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Study on Dynamic Response and Progressive Damage Process of Rocky Slopes under Seismic Action

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Abstract: *China is a country with frequent seismic disasters, so it is of great significance to explore the effects of earthquakes on slope stability to study the safety and protection of slope engineering. The loading of seismic waves easily leads to slope instability, and the effect of the loading amplitude on various slope parameters needs to be further studied. This paper uses the FLAC3D numerical simulation software to establish a slope model with three fixed directions at the bottom. The loading values of seismic waves with amplitudes of 0.1g, 0.2g, 0.4g, 0.6g, 0.8g, and 1.0g are input into the model to compare and analyze the dynamic response of rocky slopes under the input of accelerations with different amplitudes and combine with the analysis of the cloud diagrams of various parameters of the slope, which shows that: the results of numerical simulations can cause the slope instability, and the influence of the loading amplitude on the parameters of the slope needs to be further investigated. The results show that the numerical simulation results can better reflect the effect of seismic wave loading. The increment of displacement and shear strain increases exponentially with the amplitude, and the stress shows an increasing and decreasing trend. Under the action of high-intensity earthquakes, the slope is most seriously damaged in the XZ direction. When the input acceleration reaches 1.0g, the local plastic deformation accumulates to form a through-sliding surface, and the slope appears to be seriously damaged and unstable. Basically, an earthquake causes gradual damage to a rocky slope: first, the slope stabilizes itself, then the soil at the slope's top undergoes plastic deformation, and finally, the slope tends to slide and sustain damage.*

Keywords: *Slope, Seismic Loading, Acceleration, Displacement Response, Plastic Deformation, Shear Strain Increment*

1. Introduction

China is located between the world's two major seismic zones, the Pacific Rim Seismic Zone and the Eurasian Seismic Zone, and the development of seismic fault zones is relatively obvious. China's seismicity is high in frequency and intensity, shallow in origin, and widely distributed, making it a country with serious seismic hazards; on May 12, 2008, the Ms 8.0 Wenchuan earthquake that struck the Longmenshan Fracture Zone in Sichuan Province triggered more than 50,000 geologic hazards, such as landslides, avalanches, and mudslides, which resulted in a large number of deaths and injuries[1]; On January 8, 2022, a magnitude 6.9 earthquake occurred in Menyuan, Qinghai, which caused severe damage to local transportation, municipal and other infrastructures. The seismic deformation and damage of roadway slopes are in various forms, especially in the southwestern region; these slopes are easily destabilized under seismic loading. Once the landslide occurs, it will significantly threaten the safety of road surfaces and people's property. Therefore, the stability analysis and study of embankment slopes under seismic action is of great theoretical and practical significance in reducing the losses caused by seismic landslides.

Currently, the stability analysis of embankment slopes under seismic hazards has attracted the attention of many scholars and achieved relevant research results, such as Xie Yi et al.[2] used finite element numerical simulation to analyze the difference between two types of slopes in terms of displacement pattern and acceleration response, and explored the effect of the initial water content of the soil on the seismic response of unsaturated slopes.Ye Zhicheng et al.[3] used GEOSTUDIO modelling to analyze the stability of slopes under seismic conditions coupled with rainfall. They concluded that combining the analysis with the minimum average factor of the safety and permanent displacement methods can improve judgment accuracy. Yang Rui et al.[4] investigated the effect of soil tensile strength on highway slope stability under seismic loading by modifying the linear Mohr-Coulomb criterion based on the upper limit finite element method. Based on the limit analysis upper limit theorem and strength

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discounting technique, Luo Wei et al.[5] investigated the variation rules of seismic effect ratio coefficient, overloading at the top of the slope and nonlinear coefficient by combining the nonlinear damage criterion. Li Mei et al.[6] used the material point method to analyze the change characteristics of peak acceleration of seismic load when strain softening is considered or not in the static calculation. Sun Hao[7] used the finite discrete element method to simulate the dynamic response of slopes under seismic action numerically and verified the reliability of the simulation results of FDEM.

