLUSIONS AND RECOMMENDATIONS

The physical and geotechnical conditions and properties of the basal peat are key contributory site factors commonly attributed to blanket bog failures. These are critical to an adequate understanding of, and ability to analyse and model, the stability or susceptibility to failure of peat deposits. Although engineers engaged in construction projects on peatlands have used „index" physical properties of peat and standard geotechnical tests to provide data for their purposes, recent investigations of natural peat failures in Ireland suggested that standard testing methods may be suitable for application to problems involving natural instability of blanket bogs or for the design and construction of tracks (e.g. windfarm access roads) on peatlands, although this research perhaps shows that those studies may have been over-cautious about the validity of some of the standard methods. The findings of this research suggest that there are links between botanical, chemical and physical properties that can be used to assess upland blanket bogs for instability. Specifically, six major conclusions can be drawn from this research.

1. Blanket peat dominated by monocotyledons (with mainly *E. vaginatum*) is likely to be susceptible to failure because: (1) its effective structural properties, specifically the higher degree of humification and lower fibre content of its basal peat compared to the surface peats, cause this basal peat to have very low strength and thus also a very low bearing capacity; (2) monocotyledons have morphological features that promote failure, such as parallel venation of its leaves and stems that could promote shear failure, and most or all of the tissues of these monocotyledons in the basal peats are small, partly or completely broken or torn as a result of humification, therefore the intra-particle water would escape as readily as would the inter-particle water when peat is loaded, therefore promoting flow; and (3) it has biological and chemical characteristics that may lead to structural weakness and contribute to failure, such as being host to a hydrocarbon-producing aphid *Colopha compressa* that lives in the root of *E. vaginatum*, for example, or the genesis of hydrocarbons such as bitumen from its lignified tissues as the peat matures at depth.

2. The comparable values of peat strength of 2-4 kPa obtained from triaxial and tensile tests, and the results obtained from direct shear tests, show that standard approaches to geotechnical testing of peat appear capable of indicating the undrained shear strength of peat at normal loads representing *in situ* conditions. However, such applied stress conditions are significantly less than the normal lower limits of the working ranges of the (shear) strength testing equipment, so even the strengths obtained may be overestimates arising from frictional or other resistance within the equipment mechanisms. The associated degree of uncertainty in the results is not known, but the consistency of the results suggests it to be low. Shear vanes overestimate the undrained strength, the divergence from true strength probably increasing as the shear strength increases with very low values (e.g. 2-4 kPa) probably reflecting true values reasonably well because highly humified peat with shear strengths of this magnitude have relatively few fibres to impede the effectiveness of the vane.

3. Existing peat classifications have limitations but other alternatives, based on the properties of peat that influence peat strength such as the MFC („Modified Fibre Content") scheme presented in this study, are likely to improve the assessment of peat stability. The anatomy and morphology of the original plants determine the degree of humification and fibre content of peat, and the latter measures have been demonstrated to be consistently applicable across three sites according to the MFC scheme. The present limitation of this finding is that the three sites were similarly dominated by monocot peat.

4. Hydrocarbons, and in particular bitumen, were found at all three study sites, and in far greater abundance than any previous reports had indicated. These substances may act as lubricants by reducing the friction and/or cohesion between peat particles, or indeed between discontinuous surfaces of limited extent, within the basal layer (s) of the peat. As such, they represent a potential contributory factor to the occurrence of failure of the blanket bogs at the study sites, and may have a similar influence at other locations where the bog is as yet apparently unaffected by mass failure.

5. Many commonly measured properties of peat such as water content, loss on ignition, permeability and bulk density, appear to be unrelated to each other within any given mass of blanket peat. This finding is consistent with previously published work. In addition, however, this study has shown them to be similarly unrelated to other properties that appear to be more directly indicative of weakness and thus potential instability of the peat such as humification and fibre contents. Therefore, although useful to characterise the peat for comparison with previous studies and in order to add to the knowledge-base of peat characteristics from different locations and facilitate future meta-analyses of such data, this study has shown that measurements of water content, loss on ignition, permeability and bulk density as measured in this study cannot be used as indicators of potential peat instability at any particular site.

6. It is considered likely that other blanket peats may be similarly too highly humified to support more sophisticated botanical analyses than those presented in this thesis. However, the results of this study demonstrate value in testing this approach on peat from other parts of the British Isles that may be expected to have different constituent plant compositions.

The findings of this study have substantially contributed to our understanding of the influences of peat properties on blanket bog instability. These can be used by managers or practitioners to complement current guidance for upland blanket peat stability and hazard risk assessments that occur as a result of climate change. However, an important limitation needs to be considered. In view of the number of landslides that have occurred on upland blanket bogs in Ireland and the British Isles, the current study was unable to analyse all of the variables or to investigate many sites. In fact the research was carried out exclusively within a relatively small region of western Ireland within which there was much less diversity of plant remains in the peat than had been anticipated. Therefore, with a small and localised sample size, caution must be applied as the findings may not be transferable to all blanket bogs. Furthermore, the peat at the study sites may be different from the peat in other parts of the British Isles where peat failure has frequently occurred.

Future proposed research from this study should include the following:

1. This research has demonstrated that the tensile strength may be used as an indicator of peat instability. It suggested that the magnitude of the tensile strength depends not only on the fibre content and type, but also on the fibre dimensions. Therefore, experimental investigations are needed to assess fibre contents and size distributions for the weak basal peat. Furthermore, the size distribution curves obtained from the measurement of individual fibre dimensions in basal peat samples with known degrees of humification should be investigated, ideally using techniques such as magnetic measurement of sediments, programs such as „Shape" or electron microscopopy or spectrographic analysis. The production of these size distribution curves should: (i) improve knowledge of the general strength characteristics of weak peat including the fibre dimensions that critically influence its geotechnical strength properties; and (ii) improve the reliability of peat stability analyses and landslide hazard and risk assessments.

2. The link between the tensile strength of peat and its structural parameters including the types, content and dimensions of fibres and the degree of humification, suggests that these parameters can be used to predict peat strength for stability assessments. For example, a stratigraphy description using an auger or macrofossil analyses of small peat samples (i.e. 10 mm × 10 mm × 5 mm as opposed to 100 mm × 100 mm × 20-80 mm for a tensile strength test for example) could enable the dimensions of its fibres to be predicted and used to derive peat strength values using an appropriate tool. Modelling peat strength can also be used to explore and gain new insights into peat strength. A suitable model could be added to existing slope stability analysis programs which do not contain algorithms for peat material, and are based purely on standard mineral soils mechanics. Modelling of the tensile strength using its structural parameters requires the construction of a tensile (or/and shear) strength instrument that can measure highly humified peat samples, fibrous peat and other material for stability assessment, which could enable the quantification of the influences of different peat constituents on blanket bog instability. The quantification of any relationship(s) between the constituents of weak basal peat should: (i) enable the development of more appropriate models to predict peat strength using macrofossil analyses of small core samples, for example; (ii) reduce the cost and time needed for significant excavations to obtain geotechnical samples for stability assessments and analyses; and (iii) cause less disturbances to the hydrology of the peat system and its structure, therefore reducing environmental impacts of significant intrusive site investigations.

3. The lack of statistical relationships between water content, loss on ignition, permeability and bulk density could be owing to the use of inadequate sample sizes. The influence of sample dimensions on relationships between water content, LoI, saturated bulk density and saturated hydraulic conductivity of different blanket bogs should therefore be investigated. Values of peat hydraulic conductivity reported in the literature also vary considerably. Therefore a standardised method for measuring this parameter should be adopted for peat. Investigating the permeability of different types of peat using different instruments (i.e. falling head and constant head apparatus) and different sample

sizes, and a large number of trials, could help identify the best method for peat characterisation. Standardising methods for measuring the structural properties of different peats: (i) brings consistency among managers, practitioners and scientist involved with peat ; (ii) could improve knowledge of the impact of environment gradients like hydrology, ecology, hydrogeology for example on blanket peat; (iii) could facilitate improvement of the assessment and quantification of the effect of the predicted increasing rainfall (especially in the British Isles) on blanket peat; and (iv) could reduce the number of parameters that would need to be investigated, and hence the time and resources required, to characterise peat deposits.

4. This study suggested: (i) that microorganisms like the aphid *Colopha compressa* that lives in the root of *E. vaginatum* secrete hydrophobic compounds that are ultra-hydrophobic therefore can influence peat instability; (ii) that the fluidity of the hydrocarbons can be increased by the activity of thermophilic fungi; and (iii) the strength of peat depends on the chemical compounds that make up the material. Therefore, research on the microorganisms living in the basal upland peat and its chemical compounds is required to improve our understanding of their potential influences on peat instability. More studies on peat rheological properties to find out the critical temperature at which the hydrocarbons melt and influence peat fluidity could also improve our understanding of the influences of hydrocarbons and temperature on peat stability. Further research on the biological, chemical and rheological properties of peat could: (i) enable the assessment of the effect of the predicted increase in temperature in the British Isles on peat landslides for hazard management; and (ii) enable the use of smaller peat samples to characterise peat for its chemical, biological and rheological properties based on its macrofossil content during risk assessment, and reduce the cost necessary for significant excavations needed to obtain large samples for strength test and also reduce the environmental impacts of significant intrusive site investigations.

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APPENDICES

APPENDIX A. Environmental settings and peat physical properties at the three landslides

This appendix presents the environmental settings, *in situ* peat descriptions and detailed physical characteristics of the peat profile/monolith zones at the landslides presented in Chapter 4 as estimated or measured in the field or laboratory, and delimited after cluster analyses of the data collected.

Table A. 1. Geology, hydrology and hydrogeology of the three landslides.

Category of information	Type of information	Straduff Townland landslide	Slieve Rushen landslide	Slieve Anierin landslide
Geology	Peat thickness and description	Varies between 1.15 m and 2.85 m (See Figure A1)	Varies between 0.8 m and 3.33 m (See Figure A1)	Vary between 1.44 m and 3.08 m (See Figure A1)
	Topography	(See Figure 4.2)	(See Figure 4.3)	(See Figure 4.4)
	Bedrock 1:100,000 solid geology[1]	LH (lackagh sandstone formation) Fluvio-deltaic and basinal marine (turbiditic) shale, sandstone, siltstones and coal	GB (Glenade sandstone formation)	LH (Lackagh sandstone formation)
Groundwater and hydrology	Aquifer type[2]	Pi (poor aquifer-bedrock which is generally unproduction except only in local zones)	Lm (locally unimportant aquifer-bedrock which is generally moderately productive)	Pi (poor aquifer-bedrock which is generally unproductive)
	National vulnerability[3]	Moderate vulnerability	Extreme	Extreme
Surface water	River Basin District Boundaries	Shannon	North western	Shannon
	National Draft Generalised Bedrock Map[4]	NSA (Namurian sandstone)	DS (Dinantian sandstone)	NSA (Namurian sandstone)
	Surface water and drainage	Within a network of drainage and closest situated within 50-300 m to rivers Arigma and Cadogever	Within a network of drainage and closest situated within 50-300 m to Bellaboy and Brackel Loughs	Within a network of drainage and closest situated within 50-100 m south to Stony river- tributary to Lough Allen

Notes There are no wells within 1 km of the site that could be impacted by any pollution. The site is surrounded by either grassland or coniferous forests. There are no sites of mining heritage within 50 m of the bog flow. [1] Contains bedrock geological information on stratigraphy, igneous, lithology and diagenetic codes, their unit names and brief descriptions (GSI, 2012); [2] Based on hydrogeological, lithological and structural properties (GSI, 2012); [3] Represent the intrinsic geological and hydrogeological characteristics that determine the ease with which groundwater may be contaminated by human activities (GSI, 2012); [4] Bedrock units created by grouping bedrock formations and members based on their hydrogeological properties and other factors (GSI, 2012)

Table A. 2. Environmental impact of the three landslides.

