EFFECT OF RAINFALL INTENSITY AND DURATION ON STABILITY OF NATURAL SLOPES OF UNSATURATED FINE SOILS

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Abstract - Rainfall infiltration is a major cause of slope failures in soft and cohesive soils. The water infiltration increases the pore water pressures, ground water level and decreases the matric suction of unsaturated soils, which has been proved as a critical factor for stability of slopes. As a result of increased pore water pressure and decrease in matric suction, the shear strength of the soil decreases which increases the likelihood of the failure of slope. This paper investigates the failure mechanism of natural slopes subjected to high and low intense rainfall with various duration of rainfall events. Finite element analysis was carried out using commercially available PLAXIS 2D software, which is considered to be a comprehensive tool for geotechnical modelling. It was observed that in addition to slope geometry, soil physical characteristics and hydraulic properties, rainfall intensity and duration also play a key role in stability of unsaturated soil slopes.

Keywords- unsaturated slopes, matric suction, pore pressure, slope stability.

1 Introduction

Rainfall-triggered slope failures are widespread geological disasters in many parts of the world, especially in the high tropical areas, which are extensively covered with residual soils. [1]; [2]; [3]. These slope failures are normally shallow with usual depth of slip surface of 1 to 3 m oriented parallel alongside the slope surface [4]; [5]; [6]. During the rainfall events, the water infiltrates into the soil which causes reduction in matric suction, which causes a significant reduction in shear strength of soil and hence failure occurs. [7]; [8]; [9][10][11]. Numerous researchers have conducted numerical studies as well as laboratory experimentations to get detailed understanding of failure mechanisms of slope failures due to rainfall infiltration. (i.e. [12]; [13];[14]). Merat et al. ([15]) conducted a study on 84 landslide events occurs in the Tizi-Ouzou region of North of Algeria, and reported that more than 65% of landslides occur because of climate change including rainfall and snow. The study showed a great relationship between landslides and climate conditions. Stability controlling parameters of slopes, which have been studied by different researchers [16], [15]; [18], include the permeabilities of soils, saturation degree, slope geometry, existence of ground water table, duration and intensity of rainfall event. Various computational programs can be used to simulate the rainfall events for stability analysis including PLAXIS, Geo-Studio, ABAQUS, etc. Usually, limit equilibrium methods are adopted by researchers due to their simplicity, but they have limitations. With advancements in numerical methods, couple flow-deformation analysis options have been included in different tools. It allows researchers to simulate the flow analysis and stability analysis at same time.

A parametric study [15] conducted with different stability controlling factors including the rainfall intensity and duration, degree of saturation, and hydraulic properties of soils concluded that these parameters play an important role in stability of slopes. The pore water pressure varies with variation of these parameters and hence factor of safety varies. [19] conducted finite element modelling for stability analysis of unsaturated soil slopes and reported that rainfall infiltration causes a reduction in matric suction and increase in moisture content, which increase pore water pressure and thus results in reduction of safety factor for slope.

