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Study on the Variation of Physical and Mechanical Parameters of Gravel Soil Accumulation along Elevation under Rainfall

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Abstract: Rainfall is one of the main factors that induce landslides. In order to study the effect of rainfall on the physical and mechanical parameters of accumulation landslides, the Shuping landslide in the Three Gorges Reservoir area is taken as the object. By simulating the effect of typical rainfall, different elevation samples were taken in the physical model, and the permeability test and direct shear test were carried out at the sampling points to study the evolution law of permeability coefficient and shear strength parameters. The stability analysis of Shuping landslide accumulation body considering the change of parameters along the elevation was carried out. The results show that ignoring the variability of parameters along the elevation due to long-term rainfall will lead to overestimation of slope stability and unsafe design results. After 60 hours of rainfall, from the top to the bottom of the slope, the permeability coefficient k and internal friction angle φ of the accumulation of the landslide decrease linearly, and the cohesive c increases linearly. Compared with the initial model, k and φ at the highest sampling point increased by 10% and 2.22%, c decreased by 21.09%, while k and φ at the lowest sampling point decreased by 2.5% and 6.96%, respectively, and c increased 111.9%. When there is a combined effect of rainfall and reservoir water level in the same elevation, that is, considering the variation of parameters along the elevation of the landslide, compared with the action of the reservoir water level alone, the maximum deformation of the X direction of the 145m and 175m water level increased by 12.81% and 42.52%, respectively, and the stability coefficient decreased by 7.874% and 11.8%, respectively. The research results have reference significance for the stability analysis of accumulation landslides under rainfall conditions.

Keywords: Accumulation; Model test; Variability; Permeability coefficient; Shear strength parameters.

1 Introduction

Landslides are one of the more common geological disasters in the Three Gorges Reservoir area, which seriously affect the safe operation of waterways in the reservoir area, the safety of life, and the property of the people in the reservoir area. Therefore, it is essential to seriously study the stability of the slope in the reservoir area. Many factors cause slope instability, but statistical data suggest that most slope failures are caused by rainfall infiltration (Ali et al. 2013; Jian et al. 2009). At present, on-site monitoring and laboratory tests are the main methods to study the stability of landslides (Wang et al. 2016; Yang et al. 2017; Dai et al. 2020). A large number of model tests are used to study the stability, deformation characteristics, and failure mechanism of landslides in the Three Gorges Reservoir area underwater level fluctuations and rainfall conditions (He et al. 2018; He et al. 2020; Wang et al. 2018). Xiong et al. (2019) conducted model tests with three different combinations of rainfall and reservoir water level to explore the effect of rainfall infiltration on slope stability. Li et al. (2021) used a physical simulation model to simulate rain-induced landslides under different rainfall intensities. In addition to rainfall and other external factors, the variability of rock mass itself determines the uncertainty of geotechnical engineering and also has an important impact on slope stability (Griffiths and Fenton 2004). Schieber (2011), Huang et al. (2013) and Hua et al. (2021) used random field theory and geostatistical theory to study the spatial variability of rock and soil parameters of accumulations. Jiang et al. (2018) predicted the reliability of soil slopes based on the spatial distribution of soil properties of field test data and monitoring data. Zhang et al. (2021) established a rock slope model with weak layers, and proposed a stability evaluation framework for rock slopes with weak layers considering the spatial variability of rock strength characteristics by using the random field method. Mori et al. (2020) studied the effect of soil shear strength parameter variability on sliding distance by stochastic field simulation and proposed a probabilistic framework to evaluate sudden landslide hazards caused by the failure of loose-fill slopes.

