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FLAC3D implements coupled numerical analysis of nonlinear response of groundwater seepage and slope stability.

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Abstract Slope stability is directly related to engineering safety, and the nonlinear action mechanism of groundwater infiltration, as an important factor affecting slope stability, still needs in-depth study. Based on the numerical simulation method of FLAC3D, this study systematically analyzes the mechanism of nonlinear influence of groundwater infiltration on slope stability, and investigates the influence of different water level heights and inclination angles of structural surfaces on the slope safety coefficient. The study used Mohr-Coulumb model to construct the slope analysis model, and combined with Darcy's law and finite element strength reduction method to calculate the slope stability. The results show that: when there is no structural surface, the slope safety coefficient decreases from 1.39 to 1.00 when the water level rises from 50m to 85m; when there is a structural surface, the slope safety coefficient of the structural surface inclination of 15° decreases by 0.67 with the rise of the water level, and decreases by 0.49 when the structural surface inclination of 20°; when the water level reaches 85m, the slope safety coefficients of the structural surface inclination of 15° and 20° decrease by 0.52 and 0.49 respectively. When the water level reaches 85 m, the coefficients of safety are 0.52 and 0.69 for 15° and 20° of structural surface inclination, respectively; the slope stability coefficient increases from 1.08 to 1.49 when the depth of groundwater level increases from 10 m to 30 m. The study confirms the significant effect of the position of structural surface within the slope on the slope safety coefficient, and clarifies the nonlinear relationship between the change of groundwater level and the stability of slopes. Based on the results of the study, control measures such as increasing hydrogeological investigation, strengthening hydrological monitoring, adopting engineering means of seepage control and strengthening drainage diversion are proposed, which provide theoretical support for slope stability design and disaster prevention.

Index Terms FLAC3D, groundwater infiltration, slope stability, nonlinear variation, structural surface inclination, safety factor

I. Introduction

Changes in the rise and fall of the groundwater level can also cause a series of problems, commonly including soil salinization, liquefaction of fine sand and pipe surge, uplift and water seepage from underground caverns, corrosion of man-made structures as well as seawater intrusion, and ground subsidence, etc. [1]-[3]. In addition to this, dynamic changes in the rise and fall of the groundwater level can also cause slope instability. In the natural environment, most of the slope instability is related to the reduction of strength parameters of geotechnical bodies caused by rainfall, but there are also some specific cases where landslides are generated mainly due to the rise and fall of water level [4]-[6]. In such cases, the more typical is the reservoir bank slope destabilization damage caused by the change of water level in reservoirs, and channel slope destabilization damage caused by the channel through the water-break, slope destabilization brings destructive disaster to the project, and once the slope destabilization problem occurs, the damage caused by it is often very large [7].

The influence of groundwater on slope stability is multifaceted, and the influence effect of groundwater includes at least two aspects, one of which is the weakening effect of water on strength parameters. The two shear strength indicators of the soil, their actual magnitude depends on these physical properties such as the pore ratio of the soil, the friction characteristics of the particles, the particle size gradation, the overconsolidation ratio and the water content in the soil [8]-[10]. The second is the direct mechanical effect, where the action of water reduces the suction between soil particles, while the presence of pore water pressure affects the force behavior of the soil [11], [12]. Many bank slopes are destabilized and damaged during the steep drop of reservoir water level, in addition to the change of slope stability due to the increase of effective gravity in the steeply dropping part of the geotechnical body due to the disappearance of buoyancy support force, the steep drop of water level causes the seepage movement of groundwater within the geotechnical body and generates the infiltration force which is an important factor that leads to the slope destabilization [13], [14]. Among them, the magnitude of infiltration force is related to various factors such as the shape of infiltration line, permeability coefficient of the geotechnical body, the size of the saturated area of the geotechnical body and the inclination angle of potential sliding surface [15]. Currently, there is no accurate calculation method, in which the determination of the infiltration line within the slope is more complicated, and its shape is related to the infiltration coefficient of the geotechnical body, the degree of water supply, and the rate of descent of the reservoir water level.