Rainfall events are thought to play a key role in rainfall-induced slope failure due to their intensity, length, antecedent condition, resolution, and pattern. [8], [20], [21]; [22]. Intense rainfall has been identified as a triggering factor for many slope failures worldwide, and it is widely accepted that many slope failures have occurred during prolonged rainfall. [23]. It is well understood that antecedent rainfall significantly contributes to rainfall-induced failures of low-hydraulic conductivity slopes, but probably contributes less significantly to those of high conductivity slopes. [24]. Rainfall resolution is often critical in determining the amount of precipitation infiltration that might contribute to slope failures since rainfall intensity varies. Thus, in the investigation of rainfall-induced slope collapse, using high-resolution rainfall data (hourly rather than daily rainfall data) may yield more accurate results, as suggested by [20]. Furthermore, a specific rainfall pattern caused the least stable slopes, the lowest minimum factor of safety, and the shortest time to reach the minimal factor of safety (high intensities in the beginning, followed by a constant decline towards the end of the rainfall)[21]. The relationship between rainfall events and soil hydraulic characteristics influences the quantity of rainwater penetration required to decrease surficial soil suction, which can cause a slope failure. When the rainfall intensity is almost equivalent to the soil hydraulic conductivity, the incident rainfall can theoretically be completely absorbed into the soils. Rainwater infiltration in this situation is most capable of decreasing surficial soil suction to a critical level. Rainfall of modest intensity will penetrate completely into the surficial soil, but it may not be enough to decrease the soil's suction. When rainfall is especially intense, however, rainwater will move to runoff in part. Because strong rainfall is usually of shorter duration, precipitation penetration may be insufficient to lessen soil suction. Matric suction is a crucial factor in shallow slope failures, according to several studies [12], [25] [26], [8]. When precipitation infiltrates the slope surface, matrix suction decreases and the wetting front slides down until it reaches a depth where the slope's shear strength can no longer sustain slope stability. This type of failure occurs more frequently on slopes with low hydraulic conductivity than on slopes with high hydraulic conductivity, such as clean sand. [12]. Infiltration can only attenuate suction of the surficial soils to shallow depths in the first example, resulting in a shallow slope collapse mechanism. Given the fact that rainfall and soil parameters are the determining factors, coupled investigations of seepage and slope stability are now routinely used to assess rainfall-induced slope instability. In both seepage and slope stability analyses, the deterministic approach is widely used. This paper investigates the failure mechanism of slope subjected to low and high intense rainfall of short and long duration. A uniform soil slope with same shear strength is analyzed using finite element methods. The results of finite element analysis is presented in following sections.

2 Slope geometry and material properties

Commercially available finite element tool PLAXIS 2D was used for this study which is a persuasive program which can help users in characterizing geotechnical problems in a realistic manner. This study investigates the impact of low and high intense rainfall with short and long duration on factor of safety and total displacements. For this purpose, a series of finite element analyses were done. The two-dimensional finite element method was used with 15-node plane strain model using the PLAXIS 2D computer program. The studied parameters include the rainfall intensity (mm/hr), and durations of the rainfall (hours). Figure 1 shows the typical geometry of the slope used in the numerical analysis. Two sets of rainfall events were considered, high-intensity rainfall (60mm/hr, 90mm/hr and 120mm/hr) and low-intensity rainfall (5mm/hr, 10mm/hr and 20mm/hr) with different durations (01hr, 03hrs, 06hrs, 12hrs, 24hrs, 48hrs and 96hrs). The hardening soil model was used to model the nonlinear behavior of the soil. This constitutive model is an advanced soil models and can be used to simulate various types of soil. Published literature provided the material parameters of the soil employed in this investigation. The soil index and shear strength properties are summarized in Table 1 and Table 2, respectively. The Van Genuchten model was used to simulate the soil-water characteristic curve which is a significant parameter in terms of unsaturated slope stability. Figure 1 displays the typical generated mesh for full-scale slope geometry and boundary conditions. The vertical boundaries of the model were supposed to be deformable vertically and fixed laterally, whereas the bottom boundary was assumed to be fully fixed. For the flow water boundary conditions, the vertical boundary conditions were assumed to be permeable and the bottom boundary was assumed to be impermeable. It is assumed that the water table is located 20 m below the ground surface.