Potential receptors at risk	Environmental impacts		
	Straduff Townland bog failure	**Slieve Rushen peat failure**	**Slieve Rushen peat failure**
Human health	There were no fatalities.	The site is very remote from main routes, residential areas and public space (>1000 m). Therefore, no impact on human was registered.	The site is very remote from main routes, residential areas and public space (>1000 m). Therefore, no impact on human heath was registered.
Ecology	Located within the Carrane Hill bog Natural Heritage Area (NHA). There were significant on-site and off-site ecological and conservation impacts, e.g. hydrological changes and colonisation of the failed site by Ericales species (e.g. *Calluna vulgaris)*; destruction of the woodland adjacent to the blanket bog.	Located within Natural Heritage Area Slieve Rushen bog (NHA). Same ecological impacts as Straduff bogflow although have not been assessed.	Located within Natural Heritage Area Cuilagh-Anierin upland (NHA) and Lough Allen Special Area of Conservation (SAC). Impacts on ecology have not been assessed.
Groundwater	Impacts of the landslide on surrounding groundwater have not been evaluated.	It is unlikely that any major groundwater - surface water interactions occur. Baseflow to rivers and streams is likely to be relatively low.	. It is unlikely that any major groundwater - surface water interactions occur.
Surface water	The impact of the landslide has not been assessed. Potential impact of the landslide on fauna in Lough Allen and surrounding rivers.	Potential impact to fauna in surrounding water features. The impact of the landslide has not been assessed.	Stony River (tributary to Lough Allen) runs downstream from the landslide and was impacted by the flow, although no systematic assessment was carried out.
Built environment and economical impacts	Road (R284), Straduff Townland village Community Centre and other infrastructure including sewage works.	Risk was considered to be very low because there was no road, public space and residential properties downstream	Just like the Slieve Rushen landslide there was no impact on the built environment.

Table A. 3. Results of the surface vegetation survey at Straduff Townland landslide and at Slieve Anierin landslide.

	Quadrat location at Straduff Townland landslide					**Quadrat location at Slieve Anierin landslide**				
Plants	**A5**	**/B2**	**B5**	**D2**	**/D6**	**C1**	**D3**	**A6**	**B2**	**D0**
Calluna vulgaris	F	F	F	F	F	A	A	A	A	A
Erica tetralix	F	F	F	0	0	F	F	F	F	F
Eriophorum angustifolium	F	O		F			F	F	F	A
Eriophorum vaginatum	A	A	A	A	A	F	O	A	O	O
Narthecium ossifragum	O	O	O	O	O	O	F	F	A	0
Trichophorum cespitosum/ Scirpus cespitosus	O	O	O			A	F		F	A
Racomitrium lanuginosum	O	O	O			O	A	F	A	
Sphagnum capillifolium	O					F	F	F	F	F
Sphagnum papillosum	O	O				F		F		
Cladonia uncialis	O					F			A	
Unidentified moss						R				

Notes A=Abundant, F=Frequent, O=Occasional and R= Rare

SITE SURVEYS

The results of the survey carried out at Transects AA‟ to HH‟ (Figure 4.1a) are presented in the following sections. Transect AA‟ waslocated in the intact peat 5 m from the margin at the head of Straduff Townland landslide and Slieve Anierin landslide. It was located in the intact peat at 7.5 m from the margin at the head of the Slieve Rushen landslide. Transects BB‟-EE‟ were located 50, 100, 150 and 200 m downslope of the head of all the three landslides respectively. Transects FF‟, HH‟ and GG‟ show the peat stratigraphy along the slope across the sites. The topography and peat stratigraphy along transect Z1Z2, was undertaken at the Straduff Townland landslide in order to assess the extent of the clay layer encountered at the base of the peat. Figure 4.2b presents the sampling locations at the Straduff Townland landslide. Peat depths at the points investigated are presented in Figure 4.1c.

Straduff Townland landslide

The average peat depths along Transects Z1Z2 and AA‟, sampling point A6a, and Transects BB‟-EE‟ were 2.4, 2.2, 1.9, 2.5, 2.4, 2.5 and 2.5 m respectively. Figure 4.2 shows the topography and peat stratigraphy along Transect AA‟. Figure 4.2 (Transect A) shows that there was a slight gradient toward the west between sampling points A3 and A6. The peat stratifigraphy along Transect AA‟ was very similar to that of the profile with only minor differences including the strata boundaries and peat depths. A legend for peat stratigraphy diagram is presented in Figure 4.2. Four different units (1-4, top to bottom) (excluding the mineral substrates) with diffused boundaries were identified as presented in Figure 4.2. These were: (1) fibrous and slightly humified peat, (2) moderately humified peat, (3) strongly humified peat and (4) highly to very humified and/or greasy peat. The identifiable macrofossil content was predominantly monocotyledons with *Eriophorum* spp. and the degree of humification generally increased with depth. The basal peat was not stratified, completely humified with low to nil elasticity, tensile strength and fibre content. The mineral substrate beneath all of the peat profiles investigated comprised angular pieces of pale coloured sandstone in a clayey matrix. Figure 4.4a shows irregular bedrock topography. The clay layer was thicker (approximately 0.015 m) in auger sampling points A4 and A6 (Transect A). The deeper peat profiles were located to the east. The shallowest peat was encountered at auger sampling point A6 located at the head of the landslide and at location A2.

Although the number of sample points investigated (Figure 4.2) was limited, the bog surface along the Transect BB‟ showed a concave shape and the mineral substrate showed a convex form. The mineral surface also showed a convex shape at Transect CC‟. Bedrock levels within the source area along Transects DD‟-EE‟ could not be determined due to the highly unstable saturated, fissured and weak peat in the deposition zone that could not be probed. The clay layer encountered in auger sample points A4 and A6 extended to Z2 only and was not encountered in Z1. Peat stratigraphy and the nature of the underlying geology were consistent across the site.

The consistency of the peat stratigraphy, as revealed along the transects, suggests that there is likely to be little variation throughout the site and that detailed analyses of a single profile could therefore provide a reliable indication of stratigraphic changes. In conclusion, although the number of sample points investigated was limited, the survey revealed a convex mineral substrate shape. Greasy layers were encountered at random location across the site (i.e. locations A6a, A5 and A7).

Slieve Rushen landslide

Peat depths across the points investigated are presented in Figure 4.1c2. Peat depths varied between 0.8 and 3.4 m and the mean peat depths along Transect AA‟, samplings points A5a-b and Transects BB‟-EE‟ were 1.9, 2.2, 1.8, 1.8, 1.8, 2.3 and 2.8 m respectively.

Figure 4.3 shows the topography and peat stratigraphy as revealed by the points investigated along Transect AA‟. There is apparently irregular bedrock topography and a surface gradient downhill towards the east, but the maximum change indicated by the survey data is only 1 m height over a distance of 30 m. Unlike at the Straduff Townland landslide, no clay layer or visible greasy layers were encountered. The stratigraphy of the peat along Transect AA‟ (b) was generally similar to that of the profile described at the Straduff Townland landslide with only minor differences (e.g. the strata boundaries, the lack of clayey or greasy layers in the augered peat and also the occurrence of visible fibres at the base of the profile at the monolith sampling point). From the sampling point A7 toward the east, the peat was wetter. The peat sampled at location A9 was less humified, probably because it was dominated by more recent accumulation within the source area of an older landslide. Similarly to the Straduff Townland landslide, five different units (1-5) with diffused boundaries were identified as presented in Figure 4.3: (1) burnt peat; (2) brown and fibrous peat, (3) slightly humified peat, and (4) strongly humified to completely humified peat. The fifth layer, made of highly to completely humified and greasy peat, was encountered at the monolith sampling points only. Furthermore, the clay layer was absent from auger samples but present at the base of the peat at the sampling point. Like the Straduff Townland landslide site, the identifiable macrofossil content across the site was predominantly made of remains of monocotyledons, notably *Eriophorum* spp. and the degree of humification increased with depth. The basal peat was not stratified but was highly humified with low to nil elasticity and tensile strength. The mineral substrate beneath all of the peat profiles investigated comprised angular pieces of pale coloured sandstone in a clayey matrix.

Figures 4.3 also shows the peat stratigraphy along Transects BB‟ to HH‟ respectively. The surface and bedrock topography (a) showed a slope from B1 to B5, and planar bog and bedrock surfaces from B5 to B10. Similarly, the surface and bedrock topography (a) showed a slope from C2 to C5. These findings suggested that there was a break of slope around the sampling points B5 and C2 located at the margin of the landslide. The stratigraphy (b) was almost similar to that encountered at Transect AA‟ with reference to the peat constituents and the degree of humification throughout the profiles and again, the peat was wetter from B7.

Bedrock levels within the source area along Transects DD"-EE" could not be determined due to the highly unstable saturated, fissured and weak peat in the deposition zone that could not be probed. Peat stratigraphy and the nature of the underlying geology are consistent with previous findings at Transects A to C. At Transect HH", the peat was thinner further up the slope where the transect passed into the source area of an older landslide.

In conclusion, the peat stratigraphy survey revealed that differences in peat stratigraphy along Transects AA"-HH" seemed to be insignificant, as was the case at the Straduff Townland landslide. The peat located approximately 20 metres east of the source area showed higher water content. This area was located near the source area of an older landslide. The superficial peat (especially at depth < 0.01 m below ground level) was drier around the source area of the study landslide probably due the influence of the moorland fire or the exposure of the peat profile by the landslide that promoted evaporative drying of peat. Visual examination of the peat for determination of the spatial extent and stratigraphic distribution of the hydrocarbons revealed greasy and clay layers at the sampling point only.

Slieve Anierin landslide

Peat depths across the points investigated are presented in Figure 4.1c3. The average peat depths along Transect AA", samplings point A5a and Transects BB"- EE" were 2.3, 2.1, 2.8, 2.3, 2.4, and 2.0 m respectively. Figure4.4 also shows the topography and peat stratigraphy as revealed by the points investigated along Transect A. With regards to the surface and bedrock topography, (a) shows convex shapes. Thicker clay layers were encountered in sampling points A7 and A8 where the peat was deeper. No visible greasy layers were encountered in the highly humified basal peat at all sampling points along Transect AA". The thinnest peat was encountered in auger sampling points A1, A3 and A5. Four different units (1-4) (excluding the mineral substrate) with diffused boundaries were identified as presented and described for the Straduff Townland landslide.

Table A. 4. Summary description of the peat at the three landslides.

