Numerical analysis of influence of joint inclination on the stability of high rock slope with weak interlayer

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Abstract. In the mountainous area of southwest China, the horizontal layered steep slopes with weak intercalations are widely distributed. The stability of these slopes is often controlled by the weak intercalations and the dominant joint sets. Based on the strength reduction method, a representative numerical simulation model is established in this study, and the ubiquitous-joint model is adopted in which the properties of rock blocks and joints can both be considered, in order to analyze the influence of joint angle on slope stability and potential sliding surface of such slopes. The research results indicate that the joint inclination angle is closely related to both the safety coefficient and the potential sliding range of the slope. With the increase of joint inclination angle, the safety coefficient of the slope decreases, but the downward trend gradually becomes slower. The joint inclination angle also has an obvious influence on the sliding surface range of the horizontal layer slope with weak interlayer. The research results have certain guiding significance in the analysis of failure mechanism, hazard assessment and engineering prevention of this kind of slope.

1. Introduction

Carbonate strata are widely distributed in the southwest mountainous area of China, and the outcropping is very thick in many areas. High rock slopes with weak interlayers, such as mudstone, shale and coal measure, are also widely distributed. Due to the particularity of rock mass structure and slope structure, this type of slope is affected by the difference in lithological and mechanical properties, and the soft stratum is often more weathered. The weak interlayer often becomes the weak structural plane or the weak base which controls the development trend of slope stability. Many famous landslides or unstable slopes come from this type of slope, such as The Jiweishan landslide in Wulong, Chongqing, the Maoping landslide in Qingjiang, Hubei, the Lianziya dangerous rock in the Three Gorges of the Yangtze River, the Yangjiao dangerous rock in Wulong District, Chongqing, the Zhaojiagou landslide in Zhenxiong, Yunnan, and the Kaili rock avalanche in Guizhou. The stability of rock slope with weak interlayer has become a research hotspot which may have effects on the foundation engineering construction and economic development of mountain...
towns. Therefore, it is of great significance to make in-depth research in this aspect for the theoretical development of slope prevention and protection of people's lives and properties.

At present, the problem of how the weak interlayer affects the stability of rock slope has been concerned and studied by many scholars both at home and abroad. As early as the 1950s, foreign scholars began to study the influence of weak interlayer on the stability of rock slope[15]. With Muller as the representative, many scholars have carried out researches on the effect of weak interlayer on the failure mechanism of Vajont landslide in Italy[16-18]. B.P.Wen and A.Aydin studied the influence of clay mineral composition on the strength of soft interlayer of landslide from the microscopic point of view by adopting various technical means[19]. In domestic, Zhang et al. (1994) proposed deformation and failure modes of rock slope with weak interlayer, such as Slip-pull fracture; Pressure caused crack and Plastic flow-pull crack[20]. Gong et al. (2010) studied the influence of water content on the physical and mechanical parameters of muddy interlayer in red sandstone slope by laboratory test, and further analysed the influence on the stability of red sandstone slope by plane sliding method, and put forward the concept of critical moisture content of muddy interlayer which caused the slope stability to drop sharply[21]. Liu et al. (2013) studied the stability of the subgrade slope with soft intercalation by using centrifugal model test and numerical analysis method, and concluded that the soft intercalation would significantly reduce the stability of the subgrade slope, and lead to the failure of the slope from circular sliding to partial sliding along the weak intercalation[22]. Liu et al. (2017) used the strength reduction method to study the influence of various characteristic indexes of soft interlayer on the slope stability, and concluded that sort from heavy to light, the degree of influence of multifactor sensitivity on the stability of soft interlayer slope of carbonic mudstone is the inclination angle, internal friction angle, cohesion and soft layer thickness of the interlayer[23]. Zhao et al. (2020) analysed the influence of lithology, location, and thickness of soft interlayer on horizontal displacement and safety coefficient of slope through numerical simulation[24]. The above studies have greatly promoted the research progress in the failure mechanism of the rock slope with soft intercalation, and it is concluded that the stability of the rock slope without soft intercalation is obviously worse. However, as an important factor affecting the stability of rock slope, there are few in-depth studies on how the combined relationship between the inclination and inclination of the soft interlayer, the slope direction and the slope affect the stability and failure mode of the slope.

