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Original Article

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Hazards from lakes and reservoirs: new interpretation of the Vaiont disaster

Alan P. DYKES* https://orcid.org/0000-0003-0327-0498; e-mail: a.p.dykes@kingston.ac.uk
Edward N. BROMHEAD e-mail: edward@bromheadconsulting.com

**Corresponding author*

Centre for Engineering, Environment and Society Research, School of Engineering and the Environment, Kingston University, Penrhyn Road, Kingston upon Thames, KT1 2EE, UK

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Abstract: Hazards in reservoirs and lakes arising from subaerial landslides causing impact waves (or 'lake tsunamis') are now well known, with several recent examples having been investigated in detail. The potential scale of such hazards was not widely known at the time of the Vaiont dam project in the 1950s and early 1960s, although a small wave triggered by a landslide at another new reservoir nearby in the Dolomites (northern Italy) drew the possible hazard to the attention of the Vaiont project's managers. The Vaiont disaster in 1963 arose from a combination of disparate and seemingly unrelated factors and circumstances that led to an occurrence that could not have been imagined at that time. The ultimate cause was a very large landslide moving very rapidly into a reservoir and displacing the water. The resulting wave overtopped the dam to a height of around 175 m and around 2000 people were killed. This paper identifies and examines all of the issues surrounding the Vaiont dam and landslide in order to identify causal factors, contributory factors (including aggravating factors) and underlying factors. In doing so, it demonstrates that the disaster arose from the Vaiont dam project and cannot be attributed simply to the landslide. Underlying geological factors gave rise to the high speed of the landslide, which would have occurred anyway at some time. However, without the contributory factors that account for the presence of the reservoir, i.e. the choice of location for the project and management of the project with respect to a possible landslide hazard, there would have been no disaster. Indeed, the disaster could have been avoided if the reservoir could have been emptied pending further ground investigations. Understanding of this case provides many lessons for future dam projects in mountainous locations but also highlights an ongoing and perhaps under-appreciated risk from similar events involving other water bodies including geologically recent lakes formed behind natural landslide dams.

Keywords: Vaiont landslide; Impulse wave; Lake tsunami; Dam project; Causal factors for disaster

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1 Introduction

Mountainous regions are susceptible to frequent and often very large mass movements. Whilst these mass movements constitute hazards in their own right, there are potentially much greater associated hazards. A major landslide can block a river valley, forming a natural dam and creating a lake such as at Attabad in Pakistan in 2010 (Hayat et al. 2010). Notwithstanding the direct impacts of the landslide, two associated hazards then exist. Firstly, the landslide dam could fail in a catastrophic manner that results in potentially devastating downstream flooding (Chen et al. 2017). Secondly, a subsequent landslide into the lake could cause an impact wave capable of destroying buildings and infrastructure around the lake shore, as occurred at Alleghe, Italy, in 1771, and possibly also downstream if it overtops the landslide dam (whether or not the dam fails consequentially). At Alleghe, which is just 29 km northwest of Vaiont in the Dolomites of northwest Italy (Fig. 1), a large rockslide on 11 January 1771 created a landslide dam and lake (Eisbacher and Clague 1984; Coppola and Bromhead 2008; Dykes et al. 2013), then a smaller landslide on 1 May 1771 generated at least one wave in the lake that rose towards Alleghe village and destroyed 'the rectory, part of the church and a number of houses' (COTAC n.d.).

Constructed dams in mountain valleys, such as those for the rapidly increasing frequency of hydro-electric projects globally, mirror these scenarios. Failure and collapse of a dam results in downstream flooding, as observed many times including the Gleno Dam, Italy in 1923 with a death toll of up to around 600 (Luino et al. 2014) and Malpasset, France, which cased over 400 fatalities in 1959 (Duffaut and Larouzée 2019) at which time the Vaiont dam was nearing completion in northern Italy. Furthermore, a landslide entering a reservoir, or indeed any other lake of any origin, has the same potential to generate an impulse wave – commonly described as a 'lake tsunami' (or simply 'tsunami') in the literature – that can be similarly destructive. This is what happened at Vaiont. With 13,000 hydropower stations identified in 150 countries and the installed capacity growth rate expected to increase to address climate change concerns (IHA 2021), the global probability of another lake tsunami will necessarily increase. Understanding what happened at Vaiont continues to be relevant for minimising this growing hazard and may help with future management of the ongoing hazard associated with natural lakes, fjords and other large water bodies.

Tsunami hazards in lakes and fiords arising from subaerial landslides have received increasing attention in recent years: (i) major historical events are being re-analysed using the latest modelling and/or field geophysical and other techniques (e.g. Franco et al. 2020; Waldmann et al. 2021); (ii) evidence of previously unknown historical and pre-historical events continues to be found and assessed, such as in Swiss lakes (e.g. Spinney 2014; Strupler et al. 2020); and (iii) recent events such as at Chehalis Lake, Canada in 2007 (Wang et al. 2015) and Lake Askja, Iceland in 2014 (Gylfadóttir et al. 2017) can be investigated almost immediately. In addition to some factors not relevant to the Vaiont case, the height of an impulse wave depends strongly on the balance between the angle and velocity of impact of a large rockslide entering a lake, with the width of the sliding mass being a highly significant factor (Strupler et al. 2020). If the volume of the landslide is very large compared with the volume of water in the lake, high waves can be generated even from shallow water and may exceed the breaking-wave height threshold if the travel distance to an opposite shore is short (Freunt et al. 2007). The runup height is significantly

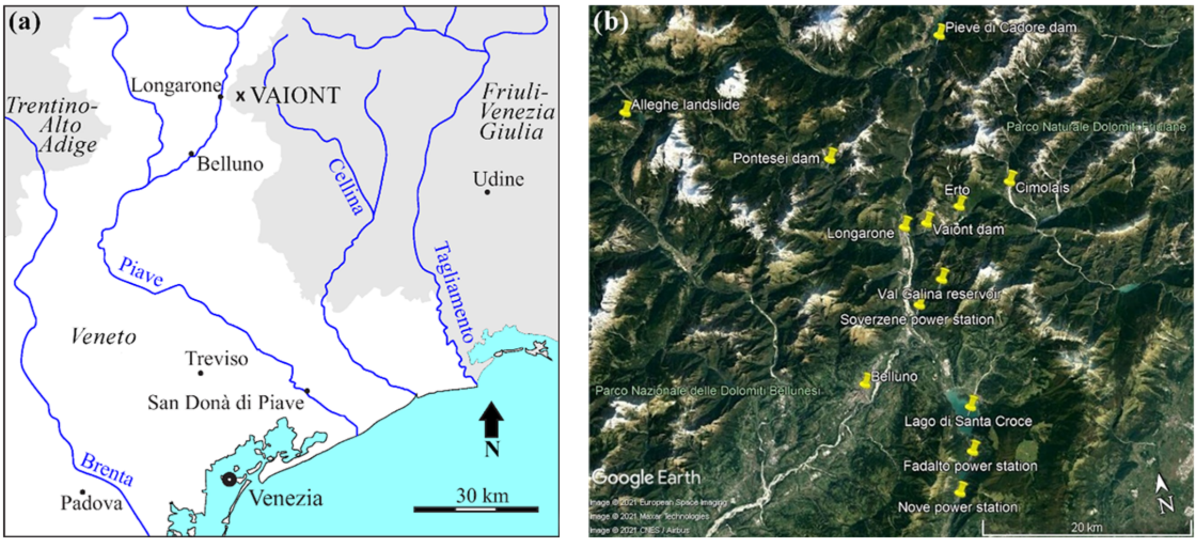

Fig. 1 (a) Location of Longarone and the Vaiont landslide north of Venice (Venezia) in northern Italy. (b) Indicative locations of relevant sites near Longarone and the Vaiont dam that are mentioned in the text. Source: Google Earth (Image European Space Imaging; Image CNES/Airbus; Image Maxar Technologies; (c) 2021 Google).

determined by the wave height and the topography beyond the shoreline impacted by the wave. Only three cases of runup >200 m higher than the original water level are known (Weiss et al. 2009): (i) the 1958 Lituya Bay rockslide-debris flow (~30 million m^3) triggered a 'mega-tsunami' with a 524 m runup on the opposite side of this Alaskan fiord (Schwaiger and Higman 2007; Weiss et al. 2009; Franco et al. 2020); (ii) the 1980 multiple rotational landslide (~2.3 km^3) that initiated the eruption of Mount St Helens in Washington State caused an impulse wave in Spirit Lake with a runup of around 260 m (Voight et al. 1983); and (iii) the 1963 Vaiont rockslide.

The Vaiont disaster was a tragic consequence of an ambitious infrastructure project in an apparently ideal mountainous location but where a particular combination of circumstances developed that could not have reasonably been foreseen at that time. The Vaiont Dam Project involved construction of a dam and reservoir that formed part of an integrated hydro-electricity generating network in the Dolomites of northeast Italy. The dam is located at 46°16'02"N, 12°19'45"E (Fig. 1a). The disaster resulted from mass failure of a mountain slope adjacent to the newly created reservoir, which caused an impulse wave up to 250 m high. Part of the wave spilled over the dam and destroyed the town of Longarone (Fig. 2). Around 2000 people died. Many previous publications about Vaiont attribute the disaster to the landslide, probably simply for brevity but nevertheless this is misleading. The hypothesis of this paper is that the Vaiont disaster was not simply due to the landslide but arose entirely because of the Vaiont Dam Project. The landslide was only one component in a complex interrelationship of disparate factors, circumstances and events – including, for example, design and operating principles of storage reservoirs for hydropower, the death of a project manager, rainfall, regional economic development and even a prediction of a large landslide based on incorrect interpretations of uncertain and inadequate geological information (Dykes and Bromhead 2018a).

