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Stability Analysis of Soft Rock Slope Considering Seepage Softening and Damage Effects

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Abstract

The geological disasters of soft rock slope instability are more and more concerned by the engineering community. Rainfall infiltration is an important factor inducing its instability. In order to analyze the change process of the dynamic stability of soft rock slopes under different rainfall conditions, an analysis method considering soft rock damage-softening-seepage effect is proposed for soft rock seepage softening and damage effects. Variation of slope seepage characteristics, stability and plastic zone distribution. The results show that soft rock slopes are mainly affected by unsaturated seepage effects during the early rainfall period. The softening effects in the transient saturated zone gradually deepen the slope stability with the extension of the softening time. The value increases gradually. Long-term light rain is more likely to cause slope instability than short-time heavy rain, and the stability has a "response delay" phenomenon. The stability coefficient and plastic failure zone of soft rock slopes are affected by both unsaturated seepage and softening effects. They gradually change from the local instability controlled by the cover of the slope to the overall instability controlled by the softening effect of soft rocks. The calculation results considering the seepage softening and damage effects of soft rocks will be more in line with the actual situation, which can provide reference value for the seepage stability management of soft rock slopes.

Keywords

Road Engineering; Soft Rock Slope; Seepage; Damage Effect; Softening Effect.

1. Introduction

Soft rock is a kind of rock mass with softer lithology, easy to be damaged and softened by water absorption. Due to the unique physical properties of soft rock, it is easy to be affected by rainfall infiltration and induce slope instability [1-2]. The rainfall-induced slope instability mainly explains the influence on the slope stability from the aspects of matrix suction, water content, soil weight and permeability [3-5]. However, the mechanism of soft rock slopes is very complicated. The soft rock softens and deteriorates when it meets with water. The shear strength decreases with the increase of softening time. In addition, the nonlinear damage effect of the rock mass causes the soft rock damage and deterioration [6], which accelerates the evolution process of soft rock slope instability. If the softening and damage effects of soft rock seepage are neglected, the dynamic stability and durability of the slope will have limitations and differences, leading to differences between engineering practice and theoretical analysis.

In recent years, scholars at home and abroad have conducted in-depth studies on the process of soft rock slope instability induced by rainfall infiltration. Fu Hongyuan et al. [7] divided the soft rock into the softening effect area according to the transient saturation zone dynamically

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changing at different rainfall moments, and studied the influence of the softening effect on the stability of the soft rock slope. Xie Jinrong et al. [8] used the indirect coupling method to simulate the softening degree of the soft rock based on the appearance time of the transient saturation zone. He concluded that the catastrophic effects of soft rock slopes are related to soft rock material properties, rainfall conditions, and distribution of transient saturation zones. Jiang Zhongming et al. [9] found that the softening effect of soft rock under long-term rainfall causes the strength parameters to continuously decrease, and combined the three factors of matrix suction, water content and softening effect to carry out dynamic stability analysis; YANG et al. [10] discussed the evolution process of the dynamic response of heavy rainfall to rock slopes for rock slopes with weak interlayers. The above research mainly considers the change process of the dynamic stability of the soft rock slope by the unsaturated seepage and softening effect, but the nonlinear damage characteristics of the soft rock cannot be ignored either. For this reason, Zeng Ling et al. [11] proposed a stability analysis method considering damage and unsaturated effects based on the Hoek-Brown failure criterion of rock mass damage, but he did not consider the catastrophic mechanism of softening effects.

Based on this, in view of the two major characteristics of soft rock seepage softening and damage effects, we compiled and revised the soft rock slope rainfall infiltration analysis program by comprehensively considering the soft rock's damage-softening-seepage effect. Taking a soft rock slope from Maitreya to Chuxiong as the research object, we analyze the variation of unsaturated seepage, stability coefficient and plastic zone under different rainfall conditions, and provide reference suggestions and basis for discussing the failure mechanism of soft rock slopes.

2. Stability Analysis Method of Soft Rock Slope

2.1. Calculation Principle

When water migration and changes occur inside a two-dimensional slope, the unsteady partial differential equation of the **unsaturated seepage process is:**

$$m_w \gamma_w \frac{\partial H_w}{\partial t} - \frac{\partial}{\partial x}\left(k_x \frac{\partial H_w}{\partial x}\right) - \frac{\partial}{\partial y}\left(k_y \frac{\partial H_w}{\partial y}\right) - Q = 0 \tag{1}$$

Where, m_w is the specific water capacity; γ_w is the weight of the water; k_x and k_y are the permeability coefficients in the x and y directions respectively; H_w is the head; Q is the flow boundary.

