Synopsis of the Thesis

Stability Analysis of Non-homogeneous Soil Slopes under Rainfall Conditions

Submitted in Partial Fulfilment of the Requirements for the Degree of

Doctor of Philosophy

by

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Synopsis

Natural slopes are non-homogeneous due to stratifications or variation in different material properties and hydraulic conditions with depth because of various geological formations and climatic conditions. Even in the case of uniform stratification, variations of different hydraulic properties like saturated permeability, and unsaturated permeability function with depth make the slope non-homogeneous in nature. Many slopes have failed due to rainfall infiltration. Presence of a water table divides the slope into saturated and unsaturated zones. Under rainfall conditions, rainwater infiltration occurs leading to the rise of ground water levels as well as the pore water pressures. The rise of pore-water pressures in the unsaturated zone leads to shallow failure of slopes under infiltration conditions. The behaviour of non-homogeneous slopes will be different from that of homogeneous slopes, particularly under rainfall conditions, which may lead to failure under critical situations. Qian et al. (2014) considered simple non-homogeneous two-layered slope commonly encountered in levees with a distinct foundation layer. Arai and Tagyo (1985) considered a three-layered slope with inclined layers. Hammouri et al. (2008) considered a multi-layered slope with the water table and tension crack. Koppula (1984), Chen and Liu (1990) and Kim et al. (2002) have considered the variation of cohesion with depth. Elkateb et al. (2003) suggested that there is a huge scope of work concerning lithological heterogeneity on the total behaviour of non-homogeneous soil media. Present research work targets to investigate the slopes of different configuration under different conditions.

The objective of the present study is to investigate the stability of non-homogeneous slopes of different forms of non-homogeneity, particularly under rainfall conditions. Mainly the heterogeneity arising due to distinct layers (lithologic heterogeneity) in a slope is focussed. The effect of coarse-grained soil (high coefficient of permeability) over fine-grained soil (low coefficient of permeability) and vice versa under infiltration conditions will be studied. Seepage behaviour of such layered configurations and its effect on the stability of the slope will be analyzed. The critical slip surfaces for different types of non-homogeneous slopes has been studied to understand the failure mechanisms.

Three different soils were selected with different mechanical and hydraulic properties to model the non-homogeneous slopes. With the help of numerical models, the effect of infiltration on non-homogeneous layered slopes was studied. Seepage analysis was performed with the finite element method and the stability of the slopes was analyzed utilizing the limit equilibrium method. Parametric studies have been attempted to investigate the influence of rainfall intensity, duration, slope angle, and slope height. The effect of transient seepage under rainfall infiltration is investigated to gain information about the changes in pore-water pressures. The factor of safety, critical slip surface, deformations and strains within the slopes will be studied.

The research work undertaken has been presented in the thesis in the following manner:

Chapter 1 introduces the topic of research, followed by the broad objective of the study and a brief structure of the thesis. **Chapter 2** provides a review of literature relevant to the present area of research. The objectives and detailed scope of work outlined based on the critical appraisal of the literature review. Several researchers considered the soil non-homogeneity in slopes in different ways.

Chapter 3 describes the materials selected for study, their basic characterization, mechanical properties, and hydraulic properties. The methods adopted for stability analyzes using the limit equilibrium method and finite element method have been discussed. To model the non-homogeneous slopes in this study, three different soils were selected. Two of these soils (Soil-1 and Soil-2) were collected locally and various laboratory tests were performed to evaluate their engineering properties. Soil-1 and Soil-2 are classified as silty clay (CL) and silty sand (SM), respectively. Properties of the third soil (Soil-3) were obtained from Kellezi et al. (2005) which was also classified as silty clay, similar to Soil-1. The gradation curves of the soils are represented in Figure. 1. The properties of the soils are tabulated in Table 1. Experimental Soil-water characteristic curves (SWCC) data for the three soils were adopted from Bordoloi et al. (2018). The Soil-water characteristic curves of the three soils were developed as shown in Figure *2*. Morgenstern and Price (1965) method in the limit equilibrium framework and strength reduction technique in the finite element framework for analysing the stability of slope has been explained.

