Stability Analysis of Rainfall-Triggered Landslides Considering the Previous Climatic Conditions

Ming Peng[1,2(✉)], Bingxin Li[1,2], and Zhenming Shi[1,2]

[1] Department of Geotechnical Engineering, Tongji University, Shanghai 200092, China
pengming@tongji.edu.cn
[2] Ministry of Education Key Laboratory of Geotechnical and Underground Engineering, Tongji University, Shanghai 200092, China

Abstract. In the past few decades, extreme rainstorms and dry weather have been occurring frequently. Despite of lots of studies on slope stability analysis, however, the study of rainfall-triggered landslides under the influence of the previous climatic conditions is less considered. This paper presents a case study on a rainfall induced landslide by taking account of three typical previous climatic conditions: normal climatic condition, extreme drought condition and extreme wet condition. Rainfall infiltration and slope stability analysis are conducted within the finite element software of Geostudio with different rainfall intensity. The analysis results demonstrate: under normal climatic condition, the rainfall intensity has no significant influence on the slope stability. Under extreme drought condition, due to the initial infiltration rate of soil is very small, long term and short intensity rainfall is easy to cause shallow landslides; short term and large intensity rainfall will result in large runoff flood. Under extreme wet condition, long term and short intensity rainfall will significantly reduce the stability of the slope, leading to deep landslides.

Keywords: Climate environment · Rainfall infiltration · Unsaturated soils
Slope stability

1 Introduction

Over the past century, the global climate change has frequently caused extreme weather events. According to the changes of temperature, rainfall and evaporation in Hong Kong area in recent decades, the trend of climate warming and frequent changes directly show the phenomena [1]. In recent years, the research on the mechanism of geological disasters caused by climate change has attracted the attention of scientists all over the world, and has become an important scientific problem in the field of geological disaster research. Wang [2] proposed the concept of extreme geological disasters and gave a grade to assess the risk of disasters. Zhang et al. [3] analyzed the effect of climate on the generation of possible geo-hazards. The previous researches are only through statistical methods to analyze the relationship between the occurrence of geological disasters and climate fluctuations. Griffiths et al. [4] analyzed the stability of

A. Farid and H. Chen (Eds.): GSIC 2018, *Proceedings of GeoShanghai 2018 International Conference: Geoenvironment and Geohazard*, pp. 233–239, 2018.
https://doi.org/10.1007/978-981-13-0128-5_27

unsaturated slopes under steady seepage and evaporation conditions by the mean of finite element method. However, the existing researches only study the effect of rainfall and evaporation characteristics on the stability of unsaturated slope, rarely considering previous climatic conditions. Therefore, this paper studies the influence of rainfall on slope stability under three previous climatic conditions.

This paper presents a case study on a rainfall induced landslide by taking account of three typical previous climatic conditions. Rainfall infiltration and slope stability analysis are conducted within the finite element software of Geostudio with different rainfall intensity.

2 Numerical Analyses

2.1 Saturated-Unsaturated Slope Model

This paper takes the Sau Mau slope in Hong Kong as the research slope model. The height of the slope is 30 m, and the slope angle is 32° (Fig. 1a). The slope consists of two soil layers; the upper layer is silt, with a porosity ratio of 0.7 and a saturated permeability of 4.93×10^{-6} m/s. The lower layer is clay, with a porosity ratio of 0.8 and a saturated permeability of 8.74×10^{-9} m/s. The following Table 1 shows the typical physical and mechanical parameters of the two soils. The boundary conditions are shown in Fig. 1b. The ground surface is subjected to either evaporation or rainfall infiltration. When the rainfall intensity is less than the saturation permeability of the surface soil, it is set to the flow boundary, otherwise the head boundary. The two sides of the slope below the initial ground water table are set to the head boundary and above the initial ground water table are set to zero flow boundary. The bottom boundary is impervious. The model uses unstructured quadrilateral and triangular meshes. As the surface conditions vary with climatic conditions, in order to deal with such a sharp boundary changes, the grid within 1 m of the slope surface is encrypted, with a total of 2975 units.

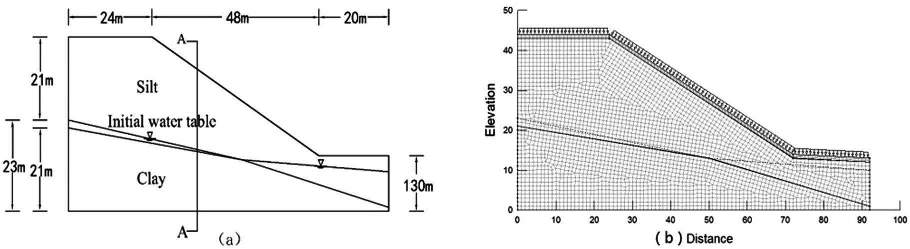

Fig. 1. Slope model: (a) Profile of the soil slope, (b) Boundary conditions and FE discretization

In the study, the soil-water characteristic curves and permeability functions for the two soils, shown in Fig. 2, are generated based on the residual saturation, porosity ratio and saturated permeability values following the methods developed by Fredlund and Xing [5, 6].

