

Article

Numerical Analysis of the Dynamic Response Law of Counter-Tilt Layered Rock Slopes

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Abstract: Counter-tilt layered rock slopes are common types of slopes that are susceptible to destabilizing damage under seismic action. Therefore, the dynamic response law of counter-tilt layered rock slopes under seismic action is of great significance for the study of slope stability. This study utilizes UDEC (Universal Distinct Element Code) numerical simulation software to vary slope geometry and seismic wave parameters, such as joint thickness, joint inclination angle, slope angle, seismic wave frequency, amplitude, and duration. The maximum displacements of the monitoring points of a slope were obtained, and the dynamic response law of counter-tilt layered rock slopes under seismic action was investigated. The results yielded the following insights: (1) The thickness of the joints of a slope is an important factor affecting the dynamic response of a slope, and with the increase in the thickness of the joints, the maximum displacement of each monitoring point of the slope will decrease. (2) The maximum displacement of a slope increases with the increase in the joint inclination angle and the slope angle. When the joint inclination angle is less than 50°, the change in the joint inclination angle has less of an effect on the maximum displacement of the slope in the x and y directions. When the joint inclination angle is more than 50°, the maximum displacement of the slope in the x and y directions increases faster with the change in the joint inclination angle, and a similar pattern is observed for the slope angle. (3) Slopes are less susceptible to damage when both the joint inclination angle and the slope angle are less than 50°, and the probability of slope damage increases significantly when both are greater than 50°. (4) The maximum displacement at each monitoring point of a slope increases with the frequency, amplitude, and duration of a seismic wave. (5) Seismic wave amplitude has the greatest effect on the dynamic response of a slope, followed by duration, and frequency has the weakest effect on the dynamic response of a slope. The conclusions drawn in this paper can be useful for the control of counter-tilt layered rock slopes.

Keywords: rock slopes; dynamic response; numerical analysis; maximum displacement



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1. Introduction

An earthquake is a common natural disaster, and slope destabilization damage caused by an earthquake is a very serious secondary disaster. Slope destabilization damage constitutes a great threat to the lives and property safety of the residents at the foot of a slope. Counter-tilt layered rock slopes are layered slopes where the slope strike is approximately parallel to the strike of the rock formation and the inclination is opposite [1]. Typically, counter-tilt layered rock slopes are relatively stable and generally do not experience flexural toppling failure. However, as the gradient and height of slope mining increase, counter-tilt layered rock slopes become susceptible to overtopping and damage under seismic action, thus posing a serious threat to projects and residents.

The methods used to study the dynamic responses of slopes under seismic action are as follows: shaking table model tests [2–5], numerical simulation tests [6–8], and centrifuge model tests [9,10]. Shaking table model tests have the advantages of accurate monitoring

results and realistic simulation effects. Numerical simulation has the advantages of low test costs and the simplification of the analysis of the stress and displacement at each monitoring point. Centrifuge model tests use centrifugal force to simulate gravity, thus enhancing the simulation of the states of slopes under a gravitational field. Therefore, these three methods are widely used in the study of the dynamic responses of slopes.

Shaking table model tests, numerical simulation tests, and centrifuge model tests can effectively simulate the flexural toppling failure process of counter-tilt rock slopes under different conditions [11–16], and the cited scholars have classified the process of flexural toppling failure on slopes into several stages. Cheng et al. [1] and Cai et al. [17] used numerical simulation to investigate the factors affecting the dynamic response of counter-tilt layered rock slopes and drew similar conclusions: the maximum displacement of a slope increases with an increasing slope angle; the maximum displacement of the slope decreases with increasing joint thickness. Ning et al. [18] used UDEC to study the trend of displacement at each monitoring point, and the results showed that the displacement at each monitoring point increased with the increase in slope height and seismic wave amplitude, and the displacement in the horizontal direction of each monitoring point was larger than the displacement in the vertical direction. Yang et al. [19] and Feng et al. [20] studied the dynamic response of counter-tilt layered rock slopes, and their results showed that the dynamic response at the top of the slope was the strongest. The analysis of factors affecting the dynamic response of slopes is one of the hot spots in current research [21–25]. Li et al. [21] found that counter-tilt rock slopes are more sensitive to the bedding inclination angle than the joint inclination angle. Liu et al. [22] further found that the frequency of a seismic wave has the greatest effect on the dynamic response of a slope, and the duration has the least effect on the dynamic response of the slope. Wang et al. [23], based on Liu et al. [22]’s study, found that the seismic wave amplitude has less of an effect on the dynamic response of slopes. Ren et al. [25] showed that seismic wave amplitude and duration were strongly and positively correlated with the dynamic response of a slope. Chen et al. [26] found that elongated blocks play a decisive role in the dynamic response of slopes. Jia et al. [27] investigated the dynamic response of slopes containing anticlinal fracture zones under seismic action, and the results showed that there was an amplification effect of acceleration on the slope surface, and the amplification effect of acceleration was most significant in the upper disk of the fracture zone. Ren et al. [28] investigated the dynamic response of slopes using the three-dimensional discrete element method and compared the results obtained with those calculated using the Newmark method. They found that the permanent displacements obtained using the Newmark method were much smaller than those obtained using the three-dimensional discrete element method.

In summary, the above scholars used shaking table model tests, numerical simulation tests, and centrifuge model tests to study the dynamic response law of counter-tilt layered rock slopes in depth. It has been revealed that slope height, slope angle, joint inclination angle, seismic wave frequency, amplitude, and duration have different degrees of influence on the dynamic response of slopes and flexural toppling failure. However, there are fewer studies on the response of counter-tilt rock slopes to earthquakes that consider horizontal and vertical displacements. This study utilized UDEC numerical simulation software to vary the slope geometry and seismic wave parameters, such as joint thickness, joint inclination angle, slope angle, seismic wave frequency, amplitude, and duration. The maximum displacements of the monitoring points of a slope were obtained, and the dynamic response law of counter-tilt layered rock slopes under seismic action was investigated. The research results have theoretical significance and application value for the stability evaluation and prevention of counter-tilt layered rock slopes.

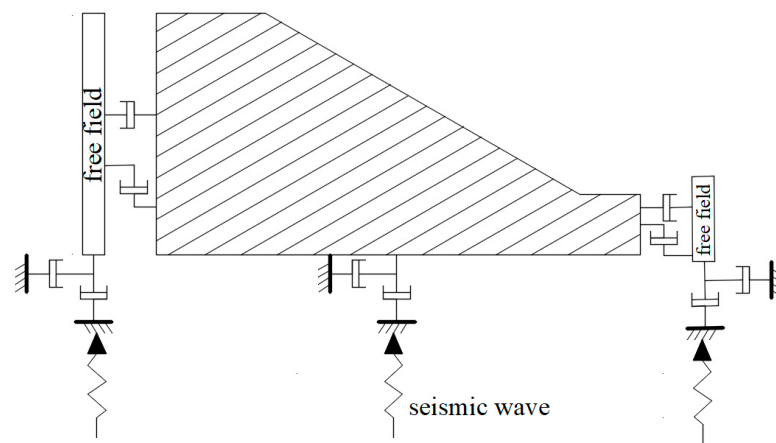


Figure 2. Boundary condition.

