Effects of Rainfall on the Stability of Lateritic Soils (Reinforced Red Coffee Soils – RCS)

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This presentation focuses on engineering in lateritic soils in Kenya, East Africa, where such soils are commonly referred to as “red coffee soils” owing to their agricultural richness for coffee plantation growing

The aim of this study was to evaluate the potential of Red Coffee soils (RCS) of Kenya as a backfill material in the construction of slopes and embankments

Although coarse grained cohesionless soils are popular as backfills for slopes / embankments / retaining walls, the extraction of such soils from river banks or near water bodies can contribute to environmental degradation resulting in drying of rivers and wasteland.

This problem can be avoided or minimised if native RCS abundant at construction sites was put into use as an alternative backfill material to coarse grained soil.

However, it is important to recognise [1, 2] that RCS is usually medium to high plasticity soils or marginal soils, hence if used as backfill without reinforcement, can lead to failures of retaining walls /slopes.

To prevent such failures, studies by [3–5] have proposed the need for proper drainage to remove uncertainty in pore water pressure build-up during a significant rainfall event.

Geosynthetic reinforced slope (GRS) backfill is normally compacted at ±2% of the optimum moisture content and this takes advantage of negative pore water pressure and matric suction in the unsaturated backfill layer. The advantage arises from the enhanced soil stiffness and shear strength mechanisms.

Non- woven geotextile can be used to improve drainage in marginal backfill embankments while simultaneously offering tensile strength in reinforcing the soil.

Unfortunately, under unsaturated soil conditions non-woven geotextile can form a barrier hence contributing to the accumulation of water in the soils above the non-woven geotextile layer [6–8].

Unfortunately, under unsaturated soil conditions non-woven geotextile can form a barrier hence contributing to the accumulation of water in the soils above the non-woven geotextile layer thereby increasing pore water pressure and occasioning failure of the geotechnical structure.

This presents a dilemma as to whether to stick with the use of environmentally degrading cohesionless coarse backfill soil or to find a solution to drainage and stability problems associated with the readily available laterite (RCS / marginal red coffee soil) as backfill material.

To solve the dilemma, this study was designed to :

(1) Investigate the effect of inclining non-woven geotextile on the drainage and stability of an embankment constructed in RCS laterite soil

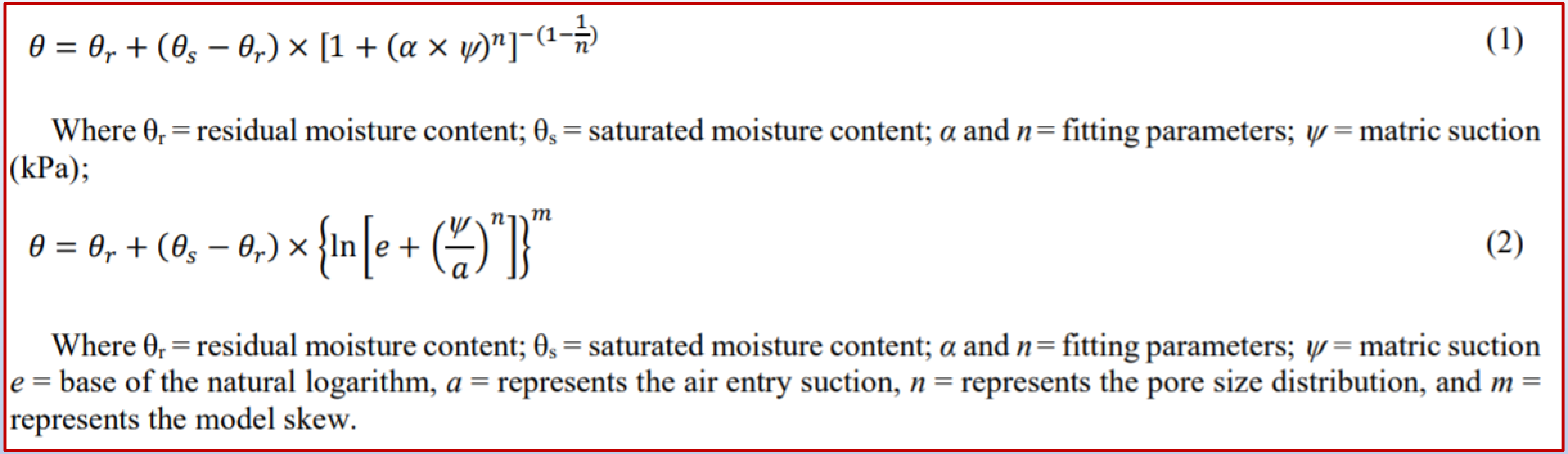
2) Determine the optimum sand cushion thickness necessary to improve drainage and stability of the RCS laterite embankment soil

Numerical modelling was implemented to simulate extreme rainfall uniformly applied to the embankment and seepage analysis carried out to calculate the factors of safety of the embankment during a major rainfall event.

FINITE ELEMENT MODELLING USING SEEP/W SOFTWARE

(a) Seepage analysis

SEEP/W Version 2012 was used for seepage analysis, with input hydraulic properties of the geomaterials being derived from the van Genuchten (equation 1) and the Fredlund-Xing model (equation 2) which are incorporated in the program.



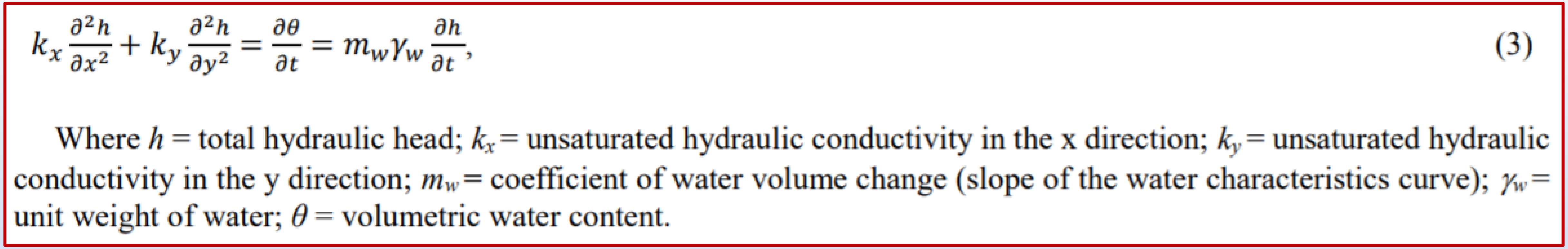
$$\theta = \theta_r + (\theta_s - \theta_r) \times [1 + (\alpha \times \psi)^n]^{-(1-\frac{1}{n})} \quad (1)$$

Where θ_r = residual moisture content; θ_s = saturated moisture content; α and n = fitting parameters; ψ = matric suction (kPa);

$$\theta = \theta_r + (\theta_s - \theta_r) \times \left\{\ln\left[e + \left(\frac{\psi}{a}\right)^n\right]\right\}^m \quad (2)$$

Where θ_r = residual moisture content; θ_s = saturated moisture content; α and n = fitting parameters; ψ = matric suction e = base of the natural logarithm, a = represents the air entry suction, n = represents the pore size distribution, and m = represents the model skew.

SEEP/W transient seepage analysis governed by the Richard's equation was used in the study. For a two-dimensional homogenous anisotropic soil, the equation is derived as in equation 3.