It can be seen that in recent years, many scholars have carried out rich research on the dynamic response and stability process of rocky slopes under seismic action, so this paper will further explore the influence of earthquakes on slope stability based on related scholars' research, and based on the analysis of engineering examples, use the software FLAC3D to establish the embankment slope model to study the dynamic response law of rocky slopes under different loading amplitudes, and use the related parameter analysis to study the influence of multiple parameters (displacement, shear strain increment, etc.) and the progressive damage process of the slope under the dynamic action of seismic hazard.

2. Numerical modeling for slope dynamic analysis

2.1 Construction and parameters of the slope model

Establish a slope generalization model, as shown in Figure 1. In order to make the model size uniform and fully consider the influence of the model boundary on the calculation results, the distance from the top of the slope to the right boundary is designed to be 2.5H. The distance from the foot of the slope to the left boundary is 1.5H, with a total height of 2H. The parameters are set as follows: The height of the model is 40 m, the height of the side slopes is 20 m, the thickness of the side slopes is 2 m, the total length of the bottom is 100 m, and the linear gradient of the model is 60°. The coordinate origin of the calculation is chosen 10 m from the left boundary at the bottom of the slope, and a total of 21 monitoring points are set up, as shown in the figure, which is used to monitor the acceleration value of the dynamic response of each point of the slope.

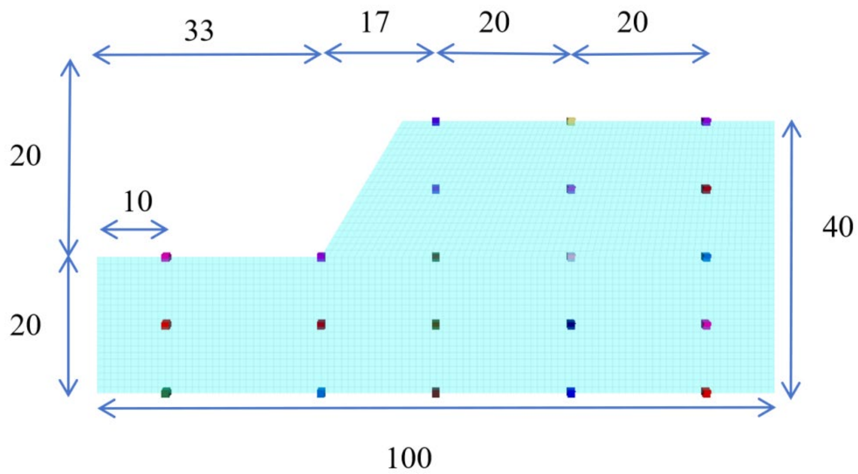

Fig.1 Calculation model of slope(Unit: m)

Based on the engineering experience and referring to the relevant literature, the mechanical parameters of the model material rock used for the calculation in this study were determined, as shown in Table 1. Free-field boundary conditions and local damping were selected for the solution[8].

Table 1 Physical and mechanical parameters of rock mass and weak interlayer

Young /GPa	Density /(kg·m^{-3})	Friction / (°)	cohesion /MPa	poisson
1.40	2000	18	50	0.3

2.2 Boundary Conditions and Dynamic Time-Range Inputs

Static Boundary Conditions: When performing static calculations, it is necessary to clarify the

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boundaries of the model, i.e., the boundary conditions set manually. The bottom of the model is fixed in three directions: the left and right sides of the model in the X-axis direction impose fixed constraints in the X-axis direction, the front and back sides of the model in the Y-axis direction impose fixed constraints in the Y-axis direction, and the Z-axis direction imposes constraints in the top and bottom sides, i.e., the expected direction, to realize the two-dimensional analysis.

Dynamic boundary conditions: This paper focuses on analyzing the dynamic response under seismic loading. Therefore, the static plastic state needs to be initialized before performing the dynamic calculations to ensure that the model response is caused by seismic loading. According to FLAC3D, the model is surrounded by a free-field boundary, and the static boundary conditions are imposed at the bottom.

Input of dynamic time series: The seismic loads are imported into the FLAC3D software in text file DAT format, and then the acceleration is applied to the boundary at the bottom of the model, i.e., Z takes the value in the range of (-0.1, 0.1). When studying the acceleration amplification effect, it is more appropriate to use the direct input of acceleration loads.