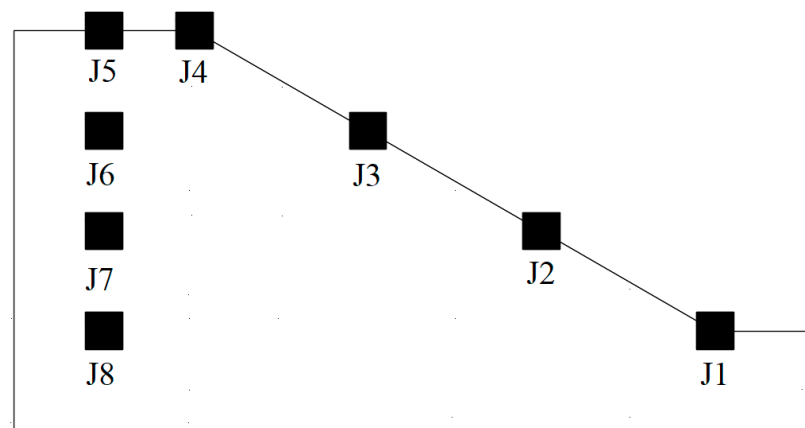


Figure 3. Establishment of monitoring points. J1: Location and number of monitoring point.

2.2. Calculation Parameters

The analyzed rock mass is prototypically limestone, and the selected rock parameters and joint parameters are shown in Tables 1 and 2.

Table 1. Rock parameters.

Material Type	Density (Kg/m ³)	Bulk Modulus (Gpa)	Shear Modulus (Gpa)	Cohesion (Mpa)	Friction Angel (°)	Tension (Mpa)
Rock	2500	25	11.5	3	35	2

Table 2. Joint parameters.

Material Type	Normal Stiffness (Gpa)	Shear Stiffness (Gpa)	Tension (Mpa)	Cohesion (Mpa)	Friction Angel (°)
Joint	3	2	0.2	0.3	17

3. Setting Damping Values and Calculating Working Conditions

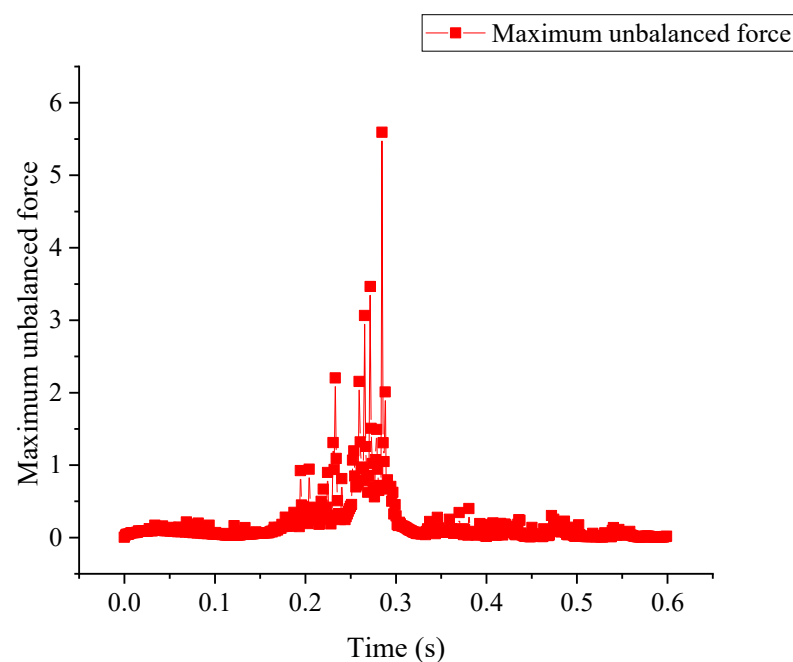
In order to ensure accurate calculation results, the type of damping used in the computational model of this paper is Rayleigh damping. The damping ratio of 0.05, which is commonly used for geotechnical bodies, was employed so as to minimize the effect of higher frequencies on the model's calculation results. The calculated working conditions of the model are shown in Table 3.

Table 3. The calculated working conditions of the model.

Joint Thickness (m)	Slope Angle (°)	Joint Inclination Angle (°)	Frequency (Hz)	Amplitude (g)	Duration (s)
1, 2, 3, 4	60	60	1	0.1	0.2
2	60	30, 40, 50, 60, 70, 80	1	0.1	0.2
2	30, 40, 50, 60, 70, 80	60	1	0.1	0.2
2	30	60	1, 2, 3, 4	0.1	0.2
2	30	60	1	0.1, 0.2, 0.3, 0.4	0.2
2	30	60	1	0.1	0.2, 0.4, 0.6

4. Numerical Simulation Results

The displacement of the slope reaches equilibrium within 0.2 s since the model has been divided into more blocks. Taking into account the long actual time of the model's computation, the loading duration of the seismic wave is 0.2 s, and the running time of the model is set to 0.6 s. By monitoring the maximum unbalanced force of the model, it can be found in Figure 4 that when the running time is 0.6 s, the maximum unbalanced force tends to be 0. It can be assumed that the model is already in equilibrium at this time, so the displacement of the slope model has also reached equilibrium.

**Figure 4.** Maximum unbalanced force of slope.

4.1. Influence of Slope Geometric Parameters

4.1.1. Influence of Joint Thickness

Figure 5 shows the effect of changes in joint thickness on the displacement response of the slope in the x and y directions at a joint inclination angle of 60°, a slope angle of 60°, a seismic wave frequency of 1 Hz, an amplitude of 0.1 g, and a duration of 0.2 s.

Figure 5 shows that when the joint thickness is 1 m, 2 m, 3 m, and 4 m, the maximum displacement of the slope is maximum when the joint thickness is 1 m and minimum when the joint thickness is 4 m. The maximum displacement of the slope gradually decreases with an increasing joint thickness, both outside and within the slope, and this trend is nonlinear. This shows that slope stability increases as joint thickness increases. From a mechanical standpoint, it can be calculated that the stiffness increases 1000 times for every 1 m increase in joint thickness. As a result, the stiffness of the joint increases with joint

thickness, which reduces the displacement of each slope monitoring point and increases slope stability.