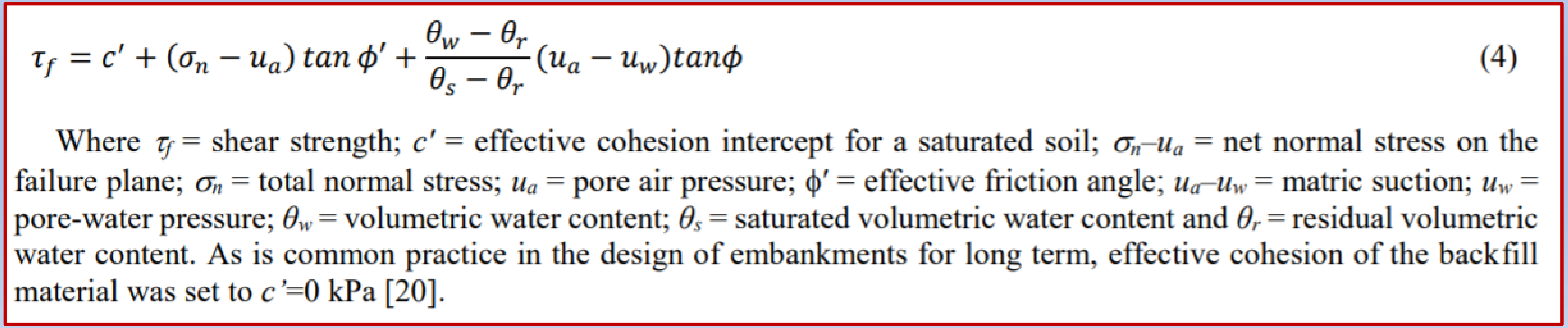


$$k_x \frac{\partial^2 h}{\partial x^2} + k_y \frac{\partial^2 h}{\partial y^2} = \frac{\partial \theta}{\partial t} = m_w \gamma_w \frac{\partial h}{\partial t}, \qquad (3)$$

Where h = total hydraulic head; k_x = unsaturated hydraulic conductivity in the x direction; k_y = unsaturated hydraulic conductivity in the y direction; m_w = coefficient of water volume change (slope of the water characteristics curve); γ_w = unit weight of water; θ = volumetric water content.

(b) Stability analysis

To determine the factor of safety, the Spencer method, which considers both moment and force equilibrium, was used in the SLOPE/W program where the unsaturated soil shear strength was calculated by implementing equation 4 that was proposed by [9].



$$\tau_f = c' + (\sigma_n - u_a)\, tan\, \phi' + \frac{\theta_w - \theta_r}{\theta_s - \theta_r}(u_a - u_w) tan\phi \qquad (4)$$

Where τ_f = shear strength; c' = effective cohesion intercept for a saturated soil; σ_n–u_a = net normal stress on the failure plane; σ_n = total normal stress; u_a = pore air pressure; ϕ' = effective friction angle; u_a–u_w = matric suction; u_w = pore-water pressure; θ_w = volumetric water content; θ_s = saturated volumetric water content and θ_r = residual volumetric water content. As is common practice in the design of embankments for long term, effective cohesion of the backfill material was set to c'=0 kPa [20].

(c) Materials and Methods – Lateritic soil and sand

Samples of RCS laterite soil and river sand were obtained from different sites approx. 30 km north of Nairobi, the capital of Kenya.

The RCS was classified as a silty clay (CL) according to the Unified Soil Classification System.

The grain distribution curve is shown in Figure 1, while various other properties of the RCS and river sand are given in Table 1.

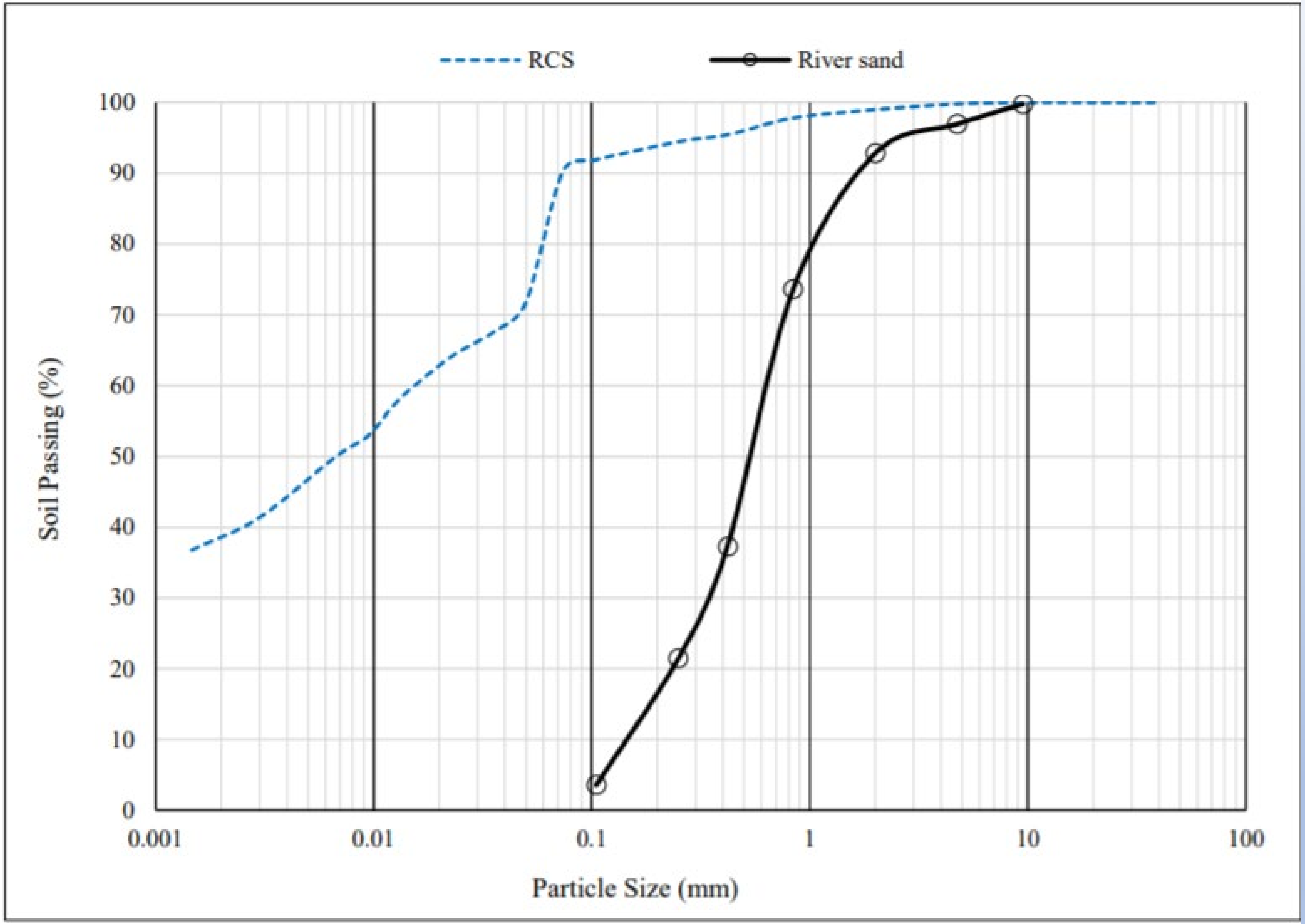


Figure 1. Particle size distribution curves for RCS and River sand used in the study