The unsaturated zone needs to consider the effect of the matrix suction on the shear strength. Therefore, we adopt the unsaturated shear strength formula under the dual stress state proposed by Fredlund et al. [12]. It is the modified equation of the change of the shear strength caused by the suction of the matrix, and its expression is:

$$\tau = c' + (\sigma_n - u_a)\, tan\varphi' + (u_a - u_w)\, tan\varphi^b \tag{2}$$

Where, $c^{'}$ is the effective internal friction angle; $\sigma_n - u_a$ is Net normal stress; $\varphi^{'}$is the effective internal friction angle; $u_a - u_w$ is the Matrix suction; φ^b is the friction angle of the matrix suction against the contribution rate of shear strength.

The shear strength of soft rock is related to saturation and softening time, and its specific value refers to the strength change of soft rock long-term softening test. It is assumed that the rainfall infiltration causes the soft rock to produce a transient saturated zone, and the soft rock starts to soften within the transient saturated zone, forming a softening effect zone, the value of which is related to the softening time and has nothing to do with the saturation. After a long-term softening test of soft rock samples, an exponential function is adopted to fit the test data, and the expression is:

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$$\left.\begin{aligned} c = exp(m_1 t + n_1 S)c_0 = exp(m_1 t)c_0 \\ \varphi = exp(m_2 t + n_2 S)\varphi_0 = exp(m_2 t)\varphi_0 \end{aligned}\right\} \tag{3}$$

Where, S is saturation; m_1, n_1, m_2 and n_2 is fitting parameters; t is the softening time in the softening effect zone.

The unsaturated shear strength formula (2) is revised, and the revised formula is:

$$\tau = exp(m_1 t)c + (\sigma_n - u_a)\, tan[exp(m_2 t)\varphi] + (u_a - u_w)\, tan\varphi^b \tag{4}$$

Because the above formula does not consider the damage effect of the rock mass, we adopt a fitting method based on the Mohr-Coulomb strength criterion and the Hoek-Brown strength criterion that the coverage area is equal. A formula for effective cohesion and effective internal friction angle considering rock mass damage is proposed [13]:

$$c = \frac{\sigma_{ci}(s + m_b \sigma_{3\,max}/\sigma_{ci})^{a-1}[s(1+2a) + (1-a)m_b \sigma_{3\,max}/\sigma_{ci}]}{\sqrt{(1+a)^2(2+a)^2 + 6am_b(s + m_b\sigma_{3\,max}/\sigma_{ci})^{a-1}(1+a)(2+a)}} \tag{5}$$

$$\varphi = arcsin\left[1 - \frac{2(1+a)(2+a)}{2(1+a)(2+a) + 6am_b(s + m_b\sigma_{3\,max}/\sigma_{ci})}\right] \tag{6}$$

Where, σ_{ci} is the uniaxial compressive strength of the complete rock mass; $\sigma_{3\,max}$ is the maximum value of the minimum principal stress; m_b, a, s is the rock mass parameter of the Hoek-Brown failure criterion expression. Its value is determined by the deflection coefficient D, the geological strength index GSI and the fitting experience paramete m_i, and the relationship is [13]:

$$\left.\begin{aligned} m_b = exp\left(\frac{\mathrm{GSI}-100}{28-14D}\right)m_i \\ s = e\left(\frac{\mathrm{GSI}-100}{9-3D}\right) \\ a = \frac{1}{2} + \frac{1}{6}\left[e^{(-\mathrm{GSI}/15)} - e^{(-20/3)}\right] \end{aligned}\right\} \tag{7}$$

The above formulas (5) and (6) are introduced into the modified formula (4) to derive the modified formula of unsaturated shear strength considering the seepage softening and damage effects at the same time:

$$\begin{aligned} \tau = {} & \frac{\sigma_{ci}\left(s + m_b\sigma_{3\max}/\sigma_{ci}\right)^{a-1}\left[s(1+2a) + (1-a)m_b\sigma_{3\max}/\sigma_{ci}\right]}{\sqrt{(1+a)^2(2+a)^2 + 6am_b\left(s + m_b\sigma_{3\max}/\sigma_{ci}\right)^{a-1}(1+a)(2+a)}}\exp(m_1 t) \\ & + (\sigma_n - u_a)\tan\left\{\arcsin\left[1 - \frac{2(1+a)(2+a)}{2(1+a)(2+a) + 6am_b\left(s + m_b\sigma_{3\max}/\sigma_{ci}\right)}\right]\exp(m_2 t)\right\} + (u_a - u_w)\tan\varphi^b \end{aligned} \tag{8}$$