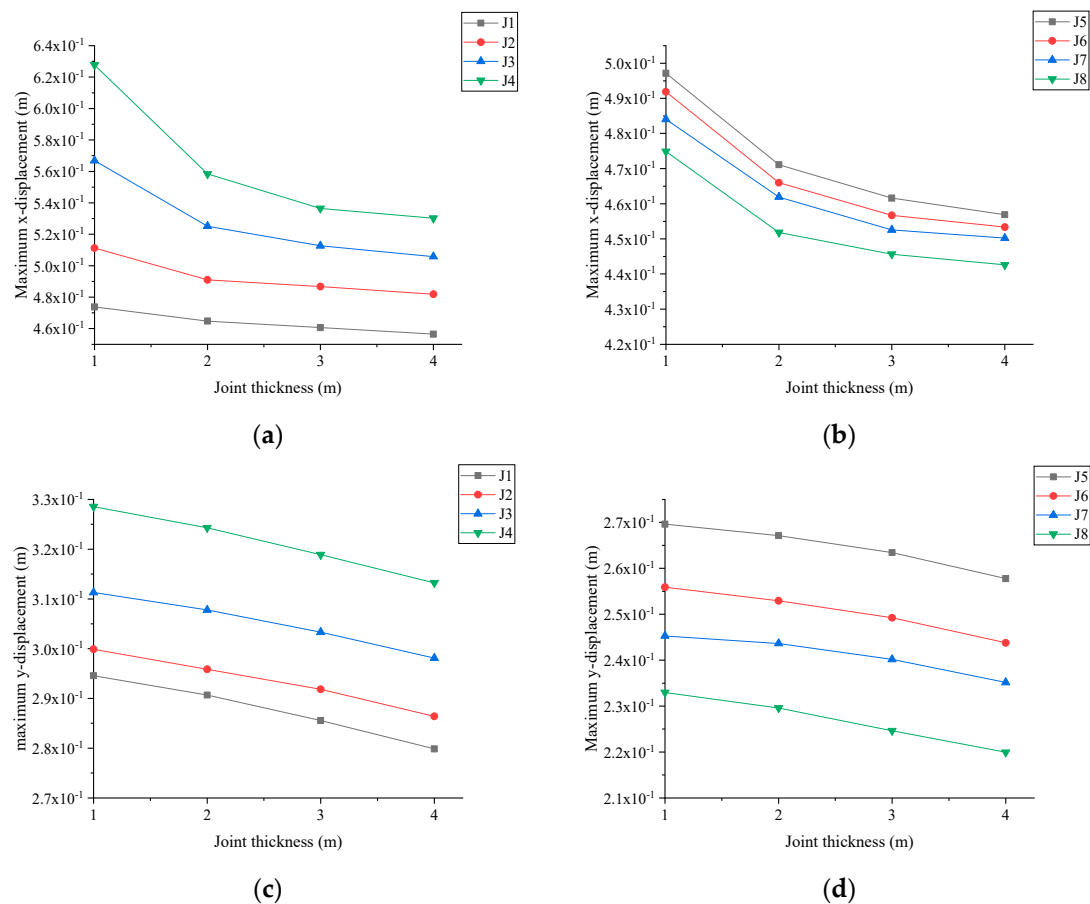


Figure 5. Influence of joint thickness on slope displacement response: (a) maximum x–displacement of the slope surface monitoring points; (b) maximum x–displacement of the inside slope monitoring points; (c) maximum y–displacement of the slope surface monitoring points; (d) and maximum y–displacement of the inside slope monitoring points.

4.1.2. Influence of Joint Inclination Angle

Figure 6 shows the effect of changes in the joint inclination angle on the displacement response of the slope in the x and y directions at a joint thickness of 2 m, a slope angle of 60° , a seismic wave frequency of 1 Hz, and an amplitude of 0.1 g and for a duration of 0.2 s.

As can be observed from Figure 6a,b, the maximum displacement in the x direction is less affected by a change in joint inclination angle when it is less than 50° . The maximum displacement in the x direction clearly increases with an increasing joint inclination angle at joint inclination angles of 60° , 70° , and 80° . In Figure 6c,d, it can be seen that the maximum displacement in the y direction exhibits an increasing and, subsequently, declining pattern as the joint inclination angle increases, and it achieves its maximum when the joint inclination angle is 60° . Cheng et al. [1] found that the x direction displacement is maximum between the joint inclination angles of 60° and 70° ; this is due to the characterization of the bending moment effect, where the joint inclination angle between 60° and 70° is the dominant interval for the occurrence of tipping. We determined that the maximum displacement in the y direction was greatest at a joint inclination angle of 60° , which is probably due to bending moment effects; confirmation of the cause requires further research.