2.3 Adjustment and input of seismic waves

The seismic acceleration time profile used in this numerical simulation is shown in Figure 2 below. In seismological studies, compression and shear waves play a crucial role. By carefully observing and analyzing the compression waves, we can gain insight into the rupture process of earthquakes and their characteristics; therefore, in the simulation, it is considered that the seismic waves are applied to the Z direction of the model, while no ground shaking is applied to the X direction and the vertical Y direction in the model.In view of the significant effect of shear waves on slope stability, seismic waves are also considered to be applied to the X-direction of the model in the simulation. In contrast, no ground shaking is applied to the Z-direction and vertical Y-direction in the model. The case of joint application of X and Z directions is also considered. In order to be able to reflect the law of ground vibration input on the seismic response of the slope, the acceleration pulse wave is used as the input, and the loading size is chosen to be 0.1g, 0.2g, 0.4g, 0.6g, 0.8g, and 1.0g, with the peak value of 1.0g, and the loading wave is shown in Fig. 2 below.

The calculation process is divided into two steps. The first step generates the initial stresses under gravity by combining the parameters and dimensions of the rock mass with reference to the boundary conditions, and the second step imports the seismic wave loading and performs the dynamic calculation.

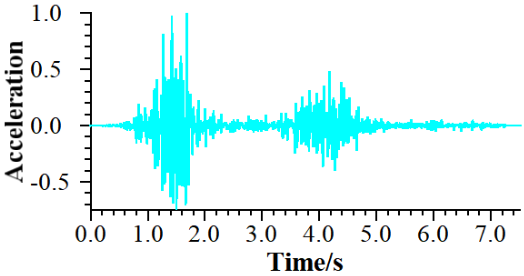

Fig.2 Seismic wave time history curve

2.4 Delineation of the grid

The simulations must ensure the accuracy of the calculations while also controlling the time and cost of the calculations. Therefore, the size of the model grid must be able to depict the propagation of seismic waves accurately and should neither be too large nor too small. According to the material properties listed in Table 1, we can see that the shear wave velocity of the rock mass in the slip zone is the lowest, at about 800 m/s. In order to obtain accurate simulation calculations within a reasonable computation time, the maximum mesh size of the model should satisfy the following conditions:

The maximum frequency that the model can accurately model can be calculated by the following equation:

$$f = \frac{C_s}{10\Delta l} \tag{1}$$

Where is the shear wave velocity, Δl is the dimension of the grid, and

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$$\Delta l \leq (\frac{1}{8} - \frac{1}{10})\lambda \quad (2)$$

Where λ is the wavelength corresponding to the highest frequency of the seismic wave.

The above equation calculates the maximum cell size for calculating the various materials in the model to satisfy the accuracy of the dynamic calculation.

3. Stability analysis of slopes under seismic action

3.1 Displacement Dynamic Response Analysis

Displacement refers to the amount of change of a point relative to another point, and in the numerical simulation analysis of slope, it represents the absolute displacement along a specific direction under the action of the earthquake, reflecting the overall or local displacement characteristics of the slope. Through the displacement analysis, the overall deformation of the slope can be visualized, which can provide a key basis for evaluating the stability of the slope.

Fig. 3 shows the curves of displacement versus amplitude of the monitoring points at the foot of the slope in the X, Z, and XZ directions of the model when different seismic amplitudes are loaded, and seismic waves are applied to the model.

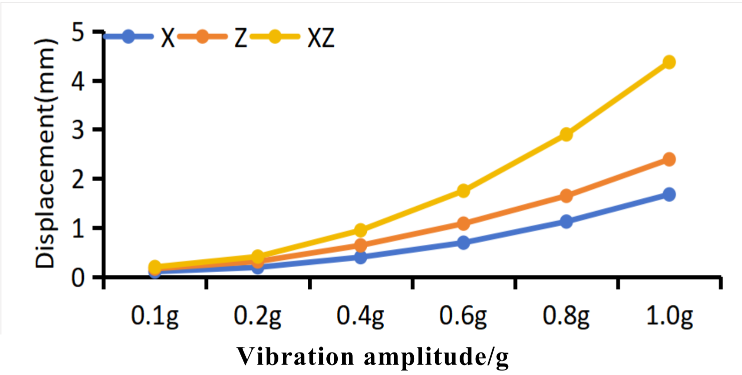

Fig.3 Displacement versus amplitude curve

Based on the data processing results and plotting analysis, we can see that the overall displacement shows a nonlinear growth, which is approximately the exponential growth trend while increasing the input acceleration from 0.1g to 1.0g. Moreover, when the acceleration reaches 1.0g, the displacement gap between the three directions reaches the maximum value. Specifically, we further analyze the displacement curve:

