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Seismic Response Laws of Rock Slopes with and without Weak Interlayer Based on Numerical Simulations

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Abstract: *To study the dynamic response law of rock slopes with weak interlayer as well as provide the theoretical basis and technical guidance for the seismic reinforcement of slope, Flac 3D software is used to simulate the loading of seismic waves on rock slopes with and without weak interlayer, and the test results show that: weak interlayer has an obvious energy-absorbing effect, and the larger the amplitude of seismic wave is, the more obvious absorption and weakening effect is; the rocky change part of the slope body is more sensitive to seismic wave and is more likely to be damaged; the weak interlayer could constantly occur residual displacement under seismic wave action, which affects the stability of the slope. The results of related data simulation and analysis can provide a certain degree of theoretical basis for slope disaster prevention and control.*

Keywords: *Rock Slope; Weak Interlayer; Dynamic Response; Ggradual Damage; Residual Displacement*

1. Introduction

In China, earthquake disasters are frequent and extremely serious, causing serious hazards to people's lives and property[1] .On December 18, 2023, a magnitude 6.2 earthquake occurred in Jixishan, Gansu Province, causing 151 deaths, 963 injuries, and 14.612 billion yuan of direct economic losses. On June 1, 2022, a magnitude 6.1 earthquake occurred in Lushan County, Ya'an, Sichuan Province, causing 4 deaths and 42 injuries. Landslides for rock slopes, as one of the important types of geologic hazards, tend to show more prominent stability problems under seismic excitations[2-4]. In particular, the down-layer rock slopes containing weak interlayers have more complex seismic response laws, causing more serious hazards, and putting forward higher requirements for engineering stability and disaster prevention[5] .

In the past few decades, the field of rock engineering in China has experienced vigorous development and achieved remarkable results. Huang Runqiu[6] and others proposed a "conceptual model" for the Wenchuan earthquake disaster, in which the deformation and damage of downdip rock slopes under strong earthquakes were investigated. Dong Jinyu[7] carried out a large-scale shaking table test study on downdip rocky slopes, and concluded that the amplification of the acceleration of the downdip structural plane is an important influence on the slope instability. However, the existence of weakly interbedded compliant rocky slopes makes the dynamic response law of slopes under seismic wave more complicated, but the current research focuses on homogeneous slopes, and there are fewer researches on slopes with weakly interbedded slopes, so it is necessary to carry out a more in-depth research in this field to improve the seismic capacity of demonstration slopes and reduce the losses caused by seismic hazards.

The purpose of this paper is to study the dynamic response laws and gradual damage process of slopes with weak interlayer under seismic action, to analyze the distribution law of dynamic displacement, stress, and shear strain increment in the interior of slopes by comparing the dynamic corresponding law and damage record of homogeneous rocky slopes and rocky slopes with weak interlayer under seismic action, and then to judge the location of the damage of the slopes, so as to provide the theoretical basis and technical guidance for the research of seismic strengthening of the slopes. The study will provide a theoretical basis and technical guidance for the research of seismic strengthening of slopes.

2. Study area

The two basic site models are three-dimensional slope models with a length of 300m, a height of 120m, and a width of 5m constructed by the drawing software CAD and the modeling software midas gts nx, in which the thickness of the soft and weak interlayer containing the soft and weak interlayer in

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the paralimnionic rocky slopes is 5 m. The lower part of the default basic site is a hard bedrock, and the physico-mechanical parameters of the rock body and the interlayer in the numerical calculations are shown in Table 1.

Table 1: Material mechanical parameters

Material Type	Density (kg/m³)	Bulk Modulus (Pa)	Shear Modulus (Pa)	Cohesion (Pa)	Friction Angle (°)	Tension (Pa)
Weak Layer	2.5×10^3	6.0×10^8	2.8×10^8	5.0×10^4	25	5.0×10^3
Rock	2.5×10^3	2.5×10^9	1.2×10^9	5.0×10^5	30	1.0×10^4

3. Numerical model setup

3.1 Software Introduction

In this paper, the dynamic response of slopes under seismic action is analyzed using Flac 3D, a three-dimensional numerical modeling software developed by Itasca Corporation, which focuses on the field of geotechnical engineering. It has powerful three-dimensional modeling functions and a variety of nonlinear material models, and can accurately simulate the dynamic response of rocky slopes with weak interlayers under seismic action. Through Flac 3D software, the deformation, damage, and stability of geotechnical bodies under seismic conditions can be studied in depth, providing scientific basis for earthquake disaster prevention and engineering design.

