Stability Analysis of Slopes on Both Sides of Highway in Geotechnical Area under Rainfall Conditions

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Abstract: The objective of this study is to correctly analyze the slope stability, strengthen the guidance of engineering construction, and ensure the safety of people's lives and property. In this study, the numerical simulation software Geo-Studio is used to simulate the stability variation rules of the slope on both sides of the highway in the rocky region when the angles of the upper and lower slope of the platform width are changed under the action of light rain for a long time respectively, and the corresponding comparison analysis is made with the corresponding natural working condition. The results show that the infiltration of rainwater has a great influence on the slope on both sides of the highway in the geotechnical area, which is mainly reflected in the decrease of the stability of the multi-level slope, the significant change of the sliding surface (including the location, size, shape, etc. of the sliding surface), the potential instability form of the slope (overall stability and local stability), and the slow but continuous change of the pore water pressure in the soil. Through the rainfall test on the highway slope, it is found that the instability mechanism of the slopes on both sides of the highway in the geotechnical area is affected by the conditions of rainfall intensity, rainfall duration, cumulative rainfall capacity, and rainfall patterns. In addition, the changes of rainfall infiltration rate in the side slope of highway in rock and soil area and the migration rules of water field in side slope are also obtained. The findings of this study can be used as a reference and basis for engineering design and construction. Moreover, the safety coefficient of the slope after renovation meets the stability requirement. Therefore, the slope engineering treatment measures on both sides of the highway can effectively deal with the hidden disaster brought by landslide deformation or instability.

Keywords: geotechnical area; safety factor of slope; stability; Geo-Studio.

1. Introduction

“Slope” refers to all geological bodies on the surface of the earth's crust with lateral free face, which is a landform landscape widely distributed on the earth's surface [1]. It is one of the most common and basic natural geological environments for human survival and engineering activities, and its stability is closely related to human life and its living environment [2]. The stability of slope is a hot and difficult problem in mining, metallurgy, water conservancy, geotechnical and other engineering fields. For highways, due to the low grade, poor alignment, narrow subgrade, and shallow excavation, slope
stability of the former highways had no significant impact on the highway, and people did not pay enough attention to the slope stability [3]. However, with the continuous development of the national economy, the highway traffic cause changes with each passing day. Especially after China put forward the great strategic composition of the development of the western region, it has greatly promoted the development of the highway traffic cause [4]. Highway grade is getting higher and higher, high digging and deep filling are inevitable, and the construction of high-grade highway under the complicated geological terrain in the western region is also increasing. If the slope problem is not handled properly, it will directly cause serious consequences [5, 6].

The forming factors of rock and soil slope can be divided into natural slope and artificial slope. The natural slope is formed under the action of natural geology and affected by geological tectonic movement, such as roadbed slope and coastal cliff. In engineering activities, slopes of different scales and different gradients are formed due to human engineering practices, such as roadbed (excavation, filling, half-digging and half-filling, etc.) slope, subway station, light rail station, foundation pit slope and dam shoulder slope of high-rise buildings, etc. [7].

Landslide disasters have a wide distribution range, high frequency, high damage and heavy economic losses, which are important tasks for disaster management in China. Rainfall infiltration is the main inducement of slope instability. The analysis of the influence of anti-slide pile reinforcement slope under rainfall infiltration conditions has important theoretical and engineering practice guiding significance for effectively preventing landslide disasters and avoiding personal safety and property loss accidents caused by serious slope damage.

2. Methodology

2.1. Limit equilibrium method

The limit equilibrium method (also known as slices method) is an early development theory of slope stability, which is currently used in engineering fields. The method assumes several possible slip surfaces, then divides the soil above the slip surface of the slope into a number of vertical strips based on the Mohr-couloomb strength theory, establishes a balance equation between the force of each strip and the bending moment of the action, and solves the safety factor of soil stability under the limit equilibrium state, and continuously tries to calculate, compare, find the lowest safety factor and the most dangerous slip surface corresponding to it. The limit balance method only considers the Mohr-couloomb failure criterion of soil and the static balance of soil slabs. By analyzing the balance of soil mass failure, the corresponding safety coefficient is obtained, ignoring the fact that soil mass is statically unstable, which to some extent destroys the rigor of the method. However, by this assumption, the balance analysis work is greatly simplified, and the corresponding damage has little effect on the accuracy of the calculation results.

Through the research and development of many scholars, the limit equilibrium theory system roughly formed a series of simplified calculation methods such as the Swedish circular arc method, Bishop method, residual thrust method and Janbu method, which not only effectively improved the use efficiency of the limit equilibrium method, but also greatly promoted the applicability of the limit equilibrium theory. Among them, the most representative Swedish arc method is calculated as follows.