When the seismic amplitude is 0.1g, the displacement of the top of the slope in the XZ direction is 0.19528 mm, which increases to 4.3668 mm at 1.0g, an increase of about 22 times; the displacement in the X direction increases from 0.10208 mm to 1.6728 mm, an increase of about 16 times; the displacement in the Z direction increases from 0.16165 mm to 2.3878 mm, an increase of about 14.8 times. Therefore, the slope displacement under seismic action has a very linear growth trend, this is because the soil has plastic deformation characteristics, the acceleration increase is very quickly non-linear deformation, which in turn leads to the slope to appear significantly larger overall deformation.

By comparing the three displacement curves in X direction, Z direction and XZ direction, the analysis shows that the displacement difference is the largest when the seismic amplitude loading magnitude is 1.0 g, and the XZ direction is the largest, which is 4.3668 mm, and the displacement in XZ direction is about 2.61 times of that in X direction, and about 1.83 times of that in Z direction, which is because the loading in both directions makes the stress change of the soil body more complicated, and the soil body is constantly subjected to the tensile-shear cyclic action of the seismic wave, resulting in a huge difference in displacement.

3.2 Analysis of stress change results

Stress has a more generalized explanation in the mechanics of materials. Under the action of external forces, a material's internal stress state will change. This stress change may cause different degrees of

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deformation and even affect its own mechanical properties. In particular, when the stress at a certain point exceeds its ultimate strength, failure will occur at that point, leading to material destruction. Therefore, analyzing the stress distribution and its evolution law is crucial for explaining and analyzing the deformation and damage of slopes.

Fig. 4 shows the curves of stress variation with amplitude at the monitoring points at the foot of the slope in the X, Z, and XZ directions of the model when different seismic amplitudes are loaded, and the seismic wave is applied to the model.

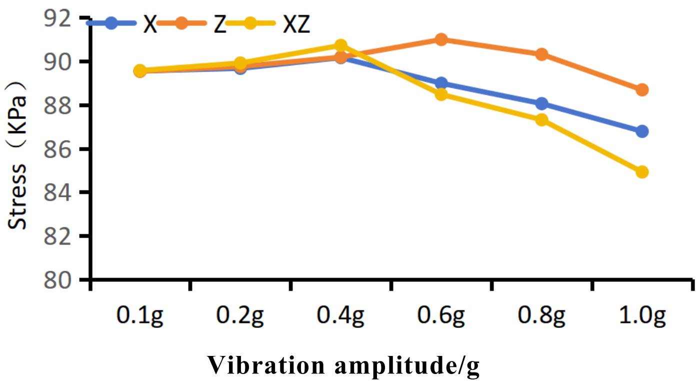

Fig.4 Stress versus amplitude curve

According to the data processing results and graphical analysis, according to the overall trend, i.e., from left to right, with the increase of the input acceleration, the stress shows a general trend of "first increase and then decrease." Specific analysis of the image shows that when the input acceleration from 0.1g to 0.4g, the stress gradually increases and reaches the maximum value; from 0.4g to 1.0g, the stress gradually decreases, showing a certain degree of stress release or damage situation.

Taking the stress in the X direction as an example, at the input acceleration of 0.1g, the stress in the X direction is 89.548 kPa, while at 0.4g, the stress in the X direction reaches 90.162 kPa, which is an increase of about 0.7% compared to that of 0.1g; and at 1.0g, the stress in the X direction decreases to 86.78 kPa, which is a decrease of about 3.7% compared to that of 0.4g. So similarly, with the increase of input acceleration, the trend of stress change in the Z direction and XZ direction is specifically analyzed; for the Z direction, when the input acceleration load is 0.1 g to 0.4 g and then to 1.0 g, the stress increases from 89.532 kPa to 90.185 kPa and then decreases to 88.685 kPa; for the XZ direction, with the increasing value of input, the stress increases from 89.57 kPa to 90.722 kPa and then decreases to 84.917 kPa.

