Numerical simulation of progressive failure of red clay slopes based on strength weakening

Jing Wu[1], Mingliang Wu[2,*], Fan Jiang[1] and Chao Liu[3]

[1]Guangxi Zhuang Autonomous Region Natural Resources Ecological Restoration Center, Nanning, Guangxi, 530028, China
[2]School of Architecture and Transportation Engineering, Guilin University of Electronic Technology, Guilin, Guangxi, 541004, China
[3]The First Geological Team of Guangxi Zhuang Autonomous Region, Guilin Guangxi 541004, China

*Corresponding author's e-mail:Wml206@outlook.com

Abstract. At present, there are relatively few domestic and foreign studies on the weakening of shear strength of red clay, and the play of residual strength of red clay has not been considered in the study of slope stability. Based on finite element analysis software, this paper carries out the influence of different sliding surface participation coefficients and geometrical forms on the slope stability of red clay slopes considering strength weakening, and the results show that: under the condition of the same water content, the safety coefficient of the slope decreases with the increase of the residual coefficient *R*; and the safety coefficient of the slope shows the trend of decreasing firstly and then increasing with the increase of the slope gradient *i*. The research results are important for the proper evaluation of the safety stability of red clay slopes. The research results have important theoretical research significance and engineering practical value for correctly evaluating the safety and stability of slopes.

Keywords: Red clay; Slope; Strength weakening; Progressive failure; Stability analysis.

1 Introduction

China is a country with extremely frequent landslide disasters, especially in the southwestern region of China, large landslides are characterized by large scale, complex mechanisms, and great hazards, which are typical and representative of the whole world [1]. China's southwest region, such as Guangxi region widely distributed red clay not only has a large pore space, high water content, high liquid-plastic limit and other characteristics, and structural strong, there is the upper hard and lower soft layered distribution characteristics, for red clay slopes are very prone to landslides[2].

Based on the research results of domestic and foreign research scholars, the main factors affecting the stability of slopes are geotechnical properties, geotechnical structure and structure, geomorphologic factors, and severe natural disasters (heavy rainfall,

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earthquakes, typhoons, etc.)[2-5]. In the study of the stability of clayey soil slopes, the change of shear strength parameter of the soil body is the key to influence the stability of the slope, and rainfall as an important factor in inducing slope instability, the main reason is still that the increase of water content will reduce the shear strength parameter of the soil body[6,7]. The progressive destruction of slopes studies the characteristics of landslide generation, the process of development and the results produced, and analyzes the influence of strength weakening effect from the perspective of the destabilization mechanism of slopes (landslides)[8,9].

Existing scholars in the slope stability analysis is mostly established on the basis of the soil body shear strength constant, which has certain limitations. In engineering design, when designers use the peak strength parameter index of soil body to calculate the slope safety factor, the result is biased toward safety and uneconomical; when they use the residual strength parameter index to calculate, the result tends to be unsafe[10]. Therefore, this paper adopts the slope stability analysis software based on the limit equilibrium method to study the weakening characteristics of the strength parameters of red clay and the progressive destruction of slopes, which is of great significance for the analysis and management of the stability of red clay slopes.

2 Engineering examples

Figure 1 shows the high slope of red clay road graben at a highway pile number K127+500, with the ground elevation of +253.88~+278.47 m. The hydrogeological conditions are mainly bedrock fissure water and pore water of the soil layer, and the soil samples have a large water content in the rainy season. The slope had a large landslide in late 2014, which seriously affected the transportation safety. The type of landslide belongs to traction landslide, and the leading edge of the landslide body has been completely slipped and destroyed, but the whole sliding surface has not been completely penetrated, and the sliding surface is still continuing to develop upwards.

3 Simplification of the correction formula for the Bishop method

Considering the residual strength characteristics of the soil body on the slope, a modified formulation of the simplified Bishop's method is proposed based on the shear strain softening model. Based on the Moore-Coulomb strength criterion, it is assumed that a part of the soil body slides along a certain sliding surface. On this sliding surface, the soil body reaches limit equilibrium everywhere, i.e., the positive stress σ_n and shear stress τ satisfy the Moore-Coulomb strength criterion. As shown in Figure 2, let the normal and tangential forces at the bottom of the soil bar be ΔN and ΔT, respectively, and we have:

$$\Delta T = \frac{c^* \Delta x \sec\alpha_i + (\Delta N - u\Delta x \sec\alpha_i)\tan\varphi^*}{F_s} \tag{1}$$

where F_s is the slope safety factor; Δx is the lateral width of the strip; α_i is the angle between the line of gravity of the first strip and the radius through the center of the bottom surface of the strip; and u is the pore water pressure, which is usually defined as the pore water pressure coefficient:

$$r_u = \frac{u}{dW / dx} \tag{2}$$

Establish the static equilibrium equations in the vertical direction as shown in Figure 2:

$$\Delta N \cos \alpha_i + \Delta T \sin \alpha_i = \Delta W \tag{3}$$

where ΔW is the weight of the soil bar.

