Calculation of stability reliability of soft base controlled unstable rock and parameter sensitivity analysis

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Abstract. There are a large number of unstable rocks whose stability are controlled by soft base layer in the mountainous areas of southwest China, and they have caused serious harm to people's lives and local economic development. Therefore, it is of great practical significance to study the stability and failure mechanism of such unstable rock. Taking the in Wulong District, Chongqing as an example, this paper analyzes the failure probability and reliability index of the unstable rock under different conditions by use of Monte Carlo method and on this basis, the sensitivity of the stability of dangerous rock mass to the main influencing factors is analyzed. The results show that the stability coefficient, failure probability and reliability index of are equal to 1.151, 26.245% and 0.642 under natural condition. However, the stability coefficient of decreases rapidly and the reliability index and failure probability increase obviously when combined with other factors such as rainfall or earthquake. The sensitivities of the influencing factors of the unstable rock are from top to bottom internal friction angle of soft layer, the horizontal seismic force, the cohesion of soft layer, the water content in the crack and the weight of soft layer. The research results can provide some reference for the stability analysis and engineering prevention of such unstable rocks.

1. Introduction

Carbonate slope is widely distributed in mountainous area of southwest China. When the slope contains soft rocks such as mudstone, shale and coal measure strata, it is easy to produce intense difference weathering, and then form geological disasters of different types and scales. These soft layers are generally stable in distribution with relatively poor mechanical properties, and have spatial discreteness and inhomogeneity, which are the main structural planes controlling the slope to occur deformation and failure like slipping or collapsing. The stability of large dangerous rock mass like Lianzi cliff dangerous rock at Yangtze river [1-2], Yangjiao dangerous rock in Wulong district, Chongqing [3-4], the Wangxia dangerous rock at Wu gorge of Yangtze river, [5], ZengZi rock in Wulong district, Chongqing and other [6] are the typical dangerous rock mass whose stability is controlled by weak rock strata. Under the trigger conditions, such as heavy rain and earthquake, these unstable rocks may lose stability and cause serious disasters. Therefore, it is of great practical
significance to study the stability of unstable rock with soft base controlled.

The physical and mechanical parameters of rock and soil and the slope system are dynamic systems, which have randomness and uncertainty. The mechanical properties of soft rock base have important influence on stability and failure mechanism of soft base controlled unstable rock. Scholars have begun to pay attention on doing researches on this field, for example, Wang et al (2016)[7] studied the influence of the strength of weak base argillaceous zebra limestone on unstable rock of thick layer by numerical simulation method, their result shows that with the decrease of the weak base strength, the unstable rocks gradually transform from steady state to unstable state.

The traditional method of slope stability evaluation simply takes the deterministic safety coefficient as the judgment standard, without considering the inhomogeneity and discreteness of the mechanical properties of the slope influencing factors, which is unreasonable. It is inevitable that there may be technical problems in slope prevention and control design using the evaluation results with traditional method. Conversely, the reliability method can fully consider the randomness and discreteness of the rock and soil parameters of the slope. Based on the understanding of the uncertainty of various factors affecting the stability of the slope and the reasonable analysis of the engineering geology of the slope system, the failure probability and reliability scale are used to describe the stability state of the slope system. At present, reliability analysis method has been widely recognized and applied in the research on slope stability analysis at home and abroad [11]. Based on the reliability theory and the calculation method for slope stability, Wang et al. (2012) [8] established the reliability and failure probability calculation methods for three types of dangerous rock mass: slump, toppling and falling, respectively. Based on the reliability theory, Li et al. (2017) [9] respectively calculated the reliability of slump type unstable rock under natural, rainstorm and earthquake condition by Monte-Carlo method. Wang et al. (2013) [10] established a reliability optimization solution method by the fracture mechanics principle for the stability of unstable rock.

In the current research on the stability of dangerous rock mass controlled by weak base, few studies have been carried out on the influence of the uncertainties, such as the physical and mechanical properties of the weak layer, the filling of crack water and the seismic load, on the stability and deformation of the dangerous rock mass. Based on this situation, considering the randomness and variability of the main influence factors of the slope stability, the stability probability of soft base controlled unstable rock was analyzed by using the Monte-Carlo method reliability in this work, and the weight of the influence of different factors on the stability of unstable rock was also analyzed, which was intended to provide some theoretical reference for prevention and control of this type of unstable rock in the mountainous area of southwest China.