The data analysis shows that when the input acceleration is 0.4g, the stresses in all three directions reach the maximum value. Then, the stresses start to decrease with the increase of acceleration. This may be related to the plastic deformation or even localized slope damage under high acceleration, leading to the redistribution and release of stress. In addition, comparing the rate of stress change for different directions, between 0.1g and 0.4g, the rate of stress growth is XZ direction > Z direction > X direction; between 0.4g and 1.0g, the rate of stress decrease is fastest in the XZ direction, which suggests that the XZ direction may be subjected to a more substantial destructive influence. Specifically, for the XZ direction, the stress decreases from 90.722 kPa to 84.917 kPa during the input velocity from 0.4 g to 1.0 g, which is about 6.4%; the same analysis shows that for the X direction, the stress decreases from 90.162 kPa to 86.78 kPa, which is 3.7%; for the Z direction, the stress decreases from 90.185 kPa to 88.685 kPa, a decrease of 1.7%, which indicates that the stress change in the XZ direction is the most drastic. It can be presumed that this direction may be the most damaged direction of the slope, which is consistent with the results of the deformation analysis above.

3.3 Analysis of results of changes in shear strain increments

The shear strain increment essentially represents the plastic deformation characteristic of a material. Under seismic action, it goes through an elastic phase and a plastic phase, where the shear strain increment is mainly used to characterize the change of plastic strain. In slope engineering, the location of shear strain increment can be used to determine the potential sliding surface of the slope, which can reflect the deformation of the local area, thus providing important support for analyzing and predicting the permanent deformation caused by the earthquake.

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Fig. 5 shows the variation curves of shear strain at the foot of the slope with different seismic amplitudes when the seismic wave is applied to the model's X, Z, and XZ directions.

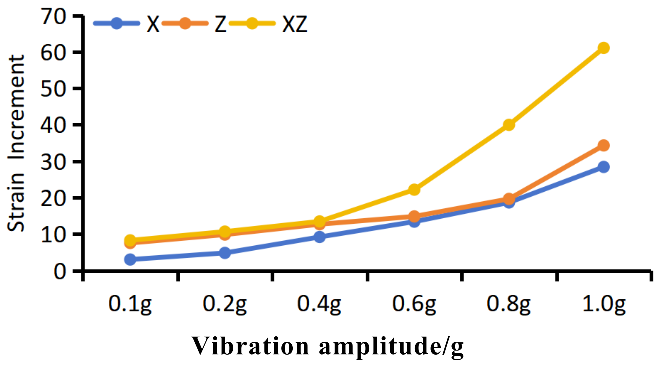
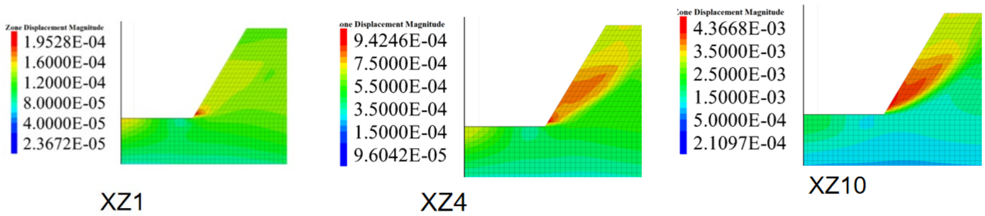


Fig.5 Maximum shear strain increment

Analyzing the overall trend, i.e., from left to right, the shear strain increment increases gradually from 0.1g to 1.0g, which indicates that with the increase of seismic acceleration, the shear deformation of the slope accumulates. The damage situation is strengthened gradually, and the slope may enter the plastic damage stage under high acceleration. For the X-direction, when the input velocity increases from 0.1g to 1.0g, the shear strain increment increases from 3.0277 to 28.416, which is an increase of 8.4 times. Similarly, for the Z direction, the shear strain increment increases from 7.5653 to 34.312, which is a 4.5-fold increase, and for the XZ direction, the shear strain increment increases from 8.287 to 61.057, which is a 7.4-fold increase. It can be seen that the shear strain increment increases most significantly in the XZ direction, reflecting that the shear damage in the XZ direction is the most serious and may be the dominant direction of slope sliding. When the input acceleration is 1.0G, the magnitude of shear strain increment is 61.057 in the XZ direction, 34.312 in the Z direction, and 28.416 in the X direction, and the order is XZ > Z > X. Then, analyzing the data, it can be seen that the shear strain increment in the XZ direction is 2.15 times as much as that in the X direction and 1.78 times as much as that in the Z direction, and it can be seen that the XZ direction is the most significant direction of slope sliding. It can be seen that the XZ direction is the most serious direction of the slope subjected to shear damage, which is consistent with the conclusion of the stress analysis. Therefore, under the action of high-intensity earthquakes, the slope is most seriously damaged in the XZ direction, and it is necessary to focus on the prevention and reinforcement initiatives in this direction during the seismic design.

