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ORIGINAL PAPER

Effects of seepage on a three-layered slope and its stability analysis under rainfall conditions

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Abstract

The seepage and stability of unsaturated soil slopes under torrential rain conditions are key issues in geotechnical and hydraulic engineering. In this work, based on the generalized limit equilibrium method, the stability of nonhomogeneous slopes with three layers was investigated. The effects of rainfall on the volume water content, pore water pressure and the stability of the slope were evaluated, and rainfall cycles and rainfall intensities were considered. The results show that the stability of the slope decreased with increasing rainfall intensity until it was destroyed. The safety factor of the slope is lowest in a period of time after the rain stops. This condition means that the slope is more prone to damage. The seepage field and stress field of the slope were significantly changed with increasing rainfall, and finally, the slope became unstable.

Keywords Slope stability · Rainfall · Finite element method · Safety factor

1 Introduction

In recent years, slope stability has been an important part of geotechnical and hydraulic engineering research (Abusharar and Han 2011; De Vita et al. 2013; Cao et al. 2017). It is of great significance for prevention from geological disasters and ensuring the safety of engineering. The stability of a slope is affected by many factors, such as the physical properties of the slope, the strength parameters of the soil, the slope geometry, rainfall and construction methods (Lim et al. 2015; Srivastava et al. 2010; Oh and Vanapalli 2010). These effects are highly correlated with each other. Hence, it is difficult to evaluate the stability of slopes. Many studies have focused on the combined effects of multiple factors on slope stability. Tschuchnigg et al. (Tschuchnigg et al. 2015a, b) studied the factors affecting the safety factor (Fs), such as grid dispersion, dilatancy angle, and friction angle. In addition, the Davis method was

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adopted to accurately estimate the Fs of extreme slopes (Lee 1968). Egeli and Pulat examined the variation in slope angle and its effect on slope stability during high-intensity rainfall (Egeli and Pulat 2011). Cho investigated the effect of the interaction between air and water during heavy rainfall on the stability of unsaturated soil slopes (Cho 2016). In summary, the current research on homogeneous slopes is comparatively mature. However, there are many slopes whose soil properties change with different spatial locations. Such slopes are called heterogeneous slopes. Therefore, it is necessary to explore the stability of multilevel slopes.

With the rapid development in infrastructure, many slope instability problems have emerged. Landslide development is strongly related to rainfall intensity, the mechanical properties of rocks, groundwater, boundary conditions, and the initial state of the slope. Among a diverse range of effecting factors, seepage is considered as a significant contributor to landslide formation and dynamics. Rainfall is one of the key external factors in the formation of landslides (Yang et al. 2017). With the increased pore water pressure and groundwater table, the increased soil matrix suction and shear strength may affect soil instability (Liu and Li 2015). Rainfall affects the stability of the slope by inducing the flow of landslides (Wang and Sassa 2001; Sorbino and Nicotera 2013). Bittelli et al. and Song et al. (Bittellia et al. 2012; Song et al. 2016) monitored the cause of landslides occurring in the field. The dominant factors triggering landslides were water infiltration and redistribution mechanisms within micro- and macroporosity rather than cumulative rainfall (Xiao et al. 2016). The slope stability of a two-layered undrained clay slope was previously studied (Lim et al. 2015). However, little information is available about the influence of rainfall intensity and period on the stability of a three-layered slope.

The essence of slope stability is the coupling of the seepage field and stress field (Xushu et al. 2012). The influence of rainfall infiltration on the stability of a slope mainly includes the following factors: the effect of hydrostatic pressure and dynamic water pressure caused by groundwater infiltration on the slope during rainfall infiltration, the weakening action of the slope material by the transient saturated areas generated by the saturated–unsaturated seepage field, and the effect of media suction on the stress field of the slope (Huang et al. 2017). Groundwater is replenished by rainfall. Groundwater alters the structure of the material by chemical or physical influences and applies dynamic and hydrostatic pressure to materials, resulting in changes in the stress field (Lu et al. 2012). The stress field affects the seepage field through the compressibility of the medium. The coupling effect of the seepage field and stress field should be considered in the analysis of slope stability under rainfall.