2. Introduction of Daxiang unstable rock

The Daxiang unstable rock is located in the left bank of the lower reaches of Wujiang River, Yangjiao Town, Wulong District, Chongqing (Fig. 1). The unstable rock with a rectangular shape is about 720 m in length, 150 m in width, 50 m in height and 530×10^4 m³ in volume. There is a large area of colluvium below the slope where the dangerous rock is located. The lithology of the dangerous rock is the hard thick layer limestone of Wujiaping Formation, the occurrence of the rock layer is 276° ∠20°. The underlying rock with a thickness of about 12 m is the soft layer of the bottom of Wujiaping Formation, which is composed of shale, coal seam and aluminum-bearing mudstone and has low strength. The soft layer is the weak base of. Limestone of Maokou Formation and Qixia Formation is located below the Wujiaping Formation. Karst grooves and caves are well developed in limestone. Cutting by structural joints, weak interlayers and strata planes, the rock mass is in block structure. The coal seam in the bottom of Wujiaping Formation is about 0.6 m thick. Due to unreasonable mining activities for a long time in history, a large number of goaf formed. Under the long-term gravity action of the upper rock mass, the soft layer at the bottom of Wujiaping Formation deforms strongly and is partially fractured and extruded. There are free surfaces in the north and east sides of slope, the southwest side develop a large dissolving ditch with a trend of 330°. A large number of tensile fractures are also developed on the top of the slope, the maximum crack width is about 2.1 m.
Fig. 1 Topography map of the Daxiang unstable rock area

According to the analysis of the geometrical morphology, the characteristics of the main structural plane and the monitoring data of dangerous rock mass, Daxiang unstable rock is in a peristaltic deformation state. Under the action of inductive factors such as rainstorm and earthquake, it may lose stability, and its failure mode is plane sliding along the underlying soft layer, and the sliding direction is 320°. After cutting out from the high position, the rockslide body may develop into a long-runout debris-flow under the restriction of specific topographic condition [12-13].

3. Reliability analysis method by Monte-Carlo simulation

The slope reliability theory holds that the factors affecting slope stability are random variables subject to certain probability distribution, so the slope stability coefficient is also a random variable subject to specific distribution. Therefore, by analyzing the probability distribution of various factors and the relationship between them and slope stability, the distribution pattern of stability coefficient can be obtained, and then the reliability and failure probability of slope stability can be calculated.

The commonly used methods to calculate the reliability include Monte Carlo method, Central Point method, JC method, Statistical Moment method, Random Finite Element method, etc. In this study, Monte Carlo method is adopted to analyze the stability and reliability, and the calculation process is simulated with Rocscience Slide, a Canadian geotechnical engineering software.

3.1 Reliability analysis by Monte-Carlo method

Monte-Carlo method is a reliability analysis method based on statistical sampling theory and with the help of computer numerical simulation to analyze and study the change process of random variables, and evaluate the slope failure probability [11]. Among the current evaluation methods, the Monte-Carlo method is a relatively accurate reliability analysis method, which has been widely used in slope stability evaluation in recent years [14-18].

Generally, the slope stability coefficient is defined as the state function:

$$F = f(X_1, X_2, \ldots, X_m)$$

(1)

Where, $X_1, X_2, \ldots, X_m$ are m independent random variables with a certain distribution law. Function $f(x)$ is the limit equilibrium analysis function used to calculate the stability coefficient of the slope.
Different methods can be selected according to the reasonable engineering geological analysis of the slope instability mechanism. \( n \) identically distributed variables \( x_1, x_2, \cdots, x_n \) are randomly selected from sample \( X \), and each variable is substituted into formula (1) to obtain a random stability coefficient \( F_i \). After \( n \) repeated calculations, the expected accuracy requirements can be satisfied, \( n \) random numbers of mutually independent stability coefficients, \( F_1, F_2, \cdots, F_n \) can be obtained. Since the ultimate instability state of the slope is \( F=1 \), if there are \( M \) random numbers of stability coefficients \( F_i \) in \( N \) sampling calculations, the slope failure probability is:

\[
P_f = \frac{M}{N}
\]  

When \( M \) is large enough, the distribution function of stability coefficient can be accurately obtained from statistical samples \( F_1, F_2, \cdots, F_n \) and the mean value is:

\[
\mu = \frac{1}{n} \sum_{i=1}^{n} F_i
\]  

The standard deviation is:

\[
\sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (F_i - \mu)^2}
\]  

Thus, the corresponding reliability can be obtained:

\[
\beta = \frac{\mu - 1}{\sigma}
\]  