Slope stability problem is an important topic in engineering construction, especially in the fields of highway, railroad, water conservancy and hydropower and mining with a wide range of engineering background. As one of the key factors affecting slope stability, groundwater infiltration can cause a series of effects such as reduction of strength of slope geotechnical body, increase of hydrostatic pressure and reduction of effective stress, which in turn leads to changes in the stable state of slopes. The influence of groundwater infiltration on slope stability has obvious nonlinear characteristics, and this nonlinearity is manifested in the nonproportional relationship between the change of groundwater level height and slope safety coefficient. In actual engineering, slope instability often occurs after heavy rainfall or during the sharp rise of groundwater level, and groundwater infiltration is often the main factor inducing slope instability. Currently, the research on slope stability under the influence of groundwater infiltration mainly focuses on qualitative analysis and experience summary, and lacks systematic quantitative research and nonlinear mechanism analysis. The slope stability evaluation method also stays at the level of traditional limit equilibrium method, which is difficult to comprehensively reflect the dynamic change characteristics of the internal stress field and displacement field of the slope in the process of groundwater infiltration. In addition, the existence of structural surface in the slope geotechnical body makes the influence of groundwater infiltration on slope stability more complicated, and the change rule of slope stability under the joint action of structural surface inclination and groundwater level needs to be explored in depth. Therefore, based on numerical simulation method, a systematic study on the nonlinear change of slope stability under the influence of groundwater infiltration has important theoretical and practical value for guiding engineering practice and disaster prevention.

In this study, the slope of a highway in Guangdong Province is taken as the research object, and the slope stability analysis model is constructed by FLAC3D numerical simulation method, and the slope safety coefficient is calculated by the finite element strength discount method. The study firstly analyzes the relationship between different water level heights and slope stability under the condition of no structural surface, and explores the influence of water level changes on slope stability; secondly, considering the existence of structural surfaces with different inclinations, the study systematically investigates the influences of structural surface inclination and water level height changes on slope safety coefficients; lastly, based on the results of the study, it puts forward targeted slope prevention and control suggestions, and analyzes the improvement effect of drainage measures on slope stability. By comparing and analyzing the changes of slope safety coefficient under different working conditions, it reveals the inner mechanism of non-linear changes of slope stability under the influence of groundwater infiltration, and provides theoretical basis and technical support for the evaluation of slope stability and optimization of prevention and control measures.

II. Slope analysis models and research methods

II. A. Parameters of the slope analysis model

The model refers to the slope of a highway in Guangdong Province, the slope length is about 50m, the maximum height is about 90m, the slope is divided into four levels, the slope rate of the first and second level slope 1:0.8, the slope rate of the third and fourth level slope 1:1, the slope is divided into artificial fill, powdery clay, sandy clay, fully weathered granite gneiss and strongly weathered granite gneiss 5 layers from top to bottom. According to the thickness of each rock layer measured by drilling holes at the top of the slope, see Table 1, in which the strongly weathered granite gneiss layer is missing data because the bottom of the layer is not explored.

Table 1: The thickness of the soil measured by the borehole

Soil name	Bottom depth	Layer thickness	Bottom elevation
Artificial soil	0.80	0.86	59.00
Powdered clay	4.01	2.98	55.75
Sandy clay	5.39	1.56	54.86
All weathered granite	11.31	5.91	48.37

The initial survey measured the stabilized water level at a depth of 24m and an elevation of 36m. The borehole point near the highway direction 22m away from the borehole measurement of the depth and thickness of each soil layer without large changes, so the establishment of the model is considered to be level. According to the field exploration results, in-situ test data and geotechnical test results, while referring to the relevant norms, to determine the value of geotechnical physical and mechanical parameters of each soil layer.

II. B.Research methodology

Slope stability analysis is a prerequisite for slope design, which determines whether the slope is unstable or not and how much thrust exists when the slope is unstable, so as to provide a scientific basis for the design of supporting structures. Slope stability analysis involves complex geological and topographical boundary conditions, nonlinear behavior of stress-strain of materials, coupled analysis of initial ground stress, water pressure, seismic loading, etc., and analytical solutions cannot be obtained in most cases. Against the background of the continuous development of computers and computational methods, numerical analysis methods represented by finite elements have been gradually popularized and applied in geotechnical engineering, and developed into a powerful computational analysis tool. In this paper, FLAC3D model and finite element strength discount method are used to systematically analyze the slope stability under groundwater infiltration.

II. B. 1) FLAC3D modeling

The Mohr-Coulumb model is used to check the slope stability, which is suitable for loose or cemented granular materials such as soil, rock and concrete, and can be used to analyze slope stability, underground excavation and other problems, and the development of plastic zone can be used to judge the slope condition. The model is selected as a block unit with a unit length of 1 m. After modeling, displacement constraints are imposed on the bottom and sides of the model.

The following parameters are needed in the $FLAC^{3D}$ software to calculate the safety factor: cohesion c, angle of internal friction φ, density ρ, bulk modulus K, and shear modulus G, and to determine the model size by the height of the side slopes and slope gradient. The bulk modulus K and shear modulus G are converted to Poisson's ratio ν and elastic modulus E by Eqs. (1) and (2):

$$K = \frac{E}{3(1-2\nu)} \tag{1}$$

$$G = \frac{E}{2(1+\nu)} \tag{2}$$

Combining the results of the field survey and the theoretical values of each material parameter, the slope parameters were set in FLAC3D.