Many methods are used to calculate slope stability (Xiao et al. 2016; Hajiazizi and Tavana 2013; Tschuchnigg et al. 2015a, b; Sun et al. 2016; Li et al. 2016; Sun et al. 2016; Chen et al. 2014; Cai and Ugai 2004). In this work, the stability of a three-layered slope under torrential rain conditions was studied. Rainfall period and density were considered. The physical parameters of the three layers of the slope were also differentiated. The generalized limit equilibrium method was adopted to calculate the Fs. The effects of rainfall cycle and density on the volume water content, pore water pressure and slope stability were investigated.

2 Theory

2.1 Rainfall infiltration on the slope

The infiltration of rainfall on the slope is shown in Fig. 1. A part of the rainwater on the slope surface cannot be absorbed by the soil. When the rainfall is relatively heavy, it is converted into surface runoff, and it flows along the surface of the slope. When the rain stops, the rainwater infiltration on the slope is gradually stopped, and the runoff slowly disappears. Figure 1 shows the process of heavy rainfall. As shown in Fig. 1a, the soil on the slope surface is unsaturated soil with high porosity and low water content. Rainfall infiltration occurs on the slope surface during the initial period of rainfall. Figure 1b demonstrates that the soil approaches saturation with further rainfall on the slope surface. In addition, a small amount of rainwater is converted into surface runoff, and the saturation decreases. The infiltration line of the soil below the slope is raised. Figure 1c shows that with continuous rainfall, the soil on the slope surface absorbs water and tends to be saturated. The water that cannot be absorbed forms surface runoff and flows along the slope surface. Figure 1d shows that after the rainfall stops, the saturated area of the slope surface begins to disappear, the surface runoff also gradually disappears, and the infiltration line decreases.

2.2 Unsaturated seepage theory

Saturated and unsaturated seepage were analysed based on Darcy's law(Calamak and Yanmaz 2017). Of particular note, calculating the seepage in unsaturated soils is difficult. The soil water characteristic curve indicates the relationship between the soil water matrix potential and water content. Hence, the permeability coefficient of unsaturated soils is changed by applying the soil moisture characteristic curve.

3 Numerical studies

3.1 Model for the slope stability analysis

The slope is located on the side of the highway from Bijie to Weining north of the Wumeng Mountains in the Yunnan-Guizhou Plateau (China) (Ruiqing 2014). Figure 2 shows the geometric information of the slope with a height of 70 m and length of 160 m. The multilevel slope consists of three materials with hydraulic conductivities of 9.72×10^{-5},

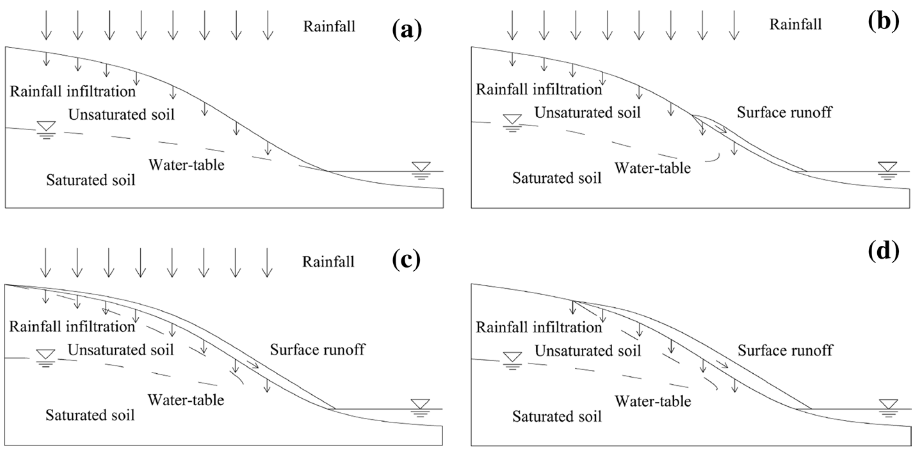


Fig. 1 Rainfall infiltration on the slope in four periods

6.94×10^{-5}, and 4.05×10^{-6} m/s; cohesive forces of 19 kPa, 30 kPa and 100 kPa; and densities of 1.68 g/cm^3, 19 g/cm^3 and 21.2 g/cm^3. In Fig. 2, the upper layer is clay with a small amount of crushed stone; the middle layer is composed of argillaceous siltstone and other rocks; the lower is a strongly weathered rock layer.