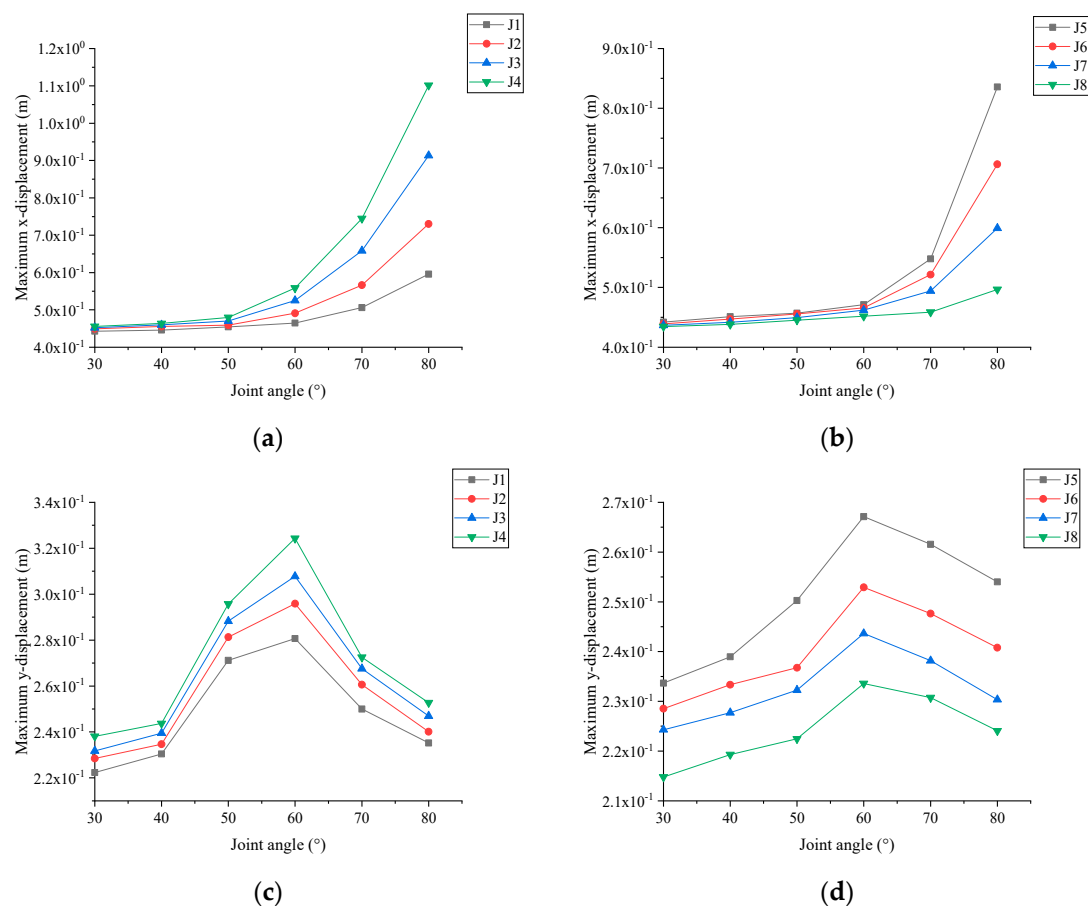


Figure 6. Influence of joint inclination angle on slope displacement response: (a) maximum x-displacement of the slope surface monitoring points; (b) maximum x-displacement of the inside slope monitoring points; (c) maximum y-displacement of the slope surface monitoring points; (d) maximum y-displacement of the inside slope monitoring points.

The maximum displacement of each monitoring point of the slope was examined in order to further reveal the impact of the joint inclination angle on the dynamic response law of a slope. Figure 7 demonstrates that when the joint inclination angle is less than 50° , the maximum displacement in the slope and at each monitoring point on the slope face is only slightly affected by the change in the joint inclination angle. However, when the joint inclination angle is greater than 50° , the maximum displacement increases quickly with the increase in the joint inclination angle. This indicates that the change in slope displacement is primarily governed by the maximum displacement in the x direction, which has a tendency similar to the change in slope displacement with the change in the joint inclination angle. This demonstrates that the maximum displacement in the x direction and the total slope displacement with the joint inclination angle have a similar pattern and that the maximum displacement in the x direction mostly controls the change in slope displacement. When the joint inclination angle is relatively low, the joint air condition is weak, the force arm of the dumping moment is shorter, and the tendency of the slope to dump is reduced. As a result, the maximum displacement of the slope is smaller. The force arm of the overturning moment grows faster as the joint inclination angle rises, especially between 70° and 80° , which increases the tendency of slope bending and flexural toppling failure and causes the maximum displacement of the slope to rise with the joint inclination angle.

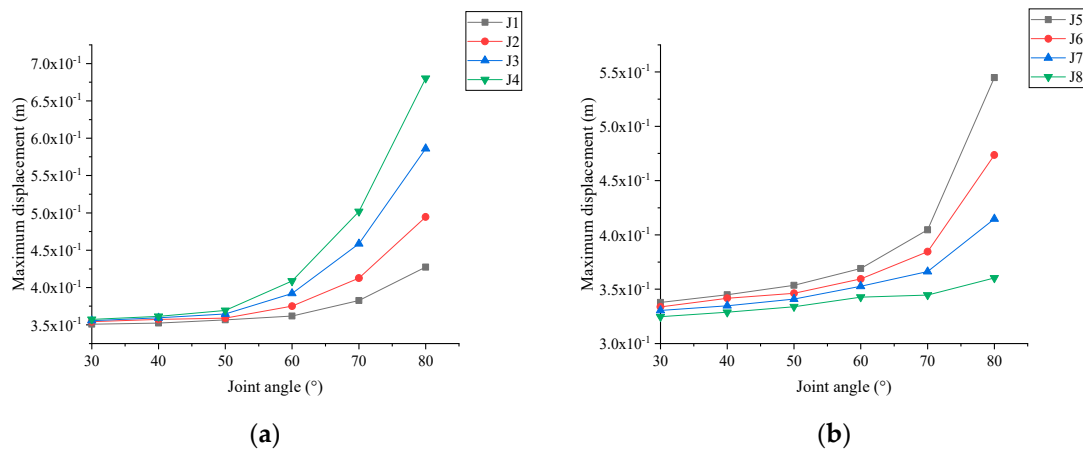


Figure 7. Relationship between maximum slope displacement and joint inclination angle slope: (a) maximum displacement of slope monitoring points; (b) maximum displacement of monitoring points within the slope.

4.1.3. Influence of Slope Angle

Figure 8 shows the effect of changes in the slope angle on the displacement response of the slope in the x and y directions at a joint thickness of 2 m, a joint inclination angle of 60° , a seismic wave frequency of 1 Hz, and an amplitude of 0.1 g and for a duration of 0.2 s.