3.2 Selection of limit equilibrium method
The limit equilibrium method is to evaluate the slope stability by dividing the slope into blocks and analyzing the stress state of each block and the whole slope based on principle of equilibrium in mechanics. For rock slope, the commonly used limit equilibrium methods include Bishop, Janbu, Spencer and Morgenstern-Price method, etc. Based on Mohr-Coulomb strength theory, Bishop method is suitable for slope with circular slip surface. However, in its assumed condition, the force between the soil strips is not considered and the torque generated by the force between the strips is ignored, so the real stress distribution in soil is ignored [19-20]. The Janbu method obeys principle of equilibrium in mechanics and moment equilibrium, and it is applicable to slope with sliding surface of any shape. However, due to the position limitation of the operating point of the joint force between bars in the hypothetical condition, using it arise the problem of not converging in calculation [21-22]. Morgenstern-Price method is a strict slice method, satisfying the balance of forces and moments both in horizontal and vertical directions. However, the assumption of the extra unknown quantity in the static indeterminate equation is not arbitrary, and the stability coefficient obtained by other methods is relatively small [23].

The stability of unstable rock is controlled by soft base, plane sliding is most likely to occur according to engineering geology analysis. Therefore, Spencer method is suitable to analyze the stability and reliability for unstable rock with non-circular sliding surface.

3.3 Sensitivity analysis
The purpose of sensitivity analysis is to analyze the influence of each variable parameter on slope stability. After determining the interval defined by the maximum and minimum values of random variables, probabilistic analysis is a sampling analysis of random variables according to the distribution function. In contrast, sensitivity analysis refers to the analysis of the uniform value of variables within the parameter interval, and only one variable is allowed to change in each iteration of sensitivity, other parameters are taken as constants with the mean value.

The general flow for sensitivity analysis in the Slide software is: for a given variable parameter, program will be within the range is divided into 50 intervals, according to the setting potential slip surface of Daxiang unstable rock, through the uncertainty analysis, using the above 50 dangerous rock mass stability coefficient value calculation to determine the weights of each variable's influence on the
stability of the unstable rock.

4. Numerical model and calculation conditions

4.1 Numerical model
As shown in Fig. 2, the Slide software uses the vertical strip limit equilibrium method to analyze the slope stability, and the given slip surface can be analyzed, or the critical slip surface of the slope can be searched by automatic search method. The numerical analysis model is established in Slide software according to the engineering geological profile of the main slip direction of Daxiang unstable rock. The model can simultaneously consider the variability of the material properties of the soft layer in the slope, the water filling height of the tensile crack at the top of slope and the horizontal seismic force.

Fig. 2 Numerical model of Daxiang unstable rock

4.2 Mechanics parameters for calculation
In the calculation model, Mohr-Coulomb model was adopted for all the materials that constituted the slope, and they were all treated as isotropic materials. It was considered that the parameter distribution was in accordance with the normal probability density function. In order to highlight the influence of key factors, only the variability of rock body and the soft base is considered in the calculation and analysis. By means of laboratory geotechnical tests and reference to the research data of geotechnical physical parameters of Lianzi Cliff unstable rock mass and Jiweishan landslide with similar engineering geological conditions of Daxiang unstable rock mass, and combined with the geotechnical investigation data, and also the research data of similar slope such as Lianzi cliff unstable rock and Jiweishan landslide, the physical and mechanical parameters of the Daxiang unstable rock mass and soft bed at the bottom was determined [1, 24-26]. Table 1 shows the detail parameter including the mean value, standard deviation, relative minimum value and relative maximum value.

| Material | Natural state | Saturated state |
|----------|---------------|----------------|
|          | Weight | Cohesion | Internal frictional angle | Weight | Cohesion | Internal frictional angle |
|         | \(\gamma^f\) (kN·m\(^{-3}\)) | \(c\) (kPa) | \(\phi\) (°) | \(\gamma^f\) (kN·m\(^{-3}\)) | \(c\) (kPa) | \(\phi\) (°) |
| Limestone | Mean value | 26.5 | 200 | 30 | 27 | 100 | 26 |
|          | Standard deviation | 0.5 | 1 | 2 | 1 | 0.5 | 2 |
|          | Minimum value | 1.5 | 3 | 6 | 3 | 1.5 | 6 |
|          | Maximum | 1.5 | 3 | 6 | 3 | 1.5 | 6 |
| Weak layer | Mean value | Standard deviation | Minimum value | Maximum |
|------------|------------|--------------------|---------------|---------|
|            | 21         | 0.5                | 1.5           | 1.5     |
|            | 34.6       | 2                  | 6             | 6       |
|            | 12.9       | 3                  | 9             | 9       |
|            | 22.5       | 0.5                | 1.5           | 1.5     |
|            | 10.9       | 2                  | 6             | 6       |
|            | 25.8       | 3                  | 9             | 9       |

4.3 Calculation conditions

To analyze the stability of unstable rock, it is necessary to consider various factors that may induce slope failure. According to the meteorological data, the rainfall in flood season in the study area accounts for 70% of the annual rainfall. Therefore, heavy precipitation is one of the main inducing factors. In the history, strong earthquakes occurred in the surrounding area of the study area, and the collapse disaster was induced in the vicinity of Daxiang unstable rock mass [3]. According to the provisions in “Seismic ground motion parameters zonation map of China” (GB 18306-2015) [27], the ground motion peak acceleration in the study area is 0.05g.