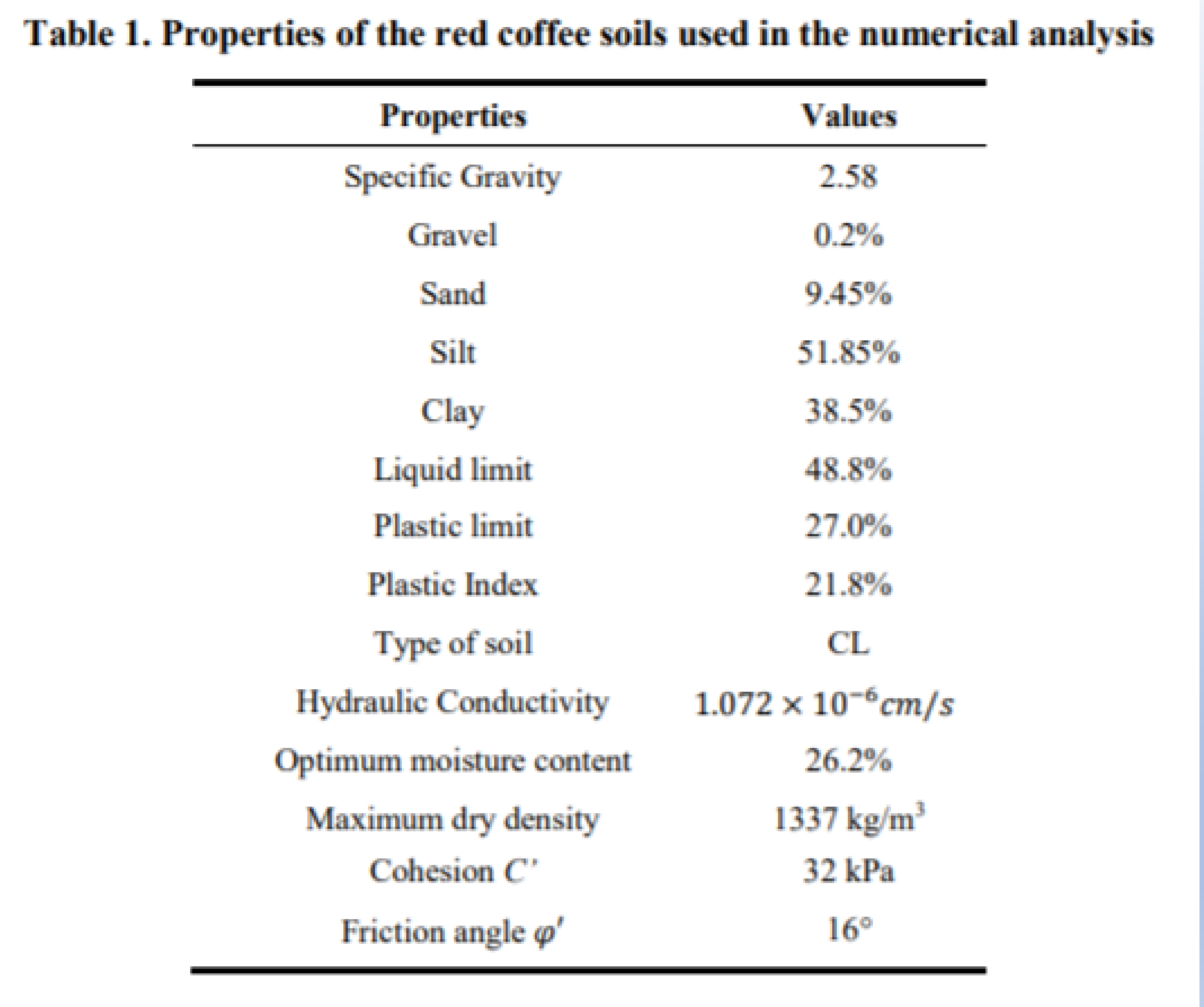


Table 1. Properties of the red coffee soils used in the numerical analysis

Properties	Values
Specific Gravity	2.58
Gravel	0.2%
Sand	9.45%
Silt	51.85%
Clay	38.5%
Liquid limit	48.8%
Plastic limit	27.0%
Plastic Index	21.8%
Type of soil	CL
Hydraulic Conductivity	$1.072 \times 10^{-6} cm/s$
Optimum moisture content	26.2%
Maximum dry density	1337 kg/m^3
Cohesion C'	32 kPa
Friction angle φ'	16°

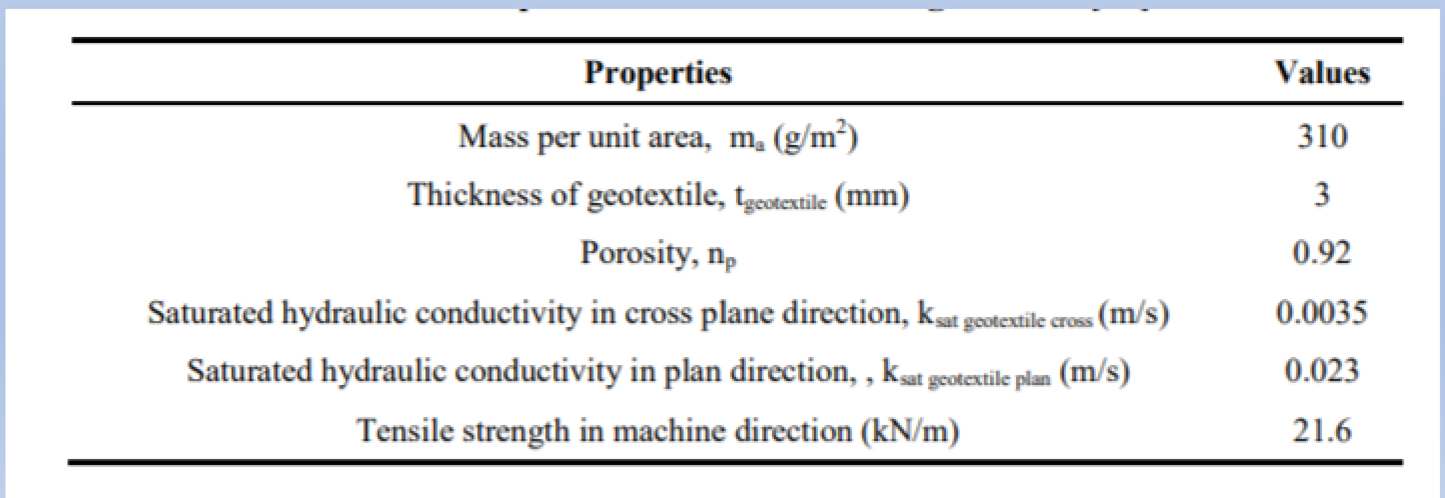
Properties of the river sand as obtained from the laboratory tests were; specific gravity of 2.68, hydraulic conductivity of 1.43×10^{-4} m/s with cohesion of 0 kPa and angle of friction of 35°.

The river sand was classified as poorly graded sand (SP) according to the Unified Soil Classification System (USCS). Grain size distribution curve for the river sand used in the study is presented in Figure 1.

Non-woven geotextile material

The non-woven geotextile material used in the numerical model was based on the properties as obtained from secondary sources and are as summarized in Table 2.

Table 2 – Properties of the non-woven geotextile (manufacturer supplied)



Properties	Values
Mass per unit area, m_a (g/m^2)	310
Thickness of geotextile, $t_{geotextile}$ (mm)	3
Porosity, n_p	0.92
Saturated hydraulic conductivity in cross plane direction, $k_{sat\ geotextile\ cross}$ (m/s)	0.0035
Saturated hydraulic conductivity in plan direction, , $k_{sat\ geotextile\ plan}$ (m/s)	0.023
Tensile strength in machine direction (kN/m)	21.6

Non-woven geotextile material continued……..