2.2. Calculation Principle

In order to consider the seepage softening and damage effects of soft rock at the same time, an analysis method that comprehensively considers the soft rock damage-softening-seepage effect is proposed. The realization process is as follows:

(1) The finite element software GEO-Studio is used to analyze the distribution of the unsaturated seepage of the soft rock slope under different rainfall conditions; the interface program is compiled to import the calculated slope pore pressure and gravity results at different times into the finite difference software Flac3D.

(2) The long-term softening test of soft rock was carried out, and the unsaturated shear strength correction formula (8) was obtained considering the seepage softening and damage effects. The FISH language was used to compile and modify the rainfall infiltration program that the effective shear strength parameters change with the softening time.

(3) In the finite difference software Flac3D, the strength reduction method is used to calculate the safety factor, and the iterative solution method is used to calculate the distribution result of the plastic zone.

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3. Analysis of Unsaturated Seepage Flow of Soft Rock Slope

3.1. Two-dimensional seepage model

Relying on the side slope of a carbonaceous slate cutting of the Maitreya-Chuxiong Expressway, the slope is simplified according to the geological conditions of the slope. The two-dimensional slope calculation model is shown in Figure 1. The overburden layer on the top of the slope is gravel-containing silty clay, and the soil below the overburden layer is strongly weathered carbonaceous slate, and the rock mass is broken. According to the "Engineering Rock Mass Test Method Standard" (GBT 50266-2013) the saturated water softening test, measured its uniaxial compressive strength of 30.25Mpa, after 30 days of softening time, it tends to be stable, the uniaxial compressive strength after saturation and stability is 6.84Mpa, which is soft Rock category. The bedrock consists of moderately weathered slate intercalated with carbonaceous slate, and the groundwater level lies at the junction of the rock formations. After pressure plate test and variable head test, the hydraulic characteristics of overburden and soft rock are obtained by fitting the Van Genuchten model [14] in Figure 2 and Figure 3.

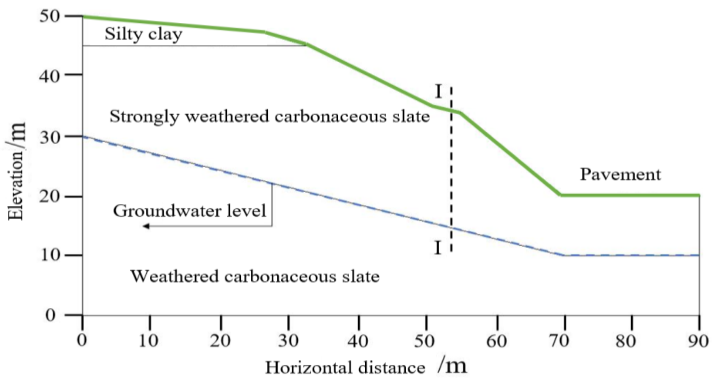

Figure 1. Calculation model

According to the national meteorological information, the rainfall in Maitreya area of Yunnan from 1981 to 2010 was mainly concentrated in July and August, and the maximum monthly historical rainfall was 344mm and 336.9mm respectively. Two extreme rainfall conditions are designed according to short-term heavy rain and long-term light rain. The long-term light rain lasts for 60 days and the rainfall intensity is 1.32×10^{-7}m/s; the short-term heavy rain lasts for 6 days and the rainfall intensity is 1.32×10^{-6}m/s.