3.2 Numerical modeling and parameterization

The modeling was done using midas gts nx software, and the first step was to draw one-dimensional graphs of the two slopes using AutoCAD, as shown in Figures 1 and 2. This step helps to accurately capture the geometry and features of the slopes. Subsequently, the drawn graphics were imported into midas gts nx software for modeling, Figures 3 and 4 show the model. In this way, it facilitates the subsequent simulation and analysis of the dynamic response patterns of different slope types under seismic wave action in Flac 3D.

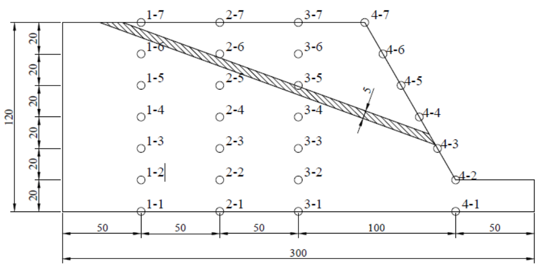

Figure 1: CAD model of Weak Interlayer slope

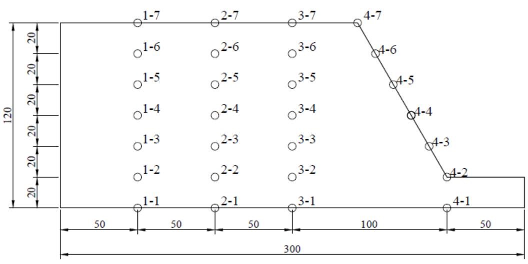

Figure 2: CAD model of Homogeneous slope

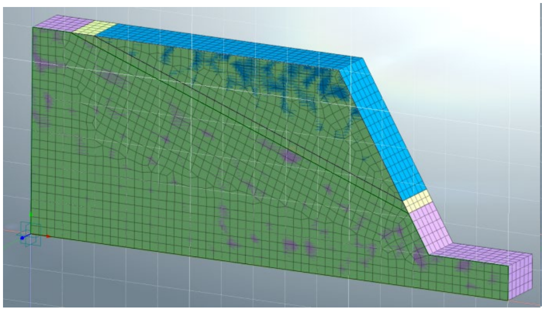

Figure 3: Midas gts ns model of Weak layer slope

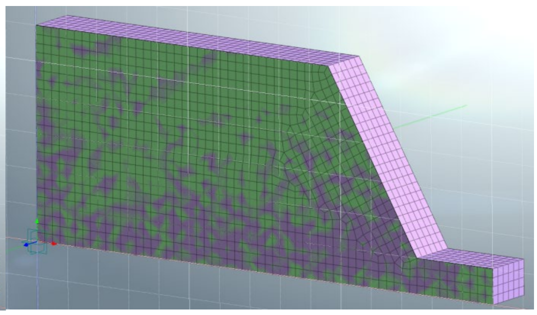

Figure 4: Midas gts ns model of Homogeneous slope

3.3 Seismic loading

During the experiment, monitoring points were set up at key locations such as in-slope and on-slope

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surfaces, and the boundary conditions were free-field boundaries. Acceleration loading was employed with amplitudes ranging from 0.1g to 0.4g and a duration of 28.43 seconds for each amplitude variation. The acceleration cloud diagram of the seismic wave loading process is shown below Figure 5-8.