This paper is not intended to be a detailed technical analysis of the underlying science of the Vaiont landslide. Neither is it a paper about what happened. It is, however, a new look at the circumstances leading to the disaster incorporating a new understanding of the landslide, from which we identify (i) key causal, contributory and underlying factors and (ii) missed opportunities to prevent a disaster. We also consider the problem from two perspectives: the state-of-knowledge in the 1950s and early 1960s, and that of a further 50+ years of advancement of relevant knowledge and experience. Where we suggest that things 'should have been done', this is meant to signify measures that could have prevented the disaster, or at least reduced its severity: no implication of failures by individuals is being made or should be interpreted. Detailed timelines of key milestones in the Vaiont project and the landslide investigations can be found elsewhere (e.g. Hendron and Patton 1985, 1986; Semenza 2001, 2010) so we do not repeat this information here. Note that in this paper we distinguish between the 'landslide', the 'dam/reservoir project' and the 'disaster', where the latter refers exclusively to events within a few minutes after the final failure of the mountain slope on 9 October 1963.

2 Background and Context

2.1 General principles of Hydroelectric Power Projects

To understand some of the issues relating to the Vaiont dam project and its management, it is necessary to understand some of the operating principles of dams and reservoirs, and specifically those relating to Hydroelectric Power Projects ('HEPPs'). Firstly, there is the difference between a storage reservoir, and an impounding reservoir. In the former case, the water is brought to the reservoir from a different catchment via a transfer tunnel, and in the latter case, the dam blocks a valley and all the water comes from the normal stream or river flow down that valley. The Vaiont reservoir was a storage reservoir, with its main water source being the very large reservoir impounded by the Pieve di Cadore dam but with some inward transfers also from the Boite-Maé system (Fig. 3). Storage reservoirs normally only require small spillways (if any); at Vaiont this was provided by a weir at the dam crest.

HEPP reservoirs also differ from water supply reservoirs in the way they are operated. Almost all the water in a supply reservoir is useful, although water quality diminishes with depth. Because of this, a common practice is to mix water drawn off from different levels so that the combination is still treatable, rather than drawing off the best water from

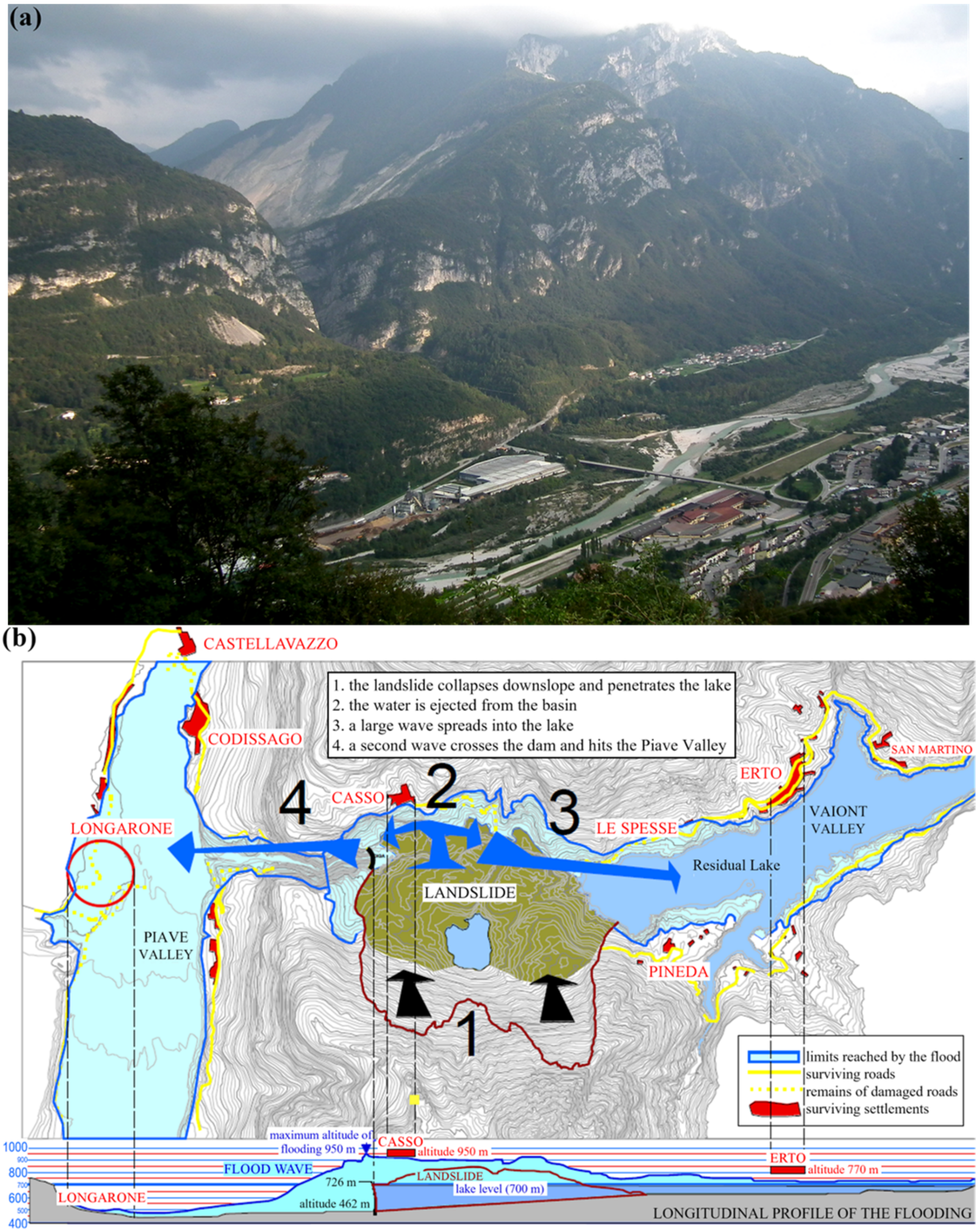

Fig. 2 (a) View from the Vaiont memorial at Podenzoi showing the landslide scar (upper left), the gorge (centre-left) and Longarone (lower right). Photo: APD. (b) Map and longitudinal section showing the extent and height of the displacement wave produced by the landslide. The red circle indicates the location and approximate extent of Longarone before the disaster. Source: Friulian Dolomites Natural Park archive (with permission).

the top of the reservoir and ending up with the bottom of the reservoir where the water may not be treatable at all. In the case of a HEPP storage reservoir, the water in the lower parts of the reservoir may not be useful because when the reservoir empties, the head reduces and so the generating capacity of the hydroelectric plant falls away. This is the case with the Val Galina reservoir, leading to the pre-Vaiont HEPP system being able to operate only for peak demands. The ideal for a HEPP reservoir is to keep it as full as possible at all times: an inability to fill the reservoir completely inhibits much of its usefulness, as is the case at Pontesei (Fig. 1b). If Vaiont could not be operated at its top water level (722.5 m) then a large part of the generating capacity that the design envisaged would not be realised.

In the construction of a storage reservoir like Vaiont that has an element of impounding, it is necessary to create a bypass tunnel while construction proceeds. Such bypasses are rarely suitable for lowering the reservoir level from a nearly full state because they are designed for the average flow of the stream/river: the hydraulic heads and therefore velocities will be too high. Moreover, the ordinary draw-off arrangements (i.e. the entry to the headrace of the generating plant) normally takes water from the upper levels of the reservoir, not least because then the whole system is much more accessible for maintenance. The precise position is determined by the minimum useful hydraulic head for the generating plant. This combination of bypass and draw-off structures makes it very difficult if not impossible to empty an impounding reservoir of the Vaiont type in an emergency. Furthermore, rapid drawdown often creates or worsens instability in the inundated slopes – i.e. it causes landslides.

2.2 Outline of the project

2.2.1 Purpose

The Vaiont dam project was conceived as a key element of an integrated HEPP infrastructure initiated in the early 20th century then intended to underpin post-war expansion of economic activity in the north of Italy. It was to incorporate some pre-war construction which included some power stations around the Lago di Santa Croce that were fed from the big dam at Pieve di Cadore. Fig. 3 summarises the entire scheme, with locations indicated in Fig. 1b. One key element was a steel tube aqueduct all the way from Pieve di Cadore down to Soverzene, which crossed the Vaiont gorge on a bridge downstream of the dam site. The length and diameter of this aqueduct meant that the hydraulic losses were