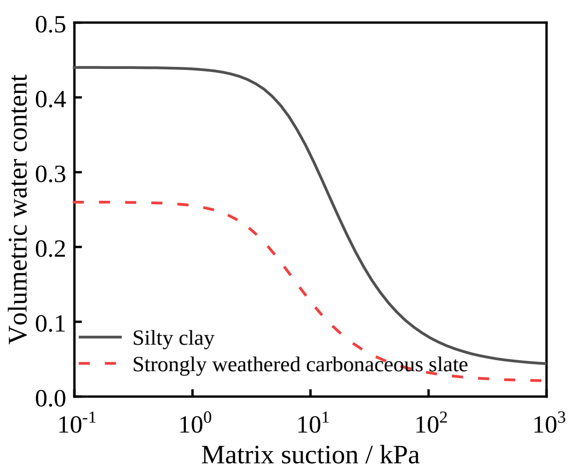

Figure 2. Soil-water characteristic curve

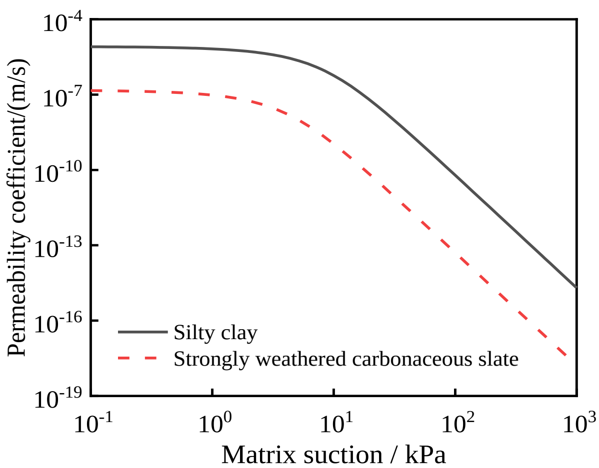

Figure 3. Permeability curve

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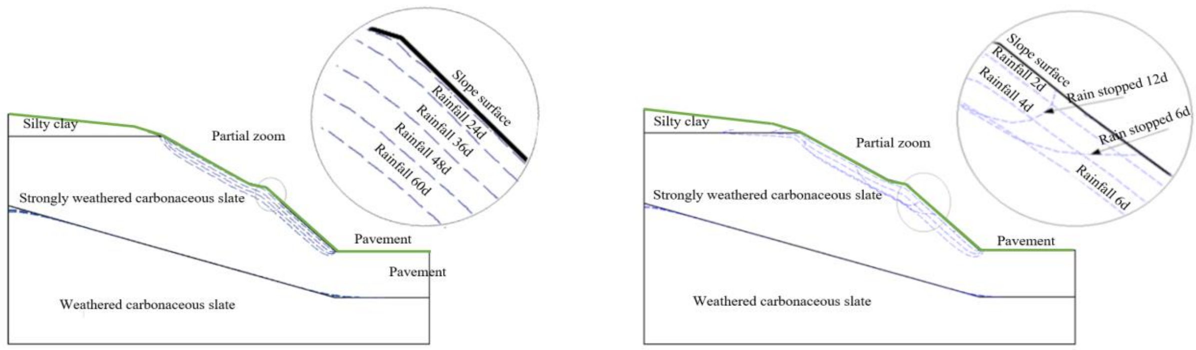
3.2. Unsaturated seepage analysis

Figure 4 shows the distribution of the slope transient saturation zone under different rainfall conditions. Under long-term light rain, the saturated permeability coefficient of the slope top cover is greater than the rainfall intensity, and the wet front expands downward in an unsaturated state. When rainwater infiltrates to the junction of the overburden and the soft rock, part of the rainwater supplements the moisture content of the overburden, and part of the rainwater infiltrates into the slope. The overburden has not formed a transient saturation zone. However, in a short period of heavy rain, the excess Rainwater gathers at the junction near the slope to form a small-scale transient saturation zone.



(a) Longt-term light rain (b) Short-term heavy rain

Figure 4. Transient saturation zone change

Under long-term light rain, due to the poor permeability of soft rock, part of the rainwater will flow along the slope to form surface runoff, which will cause the wet front to expand in the slope in a saturated state. At the beginning of the rainfall, the transient saturation zone does not expand significantly until the first rainfall. The obvious transient saturation zone only appeared in 24 days. This is because the initial water content of the slope is low and the initial permeability is small; with the increase of rainfall time, the suspended transient saturation zone continues to expand, and a large-scale transient saturation zone begins to appear on the slope. However, under short-term heavy rain, the transient saturation zone expands rapidly, and the transient saturation zone changes more than long-term light rain.