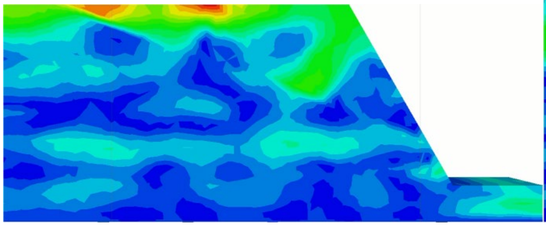

Figure 5: Acceleration Contour of Weak layer Slope at 0.7s

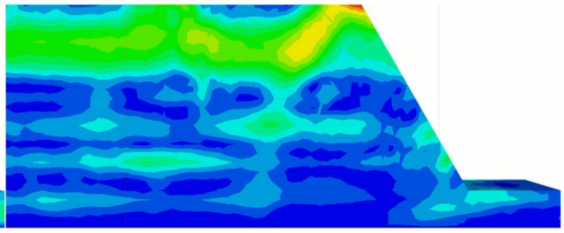

Figure 6: Acceleration Contour of Homogeneous Slope at 0.7s

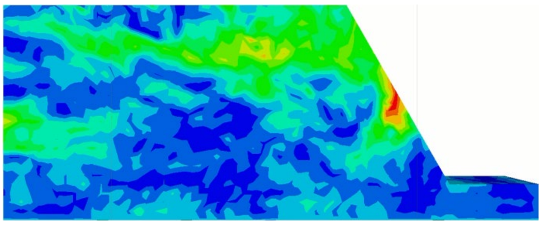

Figure 7: Acceleration Contour of Weak layer Slope at 20s

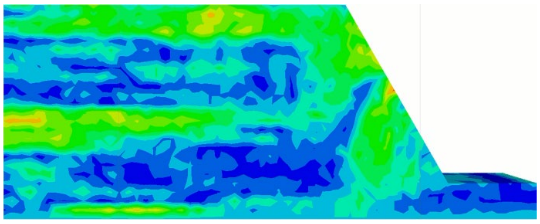

Figure 8: Acceleration Contour of Homogeneous Slope at 20s

4. Result analysis

4.1 Acceleration responses

From Figure 9 and 10, it can be seen that the acceleration increases with the increase of the relative elevation of the slope and reaches the maximum at the top of the slope for both homogeneous slopes and slopes containing weak interlayers, indicating that the slopes have an acceleration elevation amplification effect. For example, for the 1-monitoring point of the homogeneous slope, the peak acceleration increases from 1 to 2.1, 2.2, 2.5, 2.7, 3.1, and 4.1 g for the relative elevations of 0, 0.18, 0.33, 0.5, 0.68, 0.84, and 1.0. It can be seen that the acceleration increment at the top of the slope reaches the maximum of 1 g, which can be attributed to the fact that the top of the slope is less constrained and thus has a large degree of freedom.

When comparing monitoring points 1-7 and 2-5, it can be found that although both slopes have an acceleration elevation amplification effect, the homogeneous slope shows more significant acceleration elevation amplification effect compared with the weakly interbedded slope. For example, in Fig. 9, the peak acceleration increment of monitoring points 1-7 compared with 1-6 reaches 1.0 g, while the corresponding acceleration of homogeneous slopes only increases by 0.225 g. The two groups of monitoring points are separated by weak interlayers, which indicates that the weak interlayers have the effect of impeding the propagation of seismic waves and absorbing their energy.

As can be observed from Figures 11 and 12, the two side slopes have greater acceleration than the homogeneous slopes from monitoring point 4-3 on the slopes containing weak interlayers on the same monitoring points 4-4 and 4-5, which shows an opposite pattern to monitoring points 4-2, 4-6 and 4-7, which happen to be located below the weak interlayers and above the interlayers from 4-4 onwards. This suggests that the parts of the slope where the lithology has changed reduce the stability of the slope due to a more complex structural surface, leading to a greater acceleration of the rock above the entrapment.

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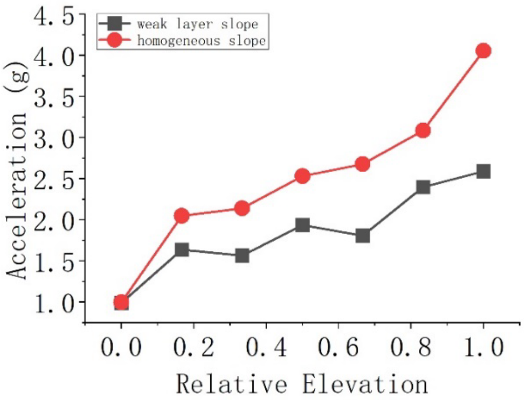

Figure 9: Peak Acceleration at 0.1g (1-Key Points)