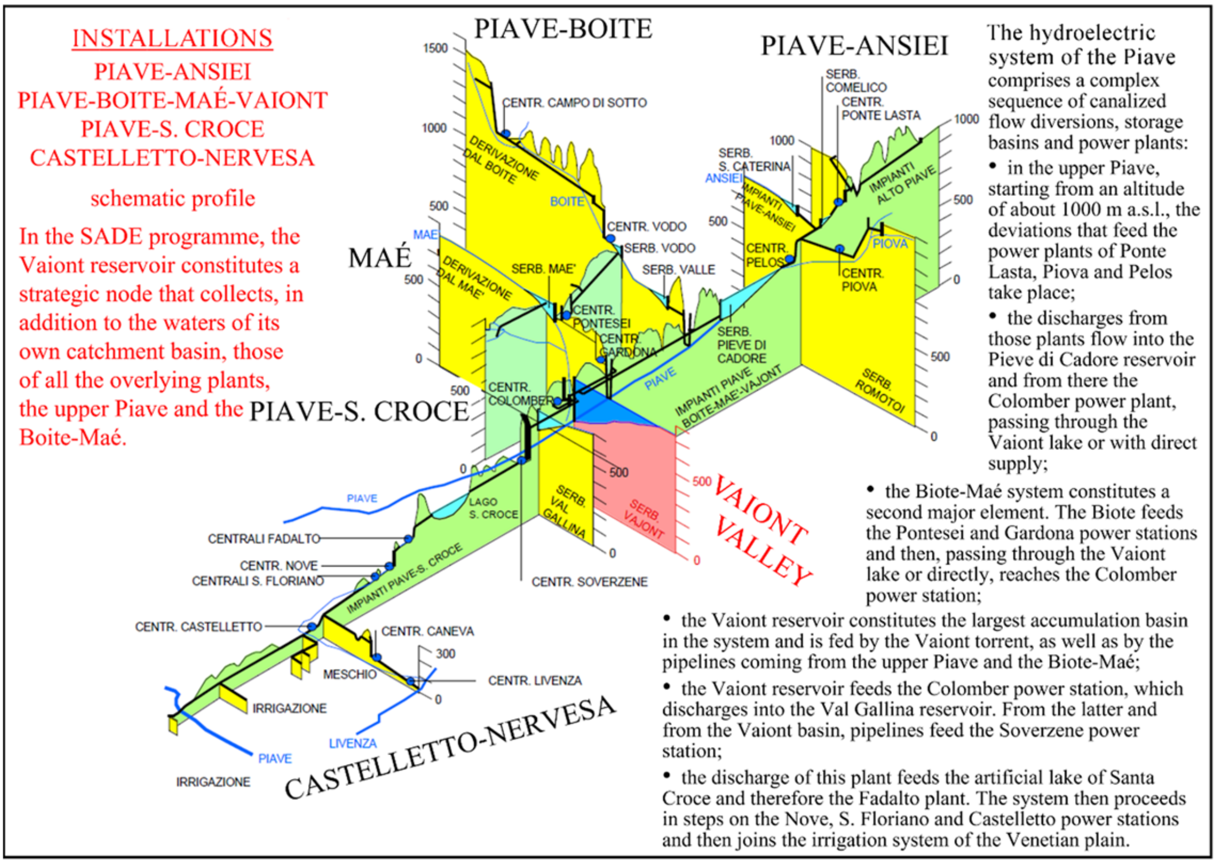

Fig. 3 Diagram showing the various elements of the entire Piave valley hydro-electric project. Source: Friulian Dolomites Natural Park archive (with permission).

Fig. 4 The Vaiont dam in 2010, almost entirely intact and subsequently made open to visitors. The Eiffel Tower is shown to provide an indication of scale for the in-situ view. Photos: APD.

considerable, which limited the power output at Soverzene. This problem was partly ameliorated by the construction of the dam in the Val Galina, the high elevation of which provides additional head to supplement the water coming down the main aqueduct, although this reservoir is too small to be used 24 hours every day (24/7). The purpose of the storage reservoirs at Pontesei and Vaiont was to provide a continuous water supply to the power stations at Soverzene and Fadalto which would then be able to operate 24/7. The key point of the whole scheme is that the entire network of power stations had to operate continuously and not merely to top-up supplies at times of peak demand.

2.2.2 Location of the site

The Vaiont gorge meets the Piave Valley at right-angles opposite the town of Longarone (Fig. 1). The top of the Vaiont dam (Fig. 4) is visible from the commercial centre of Longarone, 250 m lower (40 m above the Piave River) and only 2.1 km downstream (Fig. 5). The older residents of Longarone were concerned about the new dam, probably remembering the collapse of the Gleno Dam in 1923 (174 km WSW from Longarone), while residents of the Vaiont valley and particularly Erto highlighted the known propensity for landslides in the valley that was ignored by project managers for the dam (Barrotta and Montuschi 2018). Initial examinations of the geomorphology of the Vaiont valley by Prof. Giorgio Dal Piaz in 1928 and again in 1958 had identified no concerns about slope stability along either side of the valley (Bozzi et al. 1964, cited in Hendron and Patton 1986) – although these assessments were based on visual observations only. Following these assessments, the focus of geotechnical investigations was the stability of the rock walls of the gorge where the dam was to be constructed. The walls were found to be generally sound although some precautionary ground anchors were inserted on the abutments (WGH (Bill) Hodges, pers. comm. to ENB, c.1968). Careful attention to dam abutments was normal at that time because any dam failure would be catastrophic, but here – 20-30 years before the development of formal risk assessment frameworks – the potential consequences were recognised as being so much worse. Subsequent events showed the apparent confidence in the dam engineering to be fully justified. Conversely, the risk to Longarone from overtopping of

Fig. 5 The left abutment of the dam (indicated by the black arrow) as seen from a hotel breakfast table in Longarone. One bedding plane is highlighted in yellow to show the 'chair'-shaped structure visible in the cliff at the south side of the gorge. Photo: APD.

the dam was never considered.

2.2.3 Suitability of the site

The Vaiont gorge is a very deep and narrow gorge cut down through mostly very strong limestones (Fig. 6). As a result it had near-vertical sides for much of its lowest 200-300 m of vertical depth, particularly where it cut through the broad ridge separating the Piave valley from the Vaiont valley (Fig. 2a). The gorge provided a new post-glacial drainage path for the Erto Basin (Dykes and Bromhead 2018a), an otherwise enclosed topographic basin between the major valleys of the Piave and Cimoliana rivers, and was probably eroded very rapidly by pre-Holocene glacial meltwater (Kiersch 1964; Alonso et al 2010; Wolter et al 2014). The site was therefore characterised by large rock masses still undergoing intense stress relief (Kiersch 1964). However, the gorge was identified as being highly suitable for the dam project. A further reason for the considered suitability of this location was that the valley slopes above the rim of the inner gorge and further upstream from the gorge are sparsely populated and supported little economic activity (Di Sopra 2002). A road climbed up the gorge providing a connection between Longarone and the Cimolais valley via Erto, with side-roads to Casso and other scattered properties along the Vaiont valley. The main road was to be lost to the reservoir with a replacement – mostly the present road – being provided at a higher elevation above the planned final reservoir level.

2.3 Geology of Mt Toc

The geology and geotechnics of large mountain landslides are entwined inextricably and nowhere is this more clear than in the case of the Vaiont landslide of 1963. As the geology of the north side of Monte Toc has been described innumerable times, including in particular Semenza (1965), Müller (1968), Hendron and Patton (1985), Bistacchi et al. (2013), Massironi et al. (2013) and in the Open Access papers by Dykes and Bromhead (2018a,b), only a short summary is provided here.

The north face of Monte Toc is formed from limestones with occasional thin beds of clay (Table 1). It has been fairly conclusively demonstrated that most of the Vaiont landslide slid along one or more of these clay beds (Hendron and Patton 1985; Petronio et al. 2016), so that its occurrence was in part due to the

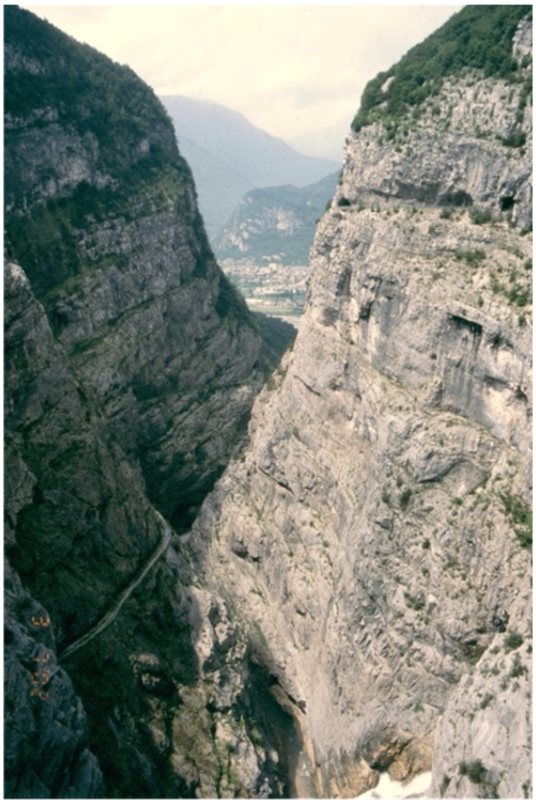

Fig. 6 View down the Vaiont gorge from the top of the dam. The stream is at the bottom-centre of this view. Photo: ENB.

stratigraphic succession. Equally importantly, the shape of the slip surface in both plan and section was determined by the bowl-shape into which the beds had been folded, thus demonstrating the importance of the structural geology and tectonic history (Bistacchi et al. 2013; Massironi et al. 2013). Initial NE-SW compression formed the regional Erto Syncline, which provided the concave form of the slip surface in cross-section, with later NW-SE compression creating the steeply-plunging Massalezza Syncline with its axis largely coinciding with the Massalezza Ditch down the middle of the eventual landslide area (Fig. 10a). While there was some minor folding and faulting, particularly in the form of complex interference patterns between the folding of the two synclines as well as other small-scale tectonic structures (Fig. 7), these effects had only a secondary influence on the morphology of the landslide mass as a whole. However, their influence was possibly more important in determining the sequence of events, most notably the failure of the upper east side which followed a short time after the main landslide (Semenza 1965, 2001, 2010; Wolter et

Table 1 Indicative stratigraphy of the left (south) side of the Vaiont valley, after Bistacchi et al. (2013) and Ghirotti et al. (2013). 'Layered' implies thinly bedded. Most of the failure occurred at, or slightly above, the boundary between the two units of the Fonzaso Formation (Petronio et al. 2016).