Depth (m b.g.l.)	Unit description at Straduff Townland landslide
0.00-0.40	Light brown fibrous peat, slightly humified, mainly monocotyledon fine fibres and low amorphous material, moderate horizontal tensile strength.
0.40-0.78	Black and moderately humified, mainly monocotyledon fine fibre peat and moderate amorphous material, moderate horizontal tensile strength.
0.78-1.22	Light brown with dark patches, very weak and moderately humified peat. Monocotyledon fine fibre limited. Low horizontal tensile strength.
1.22-1.60	Brown, moderately to strongly humified peat. Monocotyledon fine fibre present. Low horizontal tensile strength.
1.60-1.80	Dark grey, greasy, highly humified and amorphous peat. Rare and very fine monocotyledon fragments. Low to zero horizontal tensile strength.
>1.80	Pale sandstone in clay matrix, 5YR 3/1on Munsell soil colour chart.
Depth (m b.g.l.)	**Unit description at Slieve Rushen landslide, recorded in July 2010 prior to moorland fire**
0.00-0.15	Brown fibrous peat with moderately humified, mainly monocotyledon fine fibres and low amorphous material, moderate horizontal tensile strength.
0.15-0.36	Brown, less fibrous peat with moderately humified, mainly monocotyledon fine fibre peat and moderate amorphous material, moderate horizontal tensile strength.
0.36-0.58	Dark brown humified peat with monocotyledon fragments. Low horizontal tensile strength.
0.58-0.88	Dark brown decomposing peat with monocotyledon fragments. Low horizontal tensile strength.
0.88-1.58	Dark grey, highly humified and amorphous peat. Very fine monocotyledon fragments. Low to zero horizontal tensile strength.
1.58-1.64	Dark grey, greasy, highly humified and amorphous peat. Very fine monocotyledon fragments. Low to zero horizontal tensile strength.
>1.64	Sandstone in clay matrix, 5YR 3/1 on Munsell soil colour chart.
Depth (m b.g.l.)	**Unit description at the Slieve Anierin monolith sampling point**
0.00-0.76	Dark fibrous peat, slightly humified, mainly monocotyledon fine fibres, low amorphous material and moderate horizontal tensile strength.
0.76-1.56	Light brown less fibrous peat with moderately humified, mainly monocotyledon fine fibre peat, moderate amorphous material and moderate horizontal tensile strength.
1.56-1.76	Black humified peat with monocotyledon fragments. Low horizontal tensile strength.
1.76-1.78	Dark grey, greasy, highly humified and amorphous peat. Very fine monocotyledon fragments. Low to zero horizontal tensile strength.
>1.78	Sandstone in clay matrix, 5YR 3/1on Munsell soil colour chart.

Note m b.g.l.= m below ground level

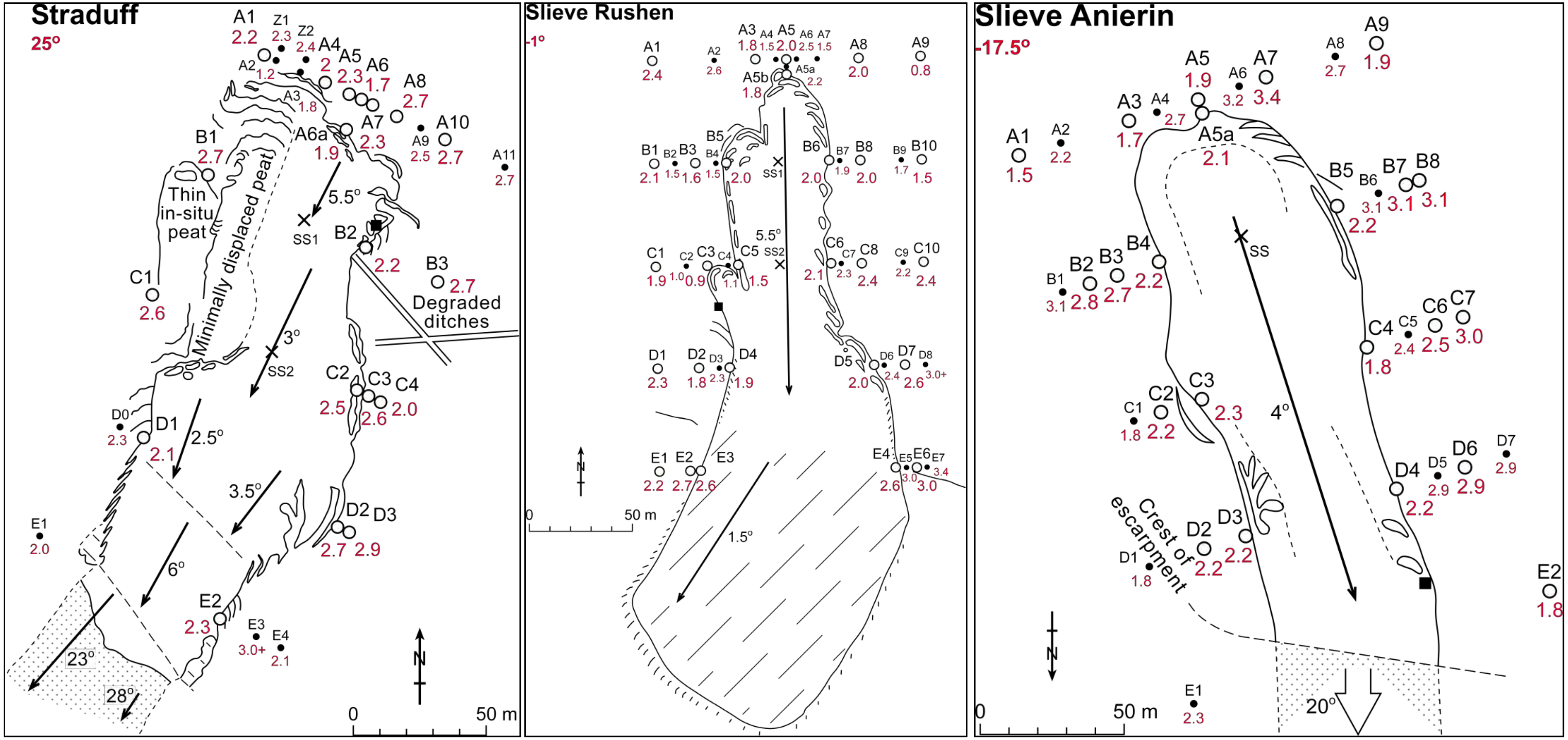

Figure A. 1. Outline geomorphological map (Dykes, 2009) showing the spatial distribution of peat depths at the (a) Straduff Towland landslide, (b) Slieve Rushen landslide and (c) Slieve Anierin landslide.

Table A. 5. Characteristics of the peat profile zones at Straduff Townland landslide as estimated in the field and delimited after cluster analysis of the data collected.

a	Parameter	Zone STD5		Zone STD4		Zone STD3		Zone STD2		Zone STD1		Mean parameter: Zones 5,4,3,2,1/Trend or comments
		R	***M***	***R***	***M***	***R***	***M***	***R***	***M***	***R***	***M***	
	Depth b.g.l. (m)	0-0.4	0.20	0.41-0.78	0.60	0.79- 1.22	1.01	1.23-1.60	1.42	1.61-1.80	1.71	0.20,0.60,1.01,1.42,1.71/increase
b	Darkness (Nig.) (0-4)	2-4	2	4	4	1	1	1	1	4	4	2,4,1,1,4 / none (variable)
	Stratification (Strat.) (0-4)	2	2	0	0	0	0	0	0	0	0	2,0,0,0,0 / 5 different
	Dryness (Sicc.) (0-4)	1	1	3	3	3	3	1	1	3	3	1,3,3,1,3 / none (variable)
	Boundary strength (Lim sup.) (0-4)	0-2	0	0	0	0-2	0	0	0	0-1	0	0,0,0,0,0 / same, nil
	Elasticity (Elas.) (0-4)	2	2	0	0	0	0	0	0	0	0	2,0,0,0,0 / 5 different
c	Humification (1-10)	4-6	6	7-8	7	8	8	9	9	10	10	6,7,8,9,10 / increase
	Wetness (1-5)	2-3	2	1-2	2	1	1	2	2	1	1	2,2,1,2,1 / none (variable)
	Fine fibre (0-3)	2-3	2	2	2	1-2	2	1	1	1	1	2,2,2,1,1 / decrease
	Coarse fibre (0-3)	0-1	0	0-2	0	0-1	0	0	0	0-1	0	0,0,0,0,0 / same, nil
	Vertical tensile strength (0-3)	2	2	2		1-2	1	1	1	0-1	0	2,2,1,1,0 / decrease
	Horizontal tensile strength (0-3)	2	2	2	2	1-2	1	1	1	0-1	0	2,2,1,1,0 /decrease
	Organic content (1-5)	4	4	4-5	5	4-5	5	4-5	5	3-5	4	4,5,5,5,4 / none (variable)
c	Fine fibre (1-5)	1	1	1	1	1	1	2	2	3	3	1,1,1,2,3 / Increase
	Coarse fibre (1-5)	3	3	3	3	3	3	2-3	2	1	1	3,3,3,2,1 /decrease

<u>Notes</u>

R = Range and M = Mean.

[a] Classification system

[b]Troel Smith (1955),

[c] von Post (Hobbs, 1986)

[d]Modified fibre content (this study)

The number of samples considered for Zones STD1 to STD5 was 20, 38, 44, 38 and 41 respectively.

Table A. 6. Characteristics of the peat monolith zones from Straduff Townland landslide as determined after cluster analysis of results of "raw" % light transmission.

Parameter	**Zone STH3**		**Zone STH2**		**Zone STH1**		**Mean parameter: Zone 3,2,1/Trend or comments**
	R	***M***	***R***	***M***	***R***	***M***	
Depth b.g.l. (m)	0-0.30	0.15	0.31-1.20	0.76	1.21-1.80	1.51	0.15,0.76,1.51,/increase
Humification [1]	4-6	6	6-8	7	8-10	9	6,7,9 / increase
Humus fraction (<0.15 mm) (%)[2]			18-24	22	15-57	27	-,22,27 / increase
Humus fraction (<0.15 mm) (%)[3]			1	1	1-3	1	-,1,1 / constant
Field water content (%)	647	647	601	854	515-1043	854	647,884,854 / no trend
Saturated water content (%)	779	779	864	864	643-1111	920	779,864,920 / no trend
Transmission (%)	70	70	21-60	39	14-31	23	70,39,23 / decrease

Note
R=Range and M=Mean.
[1]Estimated with von Post (Hobbs, 1986)
[2] Measured in the laboratory
[3]Modified fibre content (MFC) (this study)
Empty cell = Not tested.
See TableA.7 for number of samples considered.

Table A. 7. Number of samples considered for Straduff Townland landslide peat zones after cluster analysis of the results of „raw" % light transmission.

Parameter	Zone STH3	Zone STH2	Zone STH1
Humification [1]	31	90	60
Humus fraction (< 0.15 mm) [2]	0	11	60
Humus fraction (< 0.15 mm) [3]	0	11	60
Field water content	11	82	60
Saturated water content	11	10	30
Transmission	11	83	60

Notes
[1]Estimated with von Post (Hobbs, 1986)
[2] Measured in the laboratory
[3]Modified fibre content (MFC) (This study)

Table A. 8. Characteristics of the peat monolith zones from Straduff Townland landslide as determined after cluster analysis of the results of fibre content.