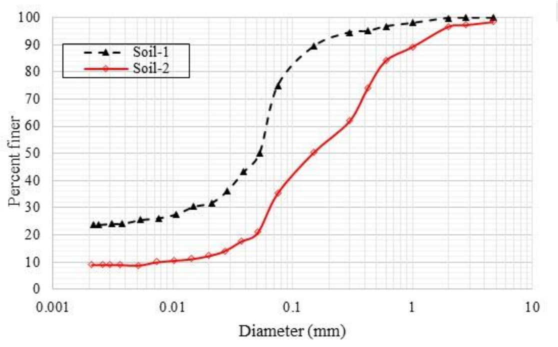


Figure. 1 Particle size distribution curves of the soils used

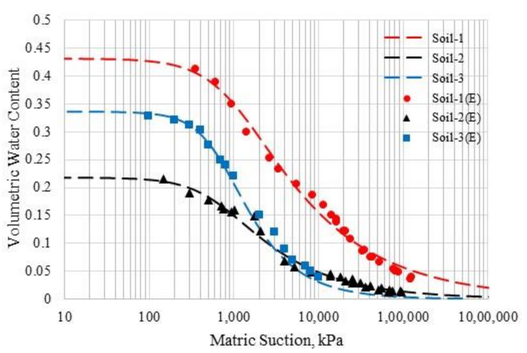


Figure 2 SWCC of the three soils used in the study

Table 1. Properties of soils used in the study

Property	**Soil-1**	**Soil-2**	**Soil-3** (Kellezi et al., 2005)
Specific gravity	2.61	2.44	2.7
Void ratio	-	-	0.78
Liquid limit (%)	46	39	41.5
Plastic limit (%)	23	Non-plastic	23.2
Water content (%)	20.3	10.92	24.6
Maximum dry density (g/cc)	1.58	1.52	-
Optimum moisture content (%)	22.4	14.8	-
USCS classification	**CL**	**SM**	**CL**
γ (kN/m^3)	17.6	16.8	19
c′ (kPa)	10	0	25
ϕ' (^{o})	30	36	18
ϕ^b (^{o})	30	36	18
Saturated hydraulic conductivity, (m/s)	8.38×10^{-6}	6.6×10^{-5}	8.3×10^{-7}

Chapter 4 presents the validation of the methodology adopted and the development of different homogeneous and non-homogeneous numerical models. The models were prepared in SLIDE2 v8 (Rocscience 2018a) and RS2 v9 (Rocscience 2018b). Two models were selected from literature (Low 1989 and by Gasmo et al. 2000) to validate the methods used for stability analysis. Different numerical models were prepared to analyze homogeneous and non-homogeneous slopes. Figure 3a illustrates a two-layered slope with different top layer and foundation layer. The top layer height is varied keeping the foundation layer constant and vice versa. The effect of moisture content on slope stability has been studied with the help of a homogeneous model and a multi-layered model (Figure 3b) with different undrained strengths.

To perform slope stability analysis under rainfall infiltration three different models were prepared. Figure 4a depicts a homogeneous slope with a water table, Figure 4b represents a two-layered slope and Figure 4c show a three-layered slope with a water surface. A typical finite element model prepared in software SLIDE2 v8 (Rocscience 2018a) is shown in Figure 5 (slope angle 35^o and slope height 10 m) to perform the steady-state and transient seepage analysis. A constant total head boundary condition was applied beneath the water table on both the sides of the slope. The portion above the water table was specified as zero nodal flux boundary. To simulate rainfall, the slope surface was specified as flux equal to rainfall intensity of 30 mm/h for 24 hours (short duration).