Fig. 1. Red clay high slopes.

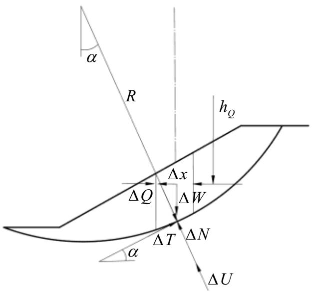

Fig. 2. Schematic diagram of simplified Bishop's method for slope stability analysis.

According to Figure 2, the safety factor is solved by balancing the moments of the whole against the center of the circle:

$$\sum_{n=1}^{N} (-\Delta T + \Delta W \sin \alpha_i + \Delta Q R_d) = 0 \tag{4}$$

where $R_d = h_Q / R$; h_Q is the vertical distance between the horizontal seismic force and the center of the circle; N is the total number of soil bars; and R is the radius of the sliding surface. ΔQ is the seismic force, horizontal seismic force $\Delta Q = \eta \Delta W$, η is the horizontal seismic coefficient.

The association of equations (1), (2) and (3) gives:

$$F_s = \frac{\sum_{n=1}^{N} [\Delta W (1 - r_u) \tan \varphi^* + c^* \Delta x] / [\cos \alpha_i (1 + \tan \alpha_i \tan \varphi^* / F_s)]}{\sum_{n=1}^{N} (\Delta W \sin \alpha_i + \Delta Q R_d)} \tag{5}$$

Introduction to finite element calculations.

3.1 Modeling and parameterization

The depth of the model foundation is taken as 15m, the height of the road graben is taken as 25m, the back wall of the landslide is 12m away from the top of the slope, and the leading edge has been completely slipped and damaged with a slope length of 15.7m, and the geometrical dimensions are shown in Figure 3. Displacement boundary conditions are used, the road traveling direction is the Y axis of the coordinate system, the roadbed cross-section direction is the X axis, the vertical direction is the Z axis, the bottom boundary imposes displacement constraints, and the top boundary is the free boundary, the calculation model is shown in Figure 3. Among them, the circular arc is the sliding surface, No. 2 is the front edge of the body that has penetrated and slipped the landslide, and No. 1 is the middle and back edge of the landslide.

The strength of the soil body at the front edge of landslide No. 2 has reached the residual strength, which is assigned to the residual strength parameter index of the soil body, and the soil body of No. 1 has a small shear displacement and has not yet reached the required shear displacement for the residual strength, which is assigned to the peak strength parameter index. The corresponding shear strength indexes for the peak strength and residual strength of the soil body under different water contents are shown in Table 1.

Table 1. Indicators of shear strength of slope soils under different water contents.

Water Content	Peak Strength		Residual Strength	
$w\%$	c/kPa	$\varphi(°)$	c/kPa	$\varphi(°)$
25	23.860	23.156	19.383	11.431
35	15.791	22.860	12.076	13.469
45	11.472	22.352	10.208	15.035
55	9.235	21.107	8.771	14.874

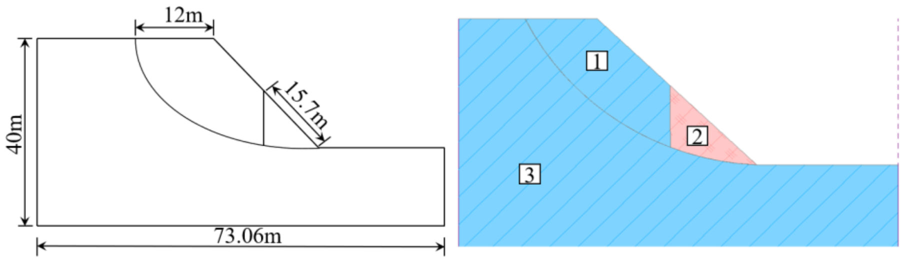

Fig. 3. Model dimensions and calculation model schematic.

3.2 Validation of model calculation results

Finite element calculation software GEO5 'soil slope stability analysis' module for the stability analysis of the slope, the type of analysis for the given sliding surface, the working condition selection of durable design conditions, all analyses are used Bishop method. The computational model determines that the soil water content of the slope is the same, and the water content is uniformly increased or decreased.