Four calculation conditions are considered in the calculation, namely are natural condition, heavy rain condition, earthquake condition, earthquake + heavy rain condition. When the heavy rain condition is analyzed, the rainfall intensity is more than 50mm/h and the duration is more than 3 hours, the slope is treated as in saturated state, and the strength parameter in saturated state of rock and soil mass is adopted, while the strength parameter in the natural state is adopted in other conditions. In order to fully consider the possible adverse situations, the horizontal seismic force that may affect the unstable rock is set as 0.2g by referring to GB50111-2009 (Code for seismic design of railway engineering) [29], and the seismic force changes follow the normal distribution. In order to make the acceleration range cover 6-9 intensity, the standard deviation was set as 0.066g, the relative minimum value was 0.198g, and the relative maximum value was 0.198g.

5. Computing result and analysis

5.1 Reliability and failure probability analysis of dangerous rock mass

Spencer method and Monte-Carlo method are used for random simulation, and parameters such as average stability coefficient, failure probability and reliability index of under various conditions are calculated by using Slide software.

20000 random samples are used by Monte Carlo simulation in the calculation. Fig. 3 shows the convergence results of the sample statistical analysis curve, it can be inferred that the curve of the four conditions is finally all tend to be gentle, indicating that in the case that the parameter distribution of rock and soil conforms to the normal distribution, the number of samples is set to be large enough, and the calculation accuracy meets the requirements.
Fig. 3 The convergence curve of statistical analysis under different conditions

Fig. 4 shows the probability density distribution of the stability coefficient of Daxiang unstable rock under different conditions, reflecting the occurrence frequency of each safety coefficient segment in the whole sample. It can be seen that under various conditions, the distribution of the overall stability coefficient of dangerous rock mass presents a good normal distribution feature, and the numerical values regularly concentrate around the median value.

Fig. 4 Probability density distribution of stability coefficient under different conditions
(a) Natural conditions; (b) Heavy rain conditions; (c) Earthquake conditions; (d) Heavy rain + Earthquake conditions

Through calculation, the relationship curve between cumulative probability and slope stability coefficient is obtained (Fig. 5). Each abscissa safety coefficient corresponds to a cumulative probability, which represents the probability value corresponding to the stability coefficient value less than or equal to this value. When the abscissa safety coefficient is equal to 1.0, it is the failure probability, and the slope failure probability under four conditions is obtained.
Fig. 5 Relationship between stability coefficient and failure probability under different conditions

Table 2 shows the calculation results of Daxiang unstable rock under various conditions. The $F_s^{\text{(deterministic)}}$ is the stability coefficient obtained by the deterministic analysis method, $F_s^{\text{(mean)}}$ is average value of the safety coefficient obtained by of the uncertainty analysis of all the samples at the defined slip surface, $P_f$ is the failure probability value equals to the ratio that the samples number for stability safety coefficient less than 1 of the total samples number, $\beta$ is the reliability index at the condition that the stability coefficient is in normal distribution.

It can be seen from the calculation results that under natural condition, the average stability coefficient of dangerous rock is 1.151, and the failure probability of dangerous rock is 26.245%. Under the condition of heavy rain, the average stability coefficient of Daxiang unstable rock is 0.944, and the failure probability of dangerous rock is 60.140%, which is about 34% higher than that in the natural condition. Under earthquake condition, the average stability coefficient of Daxiang unstable rock is 0.606, and the failure probability of dangerous rock is 97.668%. Under the comprehensive action of earthquake and heavy rain, the average stability coefficient of Daxiang unstable rock is 0.498, and the failure probability of dangerous rock is 99.508%. The reliability index of the slope under natural condition is 0.642, which is greater than 0. The reliability of the other three conditions is negative, which are respectively -0.250, -2.318 and -3.234, because the mean stability coefficient $F_s^{\text{(mean)}}$ calculated under these three conditions is less than 1.