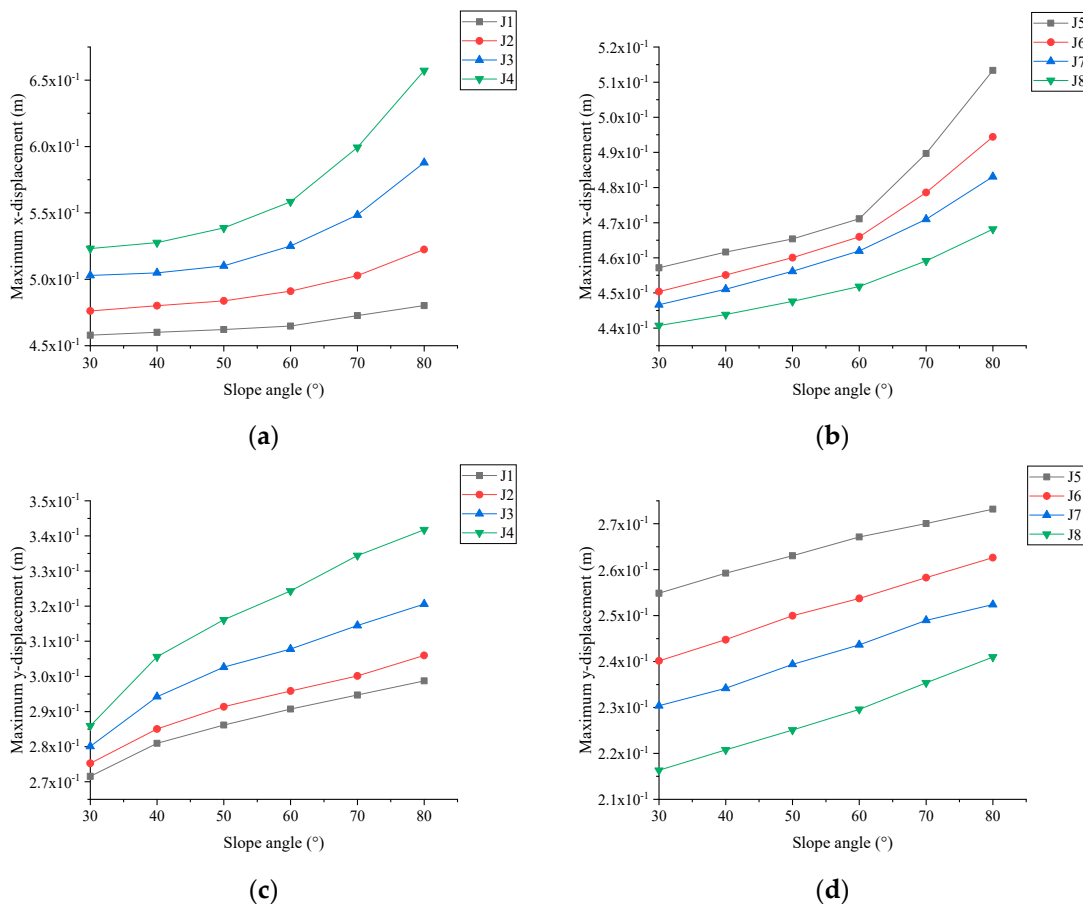


Figure 8. Influence of slope angle on slope displacement response: (a) maximum x-displacement of the slope surface monitoring points; (b) maximum x-displacement of the inside slope monitoring points; (c) maximum y-displacement of the slope surface monitoring points; (d) maximum y-displacement of the inside slope monitoring points.

Figure 8a,b show that the maximum displacement in the x direction with the change in slope angle assumes to an upward concave shape. The maximum displacement in the x direction of each monitoring point is less affected by the change in slope angle when the side slope is less than 50° . The maximum displacement in the x direction of each monitoring point increases with the increase in slope angle when the slope angle is more than 50° , and the trend in the influence of the slope angle change on the maximum displacement grows significantly. In particular, for slope angles greater than 70° , the maximum displacement in the x direction increases at the fastest rate. In Figure 8c,d, the curves of the maximum displacement in the y direction with the slope angle show a downward-convex shape, and the maximum displacement in the y direction increases with the increase in the slope angle.

4.2. Influence of Seismic Wave Parameters

4.2.1. Influence of Seismic Wave Duration

Figure 9 shows the effect of changes in seismic wave duration on the displacement response of the slope in the x and y directions at a joint thickness of 2 m, a joint inclination angle of 60° , a slope angle of 60° , a seismic wave frequency of 1 Hz, and an amplitude of 0.1 g.

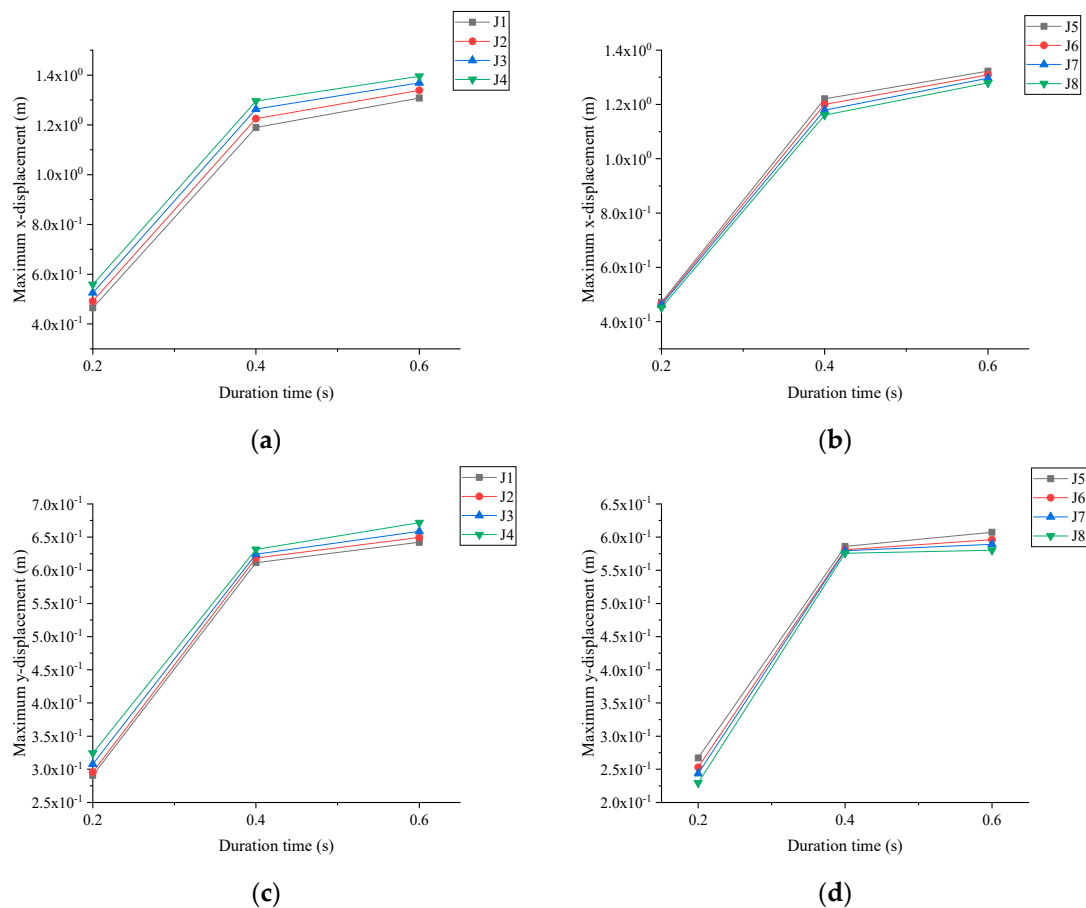


Figure 9. Influence of seismic wave duration on slope displacement response: (a) maximum x-displacement of the slope surface monitoring points; (b) maximum x-displacement of the inside slope monitoring points; (c) maximum y-displacement of the slope surface monitoring points; (d) maximum y-displacement of the inside slope monitoring points.

As shown in Figure 9, the maximum displacement of the slope surface and the inside of the slope body in the x and y directions gradually increases with an increase in seismic wave duration. The displacement change rate is higher when the seismic wave duration is between 0.2 s and 0.4 s and lower when it is between 0.4 s and 0.6 s. When the seismic wave

duration increases from 0.2 s to 0.4 s, each monitoring point on the slope experiences a sharp increase in displacement, and 0.4 s essentially marks the peak displacement value for the slope. As a result, the rate of change in the displacement for the duration of 0.4 s to 0.6 s is lower. The reasons 0.6 s was not used as the duration for the following tests are as follows: Firstly, in order to maintain the uniformity of the variables, only one parameter variable was modified at a time when studying the law of the dynamic response of the slope because all the previous studies used a seismic wave loading time of 0.2 s. Secondly, the analysis of the maximum unbalanced force revealed that the slope was already at equilibrium, so 0.6 s was not used as the duration. It can also be seen that seismic wave duration has a stronger effect on the slope's stability. As the duration of the seismic wave increases, the slope's displacement steadily increases (becoming quite large), which worsens the slope's stability.