From lab tests, the volumetric water content function of the river sand and the RCS laterite (estimated using The Fredlund and Xing's models) and those of the non-woven geotextile material (estimated through using the van Genuchten-Mualem's model) are given in Figure 2a.

The hydraulic conductivity functions of the materials as modelled with sample functions are presented in Figure 2b.

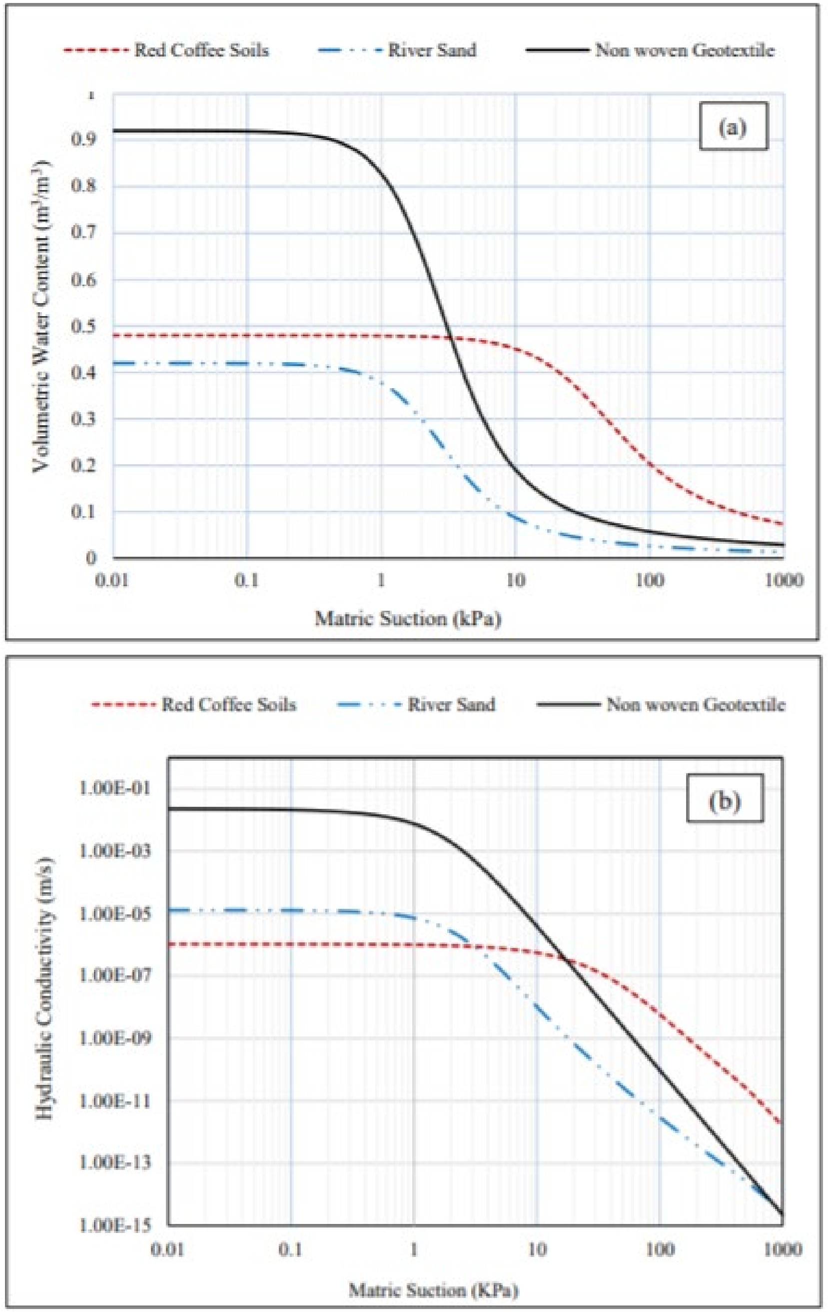


Figure 2. Hydraulic function models of river sand, non-woven geotextile and RCS (a) volumetric water content function curves (b) hydraulic conductivity function curves

From Fig. 2, it is seen that the matric suction significantly as the volumetric water content of the soils increase.

An important component in the functions is the air entry value which shows the point at which matric suction is adequate to initiate the dying of a saturated soil.

RCS has a higher air entry value 15 kPa compared to that of non-woven geotextile and river sand which stands at 0.9 kPa.

The curve of the geotextile are steeper demonstrating that water is lost rapidly in these geomaterial.

(d) Rainfall data used in model

Rainfall data for the study was taken from meteorological records spanning years 1991 to 2017.

An extreme rainfall event of 160 mm/day was recorded for the period, and lasted maximum of 2 days however in this the simulation was for 3 days rainfall duration.

Taking the embankment as a 2D structure, quadrilateral element mesh with height 0.1 m were used, adjusting the time increment in the analysis automatically (0.1 - 100 s) with 18 time steps.

The initial pore-water condition was established through a steady-state seepage analysis, prescribing a unit flux on set surface boundaries.

The values of prescribed unit flux were adjusted until when matric suction did fell below the initial soil moisture condition obtained in lab tests.

The non-woven geotextile was modelled as a line with 3 mm interface elements.

The volumetric water content data in the model was measured at a distance x=1.2 and 2.4.

To assess the effect of non-woven geotextile angle of inclination on the drainage and stability of embankments, non-woven geotextile layers inclined at angles of 0°,1°, 3°, 6°,9° and 10.5° in different embankments were modelled. The model with the non-woven geotextile inclined at zero degree is as shown in the Figure 3.

Three layers of non-woven geotextile layers were placed 0.75 m apart in the vertical direction, a fourth layer of geotextile of length 1.5 m was maintained at the base of the embankment. This fourth layer was maintained at zero degrees inclination throughout. Boundary conditions were adopted based and a series of transient infiltration analysis in SEEP/W and limit equilibrium analysis using the Spencer method. The effective cohesion of the RCS laterite was set to 0 kPa in the stability analysis.