II. B. 2) Calculation of seepage on slopes

The main theory used in this paper to analyze the groundwater seepage on the case slopes is Darcy's Law, which is as follows:

$$Q = Ak\frac{(h_1 - h_2)}{L} \tag{3}$$

maybe

$$v = \frac{Q}{A} = -k\frac{dh}{dL} = kJ \tag{4}$$

where, v is the average flow rate, or Darcy flow rate. J is the hydraulic gradient, k is the permeability coefficient, h is the head of the gauge pipe, A is the cross-sectional area, and L is the seepage length.

The continuity equation of groundwater movement can be derived from the law of conservation of mass. That is, according to the seepage field of water mass in a unit of the rate of accumulation is equal to the rate of change of the mass of water into and out of the unit with time, can be obtained seepage of water movement continuity equation for:

$$-\left(\frac{\partial v}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial v}{\partial z}\right) = S\frac{\partial h}{\partial t} \tag{5}$$

where, S is the water storage rate (the amount of water released or stored from a unit volume of aquifer due to deformation of the skeleton and expansion and compression of water when the head h changes by one unit), and t is time.

Consider the continuity equation for steady seepage when soil and water are all incompressible, i.e., steady seepage $S=0$:

$$\frac{\partial v}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial v}{\partial z}=0 \tag{6}$$

Will Darcy's Law:

$$\begin{cases} v_x=-k_x\dfrac{\partial h}{\partial x} \\ v_y=-k_y\dfrac{\partial h}{\partial y} \\ v_z=-k_z\dfrac{\partial h}{\partial z} \end{cases} \tag{7}$$

Substituting into Eq. (6), the differential equation for steady seepage flow is obtained:

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_z\frac{\partial h}{\partial z}\right)=0 \tag{8}$$

When considering the anisotropy of permeability, equation (8) can be changed to:

$$k_x\frac{\partial^2 h}{\partial x^2}+k_y\frac{\partial^2 h}{\partial y^2}+k_z\frac{\partial^2 h}{\partial z^2}=0 \tag{9}$$

When the permeability coefficient is the same in all directions, i.e., $k_x=k_y=k_z$, then the Laplace equation is:

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}+\frac{\partial^2 h}{\partial z^2}=0 \tag{10}$$

II. B. 3) Finite element strength reduction method

The finite element strength discount method overcomes the deficiencies of the traditional rigid-body limit equilibrium analysis method and can be used to analyze the stress and deformation conditions and their changes at various points during the damage process of slopes, with a large scope of application. This method is defined as the ratio of the maximum shear strength provided by the soil body inside the slope to the actual shear stress produced by the external load inside the slope under the condition that the external load remains unchanged. It is the ideal elastic-plastic finite element calculation in which the parameter of shear strength of the soil body of the slope is gradually reduced until it reaches the limiting state, and at the same time, it is obtained as the safety factor of the strength reserve of the slope, F_s, which is also the safety factor of the overall stability of the slope at this time. The discounted shear strength parameters can be expressed as respectively:

$$c_m=c/F_r \tag{11}$$

$$\varphi_m=\arctan(\tan\varphi/F_r) \tag{12}$$

where, c, φ are the cohesive force and the angle of internal friction that the soil can provide, respectively. c_m, φ_m are the cohesive force and angle of internal friction required to maintain equilibrium or actually exerted by the soil, respectively. F_r is the strength discount factor.

Different strength reduction coefficients F_r are assumed in the calculation, and the finite element analysis is carried out according to the strength parameters after the reduction to observe whether the calculation converges or not. The strength reduction factor F_r is the slope stability safety factor F_r when the critical damage is reached by increasing F_r throughout the calculation process.

III. Numerical simulation analysis of nonlinear variations

III. A. Analysis of the situation without structural surfaces

According to the actual slope and the size of the modeling set, analyze the slope stability changes in the water level within the slope height of 10, 20, 30, 40, 50, 55, 60, 65, 70, 75, 80 and 85m in 12 settings, can be obtained from the relationship between the water level changes and slope stability as shown in Figure 1. When the height of the water level in the slope reaches 70m (an unfavorable situation under heavy rainfall, with high water content in the slope), the slope stability is poor and there is an obvious sliding surface formation, with a large displacement at the foot of the slope, and there is a risk of sliding collapse.

When there is no structural surface (i.e., the soil structure of the slope is uniform), the slope safety coefficient gradually decreases with the rise of the height of the water level in the slope body, and when the water level is within the range of 10-50m, the change of the safety coefficient is small, and the safety coefficient is 1.45, which shows that the groundwater infiltration in the region of this section has a minimal effect on the stability of the slope. When the water level height from 50m gradually close to the top of the slope, the coefficient of safety gradually decreases, the higher the water level, the smaller the coefficient of safety, the coefficient of safety from 55m 1.39 to 85m 1.00. From the overall trend of the water level changes, the slope damage occurs mainly present arc sliding, and along with the rise of the water level, the impact of sliding in the plastic zone shows a slow and fast development trend.