In this study a numerical model of high rock slope with weak interlayer was designed, and the ubiquitous joint model was used to analyse the effect of joint on the slope stability, focused on analysing the influence of joint angle and joint tendency on slope stability and the potential slip surfaces location. The results can provide a reference on stability analysis and hazard assessment of rock slope with weak interlayer.

2. Calculation method and principle

2.1. Ubiquitous-joint model

Ubiquitous-joint model is an anisotropic plastic model, which is actually an extension of Mohr-Coulomb model[25]. It is used to simulate rock mass with specific orientation joints in slope material, and the joints also obey the Mohr-Coulomb Model. This model considers both the mechanical properties of the rock mass and joints, and the failure may occur in the rock mass, or along the joint surface, or both at the same time, which mainly dependent on stress conditions, the direction of the joint surface, and the mechanical parameters of the rock mass and joint surface[26].

In the ubiquitous joint model, the joint plane direction and stress state can be expressed by the components of the three directions (x, y, z) in the global Cartesian coordinate system, and the relationship between the components of the three directions (x', y', z') in the local coordinate system and the stress in the global coordinate system can be expressed as follows:

\[
[\sigma] = [C]^{-1} [\sigma'] [C]
\]  

(1)
Where \([C]\) is the direction tensor, which is equal to the cosine of the angle between the local coordinate system and the global coordinate system.

\[
[C] = [C][C]^T
\]

The tangential stress of the joint surface can be expressed by the following formula:

\[
\tau = \sqrt{\sigma_{13}^2 + \sigma_{23}^2}
\]

\[
\gamma = \sqrt{\varepsilon_{13}^2 + \varepsilon_{23}^2}
\]

### 2.1.1. Yielding rules

The generalized stress vector (used to describe the failure of the soft surface) has four components (\(n=4\)), \(\sigma_{11}''\), \(\sigma_{22}''\), \(\sigma_{33}''\) and \(\tau''\), the corresponding components of the generalized strain vector are \(\varepsilon_{11}''\), \(\varepsilon_{22}''\), \(\varepsilon_{33}''\) and \(\gamma''\). The generalized elastic stress and strain increment in local coordinate system have the following relations:

\[
\Delta \sigma_{11''} = \alpha_1 \Delta \varepsilon_{11''} + \alpha_2 (\Delta \varepsilon_{22''} + \Delta \varepsilon_{33''})
\]

\[
\Delta \sigma_{22''} = \alpha_1 \Delta \varepsilon_{22''} + \alpha_2 (\Delta \varepsilon_{11''} + \Delta \varepsilon_{33''})
\]

\[
\Delta \sigma_{33''} = \alpha_1 \Delta \varepsilon_{33''} + \alpha_2 (\Delta \varepsilon_{11''} + \Delta \varepsilon_{22''})
\]

\[
\Delta \tau = 2G \Delta \gamma''
\]

Where, \(\alpha_1\) and \(\alpha_2\) are constants related to material properties (shear modulus \(G\), volume modulus \(K\)), which can be expressed as follows:

\[
\alpha_1 = K + \frac{4}{3}G
\]

\[
\alpha_2 = K - \frac{2}{3}G
\]

### 2.1.2. Yield criterion

The joint surface yield criterion is denoted in the coordinate system of \((\sigma_{33}'', \tau'')\), as shown in Figure. 1. According to the Mohr-Coulomb yield criterion, the local failure envelope AB in the local coordinate system is defined by the Mohr-Coulomb failure criterion as \(f'' = 0\), The criterion BC of tensile failure of the envelope of tensile failure can be expressed as \(f' = 0\), and the following functions are true:

\[
f'' = \tau + \sigma_{33}'' \tan \phi_j - c_j
\]

\[
f' = \sigma_{33}'' - \sigma_j'
\]

Where, \(\phi_j\), \(c_j\), and \(\sigma_j'\) are respectively the internal friction angle, cohesion and tensile strength of the joint. Need to pay attention that for joint surfaces with non-zero friction angle, the maximum tensile strength is:
\[ \sigma_{j,\text{max}}' = \frac{c_j}{\tan \phi_j} \]  

(13)

Figure 1. Yield criterion for joints in Ubiquitous-joint model

2.2. The strength reduction method

The principle of strength reduction method to calculate the slope stability coefficient is to divide all the strength parameter of rock and soil material of the slope by the reduction coefficient \( K \). By gradually increasing \( K \), the calculation is repeated until the slope is critically damaged. At this time, the corresponding reduction coefficient is the slope stability coefficient. Zheng\[27-29\] and Zhao et al\[30-31\]. Conducted a large number of studies on the criterion and calculation accuracy of strength reduction method, and popularized the application of strength reduction method in China.