Parameter	Zone STF2		Zone STF1		Mean parameter/ Zones 2,1/Trend or comments
	R	*M*	*R*	*M*	
Depth b.g.l. (m)	1.10-1.66	1.38	1.67-1.80	1.74	1.38,1.74 / increase
Humus fraction (<0.15 mm)	15-24	19	47-57	52	19,52 / increase
Fine fibre (0.15-1.00 mm)	10-17	14	8-16	12	14,12 / decrease
Coarse fibre (>1.00 mm)	55-72	61	16-40	28	61,28 / decrease
Total fibre content (>0.15 mm)	71-82	75	32-48	40	75,40 / decrease
Ash content	3-9	6	5-11	8	6,8 / increase
LoI	91-98	94	89-95	92	94,92 / decrease

Notes
R = Range and M = Mean.
All values are in percentage (%).
14 samples were considered for Zone 1 and 56 for Zone 2.

Table A. 9. Characteristics of the peat monolith zones at Straduff Townland peat as defined by cluster analysis of the results of macrofossil content.

Parameter	**Zone ST M5**		**Zone STM4**		**Zone STM3**		**Zone STM2**		**Zone STM1**		**Mean parameter: Zones 5,4,3,2,1/Trend or comments**
	R	***M***	***R***	***M***	***R***	***M***	***R***	***M***	***R***	***M***	
Depth b.g.l. (m)	0-0.061	0.31	0.062-1.08	0.85	1.09-1.44	1.27	1.44-1.72	1.6	1.73-1.80	1.79	0.31,0.85,1.27,1.6,1.79 / increase
Charcoal fragments (0.5-1mm) (count)	0	0	0	0	0	0	0-2	0	0	0	0,0,0,0,0 / same
Charcoal fragments (< 0.5mm) (count)	1-10	3	0	4	0-10	7	0-30	8	0-5	2	3,4,7,8,2 / no trend
E. vaginatum spindles (count)	0	0	0	0	0-1	0	0-1	0	0	0	0,0,0,0,0 / same, nil
Field water content (%)	601-1175	700	659-1439	886	880-1052	962	758-876	820	515-788	670	700,886,962,820,670 / no trend
LoI (%)	95-99	96	92-97	95	94-98	96	91-97	94	72-93	84	96,95,96,94,84 / no trend, low at the base
Saturated water content (%)	779	779	864	864	957-1066	1011	643-1111	896	793	793	779,864,1011,896,793 / low at the base
Transmission (%)	27-70	53	21-54	37	17-51	27	14-31	23	19-29	22	53,37,27,23,22/ decrease
Monocot fragments (mostly *E. vaginatum*) (%)	65	83	25-70	48	40-89	56	11-50	23	13-44	29	83,48,56,23,29 / no trend
Roots (%)	5-10	9	3-20	12	1-16	5	0-5	1	0	0	9,12,5,1,0 / decrease
Unidentified organic matter (%)	5-30	8	20-61	45	9-57	38	48-88	75	56-87	70	8,45,38,75,70 / increase

Notes

R = Range and M = Mean.

The number of macrofossil samples considered for zones STM1 to STM5 was 7, 7, 9, 7 and 14 respectively (Table A.10).

Table A. 10. Number of samples for Straduff Townland peat monolith zones after cluster analysis of the results of macrofossil content.

Parameter	**Zone STM5**	**Zone STM4**	**Zone STM3**	**Zone STM2**	**Zone STM1**
Field water content	34	47	36	28	8
LoI	14	14	35	28	8
Saturated water content	11	10	10	15	5
Transmission	35	47	36	28	8
All other parameters presented	14	7	9	7	7

Table A. 11.Characteristics of the peat profile zones at Straduff Townland landslide after cluster analysis of the results of the quantitative description of the peat.

Parameter	Zone STQD4		Zone STQD3		Zone STQD2		Zone STQD1		Mean parameter: Zones 4,3,2,1/Trend or comments
	R	*M*	*R*	*M*	*R*	*M*	*R*	*M*	
Depth b.g.l. (m)	0.10-20	0.15	0.39-1.09	0.74	1.10-1.58	1.34	1.59-1.80	1.70	0.15,0.74,1.34,1.70 / increase
Dryness (0-4)	2	2	1-2	2	1-2	2	2	2	2,2,2,2 / same
Wetness (1-5)	3	3	3-4	3	3-4	3	3	3	3,3,3,3 / same
Organic content (1-5)	4	4	4-5	5	4-5	5	3-5	4	4,5,5,4 / no trend
Horizontal tensile strength (0-3)	2	2	2	2			1-2	2	2,2,-,2/constant
Humus fraction (<0.15 mm)					1-2	1	2-3	3	-,-,1,3 / increase
Fine fibre (0.15-1 mm)					1	1	1	1	-,-,1,1 /same
Coarse fibre (>1.0 mm)					1-3	2	1	1	-,-,2,1/ decrease
Total fibre content (>0.15 mm)					2-3	3	1-3	2	-,-,3,2 / decrease
Field water content (1-5)	674	647	601-1439	835	822-1052	930	515-850	748	-,-,930,748 / decrease

Notes

R = Range and M = Mean.

All parameters of the MFC are represented using a scale of 1 to 5. Fractions are graded as follows: 5 (i.e. content greater than 95% fibre); 4 (i.e. content between 95 and 80%); 3 (i.e. content between 80 and 60%); 2(i.e. content between 60 and 40%); 1 (i.e. content between 40 and 0%).

See Table A.12 for number of samples considered

Table A. 12.Number of samples considered for Straduff Townland landslide peat monolith zones after cluster analysis of the results of quantitative peat classification.

Parameter	Zone STQD3	Zone STQD2	Zone STQD1
Dryness	12	48	22
Wetness	12	48	22
Organic content	12	48	22
Horizontal tensile strength	20	48	22
Humus fraction (<0.15 mm)	0	48	22
Fine fibre (0.15-1 mm)	0	48	22
Coarse fibre (>1.0 mm)	0	48	22
Total fibre content (>0.15 mm)	0	48	22
Field water content	0	48	22

Table A. 13. Characteristics of the peat profile zones at Slieve Rushen landslide as estimated in the field and delimited after cluster analysis of the data collected.

a	Parameter	Zone SRD4		Zone SRD3		Zone SRD2		Zone SRD1		Mean parameter: Zones 4,3,2,1/Trend or comments
		R	*M*	*R*	*M*	*R*	*M*	*R*	*M*	
	Depth b.g.l. (m)	0-0.36	0.18	0.36-0.88	0.63	0.88-1.32	1.11	1.32-1.64	1.49	0.18,0.63,1.11,1.49 / increase
b	Darkness (Nig.) (0-4)	1-2	2	2-3	2	1	1	1-4	2	2,2,1,2 / low in 2
	Stratification (Strat.) (0-4)	1-2	1	1-2	2	0	0	0	0	1,2,0,0 / no trend
	Dryness (Sicc.) (0-4)	2-3	3	2	2	3	3	3-4	3	3,2,3,3 / high in 2
	Boundary strength (Lim sup.) (0-4)	0	0	0	0	0	0	0-1	0	0,0,0,0 / Nil
	Elasticity (Elas.) (0-4)	0	1	1	1	0	0	0	0	1,1,0,0 / decrease
c	Humification (1-10)	5-6	5	6	6	6	6	6-9	7	5,6,6,7 / increase
	Wetness (1-5)	1-2	1	2	2	2	2	1-2	2	1,2,2,2 / increase
	Fine fibre (0-3)	2-3	3	1-2	1	1	1	1-2	1	3,1,1,1 / decrease
	Coarse fibre (0-3)	0-1	0	0-2	0	0-1	0	0-1	0	0,0,0,0 / same, nil
	Vertical tensile strength (0-3)	1-2	2	1	1	0-1	1	0-1	0	2,1,1,0 / decrease
	Horizontal tensile strength (0-3)	1-2	2	1	1	0-1	1	0-1	0	2,1,1,0 / decrease
	Organic content (1-5)	4-5	5	5	5	4-5	5	4-5	4	5,5,5,4 / lower in 1
d	Fine fibre (1-5)	1	1	1	1	1-2	2	2-3	2	1,1,2,2 / increase
	Coarse fibre (1-5)	3-4	3	3	3	2-3	2	1-2	2	3,3,2,2 / decrease

Notes
R = Range and M = Mean.
[a] Classification system
bTroel Smith (1955),
[c] von Post (Hobbs, 1986)
[d]Modified fibre content (this study)
The number of samples considered for Zones SRD1 to 4was 31, 45, 52 and 37 respectively.

Table A. 14. Characteristics of the peat monoliths zones at Slieve Rushen landslide as determined after cluster analysis of the results of "raw" % of light transmission.

Parameter	Zone SRH3		Zone SRH2		Zone SRH1		Mean parameter: Zones 3,2,1/Trend or comments
	R	***M***	***R***	***M***	***R***	***M***	
Depth b.g.l. (m)	0.0-0.93	0.47	0.94-1.58	1.26	1.59-1.64	1.62	0.47,1.26,1.62 / increase
Humification [1]	5-6	6	6-9	6	9	9	6,9,9 / increase
Humus fraction (< 0.15 mm) (%)[2]			2-52	19	52	52	-,19,52 / increase
Humus fraction (<0.15 mm) (%)[3]			1-2	1	2	2	-1,2 / increase
Field water content (%)	83-883	442	637-935	812	640-653	646	442,812,646 / no trend
Saturated water content (%)			368-825	650	825	825	-,650,825 / increase
Transmission (%)	20-39	29	22-53	36	18-24	19	29,36,18 / lowest in 1

Notes
R = Range and M = Mean.
[1]Estimated with von Post (Hobbs, 1986)
[2]Measured in the laboratory
[3]Modified fibre content (this study)
Empty cell = Not tested.
See Table A.15 for the number of samples considered.

Table A. 15. Number of sample considered for Slieve Rushen landslide peat monolith zones after cluster analysis of results of „raw, % of light transmission.

Parameter	Zone SRH3	Zone SRH2	Zone SRH1
Humification [1]	0	64	6
Humus fraction (< 0.15 mm) [2]	0	64	6
Humus fraction (< 0.15 mm) [3]	70	65	6
Field water content	0	25	5
Saturated water content	74	65	6
Transmission	3	2	1

Notes
[1]Estimated with von Post (Hobbs, 1986)
[2]Measured in the laboratory
[3]Modified fibre content (this study)

Table A. 16. Characteristics of the peat monolith zones at Slieve Rushen bog failure peat as determined after cluster analysis of results of fibre content.

Parameter	Zone SRF2		Zone SRF1		Mean parameter: Zones 2,1/Trend or comments
	R	*M*	*R*	*M*	
Depth b.g.l. (m)	0.95-1.50	1.23	1.51-1.64	1.58	1.23,1.58/increase
Humus Fraction (<0.15mm)	2-27	17	31-52	42	17,42/increase
Fine fibre (0.15-1.00 mm)	12-21	14	18-21	19	14,19/increase
Coarse fibre (>1.00 mm)	5381	63	16-39	28	63,28/decrease
Total fibre content (>0.15 mm)	66-95	77	37-57	47	77,47/decrease
Ash content	1-11	6	11-12	11	6,11/increase
LoI	89-99	94	88-89	89	94,89/decrease

Notes
R = Range and M = Mean.
All values in percentage (%).
14 sampling points were considered for Zone SRF1and 56 for Zone SRF2.

Table A. 17. Characteristics of the peat profile zones at Slieve Rushen landslide as defined after cluster analysis of the results of macrofossil content.