3.4 Numerical simulation results cloud map analysis

The input seismic waves were analyzed by FLAC3D software, and cloud maps of the displacement, stress, and shear strain increments of the slope under this seismic action were generated.



(a) (b) (c)

Fig.6 Cloud map of slope displacement

Figure 6 shows the displacement cloud map of the slope under seismic action; the XZ direction is selected for analysis; under this seismic action, the displacement distribution of the slope shows significant spatial differences through the displacement cloud map, which can be clearly observed. The foot of the slope part of the displacement is the largest, which indicates that the region under the seismic action of the deformation of the region has occurred significantly. The overall deformation of the foot of the slope can be seen from the cloud diagram; with the increase of seismic acceleration, i.e., from 0.1g to 1.0g, the displacement of the foot of the slope gradually increases, and the degree of deformation gradually deepens, which indicates that there is a tendency for the foot of the slope to slide downward under the effect of the earthquake, which means that its horizontal shear force effect is more pronounced. Precisely, the red color of the image can reflect the depth of deformation. When the input acceleration is

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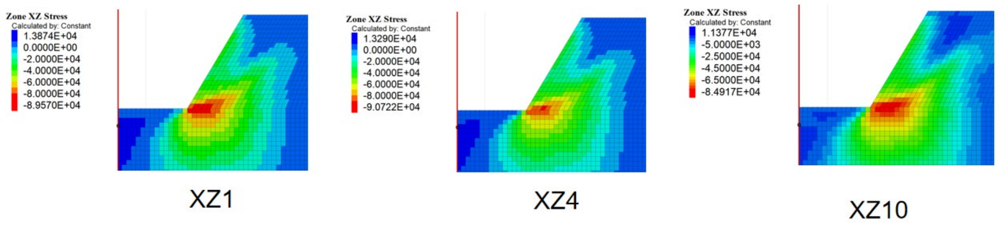
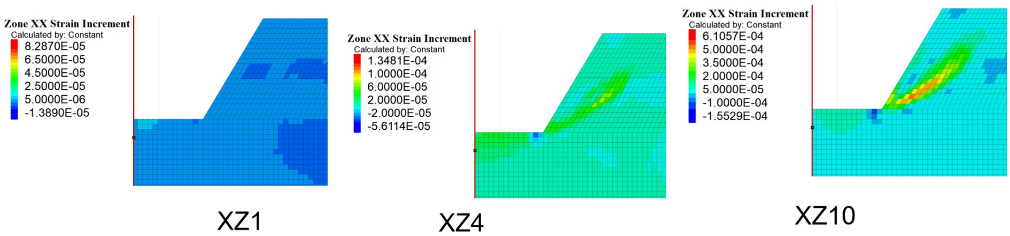
0.1g, the slope is in a slight deformation as a whole, and there is only a slight displacement at the foot of the slope, which indicates that the slope is in the elastic deformation stage at this time; when the input acceleration is from 0.1g to 0.4g, the change is more rapid; when it is 0.4g, the displacement of the foot of the slope is significantly increased, and the deep-red area, i.e., the deformation degree, is deepened, which shows that the slope Begins to enter the medium deformation stage, the foot of the slope has a tendency to slide downward, and the role of horizontal shear force is gradually prominent; from 0.4g to 1.0g, the regional image is steeper, and the change is faster; and at 1.0g, the foot of the slope displacement reaches the maximum value, and the degree of deformation is the deepest, which indicates that the slope enters the stage of severe deformation. The foot of the slope has a significant tendency to slide.