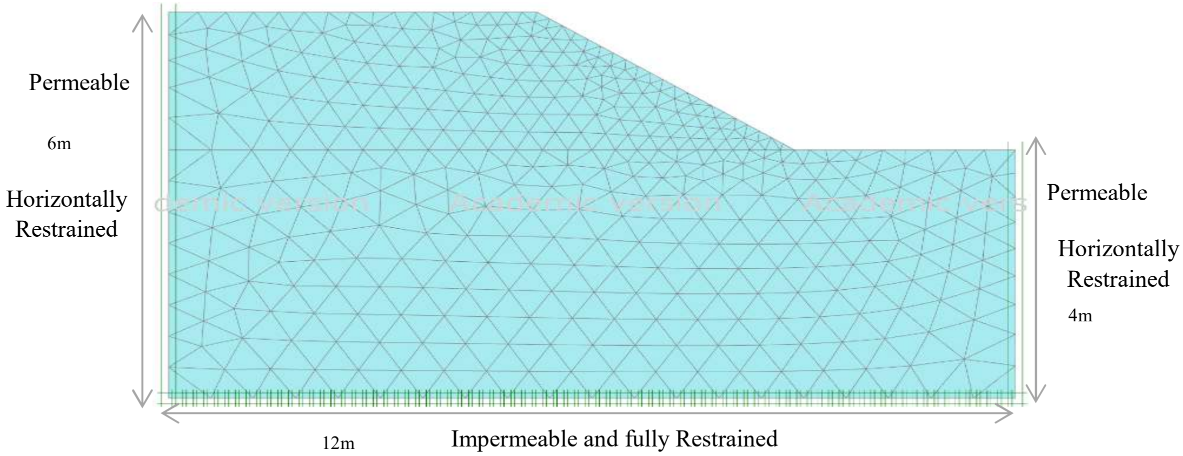


Figure 1: Slope Geometry and typical mesh

Table 1: Index Properties of Soil used for this study [27]

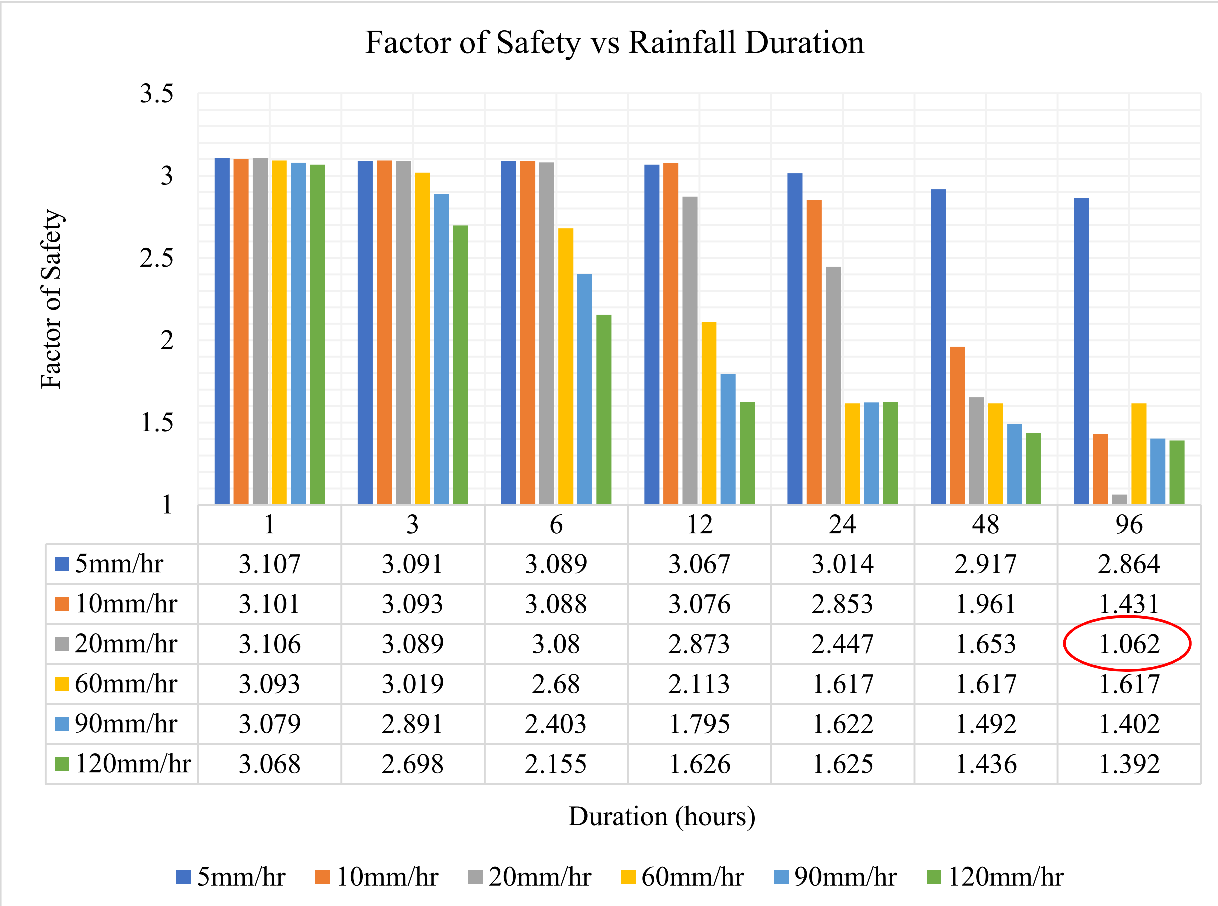
Properties	**Moisture Content (%)**	**Liquid Limit (%)**	**Plastic Limit (%)**	**Soil Classification**	**Specific Gravity**	**Unsaturated unit weight (kN/m^3)**	**Saturated unit weight (kN/m^3)**
Values	32	76	42	High Plastic silt (MH)	2.64	13.2	17.00