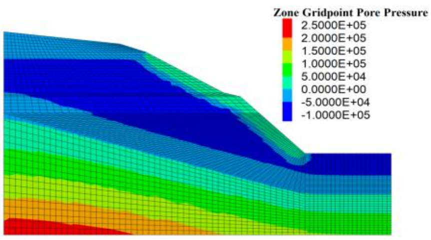


Figure 5. Cloud map of pore water pressure distribution

4. Stability analysis of soft rock slope

4.1. Equivalent model and parameters of slope

Based on the Geo-Studio two-dimensional seepage model, an equivalent three-dimensional model is established through the interface program, and the pore water pressure data of each unit is imported into the Flac3D three-dimensional model and the severity is corrected. Figure 5 shows the cloud map of the pore water pressure distribution when the light rain stops. The material adopts the Mohr-Coulomb constitutive model after considering nonlinear damage

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correction, and the cohesive force and internal friction angle of the softening effect area are corrected by FISH language.

According to the on-site exploration of the soft rock slope, combined with the CT scan test, the deflection coefficient D is 0.8, the geological strength index GSI is 20, and the empirical parameter m_i is 7. According to formulas (5) and (6), the shear strength parameters before softening and after softening and stabilization are calculated, and the relationship between the equivalent cohesion and the equivalent internal friction angle with the softening time is:

$$\left.\begin{array}{r} c' = 58e^{-0.029t} \\ \varphi' = 21.4\mathrm{e}^{-0.015t} \end{array}\right\} \tag{9}$$

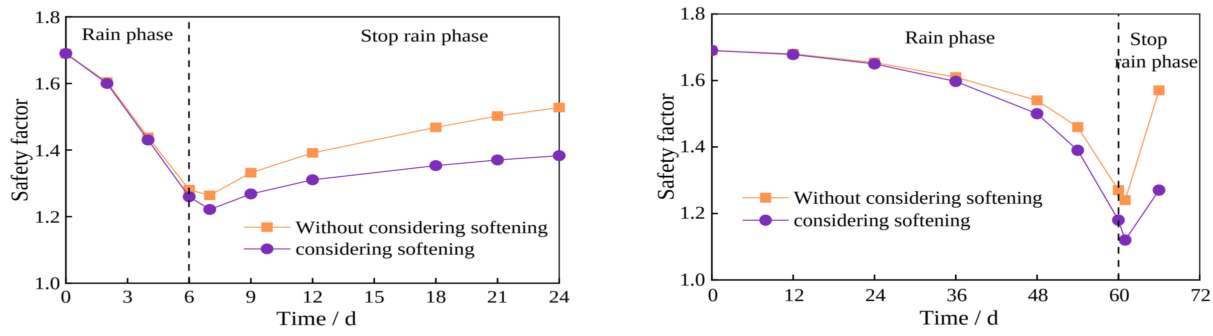
According to formula (9), the shear strength parameters of different rainfall periods are drawn up, and the program of the soft rock shear strength parameters in the softening effect area with the temporal and spatial evolution of the transient saturation zone is compiled and revised. The material parameters are shown in Table 1.

Table 1: Material parameters

Soil layer	Severe (kN/m³)	Saturation severity (kN/m³)	Cohesion(kPa) Before softening	Cohesion(kPa) After softening	Internal friction angle(°) Before softening	Internal friction angle(°) After softening	Deformation modulus (MPa)	Poisson's ratio
Silty clay	20	20	27		22		65	0.34
Strongly Weathered Slate	22.3	22.3	58	24	21.4	13.7	500	0.31
Moderately weathered slate	25	25	480		34		2200	0.26

4.2. Variation law of stability coefficient

Figure 6 shows the change rule of the safety factor of soft rock slope calculated by the strength reduction method. It can be seen from Fig. 8 that unsaturated seepage and strength softening are the main factors affecting the change of the safety factor of soft rock slope. Under short-term heavy rain, the softening effect has little effect on the safety factor, and it is mainly controlled by unsaturated seepage. One day after the rain stopped, this was because of the obvious hysteresis of the unsaturated seepage, which caused the safety factor to continue to decrease. As the rain stops, the matrix suction gradually recovers, but the soft rock shear strength parameter in the softening effect area decreases exponentially, causing the effective shear strength of the slope to decrease, and the softening effect area covers a small area and the softening effect is limited Therefore, the safety factor considering the softening effect increases slightly, while the safety factor without considering the softening effect increases significantly. Under long-term light rain, the softening effect of the early rain has little effect on the safety factor. As the rainfall continues, the softening effect gradually increases, and the margin of the safety factor increases accordingly; the change law of the safety factor after the rain stops is the same as the short-term rainstorm.