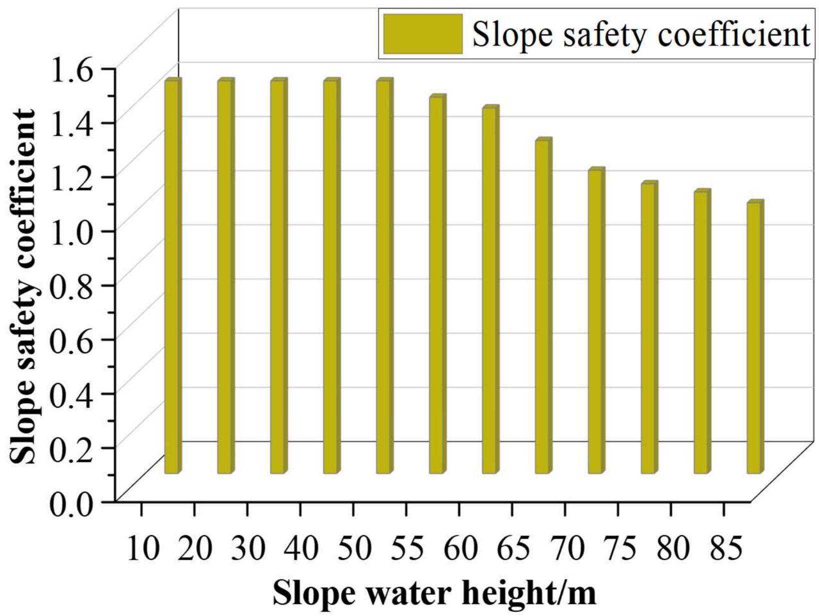

Figure 1: Slope safety factor and groundwater variation trend

III. B. Effects of changes in water levels

Based on the engineering reality, the slope structural surface inclination angle is set to 15° and 20° to establish the corresponding numerical model to analyze the influence of structural surface change as well as the height of the water level on the stability of the slope or the destruction of the viscous contact surface in these two states. When the damage occurs, the behavior of the contact surface unit by the internal friction angle and cohesion. According to the working mechanism, FLAC3D contains a cohesive contact surface, a sliding bonded contact surface, and a Coulomb slip contact surface, and the Coulomb slip contact surface is selected according to the actual contact of the geotechnical body, which is a type of sliding contact surface that only exists in the intact decision, and at the same time the stiffness parameter has a corresponding effect. When the bond strength is not set, its value can be regarded as 0. The damaged bond unit cannot withstand the effective tensile stress.

Considering the low impact on slope stability when the water level is low, the setting of the structural surface chooses the less favorable location to start the analysis, and the setting is located at the height of 55m. The law of the slope safety coefficient changing with the water level height under different structural surface inclination is analyzed, and the relationship curve between the water level height change and slope safety coefficient under different structural surface inclination is obtained, and the slope safety coefficient changes when the structural surface inclination angle is 15° and 20° are shown in Fig. 2 and Fig. 3.

Within the slope with medium and slow inclination, the safety and stability coefficient gradually decreases with the gradual rise of the water level height inside the slope, and the safety coefficients of the structural surface inclination angles of 15° and 20° decrease by 0.67 and 0.49 as a whole. When the water level rises without submerging to the structural surface, the change of safety coefficient is small, at this time, the slope safety coefficient is only affected by the structural surface inclination angle. When the water level continues to rise above the structural surface, the safety coefficient gradually decreases with the rise of the water level in a nonlinear relationship, and the safety coefficient is the smallest when the water level rises to the top of the slope, and the safety coefficients of the structural surface inclination angle of 15° and 20° are 0.52 and 0.69 respectively when the submerged surface reaches a height of 85 m. From this it can be seen that: the position of the structural surface within the slope has an obvious effect on the change of the safety coefficient of the slope, and the safety coefficient of the slope decreases to 0.52 when the slope is in a position of 15°. When the water level of the slope body is below the structural surface, the hydrostatic pressure generated has a very small effect on the safety and stability of the slope, which is negligible. When the water level of the slope body is above the structural surface, the hydrostatic pressure generated has obvious influence on the slope safety and stability coefficient.