4.2.2. Influence of Seismic Wave Frequency

Figure 10 shows the effect of changes in seismic wave frequency on the displacement response of the slope in the x and y directions at a joint thickness of 2 m, at a joint inclination angle of 60° , at a slope angle of 60° , for a duration of 0.2 s, and at an amplitude of 0.1 g.

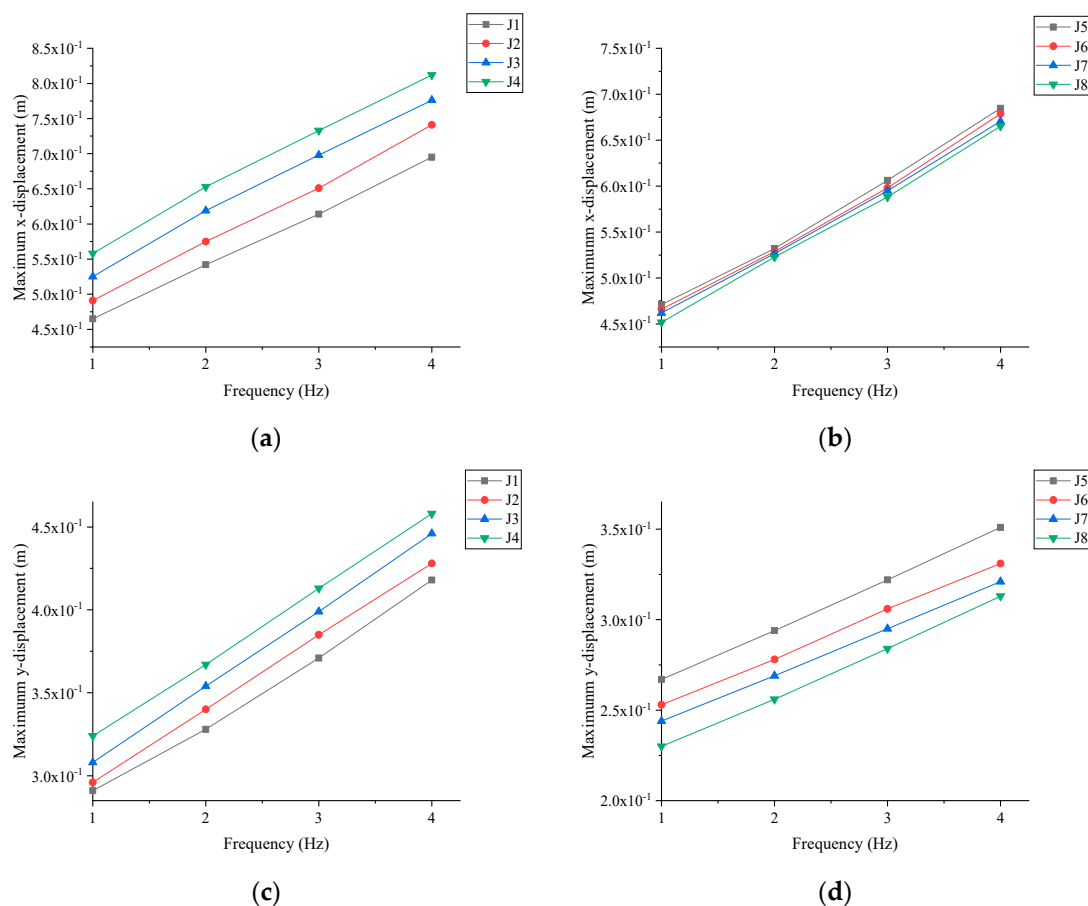


Figure 10. Influence of seismic wave frequency on slope displacement response: (a) maximum x–displacement of the slope surface monitoring points; (b) maximum x–displacement of the inside slope monitoring points; (c) maximum y–displacement of the slope surface monitoring points; (d) maximum y–displacement of the inside slope monitoring points.

Figure 10 shows that seismic wave frequency is a significant factor affecting slope stability. The maximum displacements in the x and y directions at each slope monitoring point increase as the seismic wave frequency increases, and this increasing trend is roughly linear. Additionally, the maximum rate of change in displacement at each monitoring point on the slope surface is greater than that within the slope. When the causes are examined, it

becomes clear that the slope surface monitoring points have larger displacements than the inside slope monitoring points because they are under better air conditions. The loaded seismic wave frequency is lower than the frequency of the slope's self-oscillation, and as the seismic wave frequency rises, the slope's dynamic response becomes stronger, and the displacement of each monitoring point on the slope rises along with it.

4.2.3. Influence of Seismic Wave Amplitude

Figure 11 shows the effect of changes in seismic wave amplitude on the displacement response of the slope in the x and y directions at a joint thickness of 2 m, a joint inclination angle of 60° , a slope angle of 60° , and a seismic wave frequency of 1 Hz and for a duration of 0.2 s.