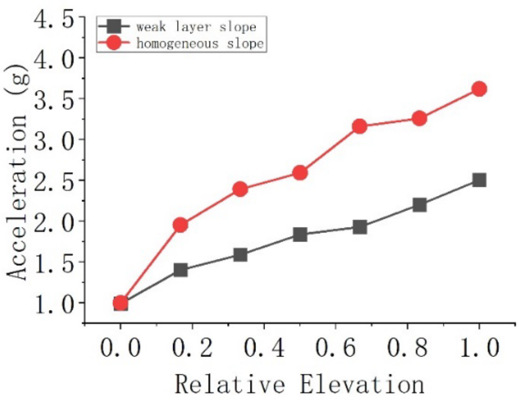

Figure 10: Peak Acceleration at 0.1g (2- Key Points)

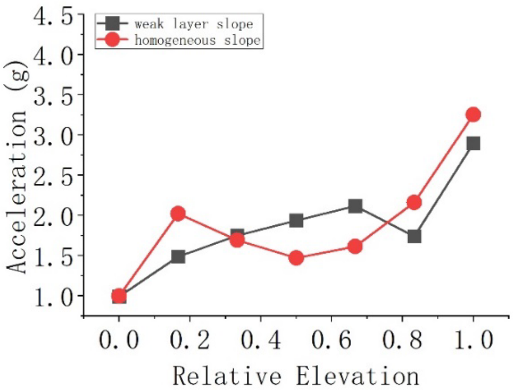

Figure 11: Peak Acceleration at 0.1 g (4-Key Points)

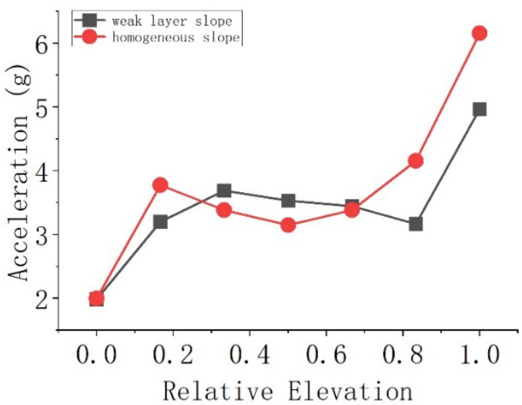

Figure 12: Peak Acceleration at 0.2g (4-Key Points)

4.2 Displacement responses

As can be seen from the Figures 13 to 18, when the seismic wave is loaded, there is almost no difference in the displacement of the monitoring points located below the mezzanine in the two side slopes, for example, monitoring points 3-1, 3-2, 3-3, 3-4, 4-1, 4-2, 4-3, etc., and the difference in the displacement response of the monitoring points located above the mezzanine is larger, for example, in Fig. 15, the difference in the displacement of the two side slopes at the monitoring points 3-5, 3-6, and 3-7 are respectively 0.043 m, 0.051 m, 0.062 m. This indicates that the mezzanine layer is the key controlling structural surface of slope stability, which has a great influence on slope stability and dynamic response.

In Figs. 13, 16, 17, and 18, with the increasing input acceleration amplitude, it is observed that the displacement difference between the homogeneous side slopes and the weakly interbedded side slopes gradually increases, for example, in monitoring point 4-4, when the input seismic wave amplitude is 0.1g, 0.2g, 0.3g, 0.4g, the displacement difference between the two slopes corresponds to 0.039 m, 0.254 m, 0.72 m, and 1.46 m. The displacement difference between the two slopes is also observed in Figs. 13, 16, 17, and 18, which shows the same pattern with the increase of input acceleration amplitude. The remaining monitoring points positioned above the interlayer exhibit a similar trend, indicating that as the seismic wave's amplitude increases, the presence of the weak interlayer influences the slope's stability. Consequently, this heightened influence of the weak interlayer significantly raises the risk of slope failure. In the slopes containing weak inclusions, the displacement value of monitoring point 4-4 is the maximum regardless of the input seismic wave amplitude, and then the displacement values of monitoring points 4-5, 4-6, and 4-7 gradually decrease. As shown in Fig. 17, when the input seismic wave amplitude is 0.3g, the displacement of monitoring point 4-4 is 0.87m, and with the increase of the relative elevation, the displacement value decreases from 0.653m to 0.559m, 0.558m, which indicates that the lithological change of the slope is affected by the displacement more obviously because of the softer interlayer and the harder rock body, which makes the structural surface more complicated.