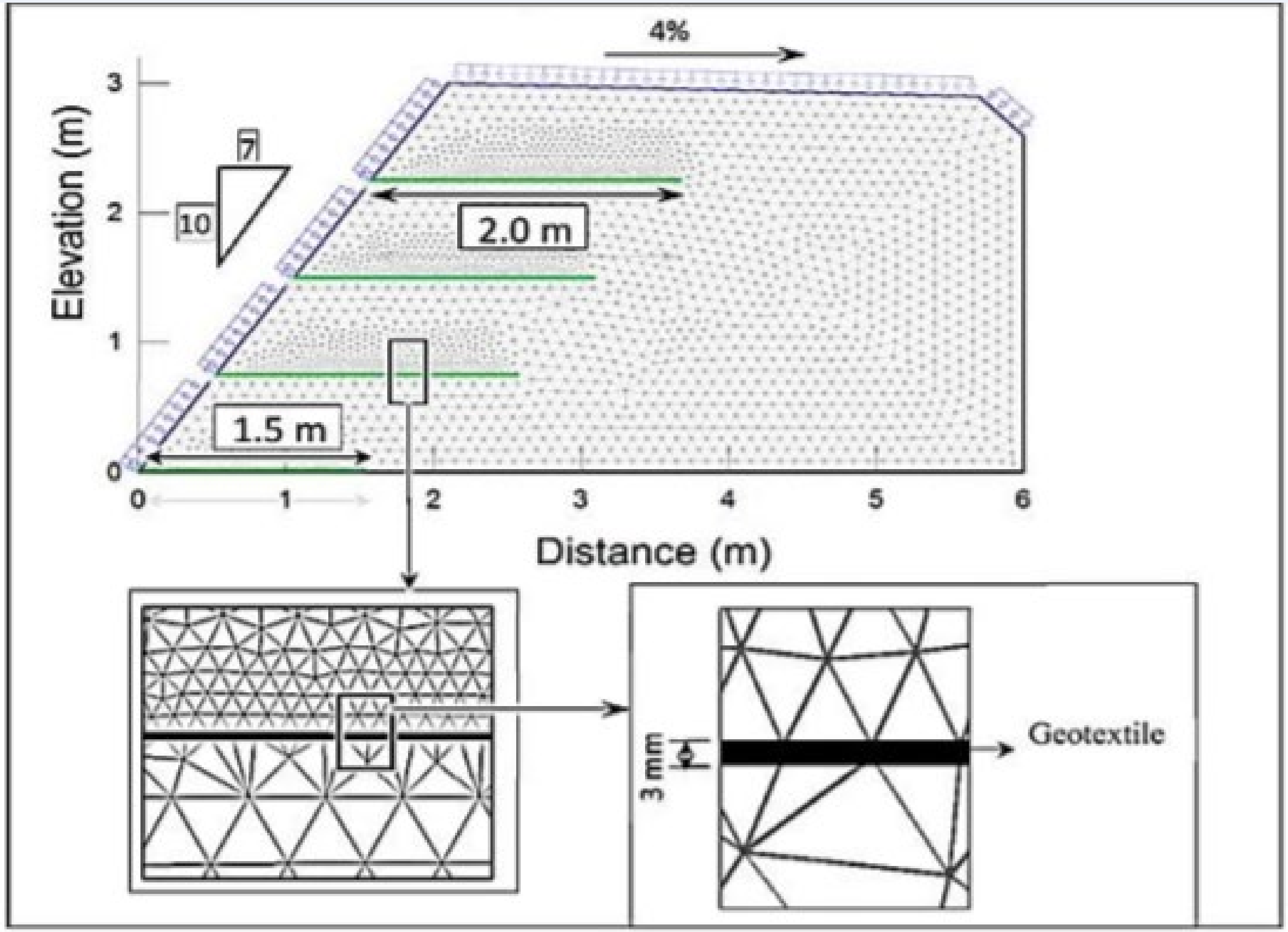


Figure 3. Numerical model setup of the RCS embankment in evaluating effect of geotextile inclination on its performance

After the optimum angle of inclination was obtained, the effect of sand cushion thickness on the drainage and stability of the RCS laterite embankments were established by introducing sand layers of different thickness to sandwich the non-woven geotextile layers.

The sand layers thickness adopted were 50, 100, 150, 200, 250 and 300 mm. These relate to the thickness on either side of the geotextile material.

The numerical model setup is as shown in Figure 4.

The non-woven geotextile layer retained their earlier vertical spacing of 0.75 m. The effect of these sand layers on the infiltration and stability was then evaluated.

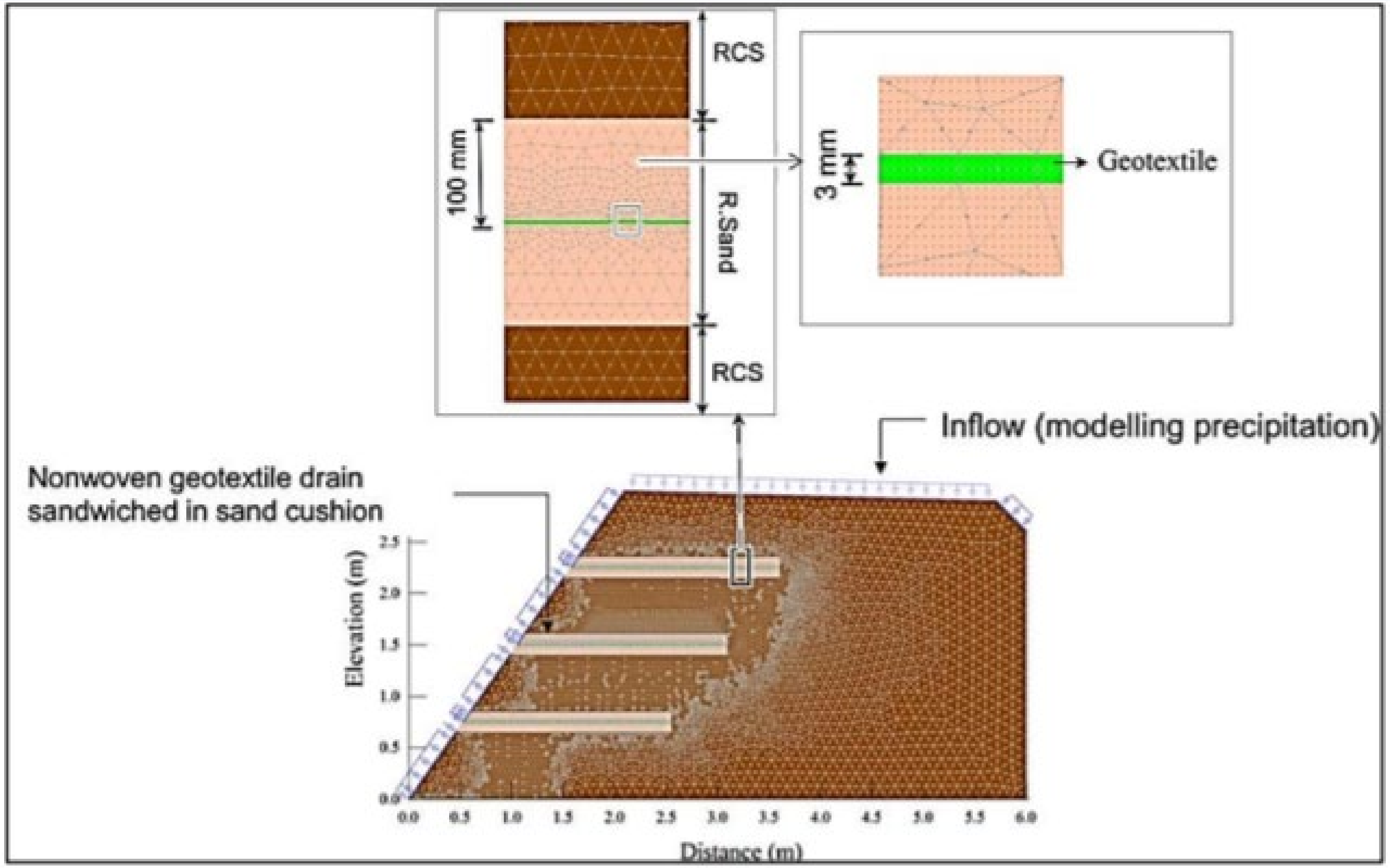


Figure 4. Numerical model setup in evaluating the effect of sand layer thickness on the performance of RCS embankments

ANALYSIS RESULTS ……

(a) Effect of geotextile inclination (G-I) on the RCS laterite embankments

The effect of inclining non-woven geotextile layers at angles of 0°, 3°, 7.5° and 9° on the pore water pressure profile in Figure 5.

Fig. 5 shows that:

(i) pore water pressure within the embankments increases with time elapsed.

(ii) There is advantage of non-woven geotextile on the performance of the RCS embankments – because irrespective of the inclination angle, the reinforced embankment performed much better with lower pore water pressures

(iii) Increasing the non-woven geotextile angle of inclination from the conservative angle of 0^0 to 3^0 resulted in the reduction of the rate of pore water pressure development in the embankment.