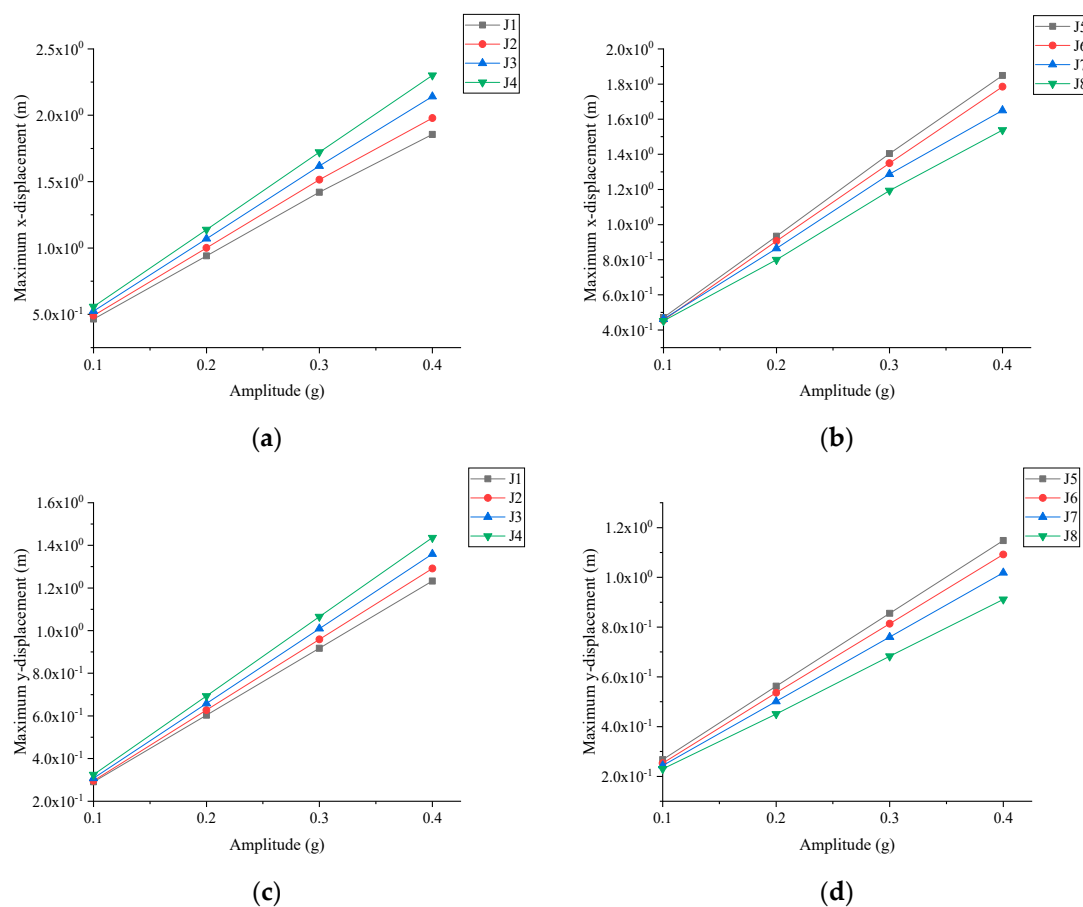


Figure 11. Influence of seismic wave amplitude on slope displacement response: (a) maximum x–displacement of the slope surface monitoring points; (b) maximum x–displacement of the inside slope monitoring points; (c) maximum y–displacement of the slope surface monitoring points; (d) maximum y–displacement of the inside slope monitoring points.

As observed in Figure 11, the stability of the slope is greatly influenced by the seismic wave amplitude, and the greater the seismic wave amplitude, the larger the slope's maximum displacement. In Figure 11a,b, it can be seen that the maximum displacement in the x direction at the monitoring points on the slope surface and inside the slope shows an approximately linear increase with the increase in seismic wave amplitude, and the rate of increase is fast. Taking the monitoring point J4 at the top of the slope as an example, the maximum displacement in the x direction is 0.558 m when the seismic wave amplitude is 0.1 g. When the seismic wave amplitude increases to 0.4 g, the maximum displacement in the x direction is 2.301 m, with a growth rate of 312.3%, and the maximum displacement in the y direction exhibits a similar growth trend to that of the maximum displacement

in the x direction. The figure also demonstrates that, in both the x and y directions, the maximum displacement at each monitoring point on the slope surface is greater than the maximum displacement at each monitoring point inside the slope. This is due to the fact that the surface of the slope has better air conditions than the inside of the slope, so the displacement of the monitoring points on the surface of the slope under seismic waves is greater than that of the monitoring points on the inside of the slope.

5. Discussion

Prior research on slopes' dynamic response has mostly concentrated on the acceleration amplification factor at each slope monitoring point [20,26,28]. In this study, the influence of each element on a slope's maximum displacement was explored using numerical simulation, which can more easily illustrate how each factor affects the slope body's dynamic response law. This study's findings demonstrate that seismic wave parameters and slope geometry parameters both have a significant impact on the dynamic response of slopes. The maximum displacement of each slope monitoring point gradually reduces with increasing joint thickness and gradually increases with an increasing joint inclination angle, slope angle, frequency, amplitude, and duration of seismic waves.

The maximum displacement of monitoring point J4 was analyzed to discover how joint thickness affects slopes' dynamic response. Figure 12a shows that the maximum displacement at monitoring point J4 gradually reduces as the joint thickness increases; this finding is consistent with the findings in Cai et al.'s [17] study. Cai et al. [17] only investigated the variation in maximum displacement with joint thickness at the slope shoulder monitoring point. In this paper, the variation in maximum displacement with joint thickness at the slope surface and at each monitoring point inside the slope was investigated, and it was found that the maximum displacement decreases with the increase in joint thickness, thus making the findings of Cai et al. [17] more convincing. In this study, the maximum displacement was less affected by joint thickness; for example, when the joint thickness increased from 1 m to 2 m, the maximum displacement at point J4 dropped by 0.01 m, while Cai et al. [17] demonstrated a 4.39 m reduction in the maximum displacement at the slope shoulder. The reason for these differing results may be the differences caused by the different model sizes, rock mass parameters, and seismic wave parameters.

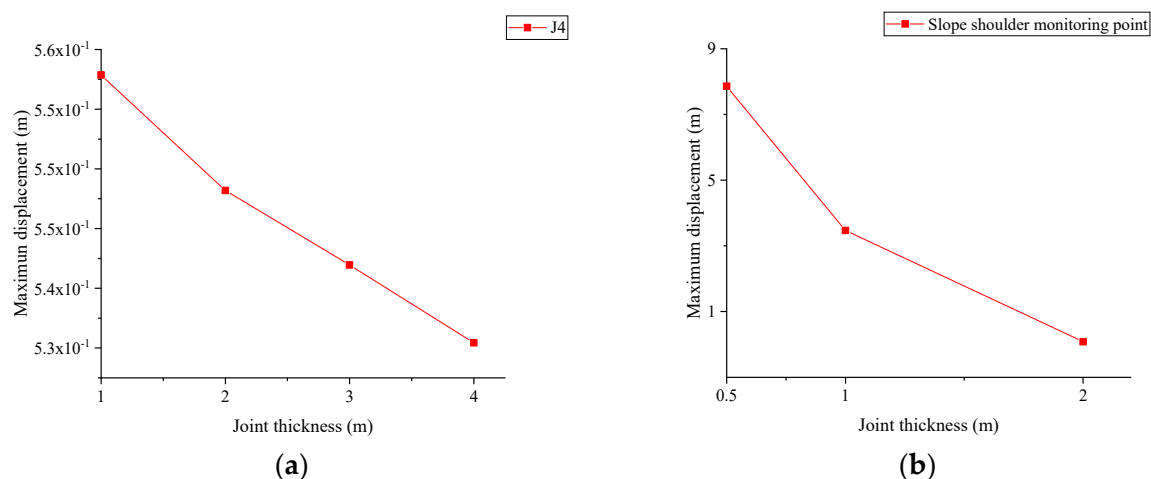


Figure 12. Influence of joint thickness on slope displacement response: (a) maximum displacement at monitoring point J4; (b) maximum displacement of slope shoulder monitoring point [17].