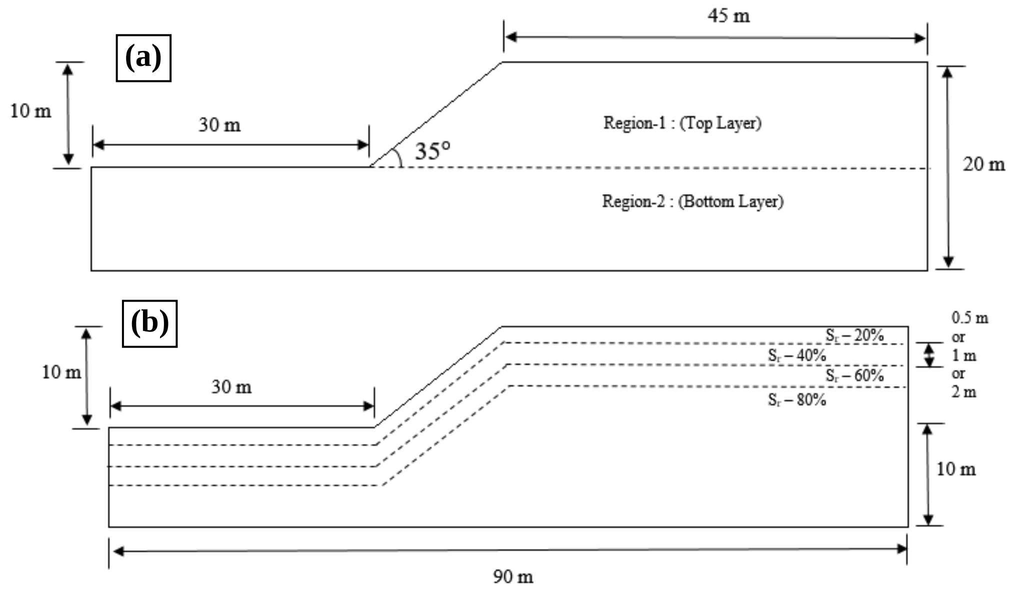
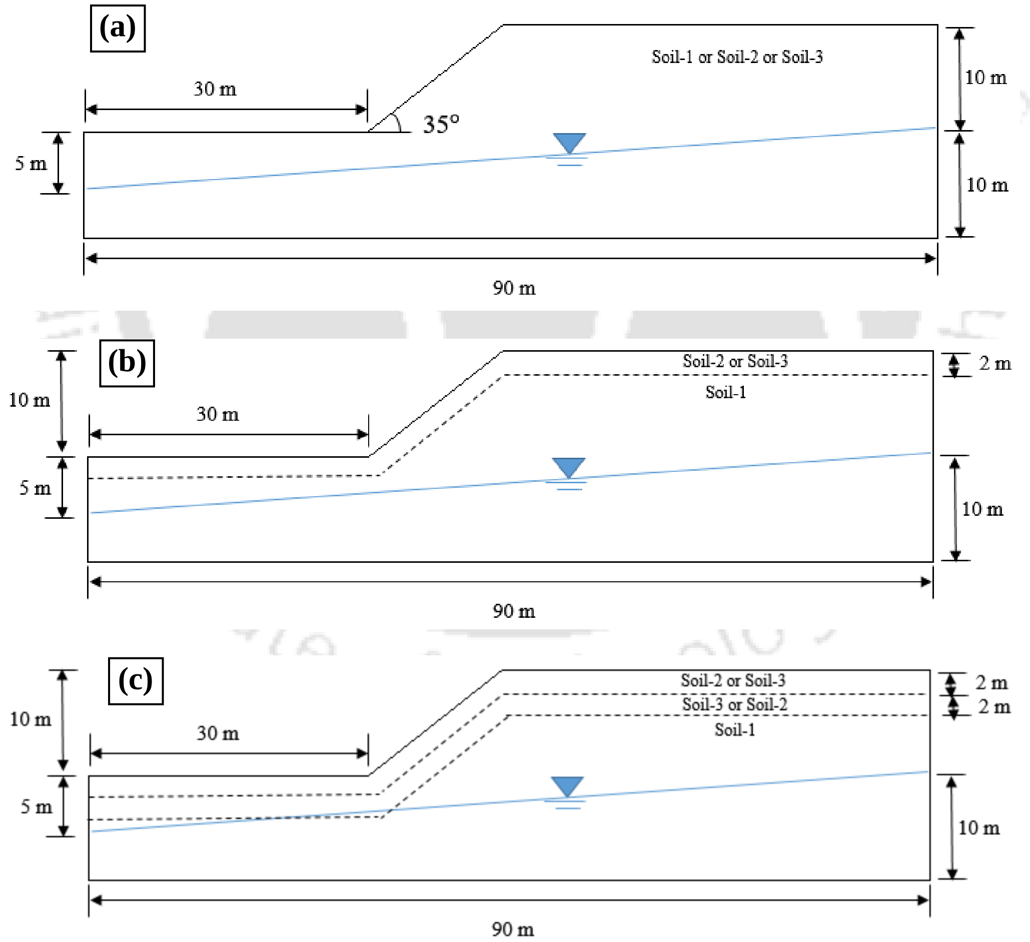


Figure 3 (a) Two-layered non-homogeneous slope model (b) Multi-layered slope model with layers representing different moisture levels increasing with depth



(c)

Figure 4 Models used for infiltration analysis: (a) Homogeneous slope (b) Two-layered slope (c) Three-layered slope