(a) Longt-term light rain (b) Short-term heavy rain

Figure 6. Safety factor change

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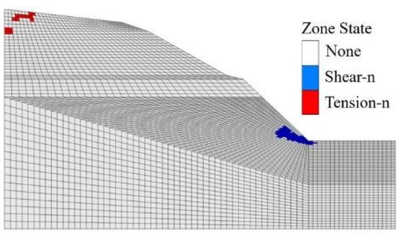
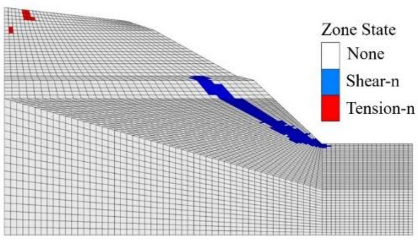
4.3. Distribution law of plastic zone

In order to study the evolution law of soft rock slope instability, the change law of the plastic zone under the most unfavorable conditions is considered. Figure 7 shows the distribution of the plastic zone of the slope considering the softening effect under the action of long-term light rain. It can be seen from Figure 7: when the rainfall is 36 days, the tensile plastic zone appears in the overburden of the slope top, and a small amount of shear plastic zone appears at the foot of the slope; when the rainfall is 60 days, The plastic zone of the overburden on the top of the slope is reduced, while the shear plastic zone gradually extends from the toe to the top of the slope, causing a larger range of plastic zone to appear in the shallow area from the toe to the middle of the slope; when the rain stops for 1 day, the plastic zone The range continues to expand upward, showing a trend of gradual penetration; when the rain stops for 6 days, the plastic zone gradually dissipates toward the toe of the slope, but there are still a large number of plastic zones in the toe and in the slope, and the dissipation speed is slow.

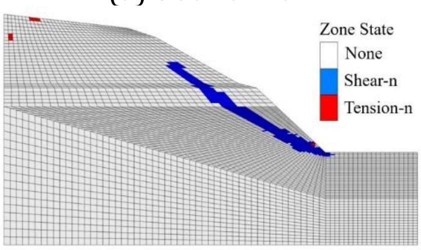
The above-mentioned law of the change of the plastic zone shows that the change of the plastic zone is mainly concentrated in the shallow layer of the slope, and its expansion speed and temporal and spatial distribution are closely related to the unsaturated seepage and softening effects of the soft rock slope. In the early stage of rainfall infiltration, the unsaturated seepage effect of the overburden on the top of the slope is greater than that of the soft rock, resulting in a decrease in the shear strength of the overburden and a significant increase in the sliding force, mainly showing local plastic failure controlled by the overburden on the top of the slope; with the duration of rainfall , The soft rock is more and more significantly affected by the softening effect, the plastic zone expands towards the top of the slope, and its changes are concentrated in the shallow area of the soft rock. Within a short period of time when the rainfall ceases, due to the low permeability coefficient of the soft rock, rainwater continues to accumulate inside the slope, causing the infiltration force within the slope to continue to expand, and the plastic zone area of the soft rock slope continues to expand toward the top of the slope; after a period of inactivity As the matrix suction dissipates and the soil's own weight decreases, the area of the plastic zone continues to decrease. However, the soft rock slope is affected by the softening effect for a long time, and the dissipation rate of the plastic zone to the toe of the slope slows down. In addition, the partial plastic failure of the soft rock slope controlled by the overburden on the top of the slope gradually transforms into an overall plastic failure controlled by the softening effect of the soft rock during the entire rainfall period. High performance, no plastic zone through the top of the slope is formed.



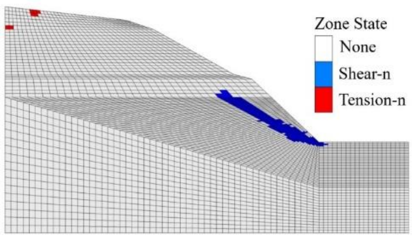
(a) 36d rainfall



(b) 60d rainfall



(c) Stop rain 1d



(d) Stop rain 6d

Figure 7. Safety factor change

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5. Conclusion

(1) In the process of rainfall, the change range and expansion speed of the transient saturated zone of short-term heavy rain is greater than that of long-term light rain; after the rainfall stops, the dissipation rate of the transient saturated area of short-term heavy rain is about 3 times that of long-term light rain.