Using the simplified Bishop method of the modified formula (5) to calculate the slope safety factor, soil parameters are used with the same parameter size of the numerical simulation, the process does not take into account the effect of groundwater and seismic forces, each soil bar soil quality is uniform and moisture content are the same, the sliding body is divided into 20 soil bars, residual coefficients R= 0.2966, the parameter n=6. The results of the calculations and the numerical simulations to make comparisons with the results, the results of the numerical simulations. As shown in Figure 4.

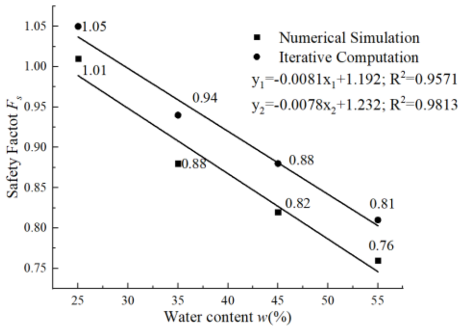

Fig. 4. Comparison of the calculation results of the two methods.

From the figure, it can be seen that the correction formula of simplified Bishop method calculates the slope safety coefficient in the same trend with the finite element calculation results, and the increase of water content will lead to the decrease of the slope safety coefficient. Under the condition of the same water content, the modified formula of simplified Bishop method is a little larger than that of numerical simulation, but the difference between the two methods is very small, taking into account the influence of groundwater and seismic force in numerical simulation on the calculation results, so it can be regarded as the same results of the two methods. In summary, the two methods can be verified with each other, and it can be concluded that the increase of soil water content will lead to the decrease of the overall stability of the slope.

4 Discussion and analysis

4.1 Effect of residual coefficients of slope sliding surface on stability

In the strip partitioning method, the ratio of the number of clods that have reached the residual strength to the overall number is defined as the residual coefficient of the landslide, denoted as R. The same slope calculation model is selected, and the residual coefficient R is defined as 0.0593, 0.1186, 0.1779, 0.2373, 0.2966, respectively, and the finite element calculation is carried out, as shown in Figure 5. The change rule between the landslide safety factor F_s and the residual coefficient R of the slope with different water content is calculated and shown in Figure 6.

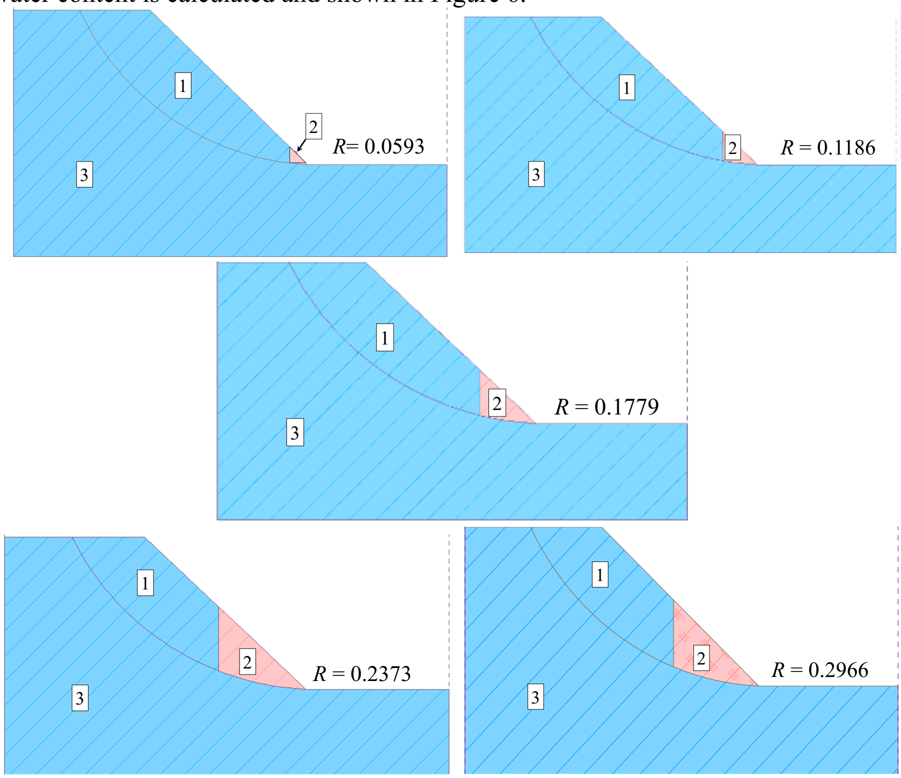

Fig. 5. Finite element computational model of residual strength R for five different groups of slopes.