Age	Stratigraphic name	Thickness (m)	Description
Cretaceous	Calcare di Soccher ('Soccher Limestone') or Biancone Formation	150+	Layered marly and cherty limestones
			Massive grey, red or greenish marly limestones
Upper Jurassic (Tithonian-Oxfordian)	Rosso Ammonitico	0-15	Fossiliferous nodular micritic limestone
Upper Jurassic (Oxfordian-Callovian)	Fonzaso Formation	10-40	Layered cherty micritic limestones with intercalated green clay layers ~5-180 mm thick
			Layered cherty micritic limestone
Middle Jurassic (Dogger)	Vajont Limestone	350-450	Massive resedimented oolitic limestone

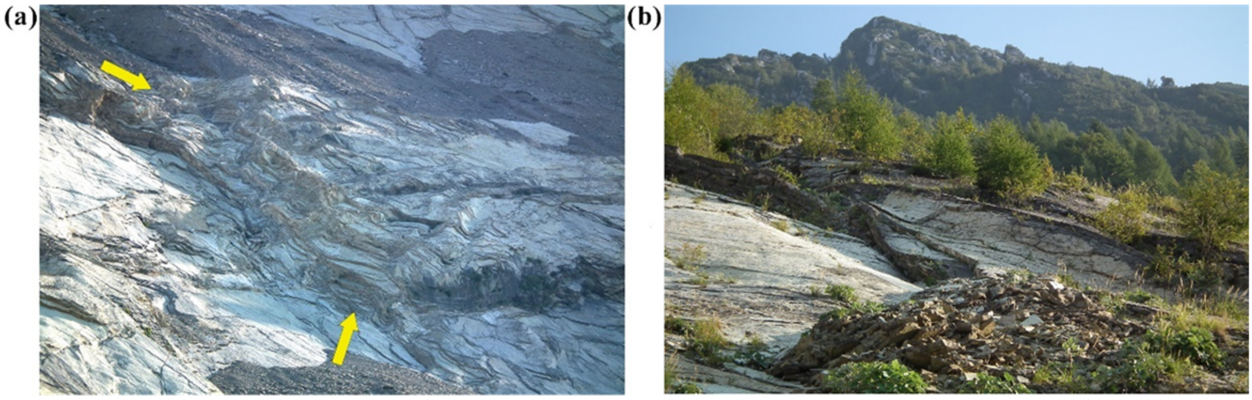

Fig. 7 (a) Interference patterns in the bedding structures high in the western part of the East side failure surface. The distance between the yellow arrows is approximately 35 m. (b) Fold and ramp structures high in the eastern part of the East side failure surface. The trees in the centre are around 5 m tall. Photos: APD.

al. 2016) but also some retrogression of the upper west side the following day (evidenced from photos in the Visitors Center of Erto e Casso in Erto village).

It was long believed that the bowl-shape (Broili 1967) had a flat, sub-horizontal base, thus appearing in cross section to be akin to a chair with a flat seat and a reclined back (Semenza 1965). This was largely because such a form is clearly visible in the cliffs that form the valley side of the Piave just south of the confluence of the main river with the Vaiont Gorge (Fig. 5). Later and better interpretations of the structure, notably by Bistacchi et al. (2013), showed that the sub-horizontal 'seat' was actually significantly inclined downwards towards the gorge: its assumed form had been largely an artifact of poor core recovery in early borehole investigations (Hendron and Patton 1985) and E. Semenza's interpretation of the resulting absence of evidence of a pre-existing shear surface or zone. It now appears that this shear surface did not exist prior to 1963. The 'chair' shape lent indirect support to the hypothesis that the landslide was a reactivation of an earlier slide, because when back-analysed (i.e. analysed to show the shear strength operative at failure) the flat 'seat' causes a low strength to be obtained (Boon 2014). However, when back-analysed with the more correct shape established by Bistacchi et al. (2013), a higher strength is obtained (Dykes and Bromhead 2018b, 2021).

At this point, the hydrology of the slope comes into play. At the time of the final failure, there were no measurements of groundwater levels and a range of shear strengths can be obtained simply by making a range of assumptions. If it is assumed that groundwater pressures are entirely absent, then the lowest strength required for equilibrium is produced. Following this approach in a 3D analysis with unit weight γ = 23 kN m^{-3} gives a friction angle for the clay layers ϕ' = 25°. This demonstrates that the clay beds were certainly not pre-sheared (i.e. $\phi' = \phi'_{peak}$), and by implication, the whole Vaiont landslide could not, therefore, have been a pre-existing landslide (Dykes and Bromhead 2018b). Instead it now appears to have comprised – largely if not entirely – an intact rock mass that had been deformed by tectonics but was most unlikely to have been a pre-existing landslide body. Furthermore, this best-case dry condition gives a 3D Factor of Safety (FS) < 1.03, i.e. effectively indistinguishable from 1.0. In reality there would probably have been some water within the landslide mass even before any submergence by the reservoir, so the available FS would have been slightly lower than this.

Semenza (2001, 2010) had identified an 'upper aquifer' and a 'lower aquifer' within the mountain slope, with water pouring from springs indicating significant macropore flows. Hendron and Patton (1985) also reported solution cavities indicating a high overall permeability below the landslide body. Dykes and Bromhead (2018a) then showed that the failure surface defined by Bistacchi et al. (2013) was probably never subjected to artesian pressures but was instead underdrained (Fig. 8), so that the 'upper aquifer' corresponded with a transient rainwater-fed perched water table on top of the clay beds in the Fonzaso Formation and the 'lower aquifer' was controlled by free drainage of the Vaiont Limestone into the gorge. The perched water table therefore imposed elevated pore water pressures on the clay beds which, in combination with the dip of those beds towards the gorge throughout the slope, led to the initiation of a progressive failure mechanism – possibly brittle microcracking as suggested by Kilburn and Petley (2003) – that may have pre-dated the Vaiont dam project by a very long time (Dykes and Bromhead 2021).

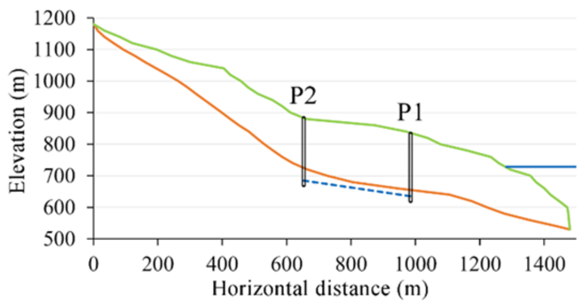

Fig. 8 Cross-section through the western side of the landslide that includes piezometers P1 and P2. Water levels recorded around November 1961 (Müller 1964) are indicated by the 'lower aquifer' (Semenza 2001, 2010) water table (broken blue line) between the piezometers. The design top water level of the reservoir (722.5 m) is shown. From Dykes and Bromhead (2018a).

In summary, therefore, the northern slope of Mt Toc comprised gently bowl-shaped bedding, dipping towards the gorge throughout, comprising mostly limestones but with thin clay interbeds at depths of up to 200 m in places. The clay layers constituted adversely sloping impermeable planes of weakness, unsupported at the toe following erosion of the gorge and susceptible to high pore water pressures arising from a rainwater-fed perched aquifer. Even if completely dry, the slope was only marginally stable prior to commencement of the Vaiont dam project. The high permeability of the limestones allowed rapid saturation by reservoir water as external water levels rose, leading to extended periods of raised joint water pressures in the limestones and corresponding pore water pressures within the clay beds across the lowest part of the failure surface compared with normally rapid drainage of the limestones following rainfall prior to inundation.

3 Management of the Project

3.1 Overview

In March 1959, while the Vaiont dam was still being built, a landslide occurred in the newly-impounded reservoir at Pontesei, a few km NW from Longarone (Fig. 1) that generated a small wave that killed a person. It proved impossible to fill Pontesei reservoir subsequently because of the risk of reactivating a further landslide near the dam. These issues led the Vaiont project manager, Carlo Semenza, to employ relevant experts to assess the risk of similar problems at his site. In addition to Prof. Dal Piaz, Austrian rock mechanics engineer Prof. Leopold Müller was brought in to advise. Müller then charged C. Semenza's son, Edoardo Semenza, a recently graduated geologist, and another young geologist Dr Franco Guidici, with a series of geological field studies. Initial investigation of the site led E. Semenza to suggest that the northern slope of Mt Toc contained a large ancient landslide that could be reactivated. Müller initially dismissed this interpretation (although he had, in August 1957, first identified the possibility of some unstable masses along the left side of the Vaiont valley) – but C. Semenza kept an open mind. This dismissal and E. Semenza's subsequent indignation when the landslide happened combined to persuade people that he had been right in every respect, leading to the scientific consensus on the landslide that still largely holds (e.g. Zaniboni and Tinti 2018) but which has recently been shown to be probably incorrect (Dykes and Bromhead 2018a).