Table 2: Shear Strength and unsaturated parameters of Soil used in this study [27]

Parameters	**Young's Modulus (kN/m^2)**	**Effective Cohesion (kN/m^2)**	**Effective friction angle (°)**	**Hydraulic conductivity (m/s)**	**Poisson's ratio**	**g_a**	**g_n**	**g_l**
Values	10000	8.0	32.0	2.32E^{-7}	0.33	0.7	1.8	0.5

3 Results and discussions

Rainfall intensity and duration are the key influencing factors for rainfall induced slope failures. An idealized homogenous slope with gradient of 1V:1.5H was analyzed under different rainfall intensities and duration. The figure 2 shows the rainfall intensity, rainfall durations applied on slope and variations in factor of safety. Rainfall intensity of 5mm/hr, 10mm/hr and 20m/hr are classified as low intense whereas, 60mm/hr, 90mm/hr and 120mm/hr are classifies as high intense. Rainfall with high intensity and short duration does not have a significant effect, whilst rainfall with low intensity and long duration reduces the factor of safety up to the critical condition. This is due to the permeability of soils which allows rainfall water to infiltrate into the slope. For 1 hour duration, the safety factor does not change significantly, as a result of the hydraulic properties of the soil. For rainfall intensity of 5mm/hr, the factor of safety doesn't change significantly because the infiltration of water was not enough to increase pore water pressure up to critical conditions, and hence the slope remains stable with a high safety factor. However, 20mm/hr rainfall intensity was found to be most crucial for slope stability as the safety factor reduced to 1.062 (i.e. on the verge of failure). Rainfall infiltration into the soil body decreases the factor of safety due to the reduction in matric suction and increase in pore water pressure.



	1	3	6	12	24	48	96
5mm/hr	3.107	3.091	3.089	3.067	3.014	2.917	2.864
10mm/hr	3.101	3.093	3.088	3.076	2.853	1.961	1.431
20mm/hr	3.106	3.089	3.08	2.873	2.447	1.653	1.062
60mm/hr	3.093	3.019	2.68	2.113	1.617	1.617	1.617
90mm/hr	3.079	2.891	2.403	1.795	1.622	1.492	1.402
120mm/hr	3.068	2.698	2.155	1.626	1.625	1.436	1.392

Figure 2: Variation in safety factor with different rainfall intensity and duration

3.1 Safety Factors of slope subjected to low and high intense rainfall

To investigate slope instability and the failure zone subjected to rainfall infiltration, the critical slip surfaces were assessed. Figure 3 shows the critical slip surfaces for modelled slope under different rainfall duration (01 hr & 24 hrs) and with higher intensity (120mm/hr) and low intensity (5mm/hr). A shallow slip surface can be seen against short duration while a deep failure surface was observed for prolonged rainfall events. Due to the hydraulic properties of fine soils, the rainfall water takes more time to infiltrate into the slope and hence delayed the failure. The slope remains stable during the rainfall events and fails after some time, depending upon the soil permeability and amount of water infiltrated into the slope. Researchers (Mahmood et al. 2011, Tsaparas et al. 2002) have proved that if the ratio of rainfall and saturated permeability (q/k_{sat}) is higher, less water will infiltrate into the ground and more water will disappear as runoff water and hence slope remain stable. Further, if the ratio is low then more water will infiltrate into the ground, resulting in an increase in pore water pressure which leads to the failure of slope. If the ratio is very low, in case of rainfall with 5mm/hr intensity, then pore water pressure would not be affected.