Parameter	**Zone SRM3**		**Zone SRM2**		**Zone SRM1**		**Mean parameter: Zones 3,2,1/Trend or comments**
	R	***M***	***R***	***M***	***R***	***M***	
Depth b.g.l. (m)	0-0.63	0.32	0.64-1.48	1.06	149-1.64	1.57	0.65,1.22,1.58 / increase
Charcoal fragments (<0.5mm) (Count)	0-5	3	0-10	6	0-10	6	3,6,6 / increase
Charcoal fragments (0.5-1.0 mm) (Count)	0	0	0	0	0	0	0,0,0 / same, nil
E. vaginatum spindles(Count)	0-4	0	0-2	0	0	0	0,0,0 / same, nil
Field water content (%)	101-883	437	83-935	693	637-807	700	437,693, 700 / increase
LoI (%)	91-99	97	89-99	95	88-95	91	97,95,91 / decrease
Saturated water content (%)			603-825	721	368-825	597	-,721,597 /decrease
Transmission (%)	20-39	29	20-53	34	18-37	27	29,34,27/ decrease
Sphagnum (%)	0	0	0-29	2	0	0	0,2,0 / high in 2
Ericales (%)	0	0	0-1	0	0-1	0	0,0,0 / same
Monocot fragments (mostly *E. vaginatum*) (%)	30-75	52	33-84	59	11-51	27	52,59,27 / lowest in 1
Roots (%)	5-10	6	0-10	3	0-3	1	6,3,1 / decrease
Unidentified organic matter (%)	15-70	53	13-60	34	49-81	68	53,34,68 / highest in 1

<u>Notes</u>
R = Range and M = Mean.
Empty cell = Not tested.
The number of samples considered for zones SRM1 to SRM3 was 9, 18 and 5 respectively (Table A.18).

Table A. 18. Number of samples considered for Slieve Rushen peat monolith zones after cluster analysis of the results of macrofossil content.

Parameter	**Zone SRM3**	**Zone SRM2**	**Zone SRM1**
Field water content	40	85	16
Saturated water content	0	20	10
LoI	5	58	16
Transmission	44	85	16
All other parameters	5	18	9

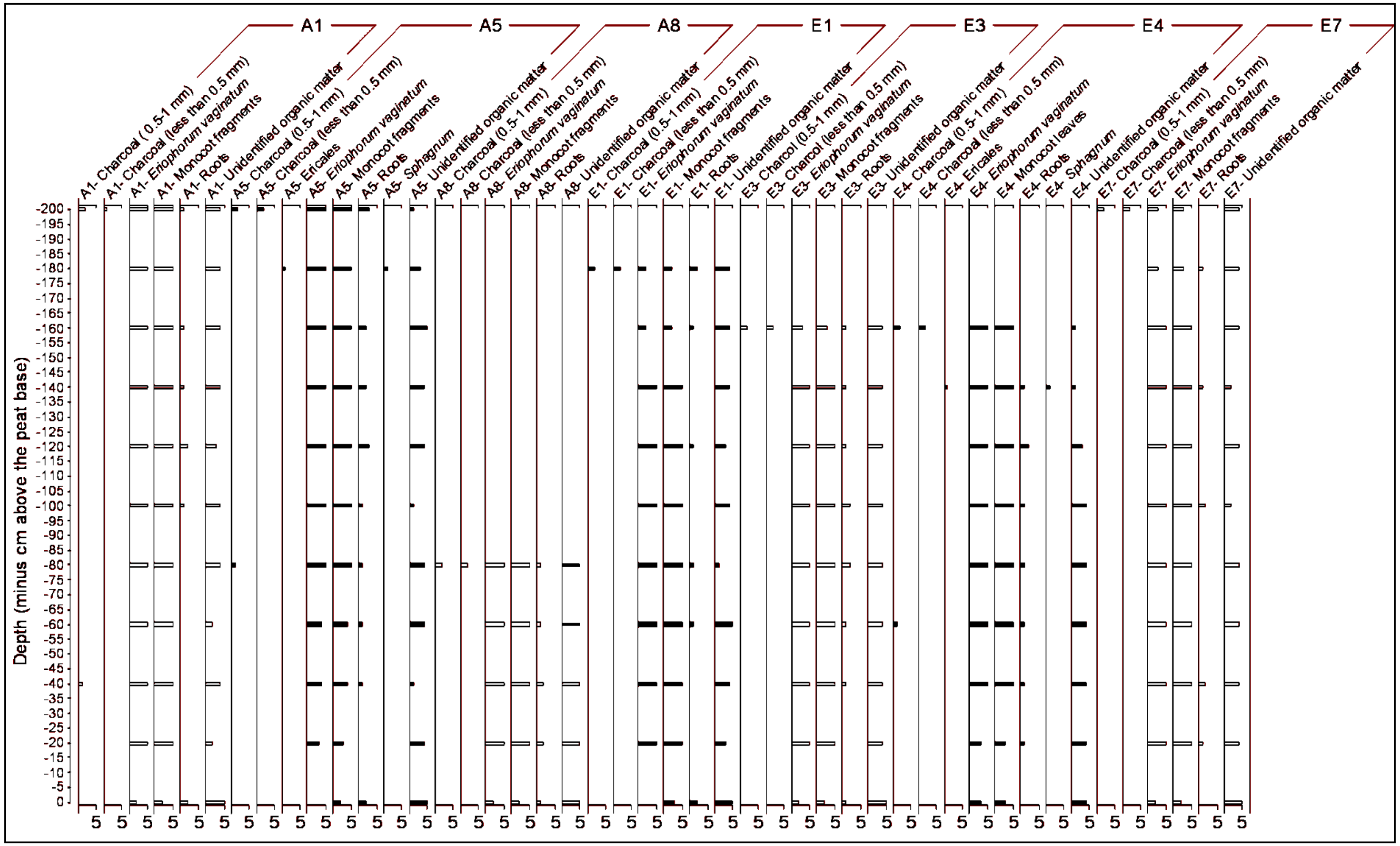

Figure A. 2. Results of macrofossil analyses for samples taken across the Slieve Rushen blanket bog.

Table A. 19. Characteristics of the peat profile zones at Slieve Rushen landslide after cluster analysis of the results of the quantitative peat description of the peat.

Parameter	**Zone SRQD3**		**Zone SRQD2**		**Zone SRQD1**		**Mean parameter: Zones 3,2,1/Trend or comments**
	R	***M***	***R***	***M***	***R***	***M***	
Depth b.g.l. (m)	0.0-0.94	0.47	0.95-1.50	1.23	1.51-1.64	1.58	0.47,1.23,1.58 / increase
Dryness (0-4)	2-3	3	2	2	2	2	3,2,2 / decrease
Wetness (1-5)	2-3	2	3	3	3	3	2,3,3 / increase
Organic content (1-5)	4-5	5	4-5	5	4-5	4	5,5,4 / low in 1
Horizontal tensile strength (0-3)					1	1	-,-,1 / single value
Humus fraction (<0.15 mm)			1	1	1-2	2	-,1,2 / increase
Fine fibre (0.15-1.0 mm)			1	1	1	1	-,1,1 / same
Coarse fibre (>1.0 mm)			2-4	3	1	1	-,3,1 / decrease
Total fibre content (>0.15 mm)			3-5	3	1-2	2	-,3,2 / decrease
Field water content	83-883	448	715-935	825	637-745	685	448,825,685 / no trend

Notes

R = Range and M = Mean.

AllMFC fractions are represented using a scale of 1 to 5. Fractions are graded as follows: 5 (i.e. content greater than 95% fibre); 4 (i.e. content between 95 and 80%); 3 (i.e. content between 80 and 60%); 2(i.e. content between 60 and 40%); 1 (i.e. content between 40 and 0%).

See Table A.20 for number of samples.

Table A. 20.Number of samples considered for Slieve Rushen landslide peat monolith zones after cluster analysis of the results of quantitative peat description.

Parameter	**Zone SRQD3**	**Zone SRQD2**	**Zone SRQD1**
Dryness	71	56	14
Wetness	71	56	14
Organic content	9	53	14
Horizontal tensile strength	0	0	5
Humus fraction (<0.15 mm)	0	56	14
Fine fibre (0.15-1.0 mm)	0	56	14
Coarse fibre (>1.0 mm)	0	56	14
Total fibre content (>0.15 mm)	0	56	14
Field water content	71	56	14

Table A. 21. Characteristics of the peat profile zones at Slieve Anierin landslide as estimated in the field and delimited after cluster analysis of the data collected.

	Parameter	**Zone SAD4**		**Zone SAD3**		**Zone SAD2**		**Zone SAD1**		**Mean parameter: Zones 4,3,2,1/Trend or comments**
a		***R***	***M***	***R***	***M***	***R***	***M***	***R***	***M***	
	Depth b.g.l. (m)	0.00-0.27	0.15	0.28-0.75	0.52	0.76-1.56	1.17	1.57-1.78	1.68	0.15,0.52,1.17,1.68 / increase
b	Darkness (Nig.) (0-4)	2	2	1-2	2	1	1	3-4	3	2,2,1,3 / no trend
	Stratification (Strat.) (0-4)	1	1	0-1	0	0	0	0	0	1,0,0,0 / same, nil
	Dryness (Sicc.) (0-4)	1	1	1-2	1	2	2	2	2	1,1,2,2 / increase
	Boundary strength (Lim sup.) (0-4)	0-1	0	0	0	0-1	0	0-1	0	0,0,0,0 / nil
	Elasticity (Elas.) (0-4)	2	2	0-2	2	0	0	0	0	2,2,0,0 / decrease
c	Humification (1-10)	5-7	6	7	7	7-9	8	9-10	9	6, 7,8,9 / increase
	Wetness (1-5)	2-3	2	2	2	2	2	1-2	2	2,2,2,2 / same, nil
	Fine fibre (0-3)	2-3	2	1-2	2	1	1	1	1	2,2,1,1 / decrease
	Coarse fibre (0-3)	0-1	0	0-1	0	0	0	0	0	0,0,0 / same, nil
	Vertical tensile strength (0-3)	2	2	0-2	2	0	0	0	0	2,2,0,0 / decrease
	Horizontal tensile strength (0-3)	2	2	0-2	2	0	0	0	0	2,2,0,0 / decrease
	Organic content (1-5)	0	0	4-5	5	4-5	5	4-5	5	-,5,5,5 /same
b	Fine fibre (1-5)	1	1	1	1	1-3	2	3	3	1,1,2,3 / increase
	Coarse fibre (1-5)	3-4	3	3	3	2-3	3	1-2	2	3,3,3,2 / low in 1

Notes

R = Range and M = Mean.

[a] Classification system

[b] Troel Smith (1955),

[c] von Post (Hobbs, 1986)

[d] Modified fibre content (this study)

The number of samples considered was 22, 79, 48 and 26 for Zones SAD1 to 5 respectively.

Table A. 22. Characteristics of the peat monolith zones from Slieve Anierin landslide as determined after cluster analysis of results of "raw" % light transmission.