At present, most of the research focuses on the deformation characteristics, failure mechanism, and probability or reliability index of landslides under rainfall, while the analysis of landslide stability from the spatial variability of landslide parameters along the elevation of accumulation body is less explored. Therefore, it is necessary to consider the spatial variability of parameters when accurately evaluating the stability of accumulation landslide. In this study, the Shuping accumulation landslide in the Three Gorges Reservoir area is taken as the object, and the physical model of the accumulation landslide under rainfall is established. The spatial variability of the physical and mechanical parameters of the accumulation under rainfall is considered, and an evolution equation between the permeability coefficient, shear strength parameter, and elevation is proposed. The stability of the Shuping landslide in the Three Gorges Reservoir area under the combined action of different reservoir water levels and rainfall is used to compare and analyze by FLAC^{3D}, and it is confirmed that rock-soil spatial variability has a great influence on landslide stability. The necessity of considering the spatial variability of parameters for landslide stability analysis is further clarified.

2 Test plan

Most of the landslides in the Three Gorges Reservoir area occur in the colluvium, which is a typical accumulation slip and is mainly affected by the strength of the accumulation and bedrock sliding zone, rainfall, and reservoir water level fluctuation (He et al. 2018). The landslide mass consists mainly of broken angular sandstone gravel, silty clay and partial loess. The sliding zone is dominated by purple breccia clay, and the bedrock is composed of siltstone and marl, which is easily disintegrated and softened by water. This landslide accumulation of rainfall physical test model constructed in paper is used to characterize Shuping accumulation landslide, and it is also representative of other accumulation landslides in the Three Gorges Reservoir area.

2.1 Model test apparatus and material

This test adopts the form of a frame model test and is mainly composed of a model groove and a rainfall control system. The schematic diagram of the accumulation body model test is shown in Figure 1. According to the prototype size of Shuping landslide, a physical model was made using the principle of geometric similarity, and the similarity ratio was 1:300. The design size of the model is 2.2 m (length) × 1 m (width) × 1.3 m (height), the model is closed around, and the top surface is open. Combing with the actual situation of the test, three materials, clay, river sand with particle sizes of 1~2 mm and 2~5 mm, and gravel (with particle sizes of 5 mm~1 cm and 1~3 cm respectively) were selected as the raw materials for this model test to fill the piles. The basic physical and mechanical parameters of the accumulation body model and the Shuping landslide soil were obtained, as shown in Table1.

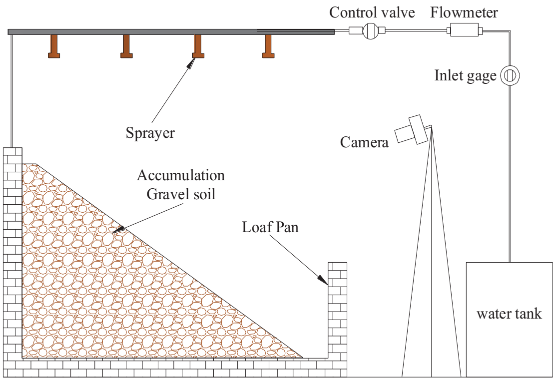


Figure 1. Test model of landslide accumulation

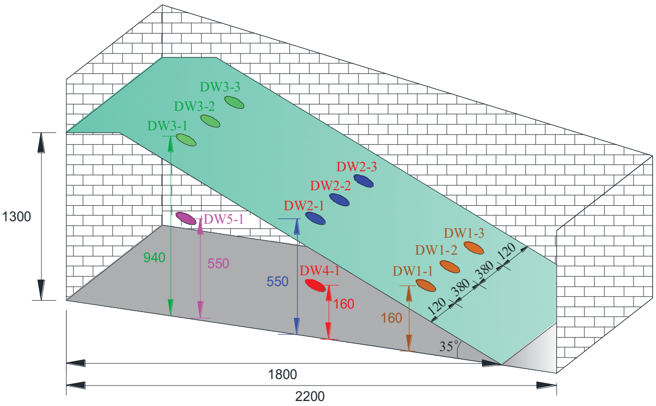


Figure 2. Layout of sampling points

2.2 Test program

2.2.1 *Sampling point layout*

To explore the variation law of the permeability and shear strength parameters of the particles in the accumulation body model after rainfall. Five points were arranged in a section along the long side of the accumulation body model to sample the accumulation particles. The first section numbers are DW1-1, DW2-1, DW3-1, DW4-1, and DW5-1 respectively. The No.1 position of the second and third profiles are numbered DW1-2 and DW1-3 respectively, and the rest of the points are numbered by analogy, for a total of 15 sampling points. Among them, the elevations of DW1 to DW5 are 16 cm, 55 cm, 94 cm, 16 cm and 55 cm, respectively. The horizontal distances from DW1 to DW5 to the foot of the slope are 40 cm, 94 cm, 148 cm, 40 cm and 94 cm, respectively. The sampling point layout is shown in Figure 2.