The unit length and width of the soil slope is taken, and it is turned into a two-dimensional plane problem for calculation. The sliding surface is set as an arc, and the sliding body is divided into many vertical soil strips with a width of b = 0.1 R. The following equation is established according to the equilibrium condition of the force.

\[ N_i = W_i \cos \alpha_i \]  

\[ T_i = W_i \sin \alpha_i \]
The shear strength on the sliding surface $\mathbf{ef}$ is as follows.

$$\tau_i = \sigma_i \tan \varphi_i + c_i = \frac{1}{l_i} \left( N_i \tan \varphi_i + c_i \right) = \frac{1}{l_i} \left( W_i \tan \varphi_i + c_i \right)$$  \hspace{1cm} (3)

Among them, $\alpha_i$ is the normal of the $i$-th soil strip sliding surface; $l_i$ is the length of the arc on the sliding surface of the $i$-th soil strip; $c_i$ and $\varphi_i$ are the shear strength parameters of the $i$-th soil strip sliding surface.

The sliding moment $M_s$ generated by the force on the sliding surface of the $i$-th soil strip on the center $O$ is:

$$M_s = T_i R = W_i R \sin \alpha_i$$  \hspace{1cm} (4)

Slope stability coefficient is:

$$F_s = \frac{M_s}{M_i} = \frac{\sum_{i=1}^{n} (W_i \cos \alpha_i \tan \varphi_i + c_i l_i)}{\sum_{i=1}^{n} W_i \sin \alpha_i}$$  \hspace{1cm} (5)

2.2. Technical roadmap

Taking the side slopes of highway in the geotechnical area as the research object, the basic physical properties, mechanical properties and water sensitivity of the typical side slopes in the geotechnical area are studied by means of tests. After fully considering the influence of soil body in rainfall infiltration and other factors, the classical slope stability analysis method is improved, and the stability calculation method suitable for slow excavation slope in geotechnical area is proposed and is applied in engineering practice. On the basis of summarizing the instability characteristics and main sliding factors of the slowly excavated slope in the study area, the slope stability analysis model is established by means of numerical simulation, and the improved calculation method for the stability of slow excavation slope proposed is adopted. The applicability of the calculation method for the stability of slow excavation
slope proposed in this research is verified by comparing the simulation results with the field monitoring data. The technical route is shown in figure 1.

3. Results and discussion

3.1. Factors affecting slope stability

Rainfall is closely related to the occurrence of landslides, and the two have a good consistency or a slight lag in time. Most of the landslides occur in the years with a lot of rainfall. Many landslides are characterized by “heavy rain and big slip, small rain and small slip”, which shows that water is an important inducer of landslides. The landslide caused by atmospheric rainfall is called rainfall landslide. Rainfall-induced landslides are the main types of water-induced landslides with the widest distribution, highest frequency and greatest harm. Rainfall landslide is a sliding phenomenon caused by the damage of slope balance under the action of rainfall and infiltration. Its effects include slow long-term slope deformation and a sudden and sharp outbreak. Both rainfall and landslides have good spatial consistency. Rainfall-type landslides are distributed in groups in areas with long rainfall, heavy rainfall and severe river erosion.

According to relevant statistics, the instability of China's slope is mostly related to rainfall, especially after the rainstorm, there are often a large number of landslides, collapses and other slope instability problems, the loss is extremely heavy. Rainfall capacity, rainfall intensity, rainfall duration and rainfall patterns have a significant impact on slope stability. And the gradient of the slope is also an important factor affecting the collapse and landslide of the road.

The landslide and collapse data above 800 prescriptions are investigated and ranked according to the average slope grade, as shown in Table 1. It is found that between 35 and 46 degrees, the type of slope damage is mostly collapsed landslide. The data in Table 1 shows that there is no landslide below 15°, most of the landslides occur between 15~35°, and most of the collapses occur on slopes with gradients greater than 35°.

| Gradient (°) | Quantity (case) | Proportion (%) | Type  |
|-------------|-----------------|----------------|-------|
| 15          | None            | 0              | Landslide |
| 15~25       | 58              | 7.25           | Landslide |
| 25~35       | 549             | 68.6           | Landslide |
| >35         | 193             | 24.1           | Collapse  |

Table 1. Slope gradient of slope landslide and collapse

![Figure 2](attachment:image.png)
In order to grasp the actual situation of slope collapse, the 1610 collapse data in the past 15 years were counted. It is found that about 79% of the collapse cases have a slope of 30°~50°, and the slope is the most at 40°, as shown in figure 2. Statistics show that most of the collapses occur on steep slopes with slopes of 30° to 50°. After analyzing the nature of the slope soil, it is found that the slope of the slope in the geotechnical area is slower than the slope of the rock, and the slope of the rock slope when collapsing is mostly 30°~40°, while the slope of the rock slope is between 30°~50°.