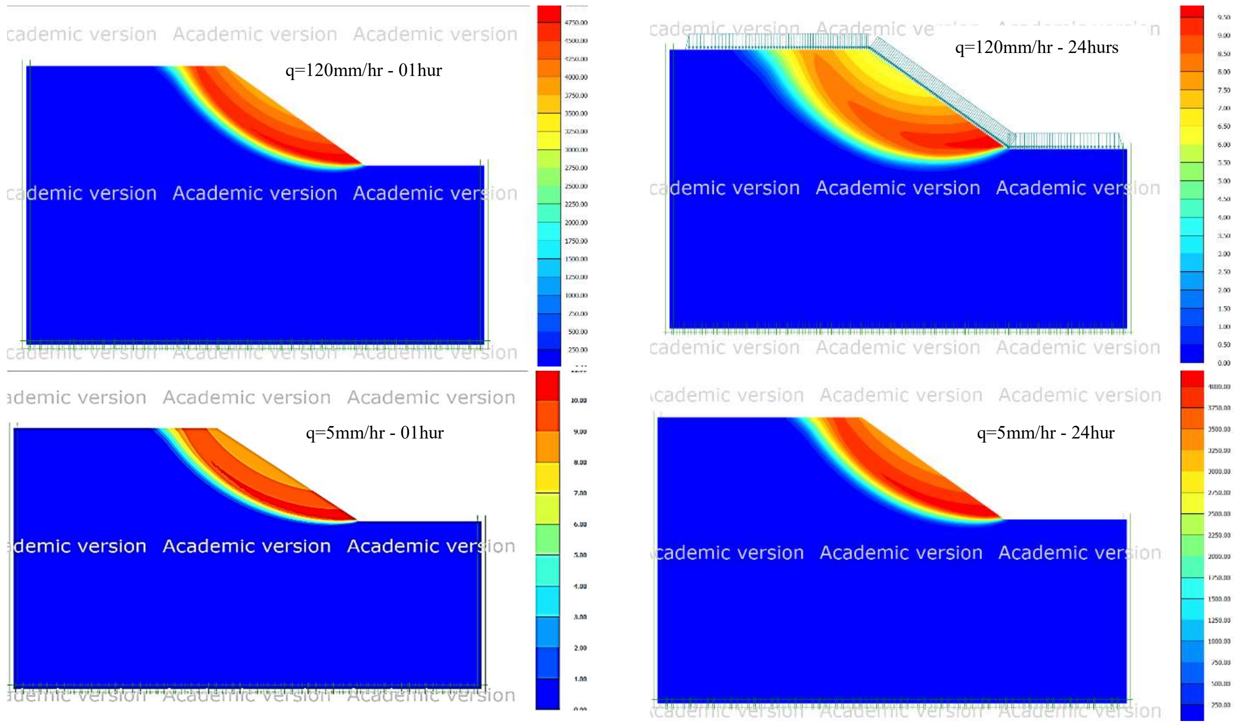
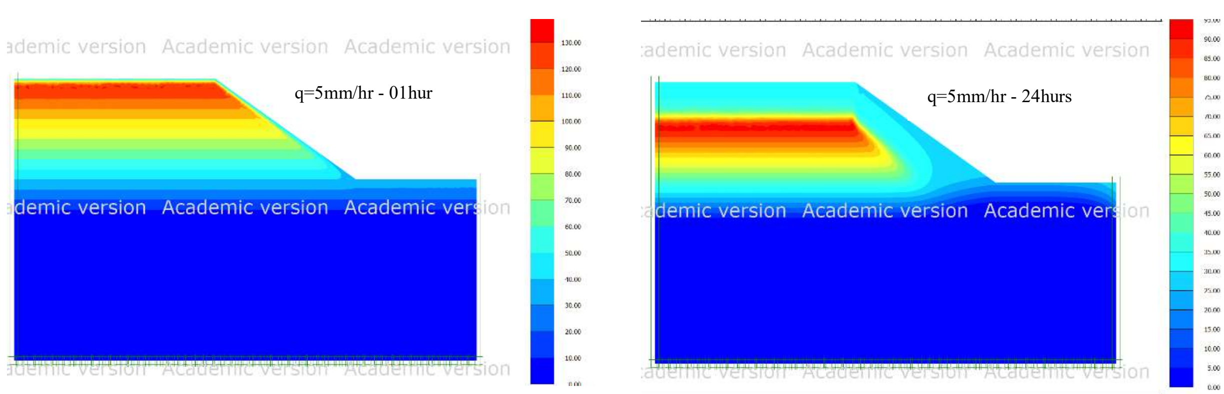