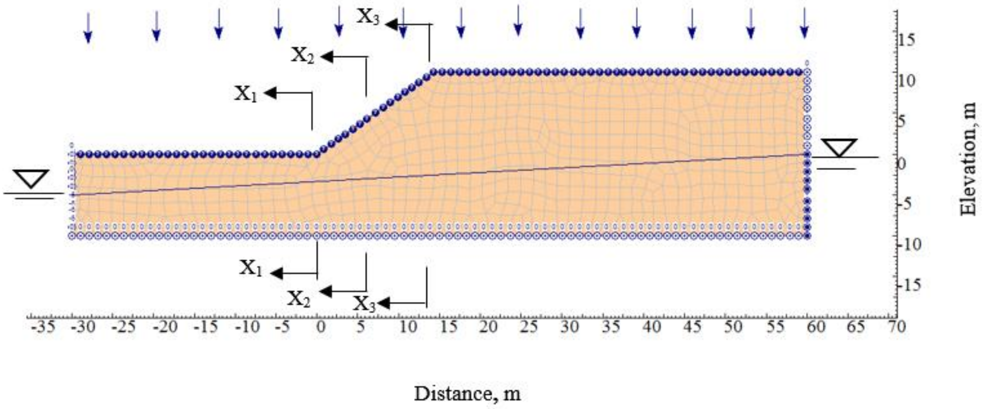


Figure 5 Model of the slope used in study for infiltration analysis

Chapter 5 presents the results of the homogeneous slopes without ground water level (GWL), with GWL and under infiltration conditions. The effects of rainfall intensity, slope height, slope angle and duration of rainfall have been studied under rainfall infiltration. The critical slip surfaces (failure surfaces) of the homogeneous slopes (without GWL) with each of the three soils obtained from LEM analyzes using SLIDE2 are shown in Figure.6. The slip surfaces are evidently different, which can be attributed to the different type of soil in each case. Slopes with Soil-1 and Soil-3 (fine-grained, CL materials) depict rotational failure mechanism (generally observed for finite slopes) while slope with Soil-2 (coarse-grained, SM material) shows translational failure mode (generally observed for infinite slopes).

The variation of factor of safety with moisture content is shown in Figure 7. The slope is having a high safety factor at 0% degree of saturation. With decrease in degree of saturation, the safety factor decreases from 2.294 to 1.1 when the saturation decreases from 0% to 80%. As the moisture content increases in the soil, the material unit weight increases and simultaneously the strength properties decrease which is a reason for the stability of the slope to decrease.

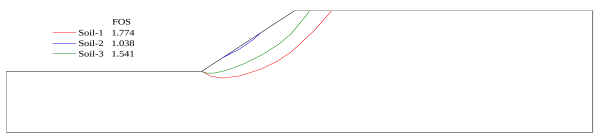


Figure.6 Critical slip surfaces for the homogeneous slopes

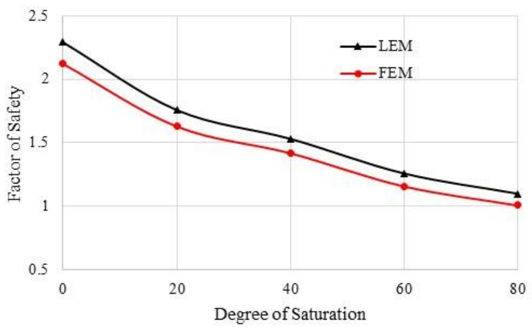
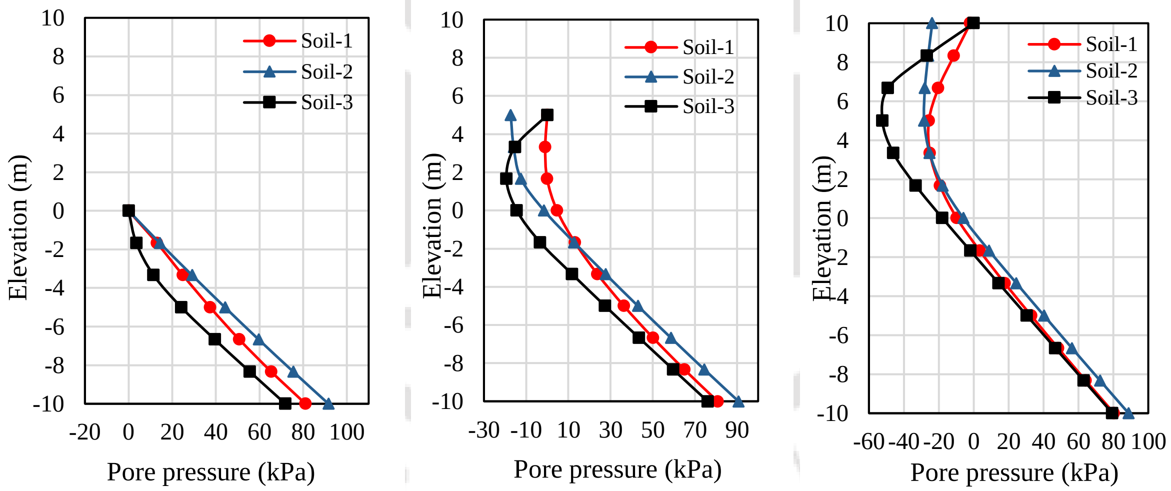


Figure 7 Variation of safety factor with saturation

Figure.8 represents pore-water pressure profiles along vertical sections under rainfall conditions and transient seepage conditions at 24 hours with three different soils for homogeneous slopes. At 24 hours, it is observed that all the three soils have positive pressures at the toe region (Figure.8a), which implies that the water level is touching the toe at this moment. At the mid-slope portion shown in Figure.8b, Soil-1 has positive pore pressures indicating water level at this depth, Soil-2 has negative pore pressure in the region of 17 kPa because the high permeability of the soil allows the water to infiltrate down without saturating the surface. For Soil-3, the pore pressure changes from zero to -19 kPa until 3.3 m depth from the surface and again starts to increase towards the positive values. At the crest portion (Figure.8c), both Soil-1 and Soil-3 exhibit zero suction at the surface where the water saturates the soil due to their low permeability. Soil-2 on the other hand, depict suction value of 25 kPa due to its high permeability. All the three soils exhibit an increase in suction from the surface reaching a maximum value of 52 kPa at 5m by Soil-3 and 28 kPa and 25 kPa by Soil-2 and Soil-1, respectively. The pore pressures become positive at a depth of 12 m from surface representing ground water level.