2.2.2 *Test scheme*

After 60 hours of rainfall (10 hours each time, divided into six times, with a cumulative rainfall of 2700 mm), the accumulation body is necessary to be stationary for 24 hours, and then the accumulation particles are sampled at each sampling point and the permeability and shear strength are measured. It was used 0.4 MPa, 0.3 MPa, and 0.2 MPa pressure water to conduct a 5 min constant head penetration test to measure the permeability coefficient, and the average value of the permeability coefficient under three-stage water pressures was taken as the permeability coefficient of each sampling point. After rainfall, the shear strength parameters of the accumulation particles were obtained by taking 3 groups of samples at each sampling point and performing the unconsolidated and undrained direct shear tests with the normal stress values of 100 kPa, 200 kPa, and 300 kPa in the YZW1000 electric direct shearing instrument.

Table 1. Physical and mechanical parameters of test landslide accumulation and Shuping landslide rock mass

Soil sample category	Density ρ/g·cm^{-3}	Stone percentage /%	Moisture content /%	Cohesion c/ kPa	Internal friction angle φ/°	Permeability coefficient k/ cm·s^{-1}	Inhomogeneity coefficient	Curvature coefficient
Shuping landslide	2.01	68	23.4	20.7	23.5	1.02×10^{-2}	30.36	1.21
Test accumulation	2.0	68	8.0	33.66	36.78	1.60×10^{-3}	28.0	1.90

3 Analysis of Test Results

To quantitatively characterize the parameter change law of the gravel-soil at different elevations of the accumulation, the parameter change rate and the phase change rate of the parameter along the down-slope direction were introduced to analyze the permeation properties and shear strength of the accumulation, as shown in Eq. (1).

$$L_i = \frac{l_i - l_0}{l_0}, \Delta L_i = \frac{l_i - l_{i-1}}{H_i - H_{i-1}}, i = n, . . . ,2,1 \tag{1}$$

where:i— Sampling point number. L_i— Parameter change rate. ΔL_i— Parameter down-slope phase change rate. l_0— Initial parameter value. l_i,l_{i-1}— Target point parameter value. H_0,H_i——target point elevation.

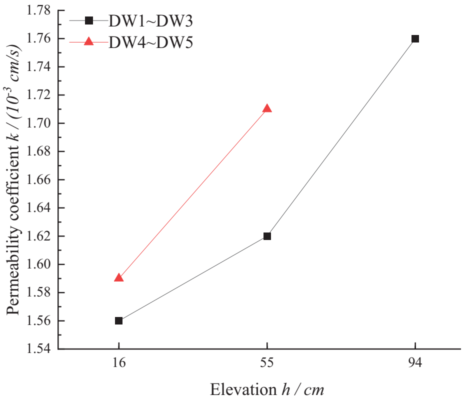


Figure 3. The relationship between accumulation permeability coefficient and elevation