### 3.2. Analysis of stability of slope under rainfall infiltration

Geo-Studio is adopted to simulate the stability of the slope on both sides of the highway under rainfall conditions, and hydraulic function needs to be input. According to the survey data of the slope, combined with the sample curve of the software, the permeability function and soil water characteristics of the rock and soil are given. According to the literature and combined with the survey data of this project, the permeability coefficient of the rock-soil is $5 \times 10^{-4}$ m/s and the natural moisture content is about 0.3.

In this study, the permeability coefficient of the rock-soil is $5 \times 10^{-5}$ m/s. In addition, according to the relevant indicators of the geological survey report, the saturated water content of the rock and soil is calculated to be 0.37. Since the permeability coefficient of the underlying bedrock is small, the permeability is not considered in the numerical calculation.

The magnitude of the stability coefficient directly determines whether the slope occurs landslide. In this study, the influence of various factors on rainfall conditions is analyzed from the change of stability coefficient of slope before and after rainfall.

The safety factors calculated according to various methods of limit equilibrium theory are shown in Table 2:

| Calculation method   | Safety factor |
|----------------------|--------------|
| Ordinary             | 0.898        |
| Bishop               | 1.012        |
| Janbu                | 1.001        |
| Morgenstern—Price    | 0.96         |

It can be concluded from the table that the stability coefficient $F_x$ of the slope under the rain conditions is 0.898–1.012. According to the calculated stability coefficient, it is known that the slope of the geotechnical area on both sides of the highway in this rock and soil area is in an unstable state.

### 3.3. Stability calculation of slopes on both sides of highway in geotechnical area

In the analysis of slope stability, the sliding body is divided into several small element cylinders on the basis of finite element, so that the slope stability analysis is transformed into the balance analysis of small cylinder. Each small cylinder is considered to be uniform. The advantage of this treatment is that it can solve the heterogeneity of the slope body and the uneven distribution of the water head. Moreover, the finite element method can be used to calculate the dynamic change of the water head at each point in the slope. Therefore, the effect of groundwater on slope stability is linked to the dynamic changes in slope groundwater.

The safety reserve factor is as follows.

$$F_x = \sum_{e=1}^{n} \left[ \gamma_e H_e + (\gamma_{se} - \gamma_e) H_e \right] \cot \alpha \tan \phi_e + 2C_e / \sin 2\alpha / \sum_{e=1}^{n} \left[ \gamma_e H_e + (\gamma_{se} - \gamma_e) H_e \right]$$ (6)
Among them, $\gamma_e - e\gamma$ is unit sliding natural bulk density, $\gamma se - e$ is unit sliding body saturation bulk density, $H_e - e$ is the vertical thickness of the unit slider, and $C_e - e$ is the cohesion on the unit sliding surface.

4. Conclusion
In this study, a large amount of domestic and foreign data about the factors affecting the stability of the slope on both sides of the highway in the geotechnical area are analyzed. Based on the field investigation and statistical analysis results, the classification of the types of slope instability and the main factors affecting the stability of the slope under rainfall conditions are proposed, that is, rainfall intensity, rainfall duration, cumulative rainfall capacity, and rainfall patterns. The finite element model under rainfall infiltration condition is established and the corresponding boundary conditions are determined, the slope rainfall infiltration is analyzed with the large-scale finite element analysis software. And the distribution of the steady state and transient water field of the slope under rainfall conditions is calculated. The conclusions are in agreement with the experimental results, indicating the correctness of the calculation method. Finally, through the numerical simulation analysis of the slope analysis software Geo-Studio, it is found that the osmotic movement of rainwater in the soil is a rapid process, especially in the soil with fine particles and more soil voids. However, the change of pore water pressure in the soil body caused by rainwater infiltration is a very slow process, which can last for more than ten days.

For the theoretical analysis of slope stability, especially when considering the effect of rainfall infiltration on slope stability, the unsaturated soil theory is adopted, that is, the problem is mainly considered from the perspective of energy conservation and momentum conservation, but in fact, the role of gas is ignored when the unsaturated theory is applied. Therefore, the study on the stability of slope on both sides of the highway in geotechnical area should be continued.

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