Table 1. Soil types and properties considered in slope stability analyses

Soil type	e	S_r (%)	k_s (m/s)	φ' (deg)	c′ (kPa)	γ (kN/m^3)
Silt	0.7	10	4.93E-06	30	5	20
Clay	0.8	15	8.74E-09	20	10	20

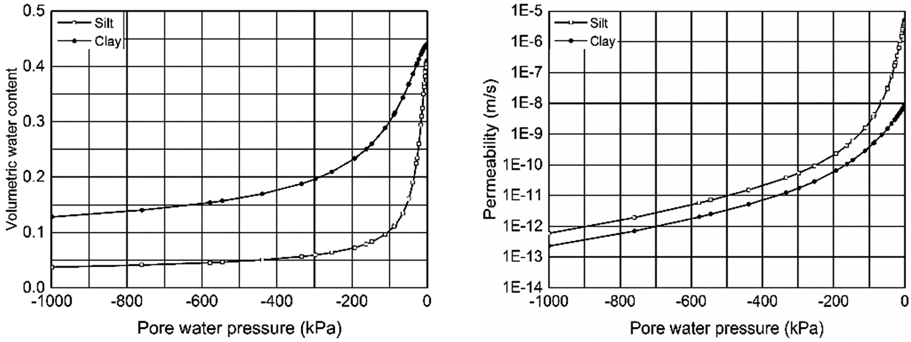

Fig. 2. The soil-water characteristic curves and permeability function for the slope soils

The constitutive equation is proposed by Fredlund and Morgenstorn [7] for unsaturated soils.

$$\varepsilon = C_t d(\sigma - \mu_a) + C_a d(\mu_a - \mu_w) \quad (1)$$

C_t and C_a are, respectively, compressibility of the soil structure with respect to changes in $(\sigma - \mu_{w})$ and $(\mu_a - \mu_{w})$, μ_a is the air pressure, and μ_w is the pore water pressure.

2.2 Simulate Previous Climatic Conditions

Three previous climatic conditions are normal climatic condition, extreme drought condition and extreme wet condition. The finite element analysis software Geostudio is employed to produce the distribution of initial pore water pressure to simulate previous climatic conditions by evaporation or rainfall infiltration, which is used to analyze rainfall infiltration and slope stability.

Normal Climatic Condition

The transient seepage analysis module is used to set initial ground water table and then automatic generate the distribution of initial pore water pressure to simulate normal climatic condition.

Extreme Drought Condition

The slope was continuously evaporated with the annual average rate of evaporation, 1402 mm/year, for 60 days on the basis of the normal climatic condition, using the transient seepage analysis module [8].

Extreme Wet Condition
The slope was subjected to a rainfall with the intensity of 17 mm/h for 7 days and then the water naturally infiltrate into the ground water table (i.e. in 13 days) on the basis of the normal climatic condition.

2.3 Rainfall Characteristics

The rainfall intensities respectively are 12, 24 and 36 mm/h. Because rainfall patterns may have potential effects on slope stability, it is assumed that rainfall intensity is constant. The total rainfall amount is set to 144 mm in the three cases.

3 Results and Discussion

3.1 Distributions of Pore Water Pressure

This section studies the influence of rainfall on the distribution of pore water pressure of slope under different previous climatic conditions. The following Fig. 3 shows the distributions of pore water pressure in different cases.