Parameter	**Zone SAH3**		**Zone SAH2**		**Zone SAH1**		**Mean parameter: Zone 3,2,1/Trend or comments**
	R	***M***	***R***	***M***	***R***	***M***	
Depth b.g.l. (m)	0.32-1.17	0.75	1.18-1.73	1.46	1.74-1.78	1.76	1.75,1.46,1.76 / increase
Humification (1-10)[1]	7-8	7	8-9	8	9-10	10	7,8,10 / increase
Humus fraction (< 0.15 mm) (%)[2]	23-32	30	19-63	35	63	63	30,35,63 / increase
Humus fraction (< 0.15 mm) (1-5)[3]	1	1	1-3	1	3	3	1,1,3 / increase
Field water content (%)	126-1982	588	514-947	772	482-529	506	588,772,506 / lowest in 1
Saturated water content (%)			552-850	676	565	565	-,672,465 / low in 1
Transmission (%)	17-55	35	26-86	42	16	16	35,42,16 / decrease

<u>Notes</u>
R = Range and M = Mean.
[1]Estimated with von Post (Hobbs, 1986)
[2]Measured in the laboratory
[3]Modified fibre content (this study)
Empty cell = Not tested.
See Table A.23 for number of samples considered.

Table A. 23.Number of samples considered for Slieve Anierin landslide peat monolith zones after cluster analysis of the results of „raw" % of light transmission.

Parameter	Zone SAH3	Zone SAH2	Zone SAH1
Humification [1]	85	56	5
Humus fraction (< 0.15 mm) [2]	9	56	5
Humus fraction (<0.15 mm) [3]	9	56	5
Field water content	84	56	5
Saturated water content	0	25	5
Transmission	85	56	5

Notes
[1]Estimated with von Post (Hobbs, 1986)
[2]Measured in the laboratory
[3]Modified fibre content (this study)

Table A. 24.Characteristics of the peat monolith zones from Slieve Anierin landslide as determined after cluster analysis of the results of fibre content

Parameter	Zone SAF2		Zone SAF1		Mean parameter: Zones 2,1/Trend or comments
	R	***M***	***R***	***M***	
Depth b.g.l. (m)	1.09-1.64	1.37	1.65-1.78	1.72	1.37, 1.72 / increase
Humus fraction (<0.15 mm)	19-47	31	54-63	59	31,59 / increase
Fine fibre (0.15-1.00 mm)	11-18	14	14	14	14,14 /same
Coarse fibre (>1.00 mm)	33-62	50	2-22	12	50,12 / decrease
Total fibre content (>0.15 mm)	50-74	64	17-36	27	64,27/ decrease
Ash content	2-15	6	9-20	15	6,15 / increase
LoI	85-98	94	80-91	85	94,85 / decrease

Notes
R = Range and M = Mean.
All values in percentage (%).
The number of samples considered was 56 for SAF2 and 14 for SAF1.

Table A. 25.Characteristics of the peat monolith zones at Slieve Anierin peat as defined by cluster analysis of the results of macrofossil content.

Parameter	**Zone SAM5**		**Zone SAM4**		**Zone SA M3**		**Zone SAM2**		**Zone SAM1**		**Mean parameter: Zone 5,4,3,2,1/Trend or comments**
	R	***M***	***R***	***M***	***R***	***M***	***R***	***M***	***R***	***M***	
Depth b.g.l. (m)	0.34-0.61	0.49	0.62-1.06	0.84	1.07-1.17	1.13	1.19-1.66	1.43	1.67-1.78	1.73	0.49,0.84,1.13,1.43,1.73 / increase
Charcoal fragments (< 0.5 mm) (count)	5-10	8	0-10	2	0-10	4	0-20	9	0-20	4	8,2,4,9,4/ no trend
Charcoal fragments (0.5-1.0 mm) (count)	0	0	0	0	0	0	0	0	0-10	2	0,0,0,0,2/ high in 1
Ericales (%)	0	0	0-1	0	0-1	1	0-1	0	0-2	0	0,0,1,0,0 / negligible
E. vaginatum spindles (count)	0-1	1	0	0	0	0	0	0	0	0	1,0,0,0,0 / high in 4
Field water content (%)	126-1029	507	130-1982	535	887-1050	938	645-947	790	482-704	579	507,535,938,790,579/ no trend
LoI (%)	99	99	92-99	98	92-98	94	85-98	96	82-96	90	99,98,94,96,90 / no trend
Saturated water content (%)							552-850	693	552-565	560	-,-,-,693,560 / low in 1
Transmission (%)	22-50	32	24-55	39	17-50	29	26-86	42	16-58	30	32,39,29,42,30 / no trend
Monocot fragments (mostly *E. vaginatum*)(%)	70-71	70	18-58	36	29	14	Oct-57	30	5-15	9	65,36,14,30,9 / variable
Roots (%)	1-4	4	7-11	9	1-11	5	1-7	3	0-3	1	4,9,5,3,1 / decrease
Sphagnum (%)	0	0	0	0	0-1	0	0	0	0	0	0,0,0,0,0 / same, nil
Unidentified organic matter (%)	25-26	26	31-74	55	65-86	78	41-85	66	84-95	89	26,55,78,66,89 / increase

Notes

R=Range and M=Mean.

Empty cell = Not tested.

See Table A.26 for number of samples considered.

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Table A. 26. Number of sample considered for Slieve Anierin peat monolith zones after cluster analysis of the results of macrofossil content.

Parameter	Zone SAM5	Zone SAM4	Zone SAM3	Zone SAM2	Zone SAM1
Field water content	25	45	12	48	12
Saturated water content	0	0	0	22	8
LoI	3	6	11	48	12
Transmission	25	45	12	48	12
All others parameters	3	6	3	12	8

Table A. 27. Characteristics of the peat profile zones at Slieve Anierin landslide after cluster analysis of the results of the quantitative description of the peat.

Parameter	**Zone SAQD3**		**Zone SAQD2**		**Zone SAQD1**		**Mean parameter: Zones 3,2,1/Trend or comments**
	R	***M***	***R***	***M***	***R***	***M***	
Depth b.g.l. (m)	0.34-1.07	0.71	1.08-1.57	1.33	1.58-1.78	1.68	0.71, 1.33,1.68 / increase
Dryness	1-3	2	1-2	2	2-3	2	2,2,2 / same
Wetness	2-4	3	3-4	3	2-3	3	3,3,3 / same
Organic content	4-5	5	4-5	5	4-5	5	5,5,5 / same
Horizontal tensile strength (0-3)			0	0	2	2	-,-,2 / single value
Humus fraction (<0.15 mm)			1	1	2-3	2	-,1,2 /increase
Fine fibre (0.15-1.00 mm)			1	1	1	1	-,1,1 /same
Coarse fibre (>1.00 mm)			2-3	2	1	1	-,2,1 /decrease
Total fibre content (>0.15 mm)			2-3	3	1-3	2	-,3,2 /decrease
Field water content	126-1982	1982	665	843	482-728	616	1982,843,616/ no trend

Notes

R=Range and M=Mean.

All MFC fractions are represented using a scale of 1 to 5. Factions are graded as follows: 5 (i.e. content greater than 95% fibre); 4 (i.e. content between 95 and 80%); 3 (i.e. content between 80 and 60%); 2(i.e. content between 60 and 40%); 1 (i.e. content between 40 and 0%).

See Table A.28 for number of samples considered.

Table A. 28. Sampling points considered for Slieve Anierin landslide peat zones after cluster analysis of the results of quantitative peat classification.

Parameter	**Zone SAQD3**	**Zone SAQD2**	**Zone SAQD1**
Dryness	74	50	21
Wetness	74	50	21
Organic content	9	50	21
Horizontal tensile strength	0	0	5
Humus fraction (<0.15 mm)	0	49	21
Fine fibre (0.15-1.00 mm)	0	49	21
Coarse fibre (>1.00 mm)	0	49	21
Total fibre content (>0.15 mm)	0	49	21
Field water content	74	49	21

Table A. 29. Physical properties of peat monoliths and multiple subsamples from the Straduff Townland landslide.

Physical property	**Sampling depth (m b.g.l.)**	**Peat type**	**Number of samples**	**Range**	**Mean**	**Standard deviation**
Field water content (Mp) (%)	**0.10-1.80**	***Monolith***	**152**	**515-1439**	**839**	**140**
Saturated Mp (%)	**0.10-1.80**	***Monolith***	**50**	**643-1111**	**879**	**136**
Combined field and saturated Mp (%)	0.01	*Surface*	25	563- 961	710	105
	0.89	*Middle*	7	775- 938	858	49
	1.80	*Base*	105	82- 1532	706	213
Loss on ignition (%)	**0.42- 1.80**	***Monolith***	**86**	**84.6-99.4**	**94.7**	**2.3**
	0.01	*Surface*	15	86.1-98.6	94.9	4.0
	0.89	*Middle*	11	88.1-98.6	95.6	3.1
	1.80	*Base*	84	81.5-99.3	94.5	4.2
Transmission (%)	**0.38-1.80**	***Monolith***	**135**	**14.0-70.0**	**32.0**	**10.0**
	1.75-1.80	*Base*	25	10.5-48.5	21.3	10.0
Saturated hydraulic conductivity (m s^{-1}), k_{Ch}	**0.01-1.80**	***Monolith***	**9**	**3.0×10^{-11} to 3.0×10^{-8}**	**7.6×10^{-9}**	**1.1×10^{-8}**
	0.01	*Surface*	3	7.4×10^{-11} to 4.0×10^{-9}	1.6×10^{-9}	2.1×10^{-9}
	0.89	*Middle*	3	1.1×10^{-10} to 2.7×10^{-9}	1.2×10^{-9}	1.4×10^{-9}
	1.80	*Base*	11	1.4×10^{-11} to 1.8×10^{-8}	1.9×10^{-9}	5.4×10^{-9}
Saturated hydraulic conductivity (m s^{-1}), k_{Fh}	**0.01-1.80**	***Monolith***	**9**	**2.3×10^{-6} to 8.6×10^{-6}**	**5.7×10^{-6}**	**3.1×10^{-6}**
	0.01	*Surface*	3	1.1×10^{-7} to 3.8×10^{-6}	2.3×10^{-6}	1.9×10^{-6}
	0.89	*Middle*	3	2.0×10^{-7} to 1.4×10^{-5}	8.3×10^{-6}	7.3×10^{-6}
	1.80	*Base*	3	1.5×10^{-7} to 1.3×10^{-5}	8.6×10^{-6}	7.3×10^{-6}
Dry bulk density (g cm^{-3})	**0.01-1.80**	***Monolith***	**9**	**0.1-0.2**	**0.1**	**0.0**
	0.01	*Surface*	3	0.1-0.2	0.1	0.0
	0.89	*Middle*	3	0.1	0.1	0.0
	1.80	*Base*	11	0.1-0.2	0.2	0.0
Saturated bulk density (g cm^{-3})	**0.01-1.80**	***Monolith***	**9**	**1.0-1.1**	**1.0**	**0.0**
	0.01	*Surface*	3	1.0-1.1	1.0	0.0
	0.89	*Middle*	3	1.0	1.0	0.0
	1.80	*Base*	11	1.0-1.5	1.1	0.1
Total fibre content (%)	1.10-1.80	***Monolith***	10	31.8-81.9	68.1	15.9

Notes k_{Ch} is the hydraulic conductivity measured with constant head apparatus and k_{Fh} with falling head apparatus. All basal peat samples were taken at 0.00-0.01 m above the peat-mineral interfaces.

Table A. 30.Physical properties of peat monoliths and duplicate subsamples from the Slieve Rushen landslide.