Figure 3: variation in slip surface with rainfall of different duration and different intensities

3.2 Variation in pore water pressure and matric suction

It has been proved that slope failure occurs due to the reduction in matric suction and a resulting increase in pore water pressure. Matric suction is the foremost variable for susceptibility analysis of rainfall induced slope failures. Slope failure is mainly dependent on the initial matric suction conditions of soils at surface and subsurface. Figure 4 shows the fluctuations in matric suction due to the rainfall infiltration. It can be observed that rainfall with short duration does not reduce matric suction significantly, whilst rainfall with longer duration does. Also, it can be seen that matric suction reduction decreased with the slope depth. Maximum suction was observed near the face of the slope whereas, with higher depth, its decreased. This is because of the presence of ground water table at higher depths.



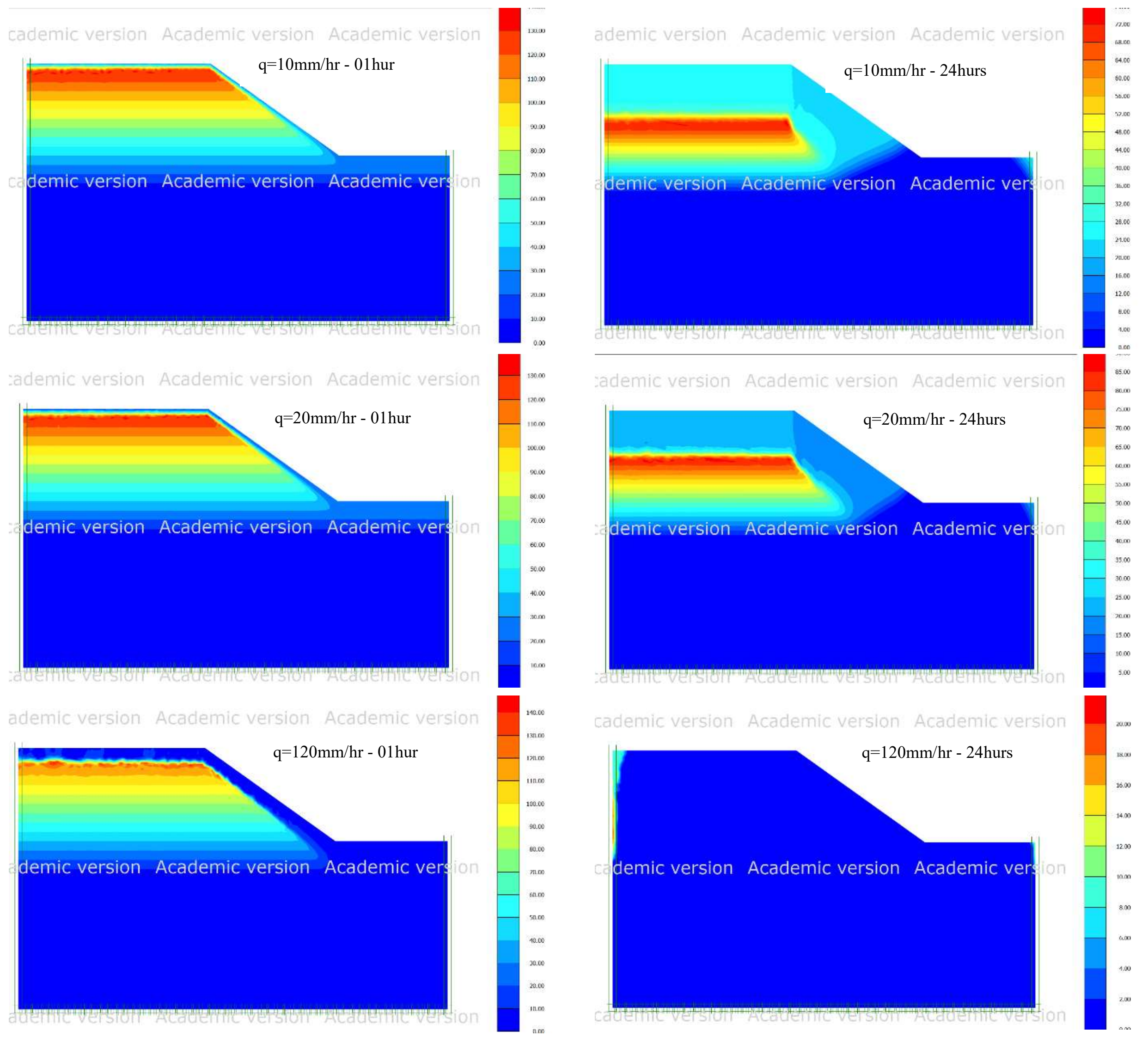


Figure 4: Variation of matric suction with different rainfall intensities and duration

4 Conclusions

The purpose of the current study was to investigate the impact of rainfall duration and intensity on slopes with low hydraulic characteristics. Finite element based numerical analysis was carried out on an idealized slope with 1V:1.5H gradient. Coupled flow-deformation analysis was carried out which allows seepage and deformation analysis at the same time. Based on this study, the following conclusions can be derived:

- In addition to the soil strength characteristics, and slope geometry, rainfall duration and intensity plays an important role in stability of slopes. The amount of infiltration depends on the hydraulic properties of soil.
- The variation in climate changes resulted in variation of matric suction profile with different time durations. There is an optimum value among low rainfall intensities at which the factor of safety is critical. 20mm/hr intensity resulted the minimum factor of safety
- The rainfall with low intensity and prolonged duration are more critical as compared to the high intensity and short duration.

5 Acknowledgment

This study was conducted in Nottingham Trent University and is part of a PhD research project. The authors highly appreciated the support and guidance provided by the University and all technical staff. Moreover, the careful review and constructive suggestions by the anonymous reviewers are gratefully acknowledged.