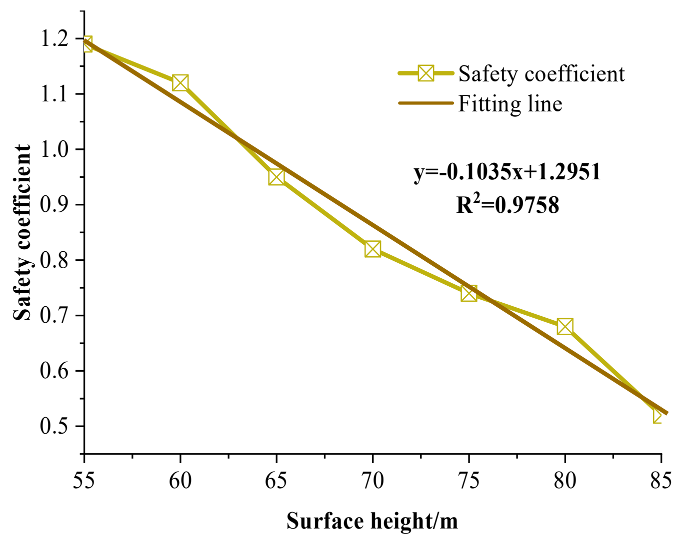

Figure 2: The slope safety factor variation diagram when the structural slope angle is 15

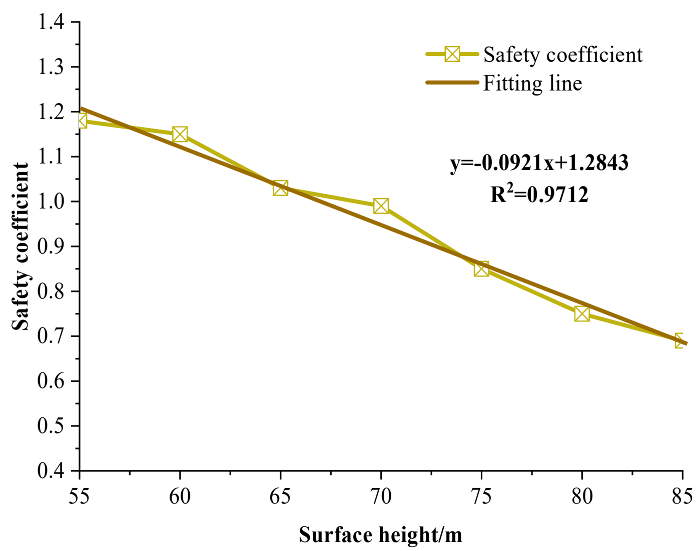

Figure 3: The slope safety factor variation diagram when the structural slope angle is 20

III. C. Effect of change in inclination of structural surfaces

The inclination angles of the structural surface were set to be 6°, 12°, 18°, 24° and 30°, respectively, and numerical simulations were carried out for each type of working conditions under each structural surface inclination angle by setting different water level heights and analyzing the effects of the structural surfaces with different inclination angles on the stability of the slopes under the change of the water level heights at 55, 60, 65, 70, 75 and 80 m, respectively. The variation of slope safety coefficient with the number of inclination at different groundwater is shown in Fig. 4. When the water level height within the slope is below 60m, the safety coefficient is higher and increases with the increase of the inclination angle of the structural surface. When the water level is 55 m, the safety coefficient increases from 1.10 for a structural face inclination of 6° to 1.29 for a structural face inclination of 30°. When the water level continues to rise above 60 m, the structural face inclination must reach at least 30° to be more stable, and slopes are unstable at an angle smaller than this. Regardless of the height of the water level within the slope, when the structural surface inclination angle is greater than 24°, the slope is more stable than in the case of smaller inclinations.

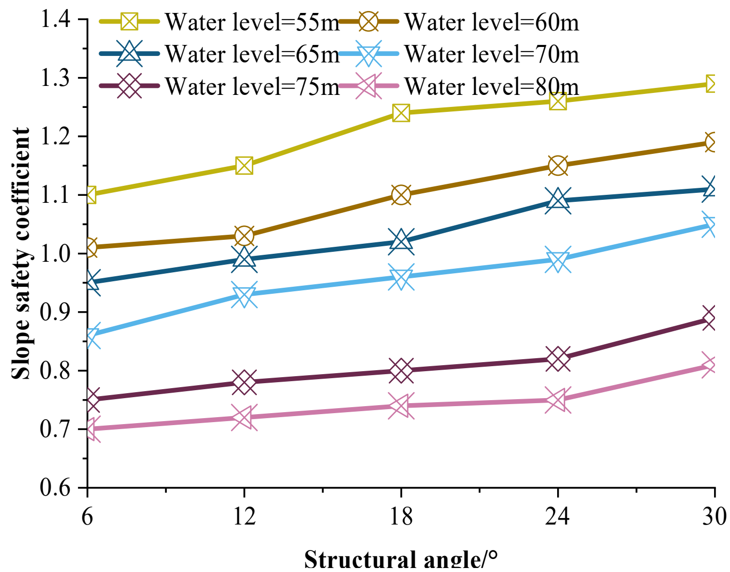

Figure 4: The slope safety factor of different groundwater level varies with dip degree

IV. Slope control recommendations and drainage impacts

IV. A. Recommendations for prevention and control

According to the results of slope stability calculations, there is a risk of slope destabilization in the case of high water levels within the slope. Therefore, in order to prevent landslide disasters, the following measures are recommended.