3.2 Infiltration of water under rainfall

The research area has a subtropical monsoon humid climate. The rainfall in this area is mostly concentrated in summer, and the rainfall is heavy. The standard of torrential rain in China is as follows (12 h total rainfall): torrential rain (30–69.9 mm), downpour (70–139.9 mm), extraordinary rainstorm (≥ 140 mm). Therefore, in this study, rain intensities of 0.00375, 0.00833, 0.015, and 0.03 m/h were investigated. Figures 3 and 4 demonstrate that the soil close to the slope surface is considerably affected. The water volume increases with prolonged rainfall duration. With the increased rainfall intensity, the effect of depth becomes relatively large. Additionally, the fluctuation range of the water content volume is widened with increased rainfall intensity. Figure 3 shows that the water volume increases with increased rainfall intensity, but the rate of increase gradually decreases. In Fig. 3, when the rainfall lasted for 9 h, the largest water volume was observed on the surface of the slope, and this volume tended to reach saturation. The area with the maximum water volume is the foot of the slope, which extends along the slope surface to the top of the slope. Rainfall affects the foot, top, and body of the slope sequentially. When the rainfall intensity is small, the rate of water content gradually increases. The water volume in the soil at the edge of each step increases faster than that inside. Thus, the edge of each step on the slope is largely susceptible to rainfall.

Figure 4 shows the changes in pore water pressure under different rainfall intensities. With increased rainfall, the pore pressure increases, but it decreases along the top of the slope to the bottom. Although the rainfall intensity increases, the pore water pressure increases faster than the rainfall intensity. The pore pressure at the top of the slope was the most variable. Figure 4c, d shows that the slope surface reaches the maximum pore water pressure. Subsequently, the value becomes stable.

As shown in Fig. 5, the rain penetrates into the surface of the slope. When the rain lasted for 2 h, the surface seepage velocity in the upper soil was the fastest. However, little rainfall infiltration was observed in the middle and lower layers. When the rain lasted for 9 h, the