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For example, in Figures 19 and 20, the displacements of monitoring points 2-6 and 4-4 in the weakly interbedded slope are 0.00736 m and 0.08313 m respectively at the end of the input seismic wave, while the displacements of the corresponding monitoring points of the homogeneous slope are 0.00037 m and 0.00023 m respectively, which are almost the same as the initial state. The displacements of the corresponding monitoring points in the slope are 0.00037 m and 0.00023 m, which are almost the same as the initial state. This is due to the fact that the residual displacements of the slope with weak interlayer occurred when it was subjected to seismic force, and the stability damage of the slope is caused by the accumulation of continuous displacements, so the weak interlayer makes the residual displacements of the slope, which reduces the stability of the slope, and may lead to the slope damage greatly.

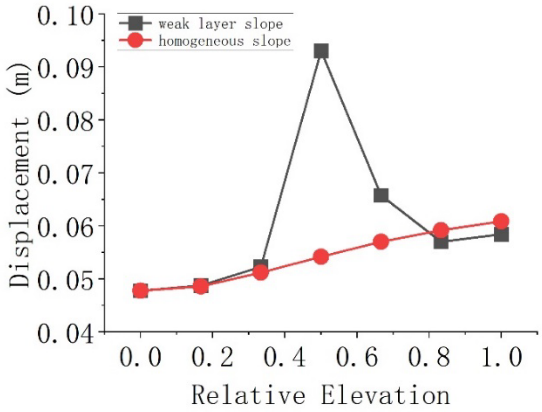

Figure 13: Peak Displacement at 0.1g (4-Key Points)

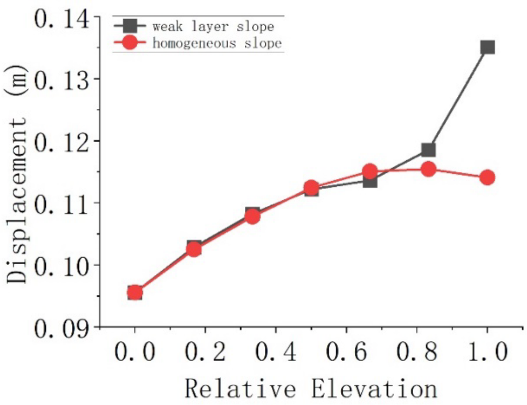

Figure 14: Peak Displacement at 0.2g (2-Key Points)

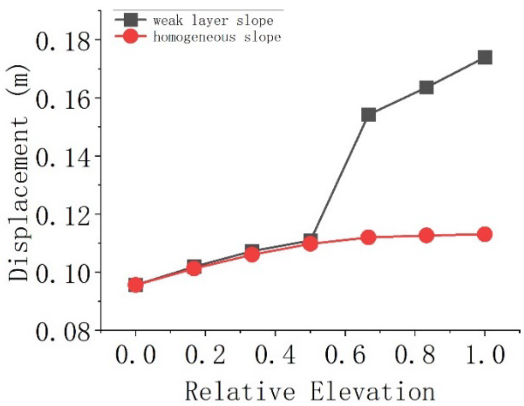

Figure 15: Peak Displacement at 0.2g (3-Key Points)

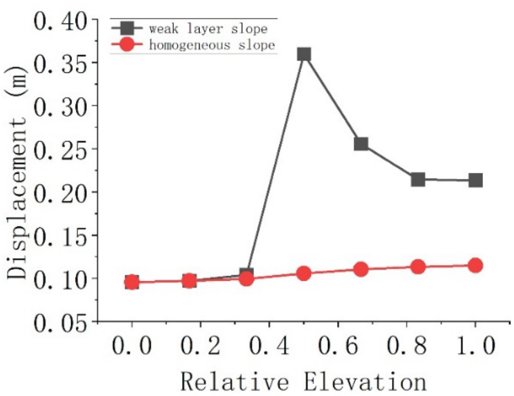

Figure 16: Peak Displacement at 0.2g (4-Key Points)

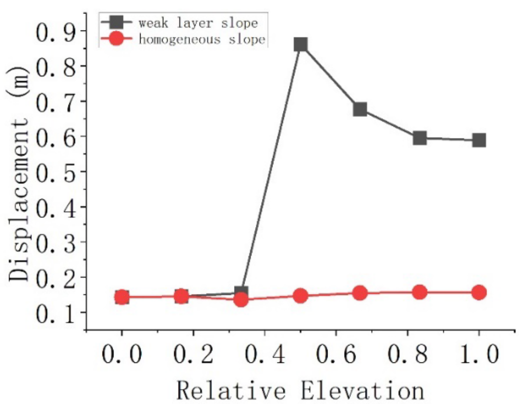

Figure 17: Peak Displacement at 0.3g (4-Key Points)