The stability of rock slope is controlled by the strength parameters of rock mass and joint in the Ubiquitous-joint model. In the implementation of strength reduction method, the strength parameters of rock mass and joint plane contained in this criterion should be reduced simultaneously. When computing, the cohesion of the rock mass \( c \), the cohesion of joint \( c_j \), the internal friction angle of the rock mass \( \phi \), the internal friction angle of the joint \( \phi_j \), the expansion angle of the rock mass \( d \), the expansion angle of the joint \( d_j \) would all be divided by the reduction coefficient \( K \). Through FISH programming, iterative calculation is realized, convergence state is judged and corresponding safety coefficient is recorded, and repeated analysis is carried out until the slope reaches the critical failure state. At this time, the strength reduction coefficient \( K \) is the final safety coefficient of the slope, as shown in the following formula\[26\]:

\[ K = \frac{c}{c'} = \frac{\tan \phi}{\tan \phi'} = \frac{\tan d}{\tan d'} = \frac{c_j}{c_j'} = \frac{\tan \phi_j}{\tan \phi_j'} = \frac{\tan d_j}{\tan d_j'} \]  

(14)

Where, \( c', \phi', d' \), \( c_j', \phi_j', d_j' \) are respectively critical parameters when the rock mass and joint surface is destroyed.

3. Numerical model and parameter setting

3.1. The numerical model

A typical horizontal soft-layer controlled high rock slope model was established. In the model, hard rock and soft rock were respectively set as solid units and are considered as continuum medium, the model was divided into 1,800 units (Figure. 2). The total height of the slope is 130m, the thickness of the soft base in the middle of the slope is about 10m. Because of low strength, weak resistance to weathering, and be easily soften by water, the weak inter layer is the main controlling structural surface of the slope stability. The slope is steep at the top and gentle at the bottom, and the overall slope angle is 45º, the upper steep slope angle is 72º, and the lower steep slope angle is 31º. The simulated joint inclination angle is 0°~90° with 10° intervals. The initial inclination of the joint surface is set at 90°, which is in line with the positive direction of the Y-axis of the global coordinate system in FLAC3D. The joint tendency was set to be consistent with the slope direction. The boundary
conditions are horizontal constraints on both sides and fixed constraints at the base. The initial stress field was consider as the gravity stress field.

Figure 2. Numerical model of the high rock slope with weak horizontal interlayer (unit: m)

3.2. Material parameters
In this numerical calculation, typical Permian mudstone and limestone distributed in Wulong section of Wujiang River in Chongqing City are selected as the representatives of soft and hard rock strata, and the physical and mechanical parameters of rock mass required for model calculation are obtained by combining the investigation report and laboratory test (Table 1). The finite difference method and strength reduction method are used in the analysis of the slope stability, and the constitutive model adopts the ubiquitous joint model.

Table 1. Material properties for the lithologic units in numerical modeling

| Media     | Bulk density/kN•m⁻³ | Elasticity modulus /Mpa | Poisson’s ratio | Cohesion/Kpa | Internal friction angle(°) | Tensile strength /Kpa |
|-----------|---------------------|-------------------------|-----------------|--------------|---------------------------|----------------------|
| Limestone | 26.5                | 28.5                    | 0.25            | 5000         | 40                        | 1000                 |
| Mudstone  | 23.5                | 11.1                    | 0.30            | 200          | 25                        | 100                  |
| Joint plane | —                   | —                       | —               | 8            | 20                        | 10                   |

4. Analysis of numerical simulation results
The above model was established and joint inclination angle, the intersection angle between trend of slope and the joint were respectively calculated as variables. The slope stability coefficient and potential sliding surface distribution under different working conditions were obtained by FISH programming in FLAC3D.