(iv) A 3^0 inclination was the optimum angle beyond no significant improvement on the pore water pressure development was observed - clearly demonstrating that inclining the non-woven geotextile material at an appropriate angle makes it more effective as a drainage material as compared to zero inclination or absence of a geotextile reinforcement in the RCS laterite embankment

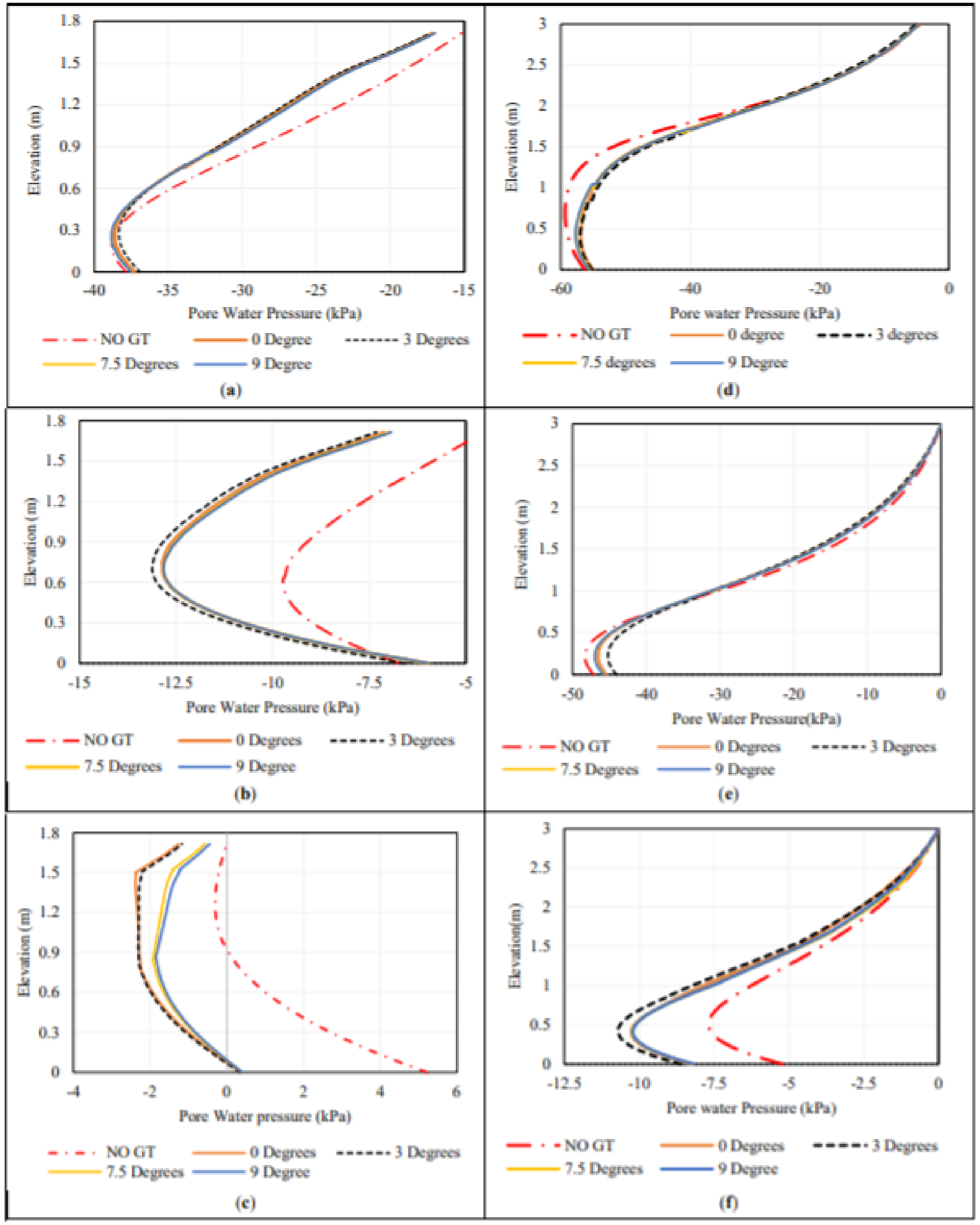


Figure 5. Pore water pressure profiles of embankments with inclined geotextile layers measured at (a) x=1.2m day 1 (b) x=1.2 m day 2 (c) x=1.2 m day 3 (e) x=2.4 day 1 (e) x=2.4 m day 2 (f) x=2.4 m day 3

Figure 6 shows the variation of factor of safety with change in angle of inclination of the non-woven geotextile layers.

Clearly, there is a general decrease in factor of safety of the embankment with accumulated rainfall.

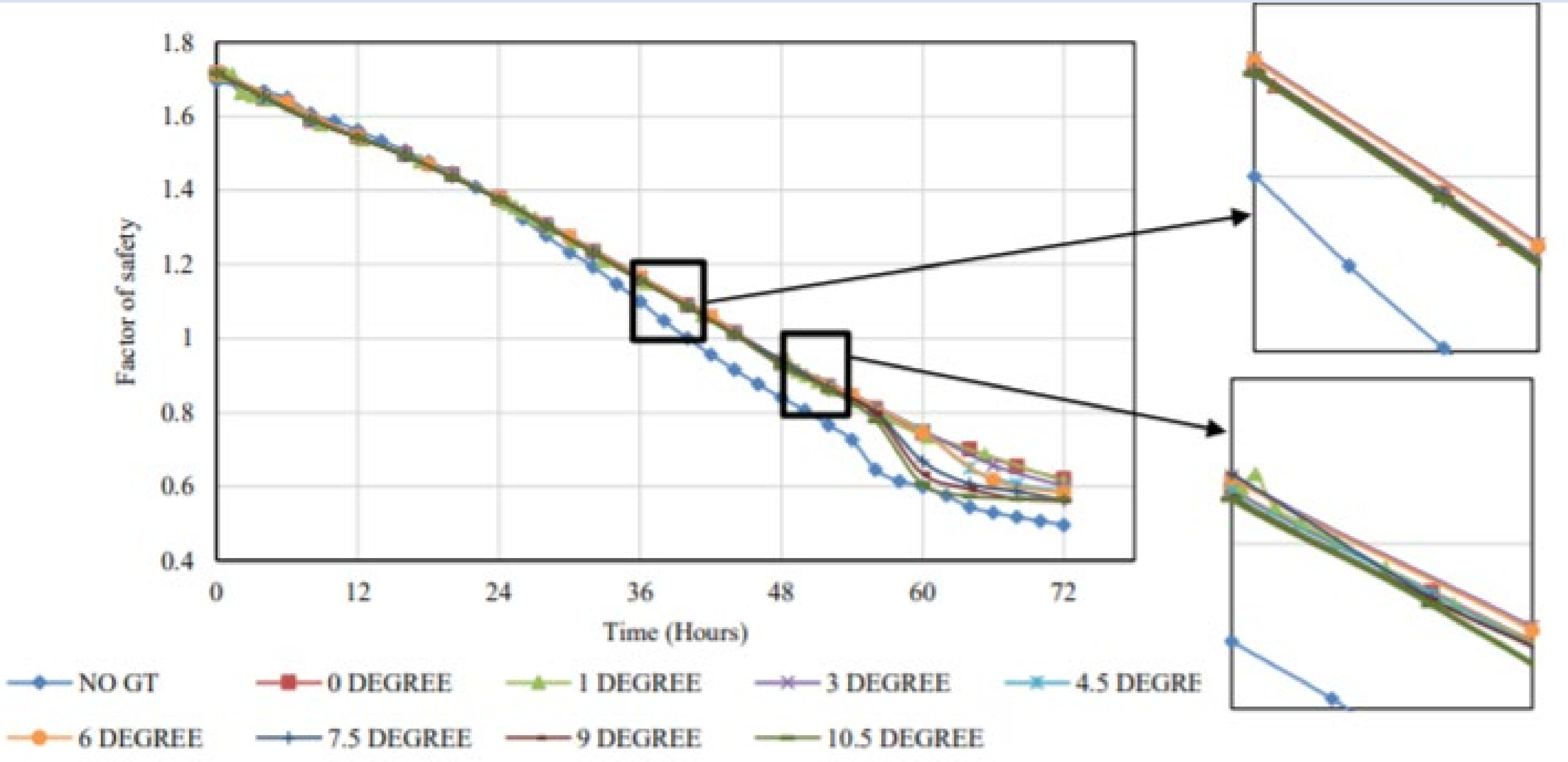


Figure 6. Variation of factors of global factor of safety with change in geotextile inclination angle