6 References

[1] E. W. Brand, "Landslides in Southeast Asia, A state-of the art report," 1984.
[2] L. Shaw-Shong, "Slope failures in tropical residual soil," *Trop. Residual Soil Eng.*, pp. 71–102, 2004.
[3] B. B. K. Huat, F. H. Ali, and S. Mariappan, "Effect of surface cover on water infiltration rate and stability of cut slope in residual soils," *Electron. J Geotech Eng*, vol. 10, 2005.
[4] J. R. Muller and S. J. Martel, "Numerical models of translational landslide rupture surface growth," *Pure Appl. Geophys.*, vol. 157, no. 6, pp. 1009–1038, 2000.
[5] J. Kim, S. Jeong, S. Park, and J. Sharma, "Influence of rainfall-induced wetting on the stability of slopes in weathered soils," *Eng. Geol.*, vol. 75, no. 3–4, pp. 251–262, 2004.
[6] Y. Matsushi, T. Hattanji, and Y. Matsukura, "Mechanisms of shallow landslides on soil-mantled hillslopes with permeable and impermeable bedrocks in the Boso Peninsula, Japan," *Geomorphology*, vol. 76, no. 1–2, pp. 92–108, 2006.
[7] D. G. Fredlund and H. Rahardjo, *Soil mechanics for unsaturated soils*. John Wiley & Sons, 1993.
[8] A. B. Fourie, D. Rowe, and G. E. Blight, "The effect of inæltration on the stability of the slopes of a dry ash dump," *Geotechnique*, vol. 49, no. 1, pp. 1–13, 1999.
[9] Q. B. Travis, S. L. Houston, F. A. M. Marinho, and M. Schmeeckle, "Unsaturated infinite slope stability considering surface flux conditions," *J. Geotech. geoenvironmental Eng.*, vol. 136, no. 7, pp. 963–974, 2010.
[10] M. F. Ayazi and A. Tangri, "Stabilization of soil nailed slope by flexible materials," *Mater. Today Proc.*, vol. 49, pp. 1950–1955, 2022, doi: 10.1016/j.matpr.2021.08.134.
[11] M. Nasiri and M. Hajiazizi, "An experimental and numerical investigation of reinforced slope using geotextile encased stone column," *Int. J. Geotech. Eng.*, vol. 15, no. 5, pp. 543–552, 2021, doi: 10.1080/19386362.2019.1651029.
[12] D. Pradel and G. Raad, "Effect of permeability on surficial stability of homogeneous slopes," *J. Geotech. Eng.*, vol. 119, no. 2, pp. 315–332, 1993.
[13] H. Rahardjo, X. W. Li, D. G. Toll, and E. C. Leong, "The effect of antecedent rainfall on slope stability," in *Unsaturated soil concepts and their application in geotechnical practice*, Springer, 2001, pp. 371–399.