IV. A. 1) Increased hydrogeological investigations

Further increase the hydrogeological investigation work. According to the relevant geological data, it can be determined that the river is the main source of groundwater seepage on the slope, but it has not been determined whether there are other sources of this seepage, and at the same time, the recharge channel, the amount of recharge, and the boundary of recharge have not been determined, therefore, hydrogeological investigation should be strengthened, in order to give the accurate hydrogeological boundaries and the recharge and discharge relationship of groundwater, and to provide a basis for the subsequent slope disaster prevention and river management.

IV. A. 2) Enhanced hydrological monitoring

Strengthen hydrological monitoring. Groundwater seepage is a non-negligible influence factor in slope stability analysis, heavy rain days rain through runoff, infiltration and other roles into the slope, the groundwater level rises rapidly, in addition to the increase in dynamic water pressure, hydrostatic pressure, erosion are also increasing, so it is particularly important to strengthen the monitoring of rainfall and water level. Strengthening the monitoring of rainfall and water level can not only obtain the changes of water level and water pressure in real time, but also provide early warning of slope damage, and provide safety guarantee for on-site production.

IV. A. 3) Adoption of engineered means of seepage control

Adoption of engineering means of seepage control. Since the river is the main source of groundwater seepage from the slope, the stability of the slope can be improved by reducing the recharge of the river to the slope.

Considering that the stratum in which the river is located does not have an obvious water barrier, the use of impermeable walls and other methods can not effectively isolate seepage, therefore, it is recommended to reduce the seepage of the river to the slope by using the method of river bottom seepage control. This method has the advantages of being economical and effective, and is the recommended method of seepage control.

IV. A. 4) 4.1.4 Enhanced drainage diversion

Strengthening drainage diversion. In view of the relationship between rivers and slopes, it is recommended to reduce the impact of water on slopes by adopting the comprehensive management method of groundwater draining and surface water diversion. The main means for the groundwater to use drying wells, water collection wells and other ways to advance the drying of groundwater into the slope, or through the construction of the ground vertical drilling or horizontal drilling under the pit to pumping, reduce the water table, the way not only to reduce the inflow of groundwater into the slopes, the drying of the water discharged into the river can be more to achieve the purpose of saving water. For surface water, it is recommended to build drainage channels, water guide ditches and other means to reduce the inflow of surface water into the slope, and to improve the stability of the slope by reducing the inflow of surface water.

The methods of pumping and evacuating groundwater also include water-sparing alleys, pit descents, and radiation wells to evacuate dry water. Water-sparing alley is to construct an alley along the direction of water accumulation, adopting the self-flow method to channel and divert the water from the high place of the water-rich area to the low place, and then divert the water collected in the low place to the water-collecting pump house and then discharge it. Pit descending method is in the slope does not affect the production of the location of the excavation of a certain depth of the water collection pit, layer by layer ring ditch to form a “back” shaped water collection pit, the bottom of the pit and the surrounding slopes of the water collection pit to the pit water collection pit, through the drainage pumps discharged to the surface of the open-pit mines. Radiation wells to drain is first constructed a large diameter shaft, and then in the shaft to the surrounding radiation construction of horizontal holes as a collection pipe, groundwater through the collection pipe convergence to the shaft, through the pumps centralized pumping to the surface of the pit. Dewatering alleys need to be arranged according to the topography and terrain and the production of open-pit mines, and the shafts are dug in the slope aquifer for pre-dewatering. Dewatering alleys are more effective in draining water, and can be used to remove water in an orderly, efficient and rapid manner, but the amount of work for dug alleys is large, and a large amount of manpower and material resources are required.

IV. B. Analysis of Drainage Impacts

Strengthening drainage diversion can reduce the impact on the slope by pumping or descending groundwater, this section from the change in groundwater level on the slope geotechnical properties of the slope and the impact of groundwater depth of the slope in two aspects, to explore the pumping or descending groundwater on the stability of the slope.

IV. B. 1) Impact on slope geotechnical properties

The water content of the slope clasts will be reduced by the significant decrease of the groundwater level caused by pumping or desludging the slope groundwater. The effect of water content on the cohesion of slope mudstone is shown in Fig. 5, and the effect of water content on the internal friction angle of slope mudstone is shown in Fig. 6. As can be seen from Figure 5: the shear strength of the slope geotechnical body changes with the change of water content, when the water content of the geotechnical body increases, the cohesive force of the geotechnical body shows a decreasing trend, and the decrease is larger, when the water content is increased from 15% to 40%, the cohesive force of the slope mudstone decreases from 75kPa to 10.16kPa, which is a decrease of 64.84kPa. When the water content of the geotechnical body decreases, the cohesion of the geotechnical body shows a tendency to increase. The cohesive force is sensitive to the change of water content and shows a nonlinear correlation with water content.