b. Effect of Sand Layers Thickness on the RCS laterite embankments

Figure 7 depicts the time dependent variation of pore pressure profiles of the embankments that incorporate varying sand cushion thickness.
It is seen that:

(i) At end of 1st day, the embankment whose non-woven geotextile layers were not sandwiched between non-woven geotextile layers recorded the lowest rates of pore water pressure.

(ii) Also at end of 1st day, the embankments whose non-woven geotextile layers were sandwiched with the thickest sand layer of 300 mm had the highest pore water pressures.

(iii) With advancement of time as the water flux passed through the embankments, pore water pressure of both soils significantly increased.

(iv) With an increase in the volumetric water content in the upper parts of the embankment the advantage of sand layer cushions emerged (sand cushions working as drainage layers).

(v) Embankments with thicker sand cushions had lower pore water pressure values.

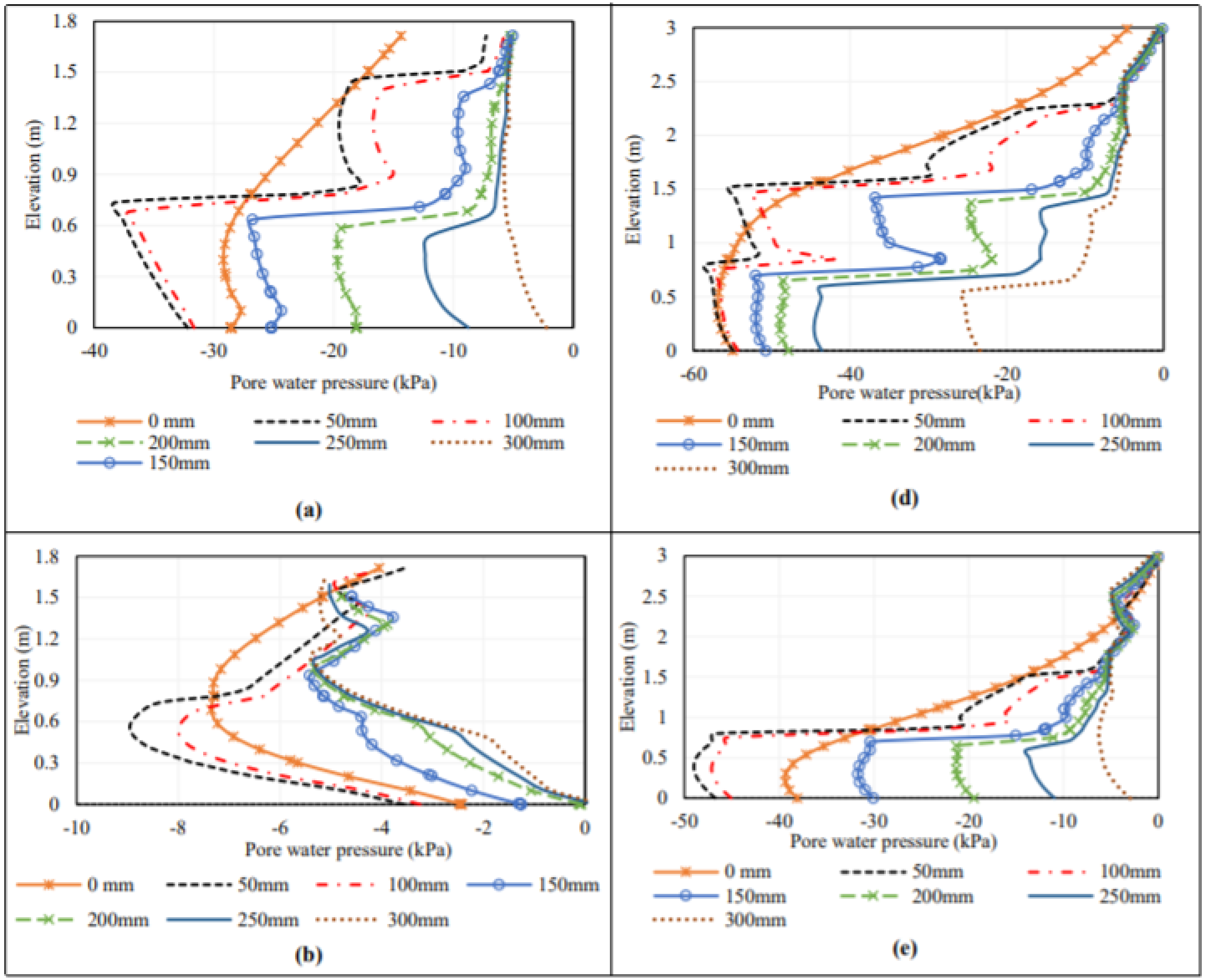


Fig. 7 continues on the next slide…………

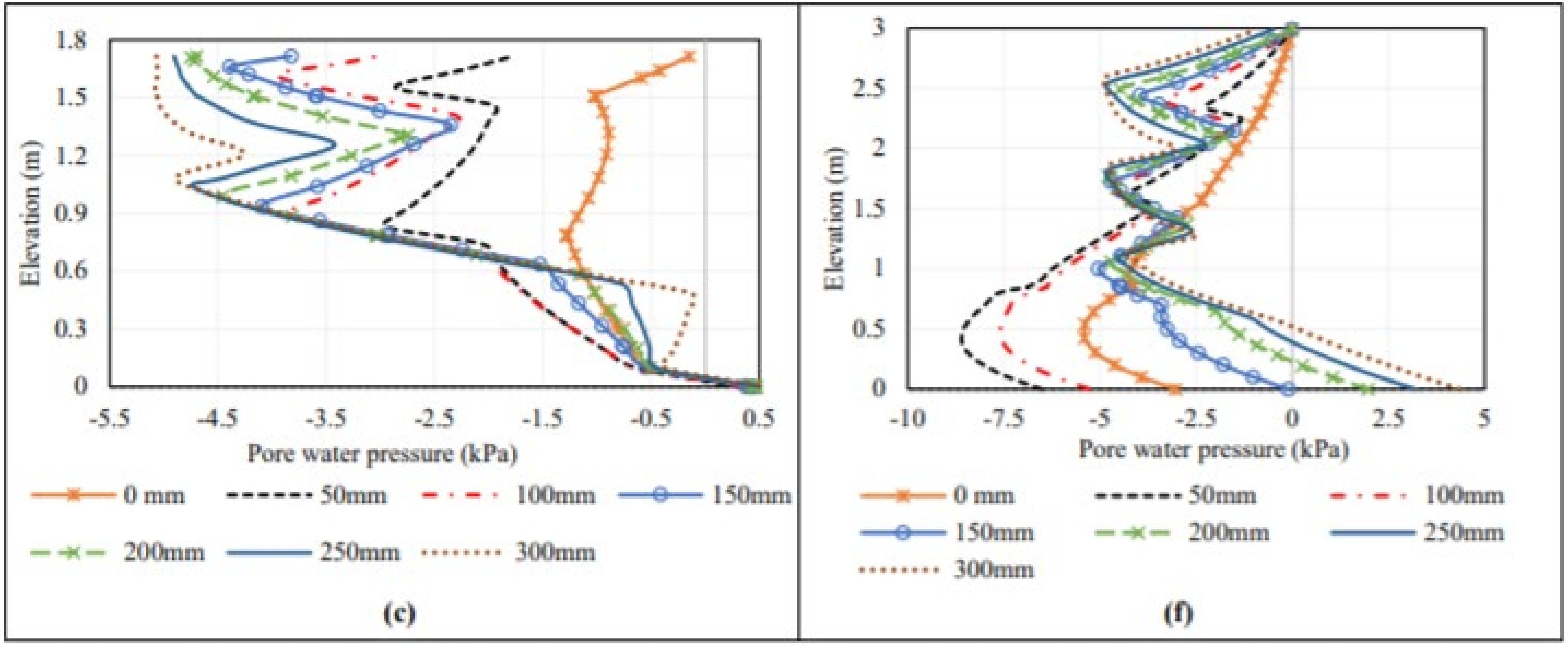


Figure 7. Pore water profiles of embankments with change in sand layer thickness at end of: (a) day one x=1.2m from toe; (b) day two x=1.2 m; (c) day three x=1.2 m; (d) day one x=2.4 m from toe (e) day two x=2.4 m and (f) day three x=2.4 m

Figure 8 presents the variation of the global factors of safety of the embankment with change in sand cushion thickness.

There was a general decline in the factors of safety of the RCS laterite embankments with increase in the rainfall duration as expected.