Physical property	Sampling depth (m b.g.l.)	Peat type	Number of samples	Range	Mean	Standard deviation
Field water content (%)	**0.24-1.64**	***Monolith***	**142**	**82 - 935**	**621**	**256**
Saturated water content	1.11-1.64	*Monolith*	30	369- 825	680	163
Field and saturated water content (%)	1.64	*Base*	84	420-892	672	110
Loss on Ignition (%)	**0.26-1.64**	***Monolith***	**79**	**88.2- 99.3**	**94.6**	**3.4**
	1.64	*Base*	44	84.4-99.8	97.2	2.8
Transmission (%)	**0.20-1.64**	***Monolith***	**144**	**18.0-53.0**	**32.0**	**6.0**
	1.59-1.64	*Base*	35	9.1-42.8	21.4	9.7
Saturated hydraulic conductivity ($m\ s^{-1}$), k_{Ch}	**1.12-1.64**	***Monolith***	**9**	3.0×10^{-11} to 4.0×10^{-9}	10^{-9}	1.6×10^{-9}
	1.64	*Base*	5	1.4×10^{-11} to 2.9×10^{-9}	6.5×10^{-10}	1.3×10^{-9}
Saturated hydraulic conductivity ($m\ s^{-1}$), k_{Fh}	1.64	*Base*	3	10^{-11} to 6.9×10^{-7}	3×10^{-7}	4×10^{-7}
Dry bulk density ($g\ cm^{-3}$)	**1.12-1.64**	***Monolith***	**9**	**0.1-0.2**	**0.1**	**0.0**
	1.64	*Base*	5	0.2-0.3	0.2	0.1
Saturated wet bulk density ($g\ cm^{-3}$)	**1.12-1.64**	***Monolith***	**9**	**1.0**	**1.0**	**0.0**
	1.64	*Base*	5	1.0 -1.1	1.0	0.0
Total fibre content (%)	**0.95-1.64**	***Monolith***	10	36.7-94.6	71.0	15.6

Notes.b.g.l. represents below ground level. k_{Ch} is the hydraulic conductivity measured with constant head apparatus and k_{Fh} with falling head apparatus. The peat samples taken along profile between 1.12-1.64 m b.g.l. were subsampled at 0.05 m intervals. All basal peat samples were taken from approximately 0.01 m above the peat-mineral interface.

Table A. 31. Physical properties of peat monoliths and multiple subsamples from the Slieve Anierin landslide.

Physical property	Sampling depth (m b.g.l.)	Peat type	Number of samples	Range	Mean	Standard deviation
Field water content (%)	**0.34-1.78**	***Monolith***	**145**	**126 - 1982**	**656**	**277**
Saturated water content (%)	1.20-1.78	*Monolith*	30	552- 850	657	128
Field and saturated water content (%)	1.78	*Base*	84	312-1180	626	151
Loss on ignition (%)	**0.40-1.78**	***Monolith***	**80**	**82.0 -99.0**	**95.0**	**4.0**
	1.73-1.78	*Base*	80	82.9-99.0	95.0	4.4
Transmission (%)	**0.33-1.78**	***Monolith***	**146**	**16.0-86.0**	**37.0**	**11.0**
	1.78	*Base*	28	7.2-50.8	21.2	12.5
Saturated hydraulic conductivity (m s^{-1}), k_{Ch}	**1.20-1.78**	***Monolith***	**9**	1.48×10^{-11} to 2.2×10^{-6}	4.0×10^{-7}	8.21×10^{-7}
	1.78	*Base*	5	3.1×10^{-11} to 3.1×10^{-8}	6.3×10^{-9}	1.4×10^{-8}
Saturated hydraulic conductivity (m s^{-1}), k_{Fh}	1.78	*Base*	3	10^{-11} to 5.8×10^{-6}	2.2×10^{-6}	3.1×10^{-6}
Dry bulk density (g cm^{-3})	**1.20-1.78**	***Monolith***	**9**	**0.1-0.3**	**0.2**	**0.1**
	1.78	*Base*	5	0.1-0.3	0.2	0.0
Saturated bulk density (g cm^{-3})	**1.20-1.78**	***Monolith***	**9**	**0.9-1.1**	**1.0**	**0.1**
	1.78	*Base*	5	0.9-1.1	1.0	0.1
Total fibre content (%)	**1.09-178**	***Monolith***	**10**	**16.6-74.0**	**56.2**	**17.4**

Note k_{Ch} is the hydraulic conductivity measured with constant head apparatus and k_{Fh} with falling head apparatus. The peat samples taken along profile between 1.20-1.78 m b.g.l. were subsampled at 0.05 m intervals. All basal peat samples were taken from 0.00-0.01 m above the peat-mineral interfaces.

APPENDIX B. Tensile strengths of peats, Probabilistic (P) slope/W simulations output graphs and mean individual PAHs contents in ng g^{-1} of dry peat from the three landslides.

This appendix presents the tensile strengths of peat, the probabilistic (P) results of slope/W simulations and the mean individual PAHs contents in ng g^{-1} of dry peats from the three landslides investigated. The totals of these individual PAHs are presented in Chapter 4 for the landslides.

Table B. 1. Tensile strength (kPa) of peat samples from the three landslides

Site	Depth (m below ground level)	Number of samples	Range	Mean	Standard deviation
ST	0.01 (Surface)	8	2.4 -5.3	3.8	1.0
	0.89 (Middle)	6	1.0 -2.6	1.9	0.7
	1.80 (Base)	16	0.04-2.4	1.3	0.7
SR	1.64 (Base)	10	0.08-2.4	1.0	0.8
SA	1.78 (Base)	14	0.04-16.0	4.0	2.1

Table B. 2. SLOPE/W model input parameters for the three landslides.

Landslide	Stratum	Unit Weight ($kN\ m^{-3}$)	Parameters	Direct shear	Triaxial	Tensile strength
Straduff Townland landslide	1	10[a]	*Friction angle, Φ (degrees)*	21[b]	n/a	n/a
			Cohesion, c(kPa)	2[b]	1.4[c]	5[a]
	2	10[a]	*Friction angle, Φ (degrees)*	15	n/a	n/a
			Cohesion, c(kPa)	1	1.4[c]	3[a]
	3	11[a]	*Friction angle, Φ (degrees)*	10	n/a	n/a
			Cohesion, c(kPa)	1	0.8	0.7

[a] From laboratory measurements, [b] Minimum value from the literature (Table 2. 10) , [c] Lowest values from Jennings (2005) for peat less than 1.5 m below ground level (Table 2. 10)

Landslide	Stratum	Unit Weight ($kN\ m^{-3}$)	Parameters	Direct shear	Triaxial	Tensile strength
Slieve Rushen landslide	1	10[a]	*Friction angle, Φ (degrees)*	21[b]	n/a	n/a
			Cohesion, c(kPa)	2[b]	1.4[c]	3.8[d]
	2	10	*Friction angle, Φ (degrees)*	21[b]	n/a	n/a
			Cohesion, c(kPa)	2[b]	1.4[c]	1.9[d]
	3	10	*Friction angle, Φ (degrees)*	14	n/a	n/a
			Cohesion, c(kPa)	1	1.3	1
Slieve Anierin landslide	1	10[a]	*Friction angle, Φ (degrees)*	21[b]	n/a	n/a
			Cohesion, c(kPa)	2[b]	1.4[c]	3.8[d]
	2	10	*Friction angle, Φ (degrees)*	21[b]	n/a	n/a
			Cohesion, c(kPa)	2[b]	1.4[c]	1.9[d]
	3	10	*Friction angle, Φ (degrees)*	15	n/a	n/a
			Cohesion, c(kPa)	1.4	1.5	1.4

[a & d] Average values from laboratory measurement of peat samples from the Straduff Townland landslide, and [b& c] Minimum values from the literature (Table 2. 10)

Note Peat profile statigraphic zone observed in the field (this study). n/a = Not applicable

Table B. 3. Hydrocarbon contents of dry basal peat at the three landslides.

Site	Hydrocarbons	Number of samples	Range	Mean	Standard deviation
ST	Bitumen (%)	20	0.4 - 12.5	6.4	2.9
	Total TPHs [1]($mg\ g^{-1}$)	20	3.6 - 38.2	16.1	8.2
	Total PAHs [2]($ng\ g^{-1}$)	20	40.0 - 43.7	41.2	0.7
SR	Bitumen (%)	23	3.2 - 20.0	7.5	3.9
	Total TPHs [1]($mg\ g^{-1}$)	23	1.5 -184.0	64.0	72.0
	Total PAHs [2]($ng\ g^{-1}$)	23	41.0 - 41.5	41.1	0.1
SA	Bitumen (%)	23	3.2 - 15.0	7.0	2.7
	Total TPHs [1]($mg\ g^{-1}$)	23	1.5- 26.5	10.5	6.3
	Total PAHs [2]($ng\ g^{-1}$)	23	41.0 - 41.5	41.1	0.1

Notes

[1] TPHs= Total Petroleum Hydrocarbons (carbon ranges n-C_{10}-C_{40}; mostly n-C_{21}-C_{36}),