(a) (b) (c)

Figure.8 Pore-water pressure profiles for homogeneous slopes with different soils after 24 hours along different sections at: (a) Toe, (b) Mid-slope, and (c) Crest

Figure.9 illustrates the variation of a factor of safety with time for three different soils. It is observed that during rainfall infiltration the safety factor of the slope decreases due to a decrease in matric suction, thereby reducing the effective cohesion in the soil. Slope with Soil-2 has the maximum initial factor of safety near to 2.6 which reduced to 1.683 at 24 hours and 1.923 at 48 hours. Out of the three soils, the lowest initial safety factor is denoted by the slope with Soil-3. From 1.996 initially, the safety factor reduces to 1.928 at 24 hours and 1.904 at 48 hrs. The change in safety factor is very small is due to the fact that water is unable to infiltrate due to the low saturated permeability (less than the rainfall intensity) and hence suction doesn't reduce significantly.

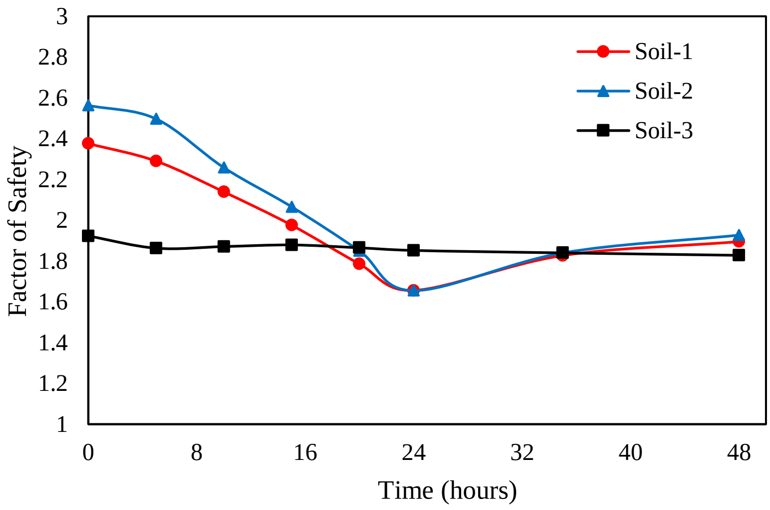


Figure.9 Variation of safety factor with time for the homogeneous slopes

Figure.10 illustrates the change in factor of safety of the slope with slope inclination for the three soils after 24 h of rainfall infiltration. The figure also depicts the initial factor of safety of the three soils before infiltration starts with dotted lines.

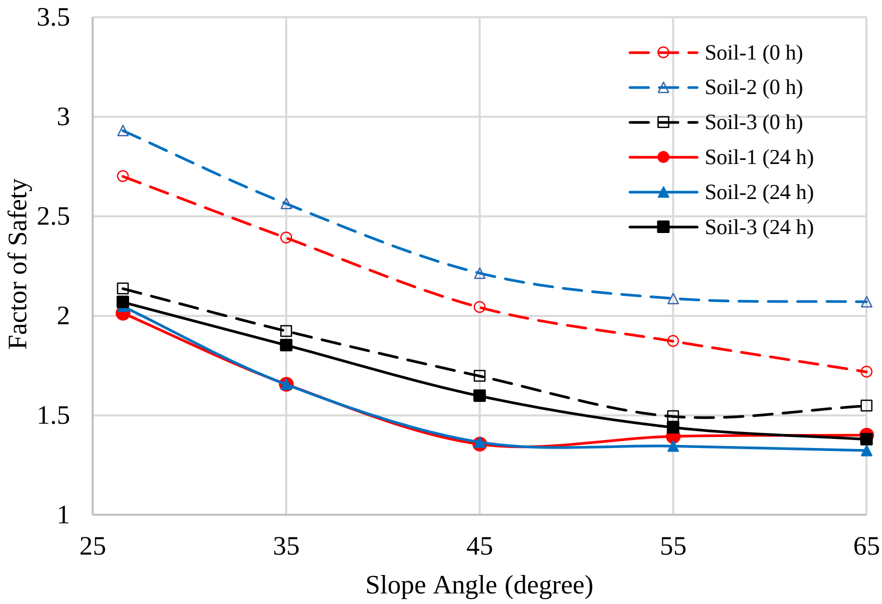


Figure.10 Variation of safety factor with slope angle for the three soils at the initial stage and after 24 h