Carlo Semenza died in October 1961 and management passed to Engineer N. A. Biadene, who had worked on the Vaiont project throughout. The loss of C. Semenza led to a critical loss of dialogue regarding the landslide problem, and neither E. Semenza nor Müller had any further communication with the Project Director (Hendron and Patton 2010). Then in March 1963, before the third and final phase of filling the Vaiont reservoir started, the entire hydropower scheme that has been developed by SADE (Società Adriatica di Elettricità) (Fig. 3) was included in the nationalisation of Italy's electricity generating industry. This transfer of the project to ENEL (the nationalised electricity industry) resulted in a new corporate structure that seems to have been initially ineffective, leaving Biadene to take all relevant decisions alone (Semenza 2001, 2010). The implication seems to have been that the new management did not understand the nature, context and potential severity of the problem and so left Biadene to take the full responsibility for every aspect of it, although we can only report what the person closest to the event had to say about this (Semenza 2010, p.160): 'Biadene had been a convinced advocate of the law for the nationalization of the electric companies. Then he realized that the new ENEL management did not have, at least at that time, a managerial capacity comparable to that of SADE.'

3.2 Management responses to landslide investigations

Many of the geological factors that predisposed the slope to failure were either not known or not understood prior to the 1963 landslide despite the unusual fact of some relevant data having been obtained during the preceding four years. Alongside the geological fieldwork undertaken by E. Semenza and Guidici, seismic surveys by Prof. P. Caloi found solid, apparently 'in situ rock' in November 1959 but (including some new traverses) 'heavily fractured, loose rock' to significant depth in December 1960 (Caloi 1966; Belloni and Stefani 1992). Between Caloi's surveys, a network of survey markers were installed on the lower western slope from which measurements of ground movements began in May 1960, with more markers being added higher up the slopes later and measurements continuing until the final failure. The observation that movements of the landslide stopped when the reservoir water level was lowered, which occurred twice at successively higher levels (Fig. 9), led to the mistaken belief by the project and company managers that movements could be controlled similarly thereafter – although in fact the drawdown periods coincided with slope drainage following periods of high rainfall. Other investigations were also commissioned by C. Semenza:

(i) Three boreholes, identified as S1, S2 and S3, were drilled in the western part of the landslide (Fig. 10) during summer 1960 but no failure surface was recognised in the cores (ultimately because there was no failure surface to be found because there was no ancient landslide: Dykes and Bromhead 2018a);

(ii) In Spring 1961 a 1:200 concrete scale model

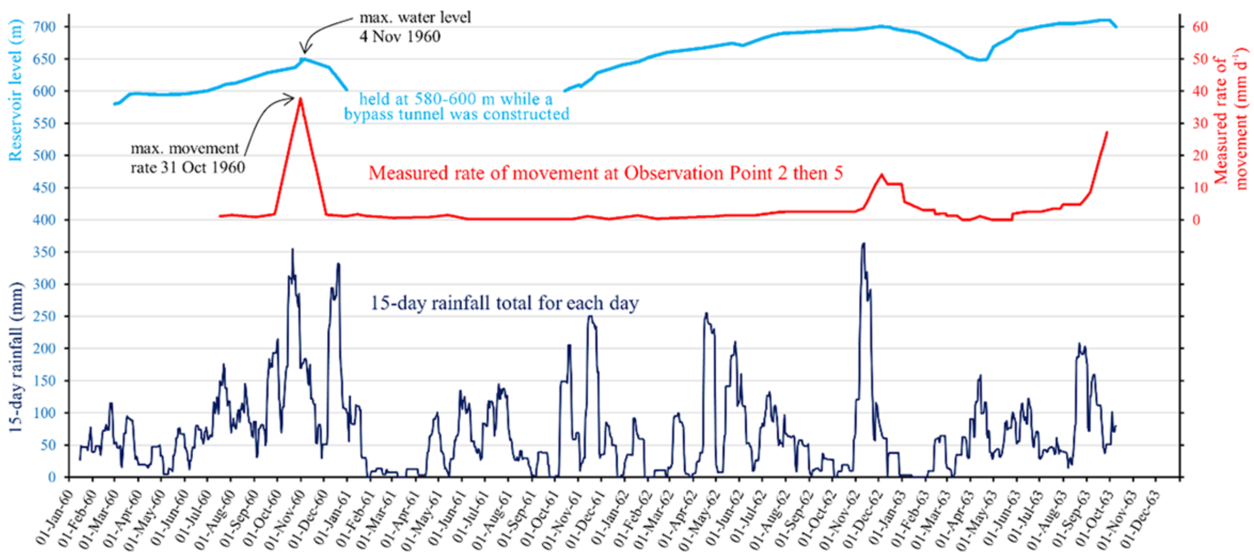

Fig. 9 Composite graph of 15-day rainfall totals at Erto, reservoir water level elevation and movement rates in the lower western part of the developing landslide for the period 15 January 1960 to 9 October 1963 inclusive. From Dykes and Bromhead (2018a) partly after Müller (1964).

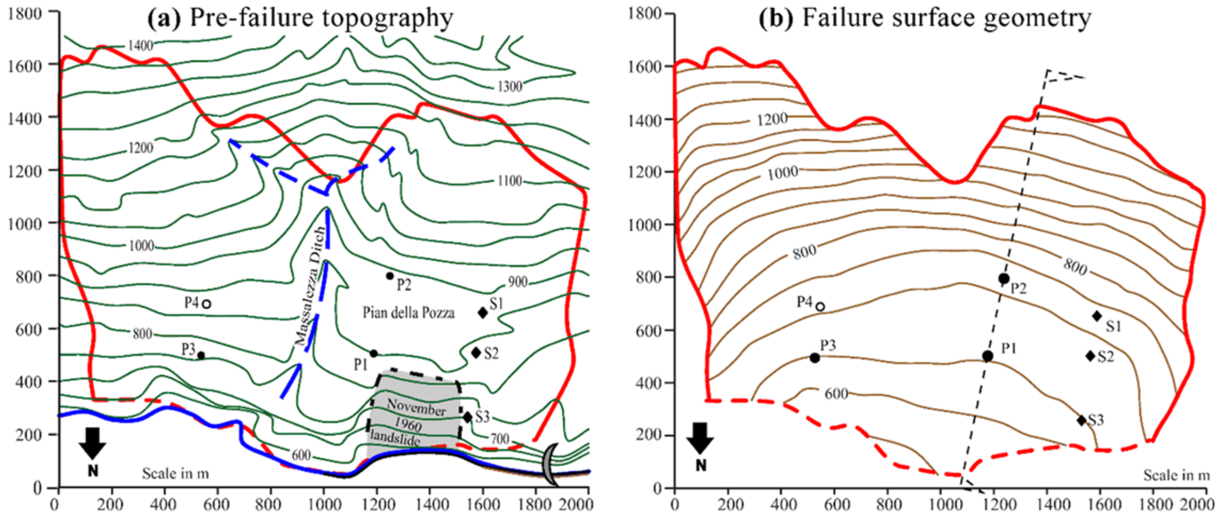

Fig. 10 (a) Map of the unstable slope before failure. The dam is at the lower right corner with the Vaiont River (solid blue line) along the bottom. Dashed blue lines indicate the two tributaries of the Massalezza Ditch. (b) Map of the failure surface according to Bistacchi et al. (2013), showing the line of the cross-section in Fig. 8. The outline of the 1963 landslide is shown by the thick red line (broken red line = outcrop of failure surface along the gorge), contours are at 50 m vertical intervals, P1-P4 are the piezometers (P4 never worked) and S1-S3 are the boreholes. Modified from Dykes and Bromhead (2018a).

of the landslide was constructed at Nove (Fig. 11) and an initial series of experiments were undertaken by Prof. Augusto Ghetti;

(iii) Between July and October 1961, four piezometers were installed in the mountain slope (Fig. 10) although P4 apparently failed almost immediately. An absence of data at P4 (Müller 1964) – assumed to be due to an absence of water – may, however, have been because it was actually seated in the unsaturated zone below the failure surface and not within the landslide mass as assumed at the time (Dykes and Bromhead 2018a). Readings from P2 were entirely misinterpreted because it, too, was seated below the failure surface but within the lower aquifer (Fig. 8).

No further 'geotechnical' investigations were undertaken following C. Semenza's death in October 1961, although Ghetti's experiments on the scale model at Nove continued until April 1962 and SADE then ENEL technicians continued to record reservoir level, piezometric levels in P1, P2 and P3, ground movements and seismic activity from a single apparatus located at the dam, to provide a day-to-day indication of what was happening. However, it seems that no scientific or technical use was made of these data until after the landslide.

3.3 Events of October 1963

The days leading up to the disaster in October 1963 suggest an apparent lack of understanding of the landslide issue beyond the ENEL-SADE management structure immediately concerned with the Vaiont project and the wider Piave Valley scheme, and an absence of higher (e.g. governmental) level of guidance, instruction or other support. A record of the various communications that did arise was compiled by Di Sopra (2002) and is summarised here. Note the further complication that the Vaiont gorge, dam and reservoir area then lay within the pre-1968 province of Udine (Friuli-Venezia Giulia region), administered from Udine, but that Longarone is in the province of Belluno (Veneto region).

Fig. 11 The 1: 200 scale model of the Vaiont landslide at Nove power station in 2013, showing the large sub-horizontal failure surface forming the assumed 'chair' shape. Photo: APD.