[2] PAHs = Total of 18 Poly Aromatic hydrocarbons investigated

ST= Straduff Townland landslide, SR= Slieve Rushen and SA= Slieve Anierin

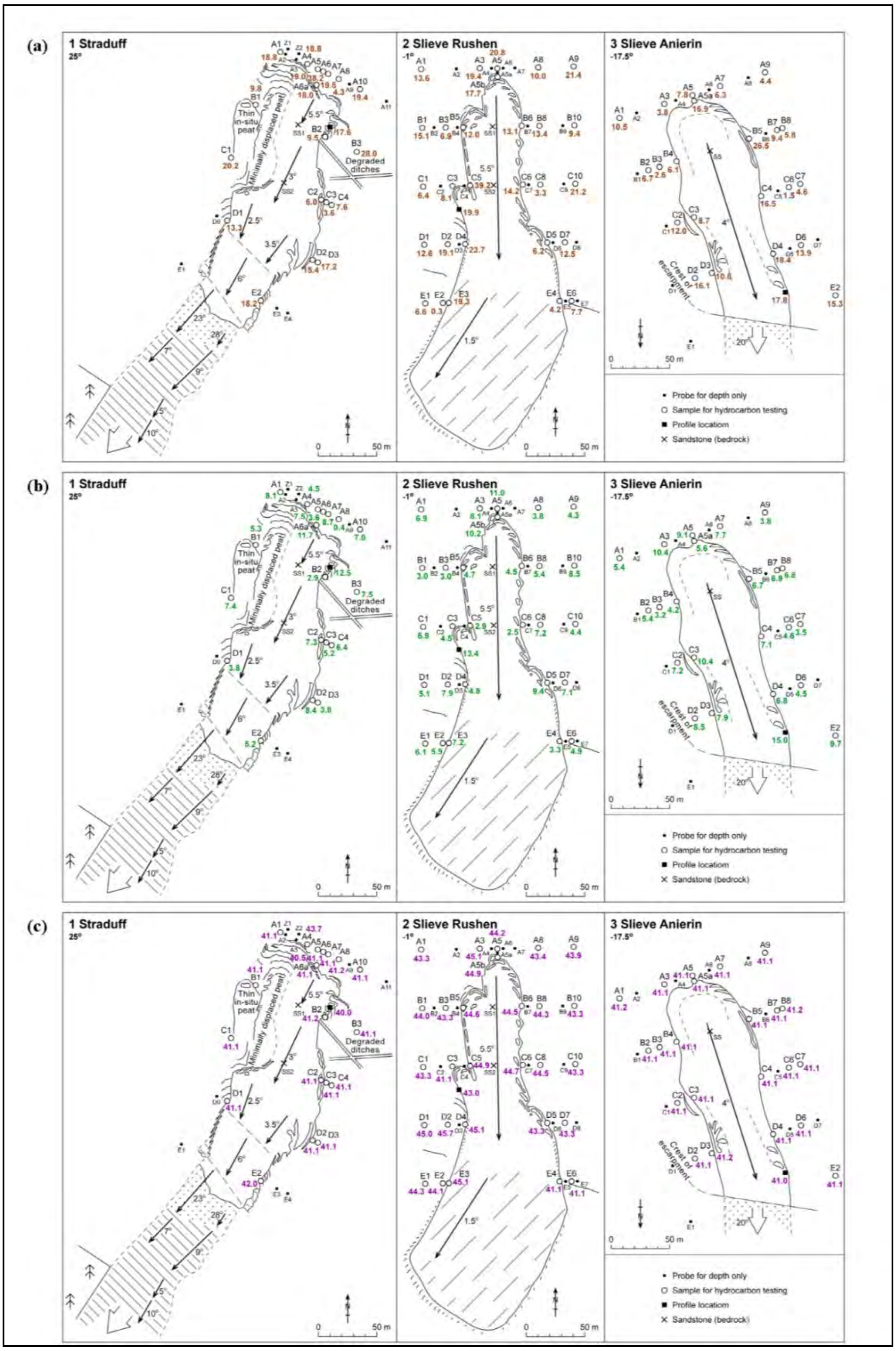

Figure B. 1. Spatial distribution of hydrocarbons in the basal peat at the three landslides (map from Dykes, 2009): (a) TPHs contents (brown numbers, mg g^{-1} dry peat); (b) PAHs contents (purple numbers, ng g^{-1} dry peat); and (c) bitumen contents (green numbers, % dry peat).

Table B. 4. Mean aliphatic and aromatic hydrocarbon contents (ng g^{-1}) in bitumen extracts from basal peat at the three landslides.

Site	**Hydrocarbon bandings**	**Number of samples**	**Average (ng g^{-1})**	
			Aliphatic	**Aromatic**
ST	C_{10}-C_{18}	8	41.8 ± 22.0	63.9 ± 45.3
	>C_{18}-C_{36}	8	335.9 ± 246.0	153.7 ± 50.4
	>C_{36}-C_{44+}	8	163.9 ± 131.0	115.5 ± 75.4
	Total (C_{10}-C_{44+})	8	238.1 ± 184.0	124.2 ± 48.3
SR	C_{10}-C_{18}	5	68.1 ±71.7	30.0 ± 1.1
	>C_{18}-C_{36}	5	216.8 ± 33.5	65.9 ± 27.6
	>C_{36}-C_{44+}	5	108.4 ± 25.5	81.0 ± 48.6
	Total (C_{10}-C_{44+})	5	152.5 ± 25.1	60.9 ± 38.1
SA	C_{10}-C_{18}	6	102.8 ± 57.6	63.4 ± 62.7
	>C_{18}-C_{36}	6	285.4 ± 170.2	94.1 ± 86.9
	>C_{36}-C_{44+}	6	121.7 ± 70.0	95.6 ± 87.7
	Total (C_{10}-C_{44+})	6	195.6 ± 123.5	81.2 ± 72.5

ST = Straduff Townland, SR = Slieve Rushen and SA = Slieve Anierin

Table B. 5. Mean individual PAHs contents in ng g^{-1} of dry peat from the Straduff Townland landslide.

Compounds	A1	A4	A5	A6	A6(a)	A7	A8	A10	B1	B2	B3	C1	C2	C3	C4	D1	D2	D3	Sampling point	Mean
Naphthalene	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Acenaphthylene	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Acenaphthene	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Fluorene	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Phenanthrene	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Anthracene	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Fluoranthene	0.3	0.6	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Pyrene	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Benz[a]anthracene	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1
Chrysene	2.7	3.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
Benzo[b]fluoranthene	0.2	0.6	0.2	0.2	0.2	0.2	0.3	0.2	0.2	0.4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3
Benzo[k]fluoranthene	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
Benzo[a]pyrene	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2
Benzo[e]pyrene	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
Perylene	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
Indeno(1,2,3-cd)pyrene	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.1	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2
Dibenz(a,h)anthracene	8.3	8.3	8.2	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3
Benzo[ghi]perylene	8.5	9.4	8.0	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
TOTAL (ng g^{-1})	41.1	43.7	40.5	41.1	41.1	41.1	41.2	41.1	41.1	41.2	41.1	41.1	41.2	41.1	41.1	41.1	41.1	41.1	41.1	41.2

Table B. 6. Mean individual PAHs contents in ng g^{-1} of dry peat from the Slieve Rushen landslide.

Compounds	**A1**	**A4**	**A5**	**A6**	**A6(a)**	**A7**	**A8**	**A10**	**B1**	**B2**	**B3**	**C1**	**C2**	**C3**	**C4**	**D1**	**D2**	**D3**	**Sampling point**	**Mean**
Naphthalene	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Acenaphthylene	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Acenaphthene	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Fluorene	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Phenanthrene	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Anthracene	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Fluoranthene	0.3	0.6	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Pyrene	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Benz[a]anthracene	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1
Chrysene	2.7	3.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
Benzo[b]fluoranthene	0.2	0.6	0.2	0.2	0.2	0.2	0.3	0.2	0.2	0.4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3
Benzo[k]fluoranthene	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
Benzo[a]pyrene	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2
Benzo[e]pyrene	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
Perylene	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
Indeno(1,2,3-cd)pyrene	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.1	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2
Dibenz(a,h)anthracene	8.3	8.3	8.2	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3
Benzo[ghi]perylene	8.5	9.4	8.0	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
TOTAL (ng g^{-1})	41.1	43.7	40.5	41.1	41.1	41.1	41.2	41.1	41.1	41.2	41.1	41.1	41.2	41.1	41.1	41.1	41.1	41.1	41.1	41.2

Table B. 7. Mean individual PAHs contents in ng g^{-1} of dry peat from the Slieve Anierin landslide.

Compounds	A1	A4	A5	A6	A6(a)	A7	A8	A10	B1	B2	B3	C1	C2	C3	C4	D1	D2	D3	Sampling point	Mean
Naphthalene	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Acenaphthylene	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Acenaphthene	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Fluorene	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Phenanthrene	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Anthracene	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Fluoranthene	0.3	0.6	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Pyrene	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Benz[a]anthracene	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1
Chrysene	2.7	3.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
Benzo[b]fluoranthene	0.2	0.6	0.2	0.2	0.2	0.2	0.3	0.2	0.2	0.4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3
Benzo[k]fluoranthene	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
Benzo[a]pyrene	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2
Benzo[e]pyrene	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
Perylene	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
Indeno(1,2,3-cd)pyrene	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.1	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2
Dibenz(a,h)anthracene	8.3	8.3	8.2	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3
Benzo[ghi]perylene	8.5	9.4	8.0	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
TOTAL (ng g^{-1})	41.1	43.7	40.5	41.1	41.1	41.1	41.2	41.1	41.1	41.2	41.1	41.1	41.2	41.1	41.1	41.1	41.1	41.1	41.1	41.2

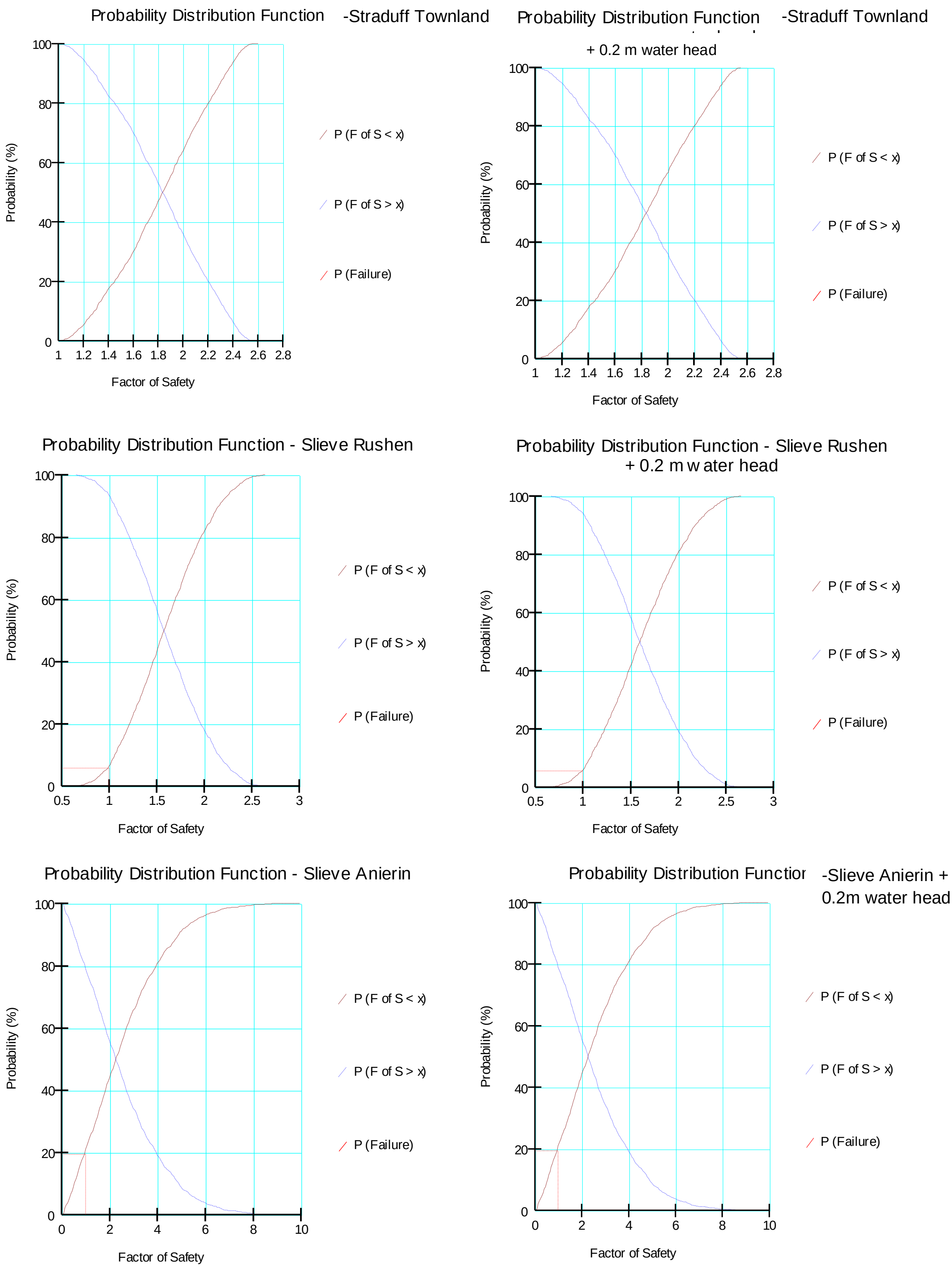

Figure B. 2. Probabilistic (P) slope/W simulations output graphs.