As can be seen from Figure 6: with the decline of the slope water table, the slope geotechnical body water content decreases, while the slope geotechnical body internal friction angle and water content is approximately negative correlation, with the increase of water content, the geotechnical body internal friction angle is a downward trend, and the internal friction angle is more sensitive to the change of water content, when the water content is increased from 15% to 40%, the internal friction angle decreases from 11.02° to 0.55°. The reason for the large decrease in shear strength after water saturation is that the soft mudstone of the slope belongs to high liquid limit clayey soil, with high content of hydrophilic material, which is obviously disintegrated by cementation, resulting in a significant weakening of the strength index.

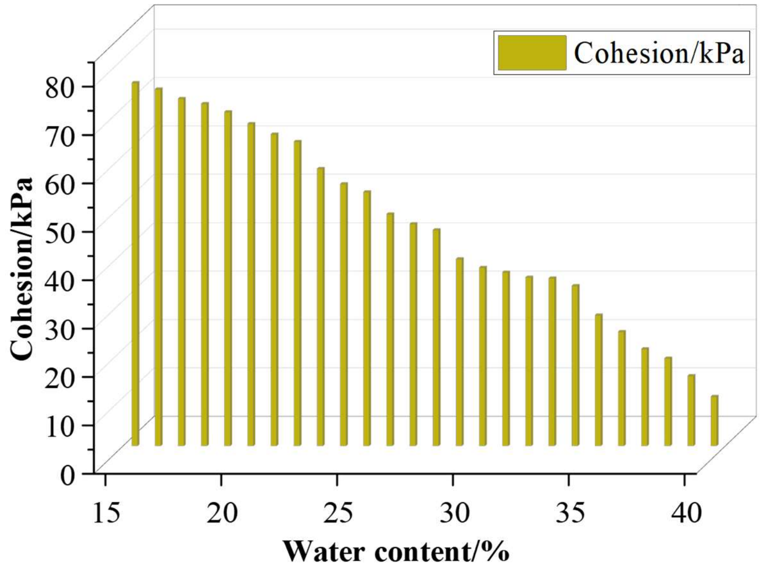

Figure 5: Effect of water content on cohesion of mudstone

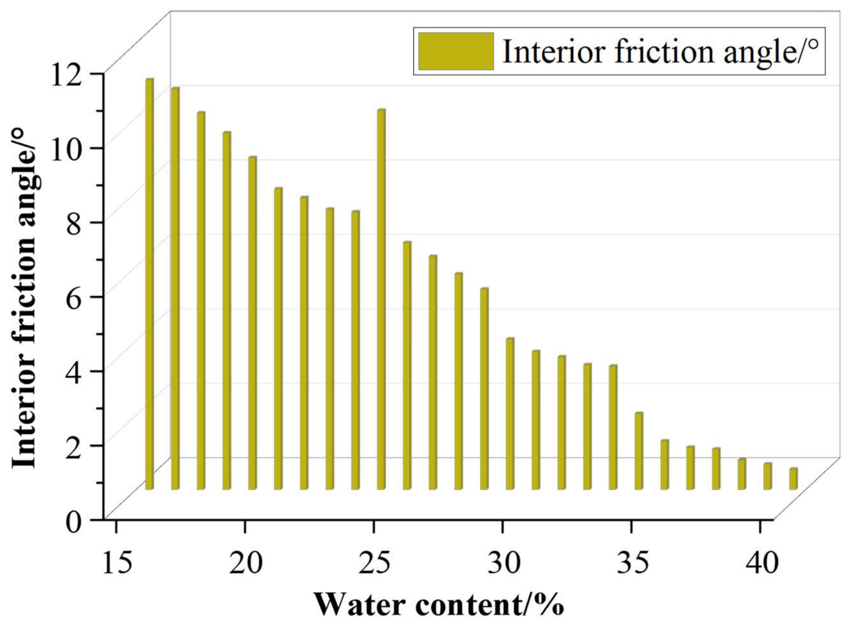

Figure 6: Effect of water content on internal friction angle of mudstone

IV. B. 2) Influence of groundwater depth on slopes

The effect of groundwater depth on slope stability is shown in Fig. 7. When the depth of groundwater table increases from 10m to 30m, the stability coefficient of slope increases from 1.08 to 1.49. When the depth of groundwater table changes from 10 to 20m, the stability coefficient increases slowly. When the depth of water table is 7~9m, the stability coefficient of slope shows a decreasing trend. When the depth of water level is 11m~22m, the stability coefficient of slope is between 1.12~1.24, and the slope is basically stable. When the depth of water level is more than 22m, the stability coefficient of slope is more than 1.27, and the slope is stable. When there is no groundwater on the slope, the stability coefficient of the slope is the highest, and the slope is relatively most stable at this time.