With acceleration of the landslide readily apparent to residents of the valley on 6 October, the Municipality of Erto registered a protest about the developing disturbances to the Prefecture of Udine (i.e. the governing authority), who requested an update from the Civil Engineers of Udine (i.e. the relevant technical department). The latter replied next day – without making their own inspections – that 'it is appropriate to remove any concern from the population of Erto'. At the same time, the 'person in charge of the construction site' reported new cracks appearing in the woods to the site manager, based on which ENEL-SADE decided it would be prudent to evacuate the landslide area within the valley.

On 8 October, both ENEL-SADE and the Prefect of Udine independently requested eviction orders from the Mayor of Erto to clear the lower slopes of Mt Toc below 730 m. The 'person in charge of the construction site' took documentary evidence of the accelerating movements to the Civil Engineers of Belluno (CEB), reminding them of the experiments showing a predicted maximum wave height of 20 m [sic] and advising them that lowering the reservoir water level any faster would increase the risk of a landslide. In any case there was little scope for any more rapid lowering at Vaiont because it was a HEPP. In response to the evidence presented, the CEB merely asked for a copy of the telegram to the Mayor of Erto requesting the evacuation. Meanwhile, Biadene inspected the valley around the dam and, on the basis of this and technicians' reports, tried to accelerate the evacuations using ENEL-SADE trucks and the local carabinieri. However, he was 'surprised' that no significant masses of rock or soil were falling along the edges of the lake.

On 9 October, the Municipality of Erto distributed posters advising residents of the danger and that they should leave as directed. The Civil Engineers of Belluno received a further report of 'alarming' acceleration of the landslide, but retained their belief that more than 30 m above the reservoir level should be safe. However, they requested instructions from the Ministry of Public Works (Dams Service). ENEL-SADE continued to seek opinions by telephone from technical and ministerial managers regarding how to respond further. No responses were provided to either organisation. A telephone operator who had heard many of the calls interjected to ask if there was any danger to Longarone and was reassured that there was not.

4 The Disaster

By 1960, what was then the tallest concrete arch dam in the world at 264 m in height (Fig. 2), blocking the lower end of the Vaiont gorge above the town of Longarone, was almost complete and filling of the reservoir had started. In October 1960 a 2 km long M-shaped crack became visible across the northern slope of Mt Toc (which defined much of the outline of the eventual landslide) and in November 1960 a large rockslide (~700,000 m^3) occurred into the half-filled gorge from the steep toeslope a short distance upstream from the dam. The geological investigations and data obtained prior to the final failure of the unstable slope, summarised in this paper, have been extensively reported, analysed and interpreted many times elsewhere (e.g. Müller 1964; Semenza 1965, 2001, 2010; Hendron and Patton 1985, 1986; Dykes and Bromhead 2018a). The disaster that eventually ensued was over within a few minutes of the failure of the last intact limestone beds beneath the NE part of the slope.

At 22.39h on 9 October 1963 the northern slope of Mt Toc failed. Up to 270 million m^3 of rock slid towards the reservoir and a short distance up the opposite slope of the gorge, travelling slightly less than 400 m in possibly as little as 30-45 seconds. The landslide displaced around 170 million m^3 of reservoir water (Franci et al. 2020) that damaged buildings in Casso, more than 200 m higher than the top of the dam, and around 25-30 million m^3 of water overtopped the dam to a depth of 175 m (Fig. 2). The resulting torrent down the gorge, with an estimated flow of 100,000 $m^3 s^{-1}$ (Viparelli and Merla 1968, cited by Franci et al. 2020), then ripped the gravels from the Piave riverbed to create a massive scour hole in what may have been a 50 m thickness of bouldery sediments (E. Semenza, pers. comm. – conversation with ENB c.1993). The force of the gravel-laden torrent then almost entirely erased Longarone (Fig. 3). The town suffered a fatality rate of 94%, one of the highest ever recorded for a dam-related flood event (Mauney 2021); the bodies of many residents were never found.

The displacement of reservoir water produced an impulse wave or tsunami around eight times higher than predicted. There are three types of tsunamigenic scenarios: (i) differential movements of the Earth's crust during earthquakes, (ii) submarine landslides involving fine sediments on relatively gentle slopes

(Løvholt et al. 2015) including lacustrine sediments (Strupler et al. 2020), (iii) large or very large subaerial landslides moving rapidly into bodies of water (Couston et al. 2015) including volcanic sources (e.g. pyroclastic flow and/or flank collapse: Freunt et al. 2007). The Vaiont slide fell into the third category but was entirely different from the other known examples:

(a) It did not involve a large mass of rock and/or debris entering a body of water at speed. Instead a large part of the thickness of the landslide mass was submerged by the reservoir prior to the final failure, so the water was displaced initially very slowly from rest – although the slide mass accelerated rapidly to a maximum velocity of around 20-30 m s^{-1} (Kiersch 1964; Müller 1964; Romero and Molina 1974; Hendron and Patton 1985 (p.8); Kilburn and Petley 2003; Ward and Day 2011; Crosta et al. 2016; Zhao et al. 2016) with displacement of the water likewise increasing rapidly in volume and speed.

(b) The landslide did not displace only some fraction – even a large fraction – of the water from the reservoir, as in all other known lake tsunami events. Instead, for the first 1800 m upstream from the dam it pushed almost all of the water out of the space it had occupied and some distance beyond the position of the opposite shore of the reservoir.

(c) The reservoir had occupied an extremely deep and narrow gorge with a steep mountain slope rising from the gorge opposite from the landslide, i.e. the site was constrained, with no wide floodplain, alluvial fan or similar low-lying topography that could allow the wave to travel and dissipate. Indeed, the leading edge of the landslide mass came to rest on the rising slope above the opposite side of the gorge (Fig. 12a). The wave was probably still growing as it hit the opposite side of the valley to produce the maximum runup of 240 m above pre-failure water level (225 m higher than the dam) just west of Casso village (Fig. 12b).

(d) Of the major controls on wave height identified by Strupler et al. (2020), the slide width at Vaiont (~1800 m) was probably significant, but neither the impact velocity nor the impact angle were relevant as there was no 'impact' (point (a) above).

Fig. 13 View across the top of the dam showing the remains of the road in the foreground (right side of the dam) and the missing parapet wall at the far right of the photo (left side of the dam). Photo: ENB.

The dam was subjected to forces many times greater than those it was designed to resist (2.4 MPa water pressure and up to 5.7 MPa thrust of 'arch' abutments) (Walters 1962). The roadway that was carried above a kind of crest spillway structure and part of the parapet wall was lost (Fig. 13), and the associated works including the small underground power plant and the above ground office building were

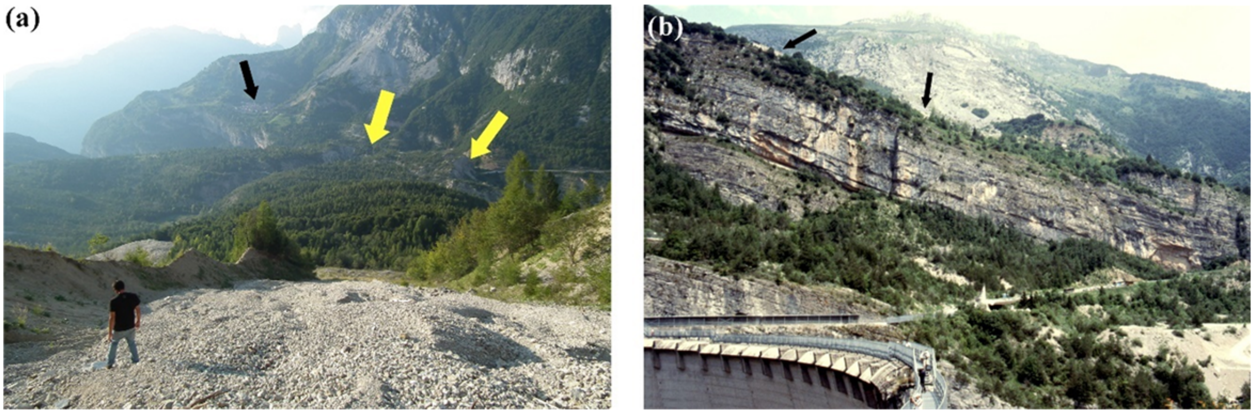

Fig. 12 (a) View downstream (to the west) across the landslide from high up the east side failure scar. The yellow arrows indicate the leading edge of the failed mass above the northern side of the gorge, and the black arrow indicates Casso village. (b) View past the dam (lower left) from the left side towards Casso (indicated by black arrows). The main part of the village is behind and above the top of the cliff (out of sight) at the lower arrow. Photos: APD; ENB.

completely destroyed, but the dam was otherwise undamaged and remains standing to this day.

5 Discussion

5.1 Causal factors for the disaster

The immediate cause of the Vaiont disaster was a very large landslide moving very quickly into a water-filled valley and displacing a very large volume of water (Dykes and Bromhead 2021). If there had been no displacement of water, there would have been no disaster. Therefore, if there had not been a reservoir in the valley, there would have been no wave and only very limited impacts to the inhabitants and infrastructure in the valley. The villages of Casso and Erto would have been entirely unaffected, as would Longarone and indeed the entire Piave valley. With the reservoir present, even a slow moving landslide would have caused a full reservoir to spill up to 10 million m^3 of water over the dam (Semenza 2001, 2010) resulting in significant impacts to Longarone, but a lowered water level in the reservoir (700 m instead of 722.5 m) would have contained most of the predicted ~30 m high wave behind the dam with relatively minor downstream impacts. The wave from the rapidly moving landslide was inconceivably large by comparison. Therefore the causal factors that gave rise to the disaster can be specified as the speed of the landslide (CF1) and the presence of the reservoir (CF2). Indeed, Semenza and Ghirotti (2000, p.95) had identified the velocity as being 'the main cause of the height of the wave ... and therefore of the destruction that ensued' – but their attempts to explain this assumed the landslide to be the reactivation of an ancient slide mass, which now appears not to have been the case.