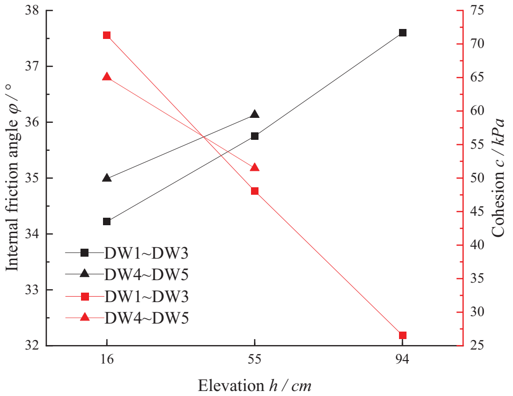


Figure 4. The relationship between accumulation shear strength and elevation

From Figure 3, it can be found that the permeability coefficient of the particles in the accumulation on the landslide surface increases gradually with the increase of the sampling point elevation, from 1.56×10^{-3} cm/s at the bottom of the landslide (DW1) to 1.76×10^{-3} cm/s at the top of landslide (DW3). Compared with the initial permeability coefficient of the accumulation particles before the rainfall, the permeability coefficient of the sampling point DW1 decreased significantly by 2.5%, while the permeability coefficient of the sampling point DW3 increased by 10%. It can be seen from Figure 4 that, compared with the initial values before the rainfall, the cohesion and internal friction angle of the accumulation particles have changed, either increasing or decreasing. For the change of cohesion, except for the sampling point DW3, which decreased by 21.09% from the initial value of 33.66kPa to 26.56kPa, the cohesion of the remaining four sampling points increased compared with the initial value before the rainfall. Among them, the cohesion of DW1 at the sampling point was the largest, from 33.66 kPa to 71.3 kPa, an increase of 111.9%. Similarly, for the angle of internal friction, except that the sampling point DW3 increased by2.22% from the initial value of 36.78 to 37.6, the internal friction angle of the remaining four sampling points decreased compared with the initial value before the rainfall. The sampling point with the largest change still appeared in DW1, which decreased by 6.96% from 36.78 to 34.22.

Table 2. Change rate of permeability coefficient and the shear strength parameter

Elevation	16 cm	55 cm	94 cm
Permeability coefficient	0.0155	0.041	0.1
Internal friction angle φ/°	1.026	0.479	-0.211
Cohesion c /kPa	-0.060	-0.023	0.022

As can be seen from the parameter values30 of each sampling point of the accumulation point, due to the action of rain, the fine particles of the accumulation point migrate from elevation to low range, and the permeability of particles is weak, and the permeability coefficient decreases linearly. The shear strength changes obviously along the elevation, the internal friction Angle decreases linearly, and the cohesion increases linearly with the elevation. To quantitatively describe the relationship between the permeability of the accumulation particles and the elevation, the average value of the parameter change rate at the same elevation was taken as the change rate of the permeability coefficient at the corresponding elevation (as shown in Table 2).

The relationship between the change rate of the permeability coefficient and shear strength parameters and the elevation is obtained, respectively, by fitting the average value of the elevation and the parameter change rate, as shown in Eq. (2):

$$\begin{cases} L_{ki} = 0.0147+1.2804h_i + 1\times10^{-5} h_i^2 \\ L_{ci} = 1.6353 - 0.0419h_i - 2.3642\times10^{-4} h_i^2, \quad i = n, \quad ...,2,1 \\ L_{\varphi i} = \text{-}0.0729+7.62\times10^{-4} h_i+2.6298\times10^{-6} h_i^2 \end{cases} \tag{2}$$

where:L_{ki},L_{ci} and $L_{\varphi \mathrm{i}}$ are the change rate of permeability coefficient, cohesion and internal friction angle at h_i. h_i is the elevation of the target point of the accumulation model.

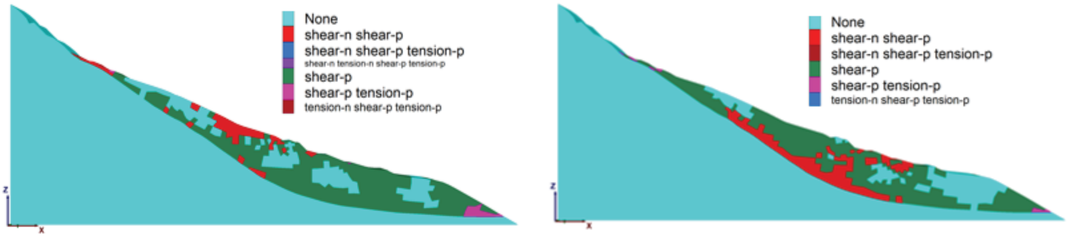
According to the above test results, the relationship between the change rate of each parameter and its parameter value is analyzed, and the relationship between the permeability coefficient and shear strength parameter and the elevation of the accumulation model can be deduced Eq. (3):