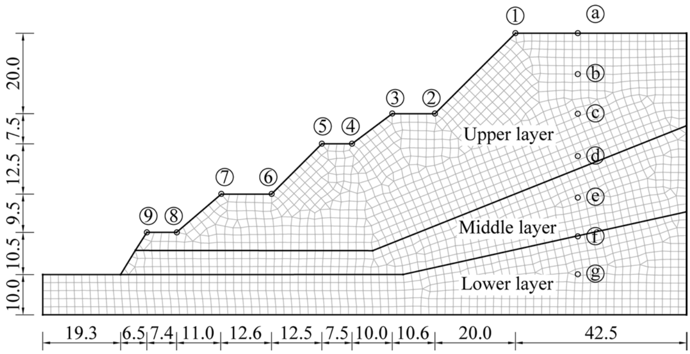


Fig. 2 Finite element model of the slope and the distribution of feature points

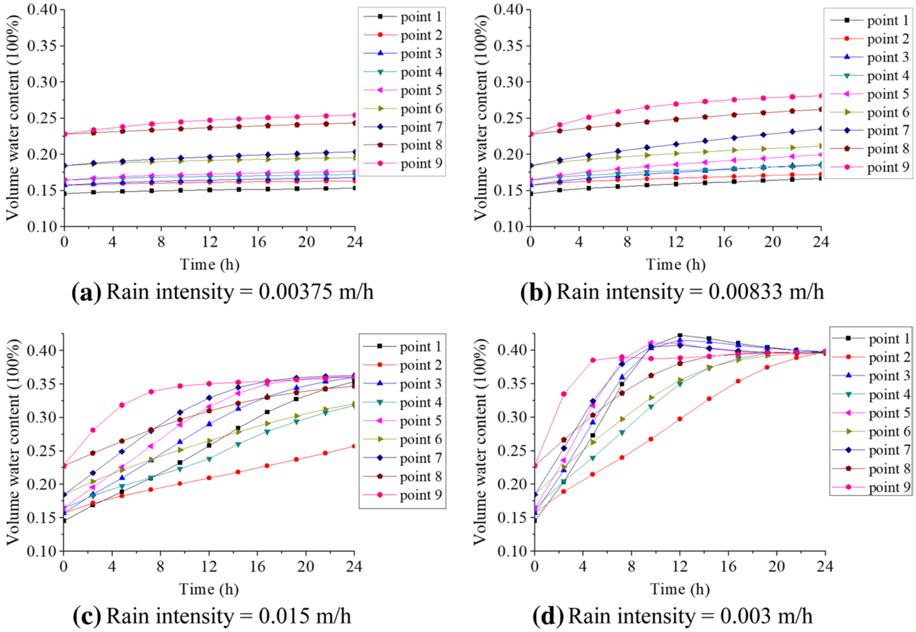


Fig. 3 Water volume content under various rain intensities

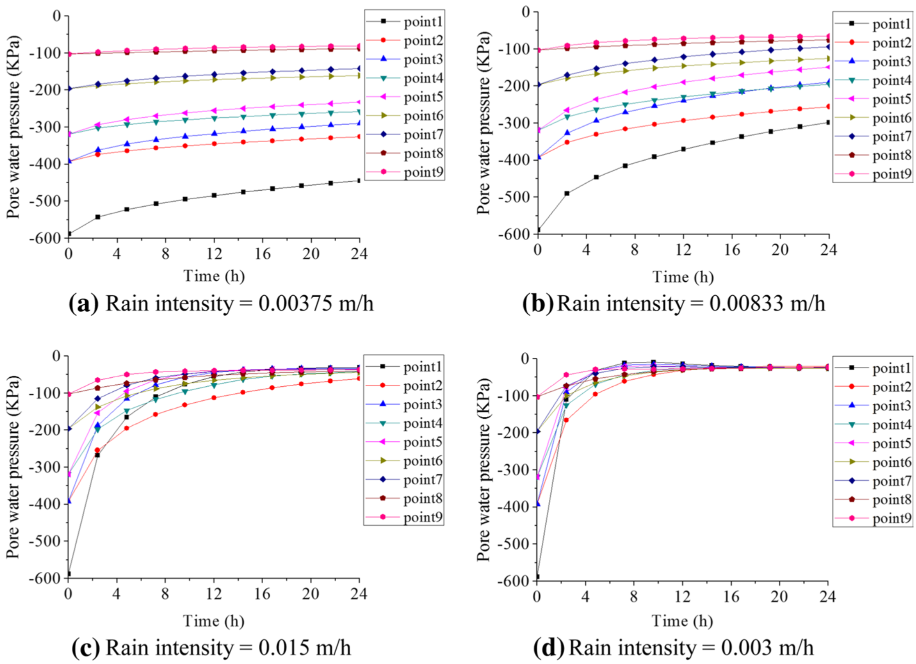


Fig. 4 Pore water pressure under various rain intensities

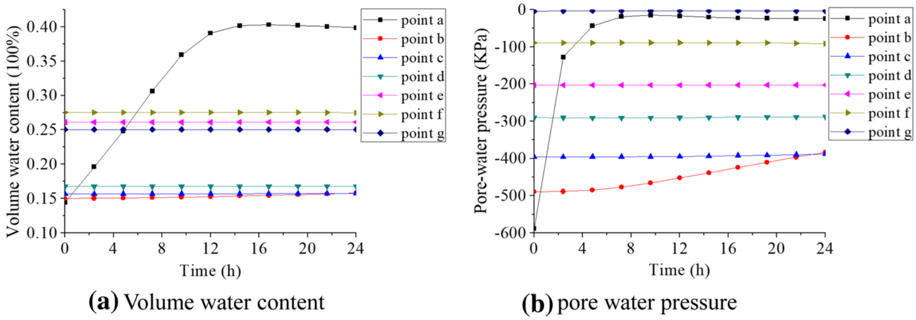


Fig. 5 Volume water content and pore water pressure (rain intensity = 0.003 m/h)