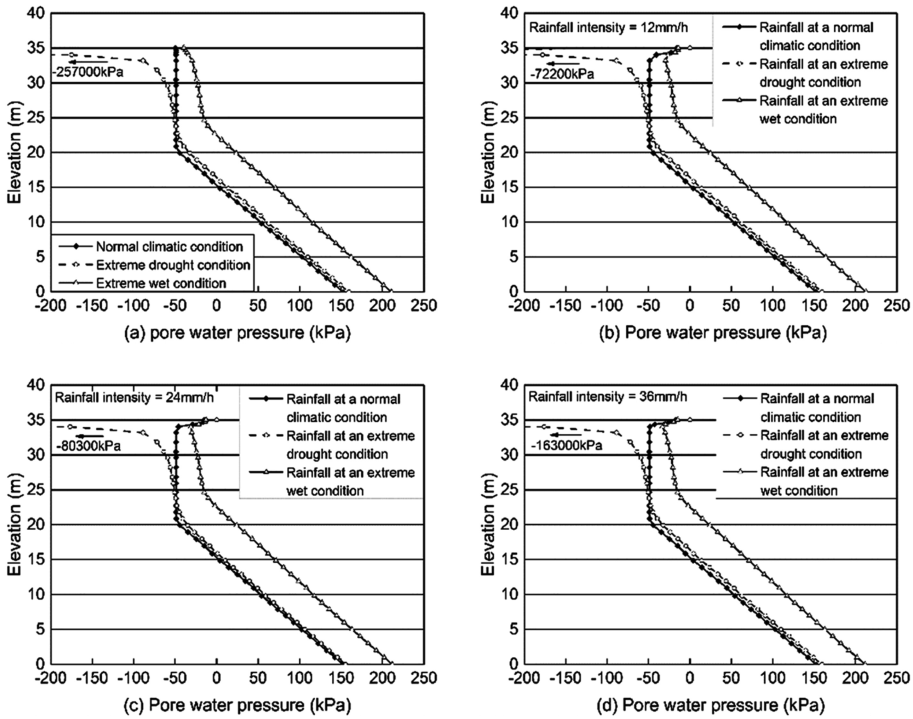

Fig. 3. Distributions of pore water pressure in the slope under different previous climatic conditions (a) 0 mm/h, (b) 12 mm/h, (c) 24 mm/h, (d) 36 mm/h

Given a rain event of a limited duration, the distribution of pore water pressure show that:

1. Under normal climatic condition, the pore water pressure of the soil on the surface increases during the rainfall process. With the increase of rainfall intensity, the depth of rainfall infiltration decreases because of the occurrence of runoff.
2. Under extreme drought condition, the pore water pressure of the soil on the shallow layer quickly becomes saturated during the rainfall process. The suction of the soil below the shallow layer is very large, which hinders further infiltration. Rainfall mainly affects the stability of slope surface.
3. Under extreme wet condition, the variation trend of pore water pressure on the slope surface soil is similar to that under normal climatic condition. The pore water pressure of slope soil is generally high.

3.2 Stability of Slope

In this section, the influence of different rainfall intensity on slope stability and slope failure form is discussed under different previous climatic conditions. Note the rainfall amount as a constant value of 144 mm (Fig. 4).

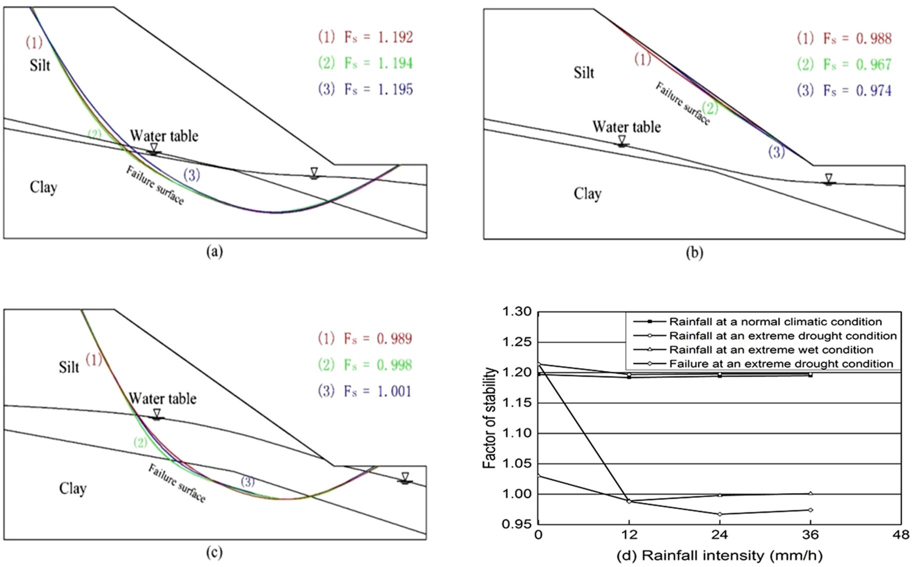

Fig. 4. Sliding surfaces of different rainfall intensity under different previous climatic conditions (a) Normal climatic condition, (b) Extreme drought condition, (c) Extreme wet condition, (d) Factor of stability

1. Under normal climatic condition, because the rainfall amount is limited to 144 mm, the slope stability is only a small drop during the rainfall process. The influence of different rainfall intensity on slope stability is very small (Fig. 4a).

2. Under extreme drought condition, because of the limited rainfall, the slope has remained stable during the rainfall process, but it is prone to cause debris flow. In order to study the failure forms of slope, different intensities of rainfall are applied until the slope is destroyed. (1) The rainfall intensity of 12 mm/h, when the rainfall reaches 288 mm, the slope is shallow sliding. (2) The rainfall intensity of 24 mm/h, when the rainfall reaches 384 mm, the slope is shallow sliding. (3) The rainfall intensity of 36 mm/h, when the rainfall reaches 360 mm, the slope is shallow sliding (Fig. 4b).
3. Under extreme wet condition, the stability of the slope is at the critical state. During the rainfall process, the slope is prone to deep sliding failure. The influence of rainfall intensity on slope stability is not significant with the same rainfall amount (Fig. 4c).