From the results of the above study, it can be seen that pumping or evacuating the groundwater on the slope can improve the strength of the rock and soil body of the slope, avoid the collapse, mudification, dissolution and so on of the rock layer with strong hydrophilicity or the weak interlayer after immersion in water, reduce the hydrostatic pressure effect of the slope body, reduce the hydrostatic pressure and the horizontal thrust of the Zhang fissure water filling in the slope, and diminish the effect of the gradient of the water pressure when the groundwater seeps from the rock and soil body of the slope and is discharged. As a result, the mechanical properties of the geotechnical body can be improved by pumping or evacuating the groundwater from the slope, which in turn improves the stability of the slope.

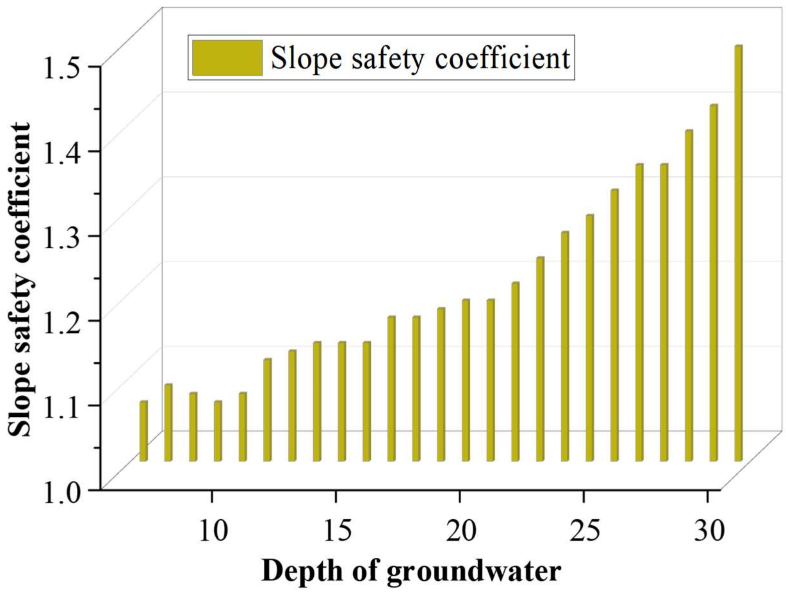

Figure 7: Influence of groundwater level on slope stability

V. Conclusion

By analyzing the nonlinear changes of slope stability under the influence of groundwater infiltration through FLAC3D numerical simulation, the following conclusions are drawn:

When there is no structural surface on the slope, there is a nonlinear relationship between the water level height and the slope safety coefficient. When the water level changes in the range of 10~50m, the safety coefficient stays around 1.45, and the change is not obvious; in the process of the water level rising from 50m to 85m, the safety coefficient decreases rapidly from 1.39 to 1.00, and the slope stability decreases significantly. Slope damage is mainly manifested as arc sliding, and the development of plastic zone shows the trend of “slow and fast”.

When the structural surface exists, the effect of water level on slope stability is governed by the location of the structural surface. When the water level is lower than the structural surface, the change of safety coefficient is small; when the water level is higher than the structural surface, the safety coefficient decreases nonlinearly with the rise of water level. When the water level reaches 85 m, the slope safety coefficients of 15° and 20° inclination of the structural surface are 0.52 and 0.69, respectively, indicating that smaller inclination of the structural surface has a negative impact on the slope stability.

The size of the inclination angle of the structure surface significantly affects the slope stability. When the water level is 55 m, the safety coefficient increases from 1.10 to 1.29 with the increase of the inclination angle of the structural surface from 6° to 30°; when the water level is more than 60 m, the inclination angle of the structural surface needs to reach 30° in order to maintain the relative stability of the slope. In general, the slope stability of the structure face with an inclination angle greater than 24° is better than that of the small inclination condition.

Groundwater depth has a positive effect on slope stability. When the depth of groundwater increases from 10m to 30m, the slope stability coefficient increases from 1.08 to 1.49. When the depth of water table is more than 22m, the slope stability coefficient is more than 1.27, and the slope is in a stable state.

For the slope stability problem caused by groundwater infiltration, it is recommended to take comprehensive prevention and control measures such as increasing hydrogeological investigation, strengthening hydrological monitoring, engineering seepage control and drainage diversion, etc., so as to effectively improve the slope stability by lowering the groundwater level, reducing hydrostatic pressure and improving the strength of rock and soil bodies.

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