(2) The minimum safety factors for short-term heavy rain and long-term light rain are 1.22 and 1.12, respectively. Long-term light rain is more likely to cause slope instability than short-term heavy rain, and the stability has a phenomenon of "response delay".

(3) The soft rock slope is mainly affected by the unsaturated seepage effect in the early stage of rainfall. With the extension of the softening time, the effect of the soft rock on the slope stability gradually deepens, and the difference between the safety factor and the safety factor that does not consider the softening effect gradually Increase.

(4) The local plastic failure of the soft rock slope controlled by the overburden on the top of the slope gradually transforms into an overall plastic failure controlled by the softening effect of the soft rock, but the overall safety of the slope is relatively high, and no plastic zone through the top of the slope is formed.

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References

[1] Y Pan, Z Liu, C.Y. Zhou. Test of disintegration characteristics of red bed soft rock in contact with water and its interface model, Rock and Soil Mechanics, Vol. 38 (2017) No. 11, p. 3231-3239. (In Chinese)

[2] H Che Han, K Liu. Design optimization of soft rock slope bolt support considering groundwater level changes, Mining and Metallurgical Engineering, Vol. 36 (2016) No. 2, p. 19-22. (In Chinese)

[3] Z.M. HE, T Yu Z.X. Cai, et al. Finite element analysis of soil slope stability considering the influence of rainfall infiltration, Mining and Metallurgical Engineering, Vol. 32 (2012) No. 1, p. 9-11. (In Chinese)

[4] H.R. Li, P Zhang, S.N Wang, et al. Study on the influence of slope stability of coal-measure strata along the slope under rainfall conditions, Chinese Journal of Geomechanics, Vol. 24 (2018) No. 6, p. 836-848. (In Chinese)

[5] W Luo. Seepage characteristics and stability analysis of overburden slopes under rainfall conditions, Mining and Metallurgical Engineering, Vol. 37 (2017) No. 4, p. 28-31. (In Chinese)

[6] W.K. Feng, Y.P. Hu, J.Z. Xie, et al. Rainfall-triggered catastrophic mechanism and stability analysis of bedding-fracturing slopes: Taking Sanxi Village landslide as an example,Chinese Journal of Rock Mechanics and Engineering, Vol. 35 (2016) No. 11, p. 2197-2207. (In Chinese)

[7] H.Y. Fu, L Zeng, G.Y. Wang, et al. Stability analysis of soft rock slopes under rainfall infiltration conditions, Rock and Soil Mechanics, Vol. 32 (2012) No. 8, p. 124-130. (In Chinese)

[8] J.R. Xie, C.Y. Zhou, Y Cheng. Seepage-softening analysis method and catastrophic mechanism of soft rock slope under rainfall conditions, Rock and Soil Mechanics, Vol. 35 (2014) No. 1, p. 197-203. (In Chinese)

[9] Z.M. Jiang, L Zeng, H.Y. Fu, et al. Dynamic stability analysis of soft rock slopes under extreme prolonged rain conditions.China Journal of Highway and Transport, Vol. 27 (2014) No. 2, p. 31-38. (In Chinese)

[10] Y C Yang, H G Xing, X G Yang, et al. Experimental study on the dynamic response and stability of bedding rock slopes with weak interlayers under heavy rainfall,Environmental Earth Sciences, Vol. 77 (2018) No. 12, p. 433-448.

ISSN: 2710-0588 DOI: 10.29556/FSE.202109_1(6).0001

[11] L Zeng, X Qiu, H.Y. Fu, et al. Stability analysis of carbonaceous mudstone embankment considering damage and unsaturated effects, Journal of Central South University (Natural Science Edition), Vol. 47 (2016) No. 10, p. 264 -272. (In Chinese)

[12] Fredlund D G, Morgenstern N R, Widger R A. The shear strength of unsaturated soils[J]. Canadian geotechnical journal, Vol. 12 (1978) No. 3, p. 313-321.

[13] H.H. Zhu, Q Zhang, L.Y. Zhang. Review of research progress and application of Hoek-Brown strength criterion, Chinese Journal of Rock Mechanics and Engineering, Vol. 32 (2013) No. 10, p. 1945-1963. (In Chinese)

[14] Van Genuchten M T. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils 1, Soil science society of America journal, Vol. 44 (1980) No. 2, p. 892-898.