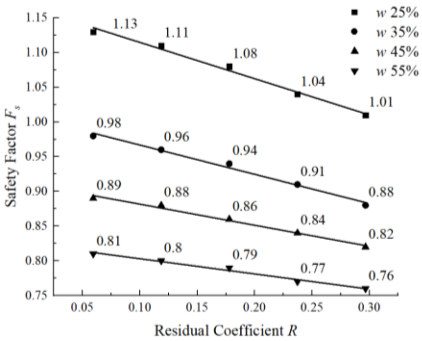

Fig. 6. Law curve of residual coefficient R and landslide

safety factor F_s under different water content rate.

From the figure 6, it can be seen that the slope residual coefficient R has a significant effect on the stability of the slope under the condition of not changing the sliding surface and slope geometry. Under the same water content condition, the safety coefficient of the slope decreases with the increase of the residual coefficient.

4.2 Influence of slope geometry on stability

For simple slopes, the slope of the slope is the key factor affecting the stability, without changing the height of the slope, define different slope calculation models with slope i of 0.932, 0.810, 0.781, 0.727 respectively (Figure 7), the model residual coefficient R= 0.0593, and the material parameters of the soil body are consistent with the previous section. The change rule between the landslide safety coefficient and slope gradient under different water content is calculated and shown in Figure 8.

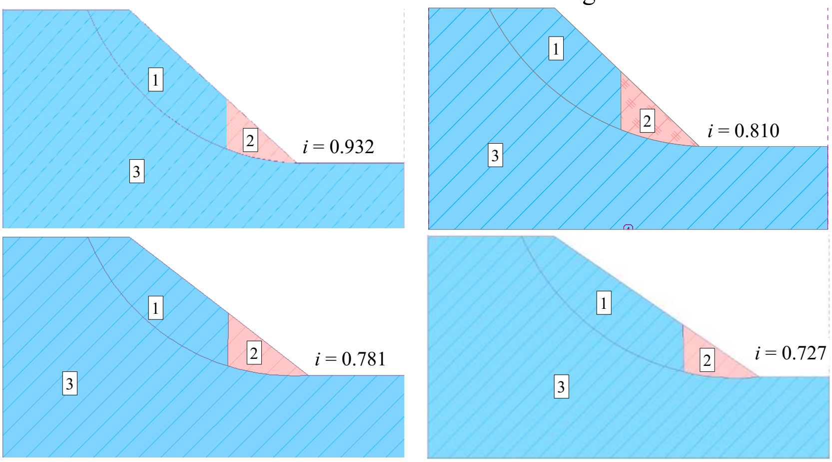

Fig. 7. Calculation model for different slopes i.

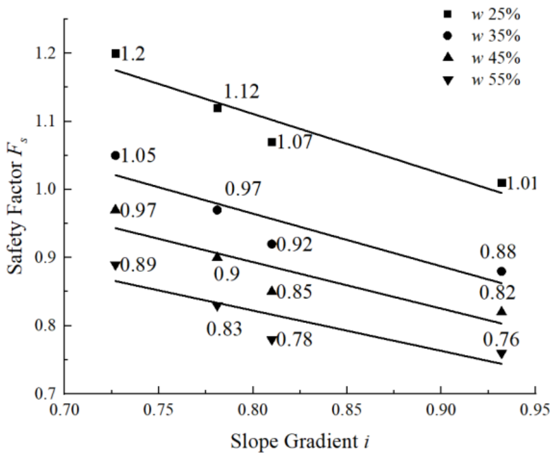

Fig. 8. Curve of slope i and the law of safety coefficient of landslide body under different water content rate.

From the figure, it can be seen that the slope gradient i has a significant effect on the stability of the slope without changing the slope residual coefficient R and the slope height. Under the condition of different water content, the slope gradient i and the safety coefficient of the landslide are basically the same. The safety coefficient of the slope decreases with the increase of slope gradient i of the slope.

5 Conclusion

(1) Under the condition of not changing the sliding surface and slope geometry, the slope residual coefficient R has a significant effect on the stability of the slope. Under the same water content condition, the safety coefficient of the slope decreases with the increase of the residual coefficient.

(2) Under different water content conditions, the slope gradient i and the slope safety coefficient are basically the same. The safety factor of the slope decreases with the increase of slope gradient i.

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