(a) (b) (c)

Fig.7 Cloud map of slope stress

Fig. 7 shows the stress cloud map of the slope under seismic action, while from the stress cloud map, it can be seen that the location of the maximum stress is still at the foot of the slope, indicating that this area is the area of stress concentration. The seismic action on the geotechnical body caused specific additional stress, resulting in stress redistribution, and the foot of the slope, as the supporting part of the slope, bears all the stresses accumulated continuously above the geotechnical body, and at the same time is subjected to the shear effect, which results in the formation of a stress concentration area, similar to the bottom of the blocks to withstand tremendous pressure. Therefore, the stress concentration phenomenon is pronounced at the foot of the slope. With the increase of seismic acceleration, the stress at the foot of the slope gradually increases, further aggravating the deformation and damage risk of the slope.



(a) (b) (c)

Fig.8 Cloud map of strain increment

Figure 8 shows the shear strain increment cloud diagram of the slope under seismic action; the shear strain increment represents the accumulation degree of plastic deformation of the slope, i.e., the plastic deformation characteristics of the slope under seismic action, which is a key index to determine the formation of the slip surface. The larger the shear strain increment, the higher the accumulation of plastic deformation of the slope, i.e., the higher the accumulation of slope strains, the higher the likelihood of triggering the formation of the slip surface. When further analyzing the shear strain increment cloud diagram, it can be seen that when the input acceleration is 0.1g, the slope as a whole is more complete; still in the elastic deformation stage, there is no apparent shear strain increment, and there is no obvious plastic deformation; the plastic deformation gradually increases, and when the input acceleration is 0.4g, the shear strain increment begins to appear in the local area of the slope. There is only a bit of prominence in the image, indicating that a potential sliding surface is being formed, but it does not lead to a slide. Potential sliding surface, but not through; the slope is in the initial stage of plastic deformation, and when the input acceleration reaches 1.0g, the shear strain increment increases significantly, and the shear strain increment at the foot of the slope reaches the maximum value; the local plastic deformation accumulates and forms a through sliding surface, which represents that the slope is damaged and destroyed.

4. Conclusions

Using FLAC3D numerical simulation software, the embankment slope model is established, and based on reasonable consideration of ground vibration input, boundary conditions, grid division, and model parameters, the change of parameters such as displacement, stress change, and shear strain increment is calculated for rocky slopes under different seismic load conditions to explore the influence of earthquakes on slope stability and the process of gradual damage, to analyze the rule of change, and to get the following conclusion:

(1) With the increase of seismic amplitude, the displacement growth of the slope is gradually accelerated, which is because the soil has plastic deformation characteristics, especially in the XZ direction, and with the increase of acceleration, the slope soon appears nonlinear deformation, the most intense deformation. The displacement of the foot of the slope is the largest, which indicates that this area is most likely to be significantly deformed under seismic action, and then the foot of the slope has a significant sliding tendency.

(2) The overall stress with the increase of seismic amplitude shows the trend of “first increase and then decrease.” When the input acceleration is 0.4g, the stress in all three directions reaches the maximum value and then begins to decline, which may be related to the plastic deformation of the slope under high acceleration or even the local damage, resulting in stress redistribution and release.

(3) After the input seismic wave, as the shear deformation of the slope accumulates, and at 0.4g, the shear strain increment starts to appear in the local area of the slope; at 1.0g, the shear strain increment at the foot of the slope reaches the maximum value, and the slope is damaged.

(4) The paper studied the vulnerable parts of the slope under seismic action, and the data monitoring showed that the damage in the XZ direction was the most serious, and the foot of the slope was also extremely vulnerable due to the accumulation of strains, so the strengthening initiatives in this location should be emphasized in the seismic design, and the vulnerable parts are the most prone to damage, so it is also necessary to do a good job in advance to strengthen the vulnerable parts of the monitoring and early warning.

Due to the conditions and technical limitations, we have only obtained some experimental data, but the results can reflect the dynamic response of rocky slopes under seismic action and the trend of the relevant parameters in the process of progressive damage in a more comprehensive way. Therefore, we will construct other more reasonable and diversified models to accurately simulate and analyze the relevant data for different state parameters in the future, in order to do a good job of monitoring and early warning measures.

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