In the early stages of the rainfall event the factors of safety of the embankments with sand cushion layers decreased with increase in the sand cushion zone. This is because of the initial matric suctions of sand (-3.5 kPa) and of RCS laterite (-60 kPa); the lower matric suction value of sand being rapidly lost as the rainfall infiltrated through the embankment. A lower matric suction contributes to the reduction in the shear strength of the sand (as per equation 4), consequently reducing the factor of safety of the embankment.

With the advancement of time it was observed that the thicker the sand cushion the higher the factor of safety values recorded for the embankments.

An embankment comprising pure RCS laterite even if reinforced with geotextile is prone to failure at around 39 hours (i.e. factor of safety fall below 1).

A sand layer thickness of 150mm is adequate for RCS laterite embankment and effectively reduces the amount of river sand needed to just 15%.

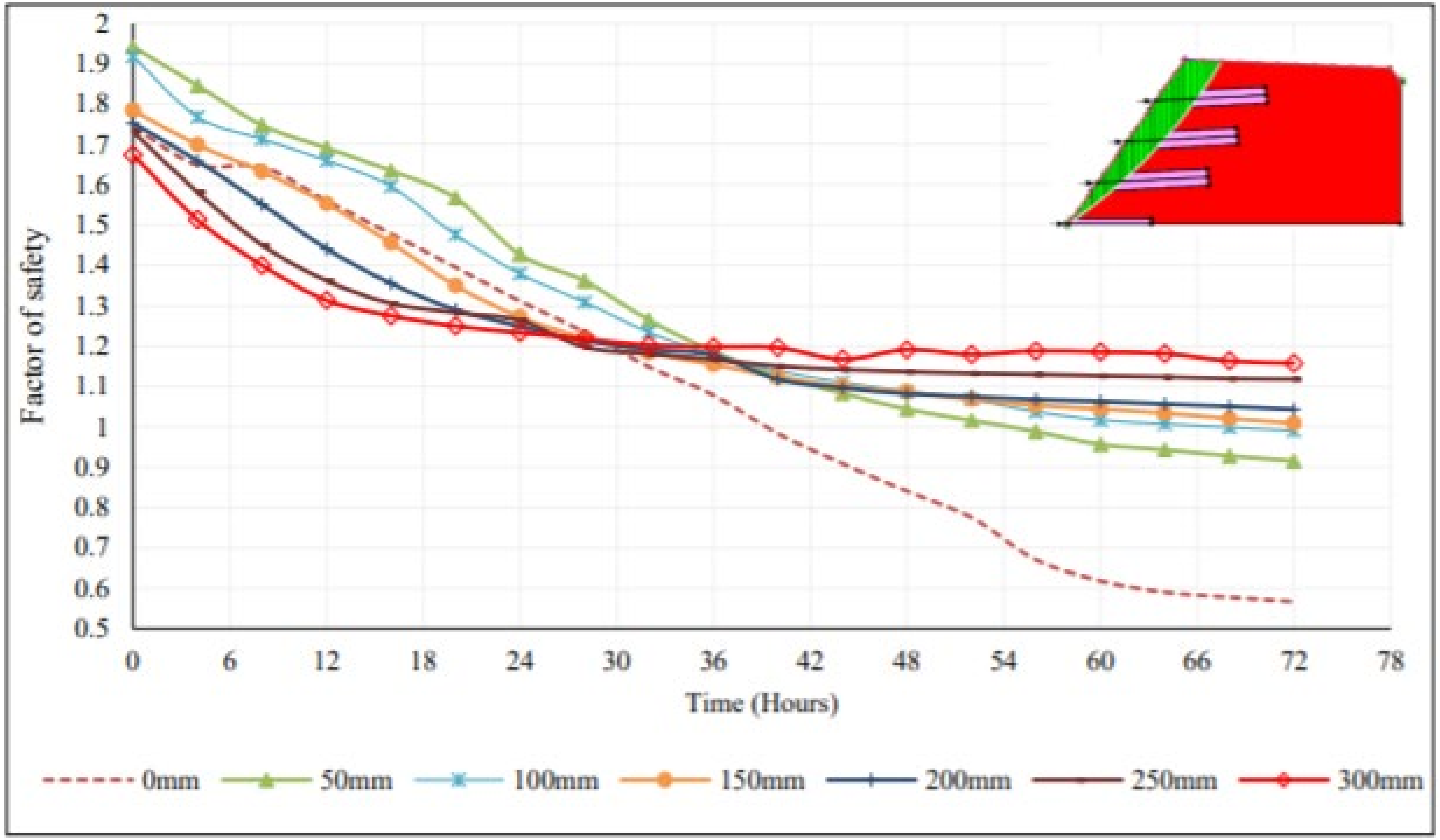


Figure 8. Factors of safety of RCS embankments with varying sand cushion thickness

CONCUSIONS

The behaviour of Lateritic soil (red coffee soil) embankments was numerically investigated and led to the following findings:

1. Non-woven geotextiles inclined at three degrees in RCS laterite embankments made them more effective in draining and dissipation of pore water pressure and became more effective when the soil interface region became saturated.

2. Inclusion of sand layers to sandwich non-woven geotextile material improved drainage consequently enhancing strength and stability of the RCS laterite embankments, with a sandwich thickness of 150mm on either side of the geotextile being adequate.

3. A sand layer of 150 mm thickness sandwiching the non-woven geotextile effectively reduced the amount of sand required to just 15% hence both saving natural resources and protecting the environment from degradation.

THANK YOU

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