Chapter 6 illustrate the results of the non-homogeneous slopes without GWL, with GWL, and under infiltration conditions. Two-layered slopes and three-layered slopes were studied with the base soil fixed as Soil-1. The effects of rainfall intensity, slope height, slope angle and duration of rainfall have been studied for two-layered slopes under rainfall infiltration. Critical slip surfaces for different combinations of soil (without GWL) for layer height h = 0.5D are shown in Figure 11. With Soil-1 as the bottom layer and Soil-2 as the top layer, the slip surface (i.e., surface named as 0.5s2s1) is shallow and near the toe of the slope. This is the only case out of four, where the slip surface is translational in nature due to the coarse nature of Soil-2. When Soil-3 is the top layer, the depth of the critical surface (0.5s3s1) increases but stays totally within the top layer itself. This is due to the high strength of the soil in the bottom layer, which has pushed the slip surface towards the top layer. The slip surfaces are controlled mainly by the type of soil present in the bottom layer of the slope. Figure 12 represents maximum shear strains developed for the non-homogeneous slope with fine-grained soil-1 as the bottom layer for layer height h = 0.5D. With Soil-2 as the top layer, the failure zone is concentrated near the surface of the slope depicting a translational type of failure for the coarse-grained soil while with fine-grained Soil-3, the failure zone passes through the toe and is much deeper than the other one.

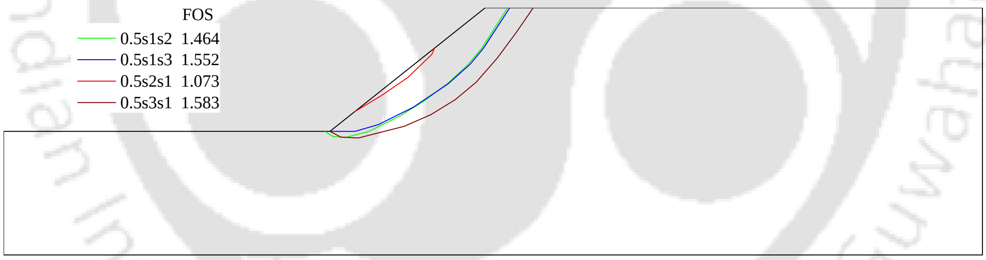
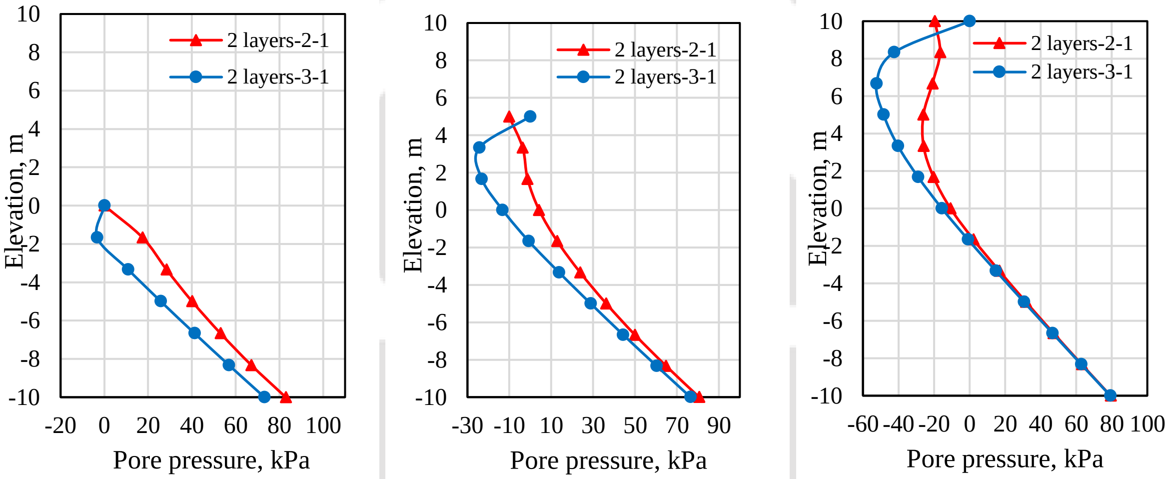


Figure 11 Critical slip surfaces for layer height $h=0.5D$

Figure 12 Maximum shear strain contours for the two-layered slope at $h=0.5D$

There are two models of two-layered slopes (Figure 13) with the bottom layer kept as Soil-1 in both the models, one contains Soil-2 as the top layer (represented by 2 layers-2-1) while the other contains Soil-3 as the top layer (represented by 2 layers-3-1). Figure 13a-c depict the pore-water pressure profiles for the two-layered slopes at three sections (toe, mid-slope, and crest) considered within the slope. The pressure profiles at 24 hours in Figure 13a illustrate that the toe region has positive pore pressures throughout its depth denoting water level is existing at this depth. At the mid-slope portion, (Figure 13b) the slope model (2-1) has a suction value of 10 kPa at the surface, which reduces to zero at 3 m depth from the surface and then follows the pressure profile for Soil-1. The slope model (3-1) has zero suction at the surface, which increases to 24 kPa due to the low permeability of Soil-3 at the top 2 m.