The effect of slope angle on the maximum displacement in the x direction was analyzed using the monitoring points in the middle and lower parts of the slope surface as research objects. Figure 13a shows that when the slope angle is less than 50° , the change in the slope angle has less of an influence on the maximum displacement in the x direction of the monitoring point, and when the slope angle is more than 50° , the maximum displacement

in the x direction is more influenced by the slope angle. The pattern of change in maximum displacement with slope angle in the x direction at monitoring point J2 in this paper is similar to that reported by Cheng et al. [1]. The findings of this study demonstrate that when the slope angle increases, the maximum rate of change in displacement at monitoring point J2 increases. When the slope angles range from 70° to 80° , the maximum rate of change in displacement is higher than at other slope angle ranges, while Cheng et al.'s [1] findings indicated that the greatest displacement in the x direction changes at the fastest rate for slope angles between 45° and 60° . When analyzing the reasons, it can be seen that the larger the slope angle, the steeper the slope, and the better the air conditions of the slope. Additionally, the required shear damage for the slope also reduces. As a result, the maximum slope displacement changes at a faster rate as the slope angle rises.

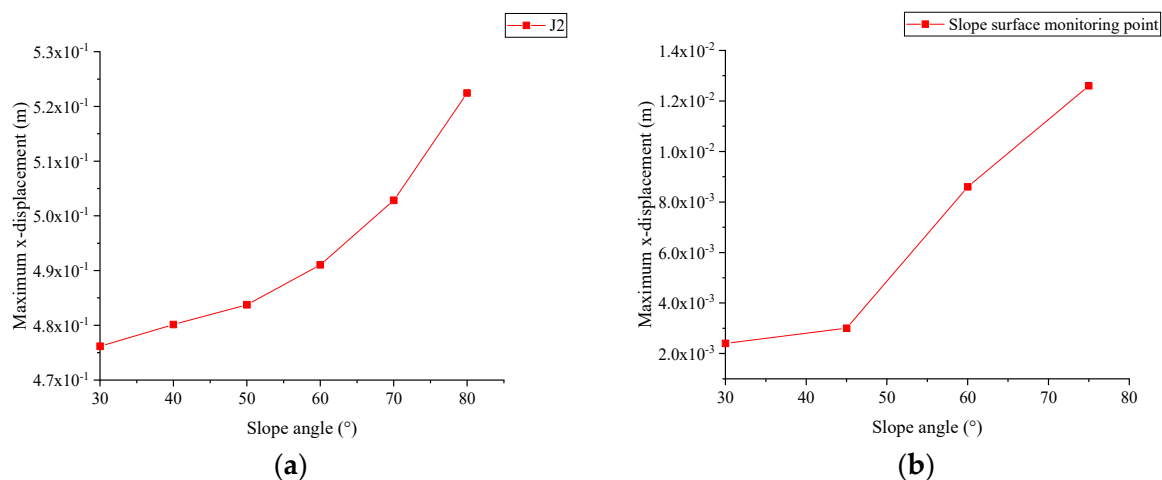


Figure 13. Influence of slope angle on slope displacement response: (a) maximum x—displacement of monitoring point J2; (b) maximum x—displacement at the same location of monitoring point J2 [1].

Ning et al. [18] found that the dynamic response of slopes enhances with an increasing seismic wave amplitude. Ren et al. [25] showed that seismic wave amplitude and duration were strongly and positively correlated with the dynamic response of the slope. These investigations were conducted in order to further investigate the effects of seismic wave frequency, amplitude, and duration on the dynamic response of counter-tilt layered rock slopes. The incremental rate of change in displacement was defined as the ratio of the maximum change in displacement to the change in seismic wave parameters at monitoring point J4 in order to evaluate the sensitivity of slopes to the frequency, amplitude, and duration of seismic waves. The rate of change of the average displacement increment is used to study the impacts of seismic wave frequency, amplitude, and duration on the dynamic response of slopes. In accordance with the calculations, the rate of change of the average displacement increment is 0.1 for seismic wave frequency, 6.4 for seismic wave amplitude, and 2.3 for seismic wave duration. It can be seen that the seismic wave amplitude has the greatest effect on the dynamic response of the slope, followed by the duration, and the frequency has the weakest effect on the dynamic response of the slope.

In this paper, the maximum displacement in the x and y directions was used to study the law of the dynamic response of slopes under seismic action. Previously, there were fewer studies on the dynamic response of slopes to maximum displacement, yet maximum displacement can reveal the influence law of the dynamic response of a slope in a clearer and more intuitive way, which is very important for future research. In addition, some of the conclusions drawn in this study are different from those in previous research, such as the conclusion that seismic wave amplitude has the greatest effect on the dynamic response of slopes, followed by duration, while frequency has the weakest effect. The findings of this paper have enriched the dynamic response law of counter-tilt layered rock slopes under

seismic action, which provides a certain reference value for the disaster prevention and control of slopes.

Through the use of UDEC numerical simulation software, the following limitations of UDEC were identified: The slopes in the numerical simulation are homogeneous, and the joints are divided according to equal thickness, but the actual situation of the slopes is more complex. This results in the fact that there will be differences between the slope model and the actual situation, and the results of numerical simulation may be different from the actual situation. It is necessary to further verify whether the obtained conclusions are correct using engineering examples. This is a limitation of the various numerical simulation software products currently available, which are not able to accurately simulate the real situation of an engineering example. Although UDEC has the above limitations, it offers great advantages in the study of slope deformation because it can model a more realistic response to the real deformation characteristics of a geotechnical body and accurately obtain the displacement data of each monitoring point, so UDEC was used to simulate the dynamic response of a slope.

6. Conclusions

In this paper, the discrete element software UDEC was used to carry out a numerical simulation analysis to study the influence of slope geometry parameters and seismic wave parameters on the dynamic response of counter-tilt layered rock slopes. The main conclusions obtained are as follows:

1. One significant element determining a slope's dynamic response is the thickness of the internal joints. The maximum displacement of each monitoring point of a slope will gradually decrease as joint thickness increases, making the slope more stable as joint thickness increases.
2. The maximum displacement of the slope increases as the joint inclination angle and slope angle increase. When the joint inclination angle is less than 50° , the change in the joint inclination angle has less of an effect on the maximum displacement of the slope in the x and y directions, and when the joint inclination angle is more than 50° , the maximum displacement of the slope in the x and y directions increases faster with the change in the joint inclination angle, and a similar pattern is observed for the slope angle.
3. A slope is more stable when the joint inclination angle and the slope angle are less than 50° ; the slope is more susceptible to damage when the joint inclination angle and the slope angle are greater than 50° .
4. Seismic wave parameters have a great influence on the dynamic response of counter-tilt layered rock slopes, and the maximum displacement at each monitoring point of the slope increases with the increase in frequency, amplitude, and duration of the seismic wave.
5. The seismic wave amplitude has the greatest effect on the dynamic response of a slope, followed by the duration, and the frequency has the weakest effect on the dynamic response of a slope.

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