$$\begin{cases} k_i = k_0(1+L_{k1}) + 2.73\times10^{-6} h_i \\ c_i = c_0\left(1+L_{c1}\right) - 0.4980h_i, \quad i = n, ...,2,1 \\ \varphi_i = \varphi_0\left(1+L_{\varphi 1}\right) + 0.0357h_i \end{cases} \tag{3}$$

where: $k_i, c_i, \varphi_i$are the value of the permeability coefficients, cohesion, and internal friction angle of the accumulation model at h_i. k_0, c_0, $\varphi_0$are the initial values of the cohesion and the internal friction angle of the accumulation model before the test, respectively. The constants in the formula are the average value of the phase change rate of each parameter. The change rate of the cohesion and the internal friction angle at h_i=0 are $L_{c1} = 1.635$，$L_{\varphi 1} = -0.0729$, respectively.

4 Analysis of Landslide Stability of Shuping Accumulation

According to the relevant geological data, FLAC^{3D} is used to establish the numerical model of Shuping accumulation. The calculation process used, the fluid-structure coupling calculation function of FLAC^{3D}. The Mohr-Coulomb criterion of the linear elastic-plastic constitutive model is used to characterize the accumulation, and the rainfall effect is simulated by the variation formula of the permeability coefficient and shear strength parameters along the elevation mentioned in the section 3. According to the actual situation, this paper set up four working conditions for simulation analysis: ①145 m reservoir water level. ②175 m reservoir water level. ③145 m reservoir water level combined with rainfall. ④175 m reservoir water level combined with rainfall.



(a) Condition 2 (b) Condition 4

Figure 5. The plastic deformation zone of the landslide under condition 2 and 4

Figure 5 shows the plastic deformation zone of the landslide under working conditions 2 and 4. Considering the working conditions under rainfall, the plastic area is larger and completely penetrating than only considering the working conditions of the reservoir water level.The safety factors are 1.27, 1.17, 1.26 and 1.11 under the four working conditions, and the displacement of landslides in the X direction is 4.75 cm, 3.76 cm, 5.36 cm and 6.09 cm, respectively. When the reservoir water level and rainfall are combined, due to the migration of fine particles inside the rainfall landslide to the toe of the slope, the physical and mechanical parameters of the landslide have variability along the elevation, resulting in the increase of the plastic zone and the gradual penetration of the slip zone, the x-direction displacement gradually increases, the reduction of the safety factor, and finally the landslide in the less stable state.

5 Conclusion

(1) Compared with the initial accumulation particles before rainfall, the permeability coefficient of DW1 decreased significantly by 2.5%, cohesion c increased by 111.9%, and internal friction angle φ decreased by 6.96%. However, the permeability coefficient of sampling point DW3 increased by 10%, cohesion c decreased by 21.09%, and internal friction angle φ increased by 2.22%. With the increase of elevation, the permeability coefficient increased linearly, the value of cohesion c gradually decreased, and the value of internal friction angle φ increased.

(2) The combined effect of rainfall and reservoir water level, that is, considering the variation of parameters along the landslide elevation, compared with the same height with only reservoir water level effect, the maximum deformation of Shuping landslide at 145 m and 175 m water levels in the X direction increased by 12.81% and 42.52%. However, the safety factor decreased by 7.874% and 11.8% respectively.

(3) After considering the variability of the physical and mechanical parameters of the accumulation landslide along the elevation, the calculated safety factor is smaller, and the stability of the accumulation is not overestimated. In other words, ignoring the variability of parameters along the elevation due to long-term rainfall will lead to overestimation of slope stability and potentially unsafe design results.

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