The geology of the south side of the Vaiont gorge and northern slope of Mt Toc constitutes the underlying factor (UF1) that gave rise to CF1. This encompasses the tectonic history and structures, stratigraphy and the geotechnics of critical lithologies, hydrogeology of the entire slope, and Quaternary and Holocene geomorphology, as outlined earlier in this paper. The speed of the landslide is explained by the halving of the mean shear strength of the entire landslide as the last resistance provided by limestone beds near the (lower) eastern margin of the landslide was lost when they failed (Dykes and Bromhead 2018b), allowing the entire mass to accelerate as widely reported.

5.2 Contributory factors behind CF2

The contributory factors that gave rise to the presence of a reservoir in the Vaiont gorge (CF2) can be defined as 'human factors' in that they encompass the socio-economic, political, engineering and management drivers and capabilities that brought the Vaiont dam project into existence. Contributory factor 1 (CO1) is the location of the project, which was defined by the purpose of the project and therefore the suitability of the specific site within the geographical scope of the wider scheme. The final height and position of the dam with respect to Longarone provided the critical ingredient for the disaster. The nature of the Piave valley floor at Longarone can be considered to be an aggravating factor (AV1), the significant depth of unconsolidated glacio-fluvial sediments occupying the glacially over-deepened valley floor (Bromhead et al. 1996) providing a source of projectiles that were ripped out of the river bed by the force of the flood from the Vaiont gorge and probably increased the resulting level of destruction.

The management of the project must be considered to be contributory factor 2 (CO2) because a disaster could have been avoided – even given the state-of-knowledge in 1963. There are several key issues behind CO2: (i) inadequate understanding of the geology of the slope; (ii) loss of continuity of project leadership due to C. Semenza's death; (iii) results from the scale model tests; (iv) belief that varying the water level could control the landslide. A potential landslide hazard had been identified (Semenza 2001, 2010), albeit based on misunderstandings of the geology of the site (Dykes and Bromhead 2018a, 2021). Carlo Semenza took the issue extremely seriously, especially given the 1959 landslide into Pontesei reservoir, and on the basis of Müller's reports and E. Semenza's findings some ground investigations and monitoring were commissioned as outlined earlier.

The 'definitive' experiments with the scale model at Nove took place in early 1962 using a modified geometry based on E. Semenza's cross-sections of the mountain slope, and measurements of ground movements and piezometer levels also continued after C. Semenza's death. However, instead of ongoing dialogue with relevant experts about what was happening, subsequent decisions appear to have been strongly influenced by 'headline results'. The first of these was Ghetti's finding that an assumed landslide duration of one minute – considered to be unrealistically fast – would produce a wave with a 30 m high runup, so that lowering the reservoir level to 700 m would reduce the potential overflow of the dam to 21,000 m^3. The second was the observation that during the first and second fillings of the reservoir, when movements of the mountain slope became significant (30 mm d^{-1} and 15 mm d^{-1} respectively), lowering of the reservoir level saw the movements stop (Fig. 9). Along with an early hypothesis to explain this from Müller (which he declared erroneous in 1964, in part because it took no account of rainfall), it gave technicians and managers confidence that they could control future movements by adjusting the reservoir level.

Mention must be made of the apparent rush to try to complete the filling of the reservoir during 1963. Semenza (2001, 2010) noted that this was not related to the political or economic processes of nationalising the industry but may have been driven by low winter rainfall during 1962-63 that had severely reduced ENEL's overall generating capacity. The degree to which this imperative overrode caution relating to the developing landslide cannot be determined, but it may be reasonable to suggest this to be a possible aggravating factor (AV2) for CO2. A further aggravating factor (AV3) under the overall CF2 is the design of the Vaiont dam project that necessarily encompassed the principles of HEPP. The impossibility of rapidly emptying the reservoir in an emergency – and the risk of this action triggering failure of the slope – were mentioned previously. Irrespective of this, ENEL was under pressure to begin generation at the newly enhanced Soverzene hydropower plant, and was therefore unwilling to completely empty the reservoir. This also explains why the model experiments to understand the maximum wave height were so central to dealing with the problem, as it would only be necessary then to draw the reservoir down to a level from which the anticipated wave would not overtop the dam.

There is a third contributory factor (CO3) which is the effect of the reservoir on the stability of the northern slope of Mt Toc. The principle of assuming minimum groundwater pressures, outlined earlier, was adopted by Dykes and Bromhead (2018b) to explore the effect of reservoir filling. In short, the reservoir water provided both support for the mountain slope on the one hand, but also a source of water that permeated into the slope and reduced the in-situ effective stresses, thus diminishing the shear strength. The two effects operate in different senses. Assuming that initially the groundwater pressures were absent gives the largest possible strength-reduction effect, from which the maximum effect of impounding the reservoir on the stability of the slope can be computed. Moreover, a long, flat 'seat' to the slip surface – as originally assumed by E. Semenza – also increases the destabilising effect of submergence. The results of the new analyses showed that while impounding and subsequent drawdown did have a negative influence on stability, it was much less than had previously been assumed. In fact, as the reservoir level rose and the water saturated the adjacent mountain slope to an elevation of 700 m, the overall 3D factor of safety (FS) of the slope with respect to shearing failure, using ϕ'_p = 25° for the clay layers, was reduced by just 3% from that of a completely dry slope, i.e. from FS = 1.026 to FS = 0.995. The uncertainties, including water in the slope prior to inundation, are such that all of these Factors of Safety are effectively indistinguishable from 1.0, so even a reduction of less than 3% was probably sufficient to bring about the (already inevitable) final acceleration and ultimate failure of the slope.

5.3 State-of-knowledge perspectives

In 1963, dam engineering was well established and the engineers would have known about many examples of previous dam failures and their causes (e.g. Walters 1962 and references therein). In particular, the collapse of the Gleno Dam in 1923 would have been well-known in Italy to the general public as well as dam engineers, and in 1954 the collapse of the Malpasset Dam in France drew much attention. Walters (1962) provides a contemporary perspective for the state-of-knowledge of dam engineering as much of it was written while the Vaiont dam and others within the Piave Valley scheme were being designed and constructed. However, this work contains no mention of large waves (impulse waves/tsunami) relating to reservoir construction or operation suggesting a widespread lack of awareness of the issue. Instances of large masses of rock triggering catastrophic waves were known by 1963, but the global speed and distribution of published accounts and studies must have greatly limited their reach. For example, Miller's (1960) USGS paper on the 1958 Lituya Bay mega-tsunami is unlikely to have achieved widespread academic circulation. This event, and others such as two damaging instances of rockslide-triggered tsunamis in Norway in the 1930s (Harbitz et al. 2014; Hughes et al. 2021), were probably unknown in Italy in 1963. On the other hand, Italy had its own historical examples including Alleghe (see Introduction) which must have been known about; then the wave produced by the landslide into the new Pontesei reservoir in 1959, with a runup against the opposite shore 20 m above the water level (Semenza 2001, 2010), led to investigations of the possibility of a similar type of event at Vaiont.

Principles of slope stability, including the effects of rainfall and the occurrence of draw-down failures of reservoir slopes were also well-known and understood by the early 1960s (e.g. Eckel 1958). The large landslide deposits of La Pineda, on the left side of the Vaiont valley immediately east of Mt Toc, and filling the Passo di Sant'Osvaldo between Erto and Cimolais (Fig. 1b), were known but not regarded as general indicators of a relatively high landslide susceptibility in the area. Techniques for analysing the stability of slopes existed and were well-established, with the slip circle method based on Fellenius (1927, 1936) being in common use in the US, UK and elsewhere by the 1950s (Daehn and Hilf 1951). Bishop (1955) introduced more accurate methods that were then computerised by Little and Price (1958). Janbu had also published methods for non-circular slips by the time Semenza had characterised the Vaiont landslide (Janbu et al. 1956; Janbu 1957). Italy may have been a few years behind so may not have had computer software – but hand calculations would have been possible using, for example, Bishop and Morgenstern's (1960) effective stress charts. However, 'residual strength' was not known at that time, and uncertainties regarding the actual shear strength would have led to results that reflected assumptions made, limiting their usefulness. On the other hand, techniques for stabilising large landslides were known: Müller's (1961) report on the Vaiont project identified several theoretically possible (but mostly practically impossible) ways of stabilising the slope of Mt Toc, based on well-established approaches.