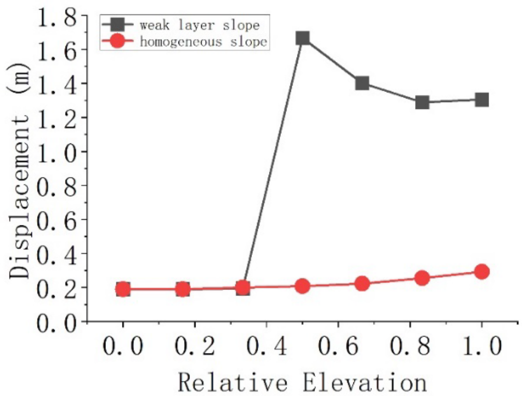

Figure 18: Peak Displacement at 0.4g (4-Key Points)

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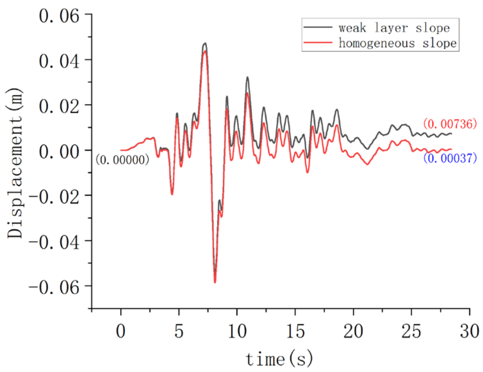

Figure 19: Displacement Time History at 0.1g (2-6)

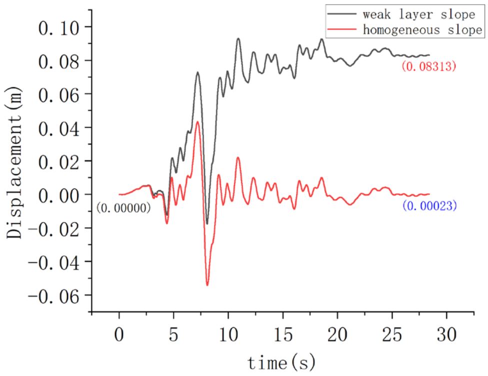

Figure 20: Displacement Time History at 0.1g (4-4)

4.3 Stress analysis

Whether it is a homogeneous slope or a slope with weak interlayer, the average value of stress at the slope surface is larger than the average value of stress inside the slope, and the stress value inside the slope is almost the same in the homogeneous slope and the slope with weak interlayer, as shown in Fig. 21-24, the stress value of 1-monitoring point inside the slope in the two slopes decreases with the increase of the relative elevation from 0.38MPa to 0.023MPa, and the decreasing tendency is the same. The slope surface stress of the homogeneous slope is larger than that of the slope with weak interlayer, for example, at monitoring point 4-4, the stress difference between the homogeneous slope and the slope with weak interlayer is 0.45 MPa and 0.625 MPa when the input seismic wave amplitude is 0.1 g and 0.2 g. This indicates that the slope surface is more affected when the slope is subjected to seismic wave action. Moreover, because the weak interlayer has the function of absorbing energy, the propagation of the stress wave in the interlayer is affected, so that the slope surface stress value of the slope with weak interlayer is smaller than that of the homogeneous slope.

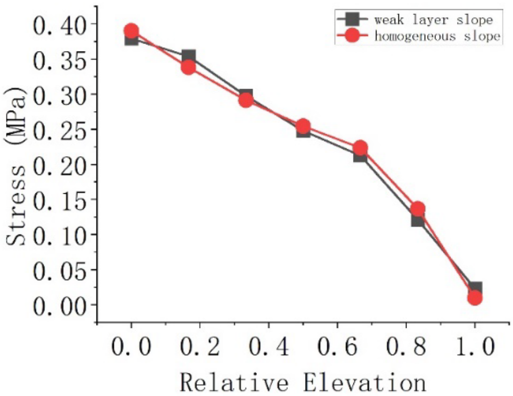

Figure 21: Peak Stress at 0.1g (1-Key Points)