(a) (b) (c)

Figure 13 Pore-water pressure profiles for layered non-homogeneous slopes after 24 hours along different sections at: (a) Toe, (b) Mid-slope, and (c) Crest

Figure 14 represents the variation in factor of safety of the slope models with time. The duration of rainfall is 24 hours after which there is no infiltration. Slope model (2-1) reaches a minimum value of 1.179 at 24 hours and regains its safety factor, which stands at 1.829 at 48 hours. Similarly, the safety factor of slope model (3-1) reduces to 2.216 from 2.411 after 24 hours ultimately reaching a value of 2.199 at 48 hours where the influence of Soil-3 is evident. The reason for the safety factor to decreases with rainfall infiltration is the reduction of matric suction with time, which reduces the effective cohesion of the soil. Once infiltration stops the suction starts to increase, which provides more strength to the slope, and hence the safety factor increases. The figure clearly indicates that presence of different soil layer at the top 2 m of slope significantly affected the *FOS* of the slope, which is attributed to the permeability properties and SWCC of the top layer soil. Figure 15 depicts the critical slip surfaces for the layered slope models after 24h. The slip surface for two-layered slope model (2-1) is relatively shallow because of the rise of water level up to the surface near the toe due to rainfall infiltration. Both the slip surfaces depict toe failure mode. The two-layered slope model (3-1) has a deep failure surface due to its high cohesive strength property.

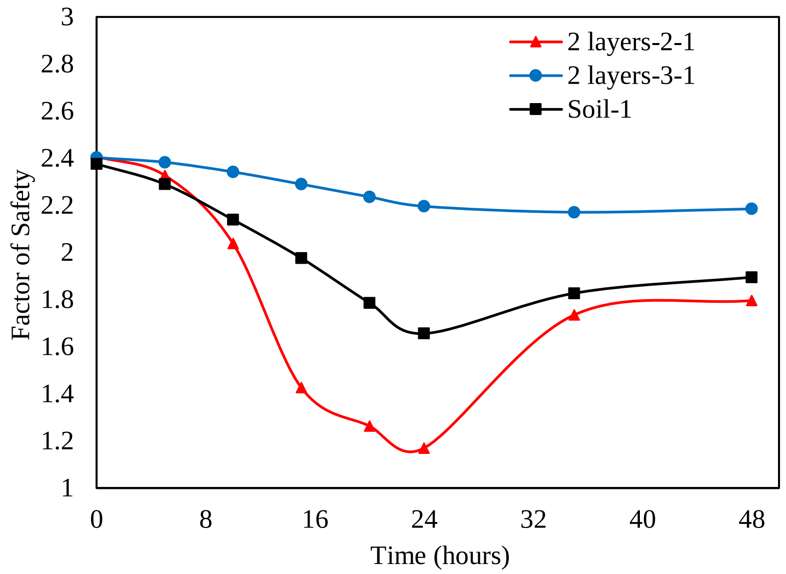


Figure 14 Variation of a factor of safety with time for the non-homogeneous slopes

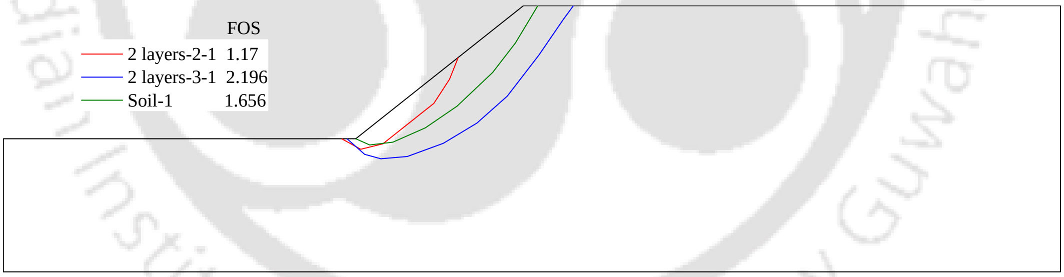


Figure 15 Critical slip surfaces for the non-homogeneous slopes after 24h

Critical slip surfaces under different rainfall intensities for the two-layered slope after 24 h is shown in Figure 16. The slip surfaces for all the intensities represent shallow slope failure except the 10 mm/h intensity. The failure surfaces are confined to the top layer only except the 10 mm/h intensity. The slip surfaces gradually extend towards the crest region with increase in rainfall intensity from 30 mm/h to 200 mm/h.