Formal conceptual and procedural frameworks for undertaking risk assessments to underpin decision-making in any field of human activity did not exist until 20-30 years after the Vaiont disaster (Aven 2016). Even if they had, given the state-of-knowledge at that time a risk-informed decision-making process would have failed to prevent the disaster. There appear to be two reasons for this, both of which stem from a basic model for the process in which 'Experts' use *Evidence* to provide an adequate *Knowledge Base* to underpin a *Broad Risk Evaluation*, which is then passed to the 'Decision Maker' for a *Decision Maker's Review* from which a final *Decision* can be made (Hansson and Aven 2014). Firstly, no evidence of a landslide had been identified before the Vaiont dam project was approved or even before construction of the dam was well advanced – although other large landslides were known in the immediate locale at La Pineda and Passo di Sant'Osvaldo. Therefore no specific risk of a landslide would have been identified, although such a risk should have been considered as part of the process. Now, in 2022, we would expect that in such a geomorphological context, a theoretical landslide risk should have been identified given the much wider knowledge base, leading to appropriate and adequate investigations to quantify the risk. Secondly, even when the risk of a landslide had become apparent and investigations were in progress, the level of risk associated with the potential consequences – for which the 1:200 scale model experiments were conducted – could not have been accurately assessed. This is because: (i) the landslide geometry (*Evidence*) used for the model was incorrect, leading to a greatly underestimated landslide velocity; (ii) the predicted wave height (*Evidence* leading to specific *Knowledge Base*) resulting from (i) was therefore incorrect, leading to the management decisions that were actually taken; and (iii) the flawed evidence of (i) and (ii), combined with a knowledge base of lake tsunamis that was limited in scope and did not contain any examples remotely comparable in scale to the actual wave, gave no-one the means to imagine such a flood down the gorge to Longarone.

Ultimately, a proper consideration of the geology was vital to understanding the landslide. New analyses of the failure surface geometry (Fig. 10b) (Bistacchi et al. 2013) and subsequent work using this geometry (Dykes and Bromhead 2018 a,b) appears to have disproved the scientific consensus of more than 50 years and provided the first explanation of the entire landslide event that can account for all of the available evidence and observations, including a simple explanation of the speed of the slide in terms of a drop from peak strength to residual strength in the early stage of the final failure in the evening of 9 October 1963.

5.4 Missed opportunities to avoid a disaster

With the benefit of hindsight, the conception and design of the entire Piave Valley hydropower scheme and indeed all stages of the Vaiont dam project appear to present several opportunities for avoiding the disaster that occurred. Identifying these opportunities provides a strong foundation for avoiding and managing similar risks in future HEPPs in mountainous regions. If the entire scheme was being designed now, there would be an absolute expectation that the mountain slopes on either side of the Vaiont gorge would be extensively investigated and analysed. It is possible that the risk of a major landslide would be deemed too high at this stage with the site being declared unsuitable.

Given that the Vaiont dam project went ahead, with the landslide hazard only being identified when the dam was almost complete, there were still opportunities to avoid a disaster. At the time, the scale of any 'possible disaster' was incomparably smaller than that which occurred, as explained previously. This fact alone can probably account for the later opportunities being missed. Key to the disaster was the presence of the reservoir (CF2), since the geology (UF1 giving rise to CF1) was an inherent characteristic of the site. The developing landslide became apparent in October 1960 as the reservoir level was approaching 650 m, then following the large rockslide of November 1960 the level was lowered to 585-600 m to allow construction of an emergency bypass tunnel. The total volume of impounded water at this level was many times less than at 700 m (the level at the time of the final failure), so holding the water at this low level for sufficient time to undertake more thorough investigations of the landslide would have greatly reduced the scale of the disaster. Perhaps more significant is the response to the acceleration of the landslide in December 1962, following very high rainfall the previous month, which was to again lower the water level – this time from 700 m to 650 m. The association with rainfall was largely missed at the time, but recognition that higher water levels led to accelerated movements could at this point have led to the water level being held at 650 m and ideally lowered further if possible, pending further investigations of the landslide.

5.5 Mountain risks

Impoundment of water in valleys behind dams can cause or reactivate landslides, particularly if the adjacent slopes comprise relatively permeable lithologies and the preceding natural state is significantly unsaturated. The slopes of HEPP reservoirs are further susceptible to instability due to rapid drawdown associated with increased generating requirements. Such effects could conceivably also arise following the rapid emplacement of a landslide dam and, in some of these cases, subsequent drainage of the new lake if the dam breaches due to erosion or deliberate engineering measures. These issues are well-known and have been afforded much attention in recent decades (e.g. Riemer 1995; ICOLD-CIGB 2002). Detailed understanding of the geology is, of course, also critical for the design and construction of the dams: as one example of the global impact of lessons from Vaiont, the Feitsui dam in Taiwan was successfully constructed between 1979 and 1987 despite the discovery of weak bedding-parallel clay layers within otherwise competent sandstones and siltstones on which one side of the dam was founded (Cheng 1987).

Both of the state-of-knowledge reports (Riemer 1995; ICOLD-CIGB 2002) also contain specific sections on impulse waves/tsunamis caused by landslides entering reservoirs or other water bodies, with Riemer (1995) suggesting that waves up to 100 m high are predicted from landslides entering China's Three Gorges reservoir in the future. Methods for identifying and assessing both the wave characteristics arising from a landslide's particular characteristics and the potential impacts, including extent of runup on slopes, dam overtopping (and possible breaching) and downstream flooding, are under constant development given the recognised need for routine implementation (e.g. Ward and Day 2011). Vaiont provides a cautionary tale, not just for dam and reservoir engineering but more widely for the assessment and management of landslide hazards in mountain areas. Table 2 summarises the factors that gave rise to the Vaiont disaster, while ICOLD-CIGB (2002) provided a list of key learning points for dam and reservoir project professionals (Table 3). Almost all of the points listed in Table 3 can be seen to address CF2-CO2-(i) Inadequate understanding of the slope (UF1), while some of these learning points can be mapped onto other specific causal factors in Table 2:

(a) Points 1,6,7,10 arise from CF2-CO3

(b) Points 3,8,10 relate to CF2-CO1

(c) Points 8 and 10 cover CF2-CO2 generally (i.e. project management)

Notwithstanding the above, we suggest that at Vaiont, the landslide was inevitable whether or not the reservoir was created, given that the geology was inherently adverse. If the Vaiont dam had not been built, the consequences of the landslide would have been relatively minor, with plenty of time to manage the problem of inundation of the valley above the natural dam. Therefore we necessarily find the factors in Table 2 to be consistent with the hypothesis, i.e. that the Vaiont disaster resulted from the Vaiont dam project and was not simply due to the landslide.

6 Conclusions

The Vaiont landslide would probably have occurred at some time after 1963 because the northern slope of Mt Toc comprised a significantly adverse combination of geological characteristics, including thin, weak clay beds that dipped significantly towards the Vaiont gorge throughout the slope. However, the disaster was caused by a huge volume of water in an almost-full reservoir being displaced by the rapidly moving landslide in a manner entirely inconceivable at the time. Therefore, the circumstances that gave rise to the existence of the

Table 2 Summary of the factors that led to the Vaiont disaster

Causal Factors (CF)	Underlying Factors (UF)	Contributory Factors (CO)	Key Issues	Aggravating Factors (AF)
CF1: Speed of the landslide	UF1: Geology of the site	-	(i) Tectonics and structure (ii) Stratigraphy and geotechnics (iii) Hydrogeology and geomorphology	
CF2: Presence of the reservoir	-	CO1: Location of the project	(i) Purpose of the project (ii) Suitability for the project (iii) Proximity of a major town (Longarone) below the dam	AV1: River bed sediments at Longarone
	-	CO2: Management of the project	(i) Inadequate understanding of the slope (ii) Loss of continuity of project leadership following Carlo Semenza's death (iii) Results from the scale model tests (ability to contain the predicted 30 m high waves) (iv) Belief that varying the reservoir water level could control the landslide	AV2: Urgent need for increased generating capacity in 1963
	-	CO3: Effect of reservoir on stability	(i) UF1 (i.e. the underlying geology)	AV3: HEPP principles

Table 3 Key lessons from Vaiont according to ICOLD-CIGB (2002, p.39).

No.	Relevant professionals and managers must remember these points:
1	Pre-existing landslides can be highly sensitive and can be reactivated with devastating results when a reservoir is formed against them*
2	The importance of a thorough understanding of the geology (lithology, structure, material properties) and hydrogeology of the reservoir rim
3	The importance of searching for, recognising and evaluating precedent evidence for past instability in the reservoir basin
4	The significance of weak seams or layers in a slope, especially if inclined towards the reservoir
5	The need for sufficiently reliable models for geotechnical analysis, with clear acknowledgement of their uncertainties and limitations
6	The effect of changing reservoir levels on slope stability
7	The significance of the joint effects of rapid reservoir level changes and the various influences of rainfall on slope stability
8	The value of reliable monitoring data, prompt data evaluation and appropriate responsive actions
9	The difficulty in predicting time of failure, landslide velocity and subsequent wave size
10	Worst case scenarios must be taken into account

Note: *Although it now seems clear that Vaiont was not a pre-existing landslide, this point remains true.

reservoir, and its high water level at the time of the final failure of a slope known to be moving for the preceding three years, mean that the disaster must ultimately be attributed to the Vaiont dam project and not simply the landslide.

The lessons from the Vaiont dam project, particularly relating to the importance of adequate assessments and investigations of the stability conditions of the reservoir slopes but also in terms of robust planning and management procedures to identify and mitigate project risks, continue to be relevant for new and even existing reservoirs. However, even though the potential hazards from subaerial landslides entering reservoirs and natural lakes and creating impulse waves/tsunamis are now well known, the ever increasing exploitation of valleys in high mountain ranges for carbon-friendly hydro-electric schemes substantially increases the risk of another 'unexpected' Vaiont-type scenario. Indeed, the risks from large landslides creating damaging tsunamis in water bodies in mountainous regions must be identified and addressed in order that appropriate monitoring and warning systems – including public information for communities identified as being at risk – can be devised and implemented. This presents a significant challenge that will not be addressed quickly.

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