[14] J. Zhou, H. Li, Y. Zhou, J. Zhang, and G. Fan, "Initiation mechanism and quantitative mass movement analysis of the 2019 Shuicheng catastrophic landslide," *Q. J. Eng. Geol. Hydrogeol.*, vol. 54, no. 2, 2021.
[15] S. Merat, L. Djerbal, and R. Bahar, "Numerical analysis of climate effect on slope stability," in *PanAm Unsaturated Soils 2017*, 2017, pp. 308–318.
[16] J. M. Gasmo, H. Rahardjo, and E. C. Leong, "Infiltration effects on stability of a residual soil slope," *Comput. Geotech.*, vol. 26, no. 2, pp. 145–165, 2000.
[17] H. Rahardjo, T. T. Lee, E. C. Leong, and R. B. Rezaur, "Response of a residual soil slope to rainfall," *Can. Geotech. J.*, vol. 42, no. 2, pp. 340–351, 2005.
[18] S. Pradhan, D. J. Toll, N. J. Rosser, and M. J. Brain, "Field monitoring of soil-moisture to understand the hydrological response of a road-cut slope.," EDP Sciences, 2020.
[19] C. W. W. Ng and Q. Shi, "A numerical investigation of the stability of unsaturated soil slopes subjected to transient seepage," *Comput. Geotech.*, vol. 22, no. 1, pp. 1–28, 1998.
[20] A. J. Hearman and C. Hinz, "Sensitivity of point scale surface runoff predictions to rainfall resolution," *Hydrol. Earth Syst. Sci.*, vol. 11, no. 2, pp. 965–982, 2007.
[21] A. Rahimi, H. Rahardjo, and E.-C. Leong, "Effect of antecedent rainfall patterns on rainfall-induced slope failure," *J. Geotech. Geoenvironmental Eng.*, vol. 137, no. 5, pp. 483–491, 2011.
[22] S. Pradhan, D. G. Toll, N. Rosser, and M. J. Brain, "An investigation of the combined effect of rainfall and road cut on landsliding," *Eng. Geol.*, p. 106787, 2022.
[23] C. I. Massey, D. N. Petley, and M. J. McSaveney, "Patterns of movement in reactivated landslides," *Eng. Geol.*, vol. 159, pp. 1–19, 2013.
[24] I. Tsaparas, H. Rahardjo, D. G. Toll, and E.-C. Leong, "Infiltration characteristics of two instrumented residual soil slopes," *Can. Geotech. J.*, vol. 40, no. 5, pp. 1012–1032, 2003.
[25] H. Rahardjo and D. G. Fredlund, *Soil Mechanics for Unsaturated Soils*. New York; Toronto: Wiley, 1993.
[26] S. W. C. Au, "Rain-induced slope instability in Hong Kong," *Eng. Geol.*, vol. 51, no. 1, pp. 1–36, 1998.
[27] R. Ullah, R. Abdullah, A. Kassim, N. Z. M. Yunus, and H. Sendo, "ASSESSMENT OF RESIDUAL SOIL PROPERTIES FOR SLOPE STABILITY ANALYSIS," *GEOMATE J.*, vol. 21, no. 86, pp. 72–80, 2021.