3.3 Analyses of Runoff

The pore water pressure is closely related to the permeability of unsaturated soil. Meanwhile, the rainfall intensity also determines the amount of rainfall infiltration. The variation of runoff rate with time in the A-A profile is as follows (Fig. 5).

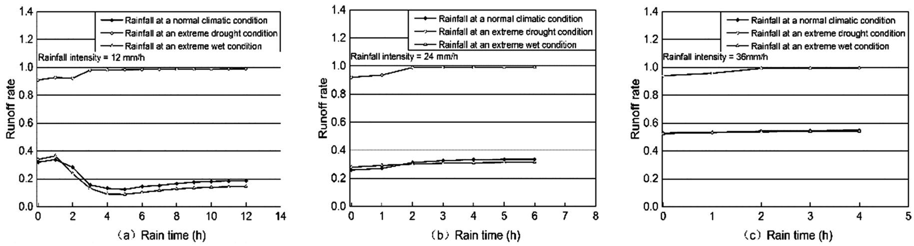

Fig. 5. Runoff rate and cumulative runoff unit area under different previous climatic conditions (a) 12 mm/h, (b) 24 mm/h, (c) 36 mm/h

1. Under normal climatic condition, with the development of rainfall infiltration, the permeability of soil in the slope surface is increased. When the rainfall intensity is 12 mm/h, most of the rainfall infiltrates into the slope, and a small part of rainfall flows in the form of runoff. With the increase of rainfall intensity to 36 mm/h, the runoff rate gradually increased to about 50%, and more than half of the rainfall infiltrates into the slope.
2. Under extreme drought condition, due to the low permeability of the surface soil, rainfall mainly flows in the form of runoff. Under different rainfall intensity, the runoff rate is over 90%. Therefore, a low intensity but longer duration of rainfall is more likely to cause large scale runoff, which can lead to urban waterlogging.
3. Under extreme wet condition, the surface soil is nearly saturated, besides the runoff rate is over 50%. Under different rainfall intensity, rainfall mainly infiltrates into the slope, and its runoff rate is similar to normal climatic condition.

4 Conclusion

In this paper, three typical previous climatic conditions are considered, and the mechanism of rainfall induced landslide under different climatic conditions is studied:

(1) Under normal climatic condition, the effect of different intensity rainfall on slope stability is not significant under the same rainfall amount. More than half of the rainfall infiltrates into the slope.
(2) Under extreme drought condition, rainfall is difficult to infiltrate into the slope. During the rainfall process, the slope has remained stable during the rainfall process, but it is prone to cause debris flow. The long duration rainfall will result in the shallow sliding.
(3) Under extreme wet condition, the ground water table rises, and the surface soil is nearly saturated. Therefore, a low intensity but longer duration of rainfall is more likely to cause deep sliding.

Based on two-dimensional rainfall infiltration, this paper analyses the stability of rainfall-triggered landslides considering previous climatic conditions. Further study will consider the stability of unsaturated slope under the three-dimensional rainfall infiltration and dynamic change of rainfall intensity with time.

References

1. Leung, Y.K., Yeung, K.H., Ginn, E.W.L., Leung, W.M.: Climate change in Hong Kong, Hong Kong Observatory Technical Note No. 107 (2004)
2. Wang, S.: Extreme Geo-disasters and risks. J. Eng. Geol. **19**(3), 289–296 (2011)
3. Zhang, L.M.: Analysis of geo-hazards caused by climate changes. In: Tenth International Symposium on Landslides and Engineered Slopes (2008)
4. Griffiths, D.V., Lu, N.: Unsaturated slope stability analysis with steady infiltration or evaporation using elasto-plastic finite elements. Int. J. Numer. Anal. Meth. Geomech. **29**(3), 249–267 (2005)
5. Fredlund, D.G., Xing, A.: Equations for the soil-water characteristic curve. Can. Geotech. J. **31**(4), 521–532 (1994)
6. Fredlund, D.G., Xing, A., Huang, S.: Predicting the permeability function for unsaturated soils using the soil-water characteristic curve. Can. Geotech. J. **31**(4), 159A (1994)
7. Fredlund, D.G., Morgenstern, N.R.: Constitutive relations for volume change in unsaturated soils. Can. Geotech. J. **13**(3), 261–276 (2011)
8. National Standard of People's Republic of China GB/T 20481-2006: The grade of meteorological drought. China Standard Press, Beijing (2006)