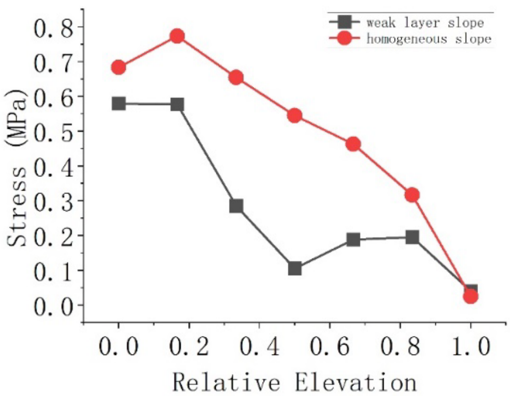

Figure 22: Peak Stress at 0.1g (4-Key Points)

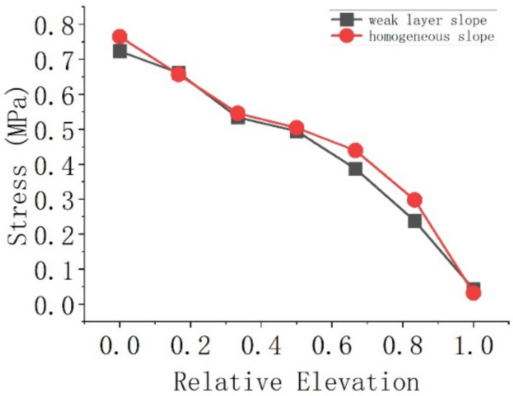

Figure 23: Peak Stress at 0.2g (1-Key Points)

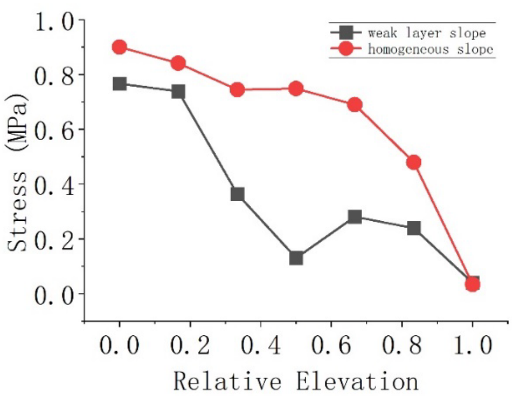

Figure 24: Peak Stress at 0.2g (4-Key Points)

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5. Conclusions

Under the action of seismic force, the damage mode of the slope has a close connection with the structure of the slope body, this paper is based on Flac 3D software by comparing the corresponding law of dynamics and damage records of homogeneous rocky slopes and rocky slopes with weak interlayers under the action of earthquakes, and analyzing the simulation data to obtain the following conclusions:

(1) Slope shows acceleration elevation amplification effect under seismic action, especially at the top of the slope with small constraints, which is the most significant. And with the increase of input seismic wave amplitude, the displacement difference between the slope with weak interlayer and the homogeneous slope is larger, so the weak interlayer has an important influence on the overall stability and safety of the slope.

(2) Comparing the peak acceleration at the top of the two slopes, the acceleration elevation amplification effect of the homogeneous slope is more significant, which indicates that the weak interlayer hinders the propagation of seismic waves, and can obviously weaken the amplitude of seismic waves. And the stress on the slope surface of the homogeneous slope is significantly higher than that of the weakly interbedded slope, which highlights the energy-absorbing effect of the weakly interbedded layer.

(3) Slopes containing weak interlayers will continuously experience residual displacements under seismic action, and the accumulation of residual displacements of slopes will affect the stability of slopes, which will lead to the destruction of slopes.

(4) The acceleration, displacement and stress of the rocky change part of the slope body show different response laws from the homogeneous rocky slope. The structural surface of the rocky part of the slope body is more complex and more sensitive to seismic waves, which can easily destabilize the slope under the action of seismic force.

The existence of weak interlayers in slopes not only increases the complexity of the dynamic response of slopes, but also puts forward higher requirements on the stability and safety of slopes. In engineering practice and geologic disaster prevention, it is necessary to fully consider the influence of complex structural surfaces in slopes, and take corresponding measures to mitigate the adverse effects and ensure the stability and safety of slopes.

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