Table 2 The calculation results of Daxiang unstable rock under various conditions

| Condition  | Description                  | $F_s^{\text{(deterministic)}}$ | $F_s^{\text{(mean)}}$ | $P_f$% | $\beta$ |
|------------|------------------------------|-------------------------------|------------------------|--------|---------|
| Condition 1| Natural state                | 1.148                         | 1.151                  | 26.245 | 0.642   |
| Condition 2| Heavy rain                   | 0.942                         | 0.944                  | 60.140 | -0.250  |
| Condition 3| Earthquake                   | 0.588                         | 0.606                  | 97.668 | -2.318  |
| Condition 4| Earthquake + heavy rain      | 0.486                         | 0.498                  | 99.508 | -3.234  |
5.2 Parameter sensitivity analysis

The sensitivity of the stability of Daxiang unstable rock to the physical and mechanical parameters ($c$, $\varphi$, $\gamma$) of soft base, seismic force and water content in fissure is analyzed under the most unfavorable condition of earthquake + heavy rain. As shown in Fig. 6, the abscissa is 0~100% to represent the variation interval of each parameter, and the ordinate is the stability coefficient of Daxiang unstable rock. According to the analysis, the slope of the sensitivity curves between the friction angle, cohesion and the stable stability coefficient are all greater than 0, showing a positive correlation law, so that when the values of these two variables increase, the stable stability coefficient $F_s$ will increase. The sensitivity curve of the internal friction angle and the stability coefficient of the dangerous rock mass is steep, and the slope of curve is much larger, indicating that the internal friction angle of the soft base has a great influence on the stability, while the change of the cohesion of the soft layer has a relatively smaller influence on the slope stability. There is a negative correlation between the horizontal seismic force and the stability coefficient. When the seismic acceleration increases, the stability coefficient decreases correspondingly, and the slope become more instable. The slope of the sensitivity curve of the relationship between the soft layer weight, the water filling amount of tensile fracture and the stability coefficient is close to or slightly greater than 0, which indicates that the two uncertainties have little influence on the slope stability under this working condition.

According to the above analysis, the method that increasing the positive correlation parameters, reducing the negative correlation parameters and weakening the relatively gentle parameters can be adopted in engineering prevention and control of this kind of unstable rock mass, so that the measures can be more economical and effective. In the prevention and control project, because the internal friction angle and cohesion of the soft layer have a great impact on the stability of dangerous rock mass, we can focus on the soft base reinforcement project (such as setting load-bearing resistance pile in the goaf) in the application of prevention, to improve the stability of the slope; Earthquake is a uncontrollable natural factor, so measures should be taken to avoid it. The weight of soft base and the amount of water filling in fracture have little influence on the stability of dangerous rock mass, so it can be less strictly controlled.

6. Conclusion
In this work, the Monte-Carlo method is adopted, and the Daxiang unstable rock in Wulong District, Chongqing City is taken as an example. Based on different load conditions, the failure probability and
reliability index of large unstable rock controlled by soft base are calculated, and the sensitivity of the stability coefficient to the main influencing factors is analyzed, and the following conclusions are drawn:

1) The stability of Daxiang unstable rock is controlled by the soft layer in the slope, and its potential failure pattern is plane sliding. Under natural condition, the stability coefficient of dangerous rock mass is equal to 1.151, the failure probability is 26.245%, and the reliability index is equal to 0.642, which is basically stable. Under the condition of continuous thunderstorms, the reliability index of unstable rock decreases and the failure probability increase. The heavy rain plays a certain role in promoting the failure of the slope. Under earthquake condition, the reliability index of the unstable rock decreases rapidly, and the failure probability is larger. Under the combined action of heavy rain and earthquake, the failure probability increases greatly, which is very unfavorable to the stability of the slope.

2) The sensitivity analysis shows that the five uncertainty factors have positive and negative sensitivity to the stability of the unstable rock, some are very sensitive, but others are not. The internal friction angle and cohesion of the soft base are positively correlated with the stability coefficient. The increase of the parameters is beneficial to the stability of the slope, and the sensitivity of the internal friction angle is particularly obvious. There is a negative correlation between the horizontal seismic force and the stability coefficient, and the increase of the horizontal seismic force is not conducive to the stability of the slope. However, the weight of soft layer and the water filling amount of tensile fracture have little sensitivity to the stability of the unstable rock.

3) Compared with the traditional deterministic method, the reliability analysis method studies the slope reliability from the point of view of probability theory to avoid "absolute", and it is more objective and accurate to evaluate the safety of the soft layer controlled unstable rock mass by the failure probability than the deterministic single stability coefficient. Reasonable countermeasures can be taken according to the positive and negative sensitivity of the influencing factors in the slope prevention and control.

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