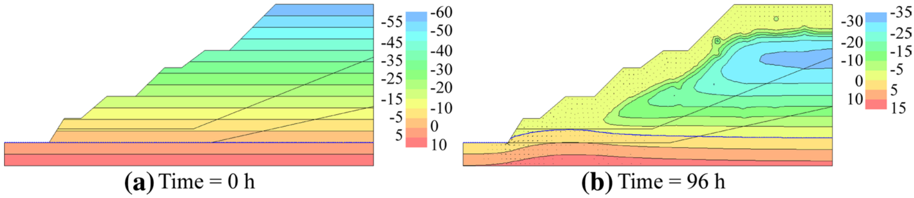


Fig. 6 Pressure head of the slope at different times (rainfall intensity = 0.03 m/h)

seepage velocity of the surface was nearly constant, and the seepage velocity decreased along the periphery of the slope surface. When the rainfall lasted for 5 h, the rain penetrated 10 m below the surface of the slope. At 20 m infiltration, the speed was considerably small. Almost no rainfall infiltration was observed in the lower layer. The reason is that the rainfall infiltrates from the surface to the inside of the slope, and the permeability of the lower layer is considerably small.

As shown in Fig. 6, the rainfall result in the raising of underground water level (marked with blue lines). With the increase in rainfall time, the area of the unsaturated zone shrinks, and the pressure head of the slope rises at 96 h. The trend of rainfall infiltration at different times is shown in Fig. 7. The rain penetrates into the surface of the slope when the rain lasts for 9.6 h. Compared with that of other areas, the surface seepage velocity of the upper soil is the fastest. When rainfall lasted for 19.2 h, the area of rainfall infiltration expanded. The rain penetrates into the slope when the rain lasts for 57.6 h. A small amount of water penetrates into the area near the surface of the slope. The velocity decreases along the periphery. The velocity of water flow on the surface is nearly constant, and the velocity is at its maximum at the toe of the slope. When rainfall penetrates the slope, almost no rainfall infiltration reaches the lower layer. The reason is that the permeability of the lower layer is considerably small, and the infiltration path is long. The area of rainfall infiltration continues to expand when the rain lasts for 96 h, and the toe of the slope was severely eroded by rainfall.

3.3 Fs under rainfall

The analysis of the stress field of the slope is mainly concerned with the variation of displacement. Therefore, the displacement nephogram of the slope in the x and y directions

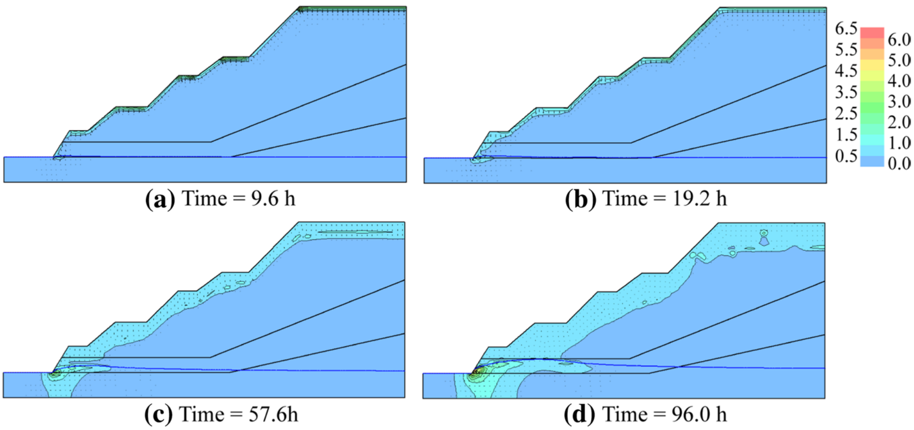


Fig. 7 XY-velocity at different rainfall times when rainfall intensity = 0.03 m/h (unit: $1*10^5$ m/s)

under rainfall is shown in Fig. 8. It can be found that the maximum horizontal displacement caused by rainfall is 0.627 m, which is located at the toe of the uppermost slope. The maximum vertical displacement is 0.909 m, which is located at the top of the slope. The foot of the slope moved upward about 0.0006 m in the vertical direction due to the squeezing effect.