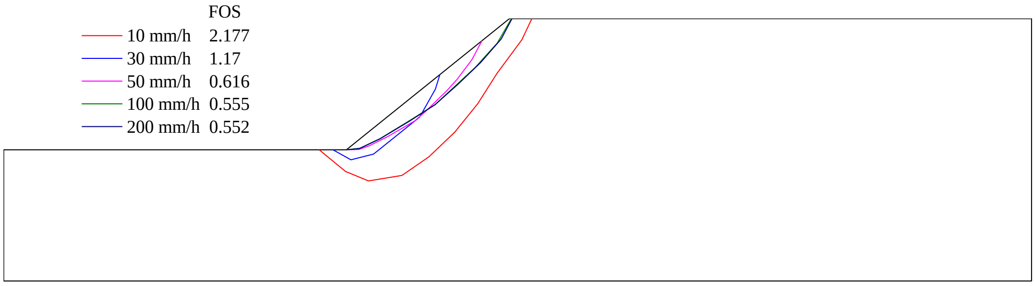


Figure 16 Critical slip surfaces for the two-layered slope after 24 h under different rainfall intensities

Chapter 7 provides the summary and discussion of the work performed in the thesis along with the conclusions and future scope of work. The main findings of the research work are as follows:

- The three soils selected showed distinct failure modes. Fine-grained soil (Soil-1 and Soil-3) showed rotational failure while coarse-grained soil (Soil-2) showed the translational type of failure.
- Consideration of ground water level (GWL) and unsaturated soil characteristics is very essential in the analysis, as the slope behaviour totally depends on the suction levels and the associated shear strength values.
- Under rainfall conditions, different soils performed differently as per their SWCC and permeability functions. Change in the suction levels and GWL levels are significantly different for the three soils adopted for the study, under identical rainfall and geometric conditions.
- For the layered slope profiles, the type of failure is governed by the soil in the top layer for a two-layered slope.
- For layered slopes, the pore-water pressure increase at the surface if there is a high permeable soil (Soil-2) at the top and the pressure decreases if there is a low permeable soil (Soil-3) at the top under infiltration conditions.
- The factor of safety for two-layered slopes is controlled by the soil in the top layer, i.e., if the top layer is of low permeability then the variation in factor of safety with time under infiltration is less due to less water infiltration.
- Critical slip surface for layered slopes was confined to the top layer when the top layer consisted of coarse-grained soil (Soil-2) under rainfall infiltration.

- The stability of the non-homogeneous slope decreased with the increase of slope height when the slope consisted Soil-3 (low k_s) while the stability of the slope with Soil-2 (high k_s) at the top remained constant under rainfall infiltration.

The study highlights the behaviour of different types of soils under rainfall consideration with due importance to unsaturated soil behaviour. As the slope behaviour totally depends on the type of soil exist at the top layers, due consideration shall be given for the non-homogeneous nature including the variation of the moisture levels and the associated changes in suction and permeability characteristics.

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List of Publications

Journal Paper:

1. Chatterjee, D., and Krishna, A. M. (2019) "Effect of slope angle on the stability of a slope under rainfall infiltration." *Indian Geotechnical Journal*, 49(2), 1-10.
2. Chatterjee, D., and Krishna, A. M. (2018) "Stability analysis of two-layered non-homogeneous slopes." *International Journal of Geotechnical Engineering*, 5(1), 1-7.
3. Chatterjee, D., and Krishna, A. M. (2019) "Stability analysis of non-homogeneous slopes under rainfall conditions." Submitted to *International Journal of Geomechanics, ASCE*. (Under review)
4. Chatterjee, D., Sarma, C.P. and Krishna, A. M. (2019) "Effect of moisture content variation on the stability of a slope." Submitted to *Geotechnical and Geological Engineering*. (Under review)

Conference Papers:

1. Chatterjee, D., and Krishna, A. M. (2019) "Stability of two-layered earth slopes under rainfall infiltration." *International Association for Computer Methods and Advances in Geomechanics, IACMAG-2019*. Paper No. 179.
2. Chatterjee, D., and Krishna, A. M. (2016) "Stability analysis of non-homogeneous soil slopes using numerical techniques." *Indian Geotechnical Conference-2016*, IIT Madras, Chennai, India. Paper No. 510
3. Chatterjee, D., and Krishna, A. M. (2015) "Seismic slope stability analysis for layered configurations." *Sixth International Geotechnical Symposium on Disaster Mitigation In Special Geoenvironmental Conditions*, IGS-Chennai-2015, IIT Madras, Chennai, India.
4. Chatterjee, D., and Krishna, A. M. (2014) "Seismic stability analysis of two-layered soil slopes." *North-East Students Geo-Congress on Advances in Geotechnical Engineering* (NESGC-2014**),** Guwahati, India, 18 Oct 2014.