4.1. Influence of joint inclination angle on slope stability coefficient

Figure 3. Relationship between stability coefficient Fs and joint angle
By numerical simulation, the law of slope stability coefficient changing with the increase of joint inclination angle from 0° to 90° at every 10° interval was obtained (Figure. 3). It can be seen that there is a close relationship between the joint inclination angle and the safety coefficient of the slope. When the joint inclination angles are 0°, 20°, 40°, 50°, and 70° respectively, the corresponding stability coefficients of the rock mass slope are 2.4, 2.02, 1.26, 1.01 and 1.01 respectively. The numerical value of joint inclination angle has great influence on the stability coefficient of slope. The stability coefficient of slope decreases gradually with the change of joint inclination, and the change trend decreases rapidly first and then slowly, until it stops decreasing. It can be seen that when the joint inclination angle is 50°, the slope stability coefficient is the minimum. This indicates that when the joint inclination angle is close to the overall slope angle, the influence on the stability of the slope is greater.

4.2. The influence of joint inclination angle on sliding surface position

The maximum shear strain rate of slope indicates that the change rate of the shear strain at each point along the slip plane is faster than that at each point along the normal direction of the slip plane at this point. Obviously, the rock and soil mass will slide more easily along this plane, which can be used as the basis for determining the potential slip plane of the slope[26]. In order to get a clear view of the range of the potential sliding surface and failure area of the slope, the contour map of the maximum shear strain rate distribution were obtained after the slope reaches the limit equilibrium after strength reduction, so as to analyze the development and change law of the plastic zone of the slope. The joint tendency was set to be consistent with the slope direction. After numerical analysis by FLAC3D, the distribution of maximum shear strain rate of the slope under different joint inclinations was obtained, as shown in Figure. 4.

Due to the existence of weak interlayer and joint, the traditional circular and arc-shaped potential slip surface of homogeneous rock mass is replaced by the folded slide surface (Figure.4). When the joint inclination angle is 0°, the critical sliding surface will develop along the horizontal direction first due to the influence of the underlying weak rock layer. With the increase of the joint inclination angle, the critical sliding surface will develop along the direction of the joint and form the potential sliding surface. When the joint inclination angle is 20° or 40°, the bottom of the sliding surface is mainly located in the position of soft rock strata. When the joint inclination angle increases to 60° and 75° respectively, the main potential sliding surface develops along the upper joint facial position of the slope, and the outlet position at the bottom is located in the weak interlayer. When the joint inclination angle is 90°, the bottom of the maximum shear strain rate surface is mainly distributed in the soft interlayer. This indicates the numerical size of the joint inclination angel obviously has a close relationship with the potential sliding range.
4.3. Influence of joint tendency on slope stability

To further analyze the influence of joint tendency on the stability of high slope with weak interlayer. In the numerical simulation, the joint tendency changed regularly from 0° to 90° with a gradient of 15°, so that the intersection angle between trend of slope and the joint changed accordingly, and the relationship between the intersection angle and the slope stability coefficient Fs was obtained (Figure. 5).

As can be seen in the Figure.5, in general, the slope stability coefficient increases, and the slope become more stable with the increase of the intersection angle between trend of slope and the joint, And the increase amplitude increases as the intersection angle increases. When the joint inclination angle is greater than 40°, the trend of increase is more obvious.

5. Conclusion

Based on the theoretical analysis of Ubiquitous-joint model and the application of FLAC3D program, numerical simulation analysis was carried out for high rock slope with weak interlayer, and the
influence of joint inclination and inclination on slope stability was analyzed. The main conclusions are as follows:

1. Based on the finite-difference software, the application of ubiquitous joint criterion and strength reduction method can simulate and analyze the stability of the rock joint slope, providing an reference for further analysis of the influence of rock mass structure on the stability of the rock slope.

2. The numerical valuval of joint inclination angle has a great influence on the slope stability coefficient. With the increase of joint inclination angle, the trend of slope stability coefficient decreases rapidly at first and then gradually slows down until it stops decreasing. When the joint inclination angle is close to the overall slope angle, it will have a major influence on the stability of the slope.

3. The numerical valuval of joint inclination angle also has a significant influence on the potential sliding surface range of the rock slope with the weak horizontal layer. When the joint inclination angle is small, the critical sliding surface will develop along the position of the weak interlayer. When the joint inclination angle is large, the critical sliding surface develops along the steeply dipping joint surface.

4. With the increase of the intersection angle between trend of slope and the joint, the slope stability coefficient increases and the stability increases. When the joint inclination Angle is greater than 40°, the trend of increase is more obvious.

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