Figure 9 shows the comparison of the rainfall at the beginning and after four days. The results indicate that with increasing rainfall time, the water level increased, the slip surface became dark, and the slip area grew large. The rain poured for four days. Figure 10 shows the variation in the Fs of the slope during rain. Under constant rainfall intensity, the Fs of slope stability decreased with increasing rainfall time. Comparing the variation in the Fs under the two kinds of rainfall intensity, we find that the Fs of slope stability decreased with increasing rainfall intensity. The Fs of the slope drops first and then rises after the rain stops. The minimum value of the Fs is not during rainfall but a period after rainfall because the rain continues to infiltrate into the slope after the rain stops. Furthermore, the substrate suction and soil shear strength both decrease. Consequently, the Fs decreased gradually. With the increased rainfall intensity, it takes longer to reach the minimum Fs of the slope. The pore water dissipation also takes a long time, and the slope shear strength cannot be restored in a short time. After the rain stopped for a longer time, the transient saturation zone gradually decreased, the matrix suction gradually increased, and the Fs increased. It is found that with the increased rainfall intensity, the decline rate of the Fs decreased rapidly due to the large total

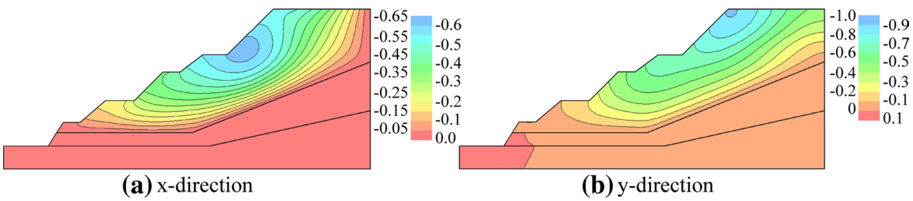


Fig. 8 The displacement nephogram of the slope at 4 days, rainfall intensity = 0.03 m/h

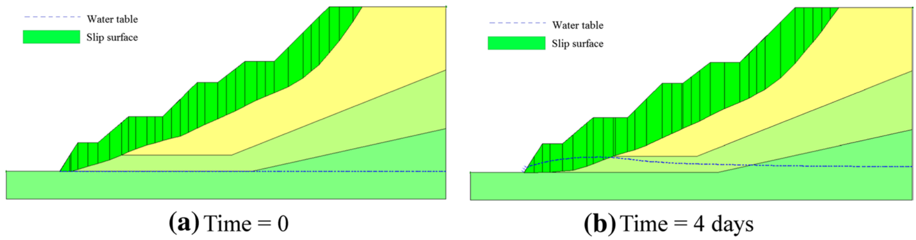
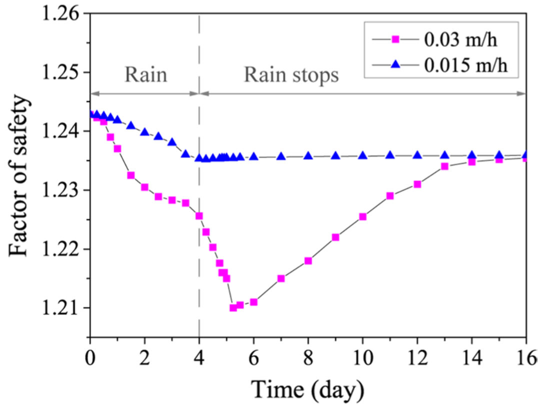


Fig. 9 Stability analysis of a slope under different periods

Fig. 10 Influence of rainfall intensity on the safety factor



amount of rainfall infiltration in the slope soil. The matrix suction was also remarkably affected. Therefore, rainfall intensity is an important parameter affecting slope stability.

4 Conclusions

The stability of three-layered slopes was investigated based on the generalized limit equilibrium method. The effects of rainfall intensity and rainfall cycle on the volume water content, pore water pressure and stability were calculated. Some conclusions are as follows:

(1) The results demonstrated that the pore water pressure and volume water content increased with increasing rainfall intensity. The area with the highest infiltration rate in the slope is moved from the surface in the direction of gravity.
(2) Under rainfall conditions, the Fs of slope stability is reduced. The Fs of the soil slope decreased with increasing rainfall intensity.
(3) When rainfall is heavy, the increased rainfall time results in rapid reduction in the slope Fs. When the rainfall stops, the Fs continues to decrease and subsequently increases after a period of time. Consequently, the slope is considerably prone to landslides. Therefore, we should pay attention to monitoring the safety of slopes during rainstorms and for a period after the rainfall stops.

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