Study on dynamic response distribution of excavated highway slope under dynamic action

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Abstract. In order to study the dynamic response distribution law of highway foundation pit slope under seismic dynamics, the dynamic response distribution law of cutting slope at different grading heights was compared and studied, and the dynamic instability model under gravity instability and seismic disturbance was established by using UDEC700 software, and the simulation calculation was carried out. The difference between static instability and dynamic instability of fractured rock slope is compared and analyzed, and the post-earthquake stress is greater than that before the earthquake. Under the action of power, the velocity at the top of the slope is greater than the velocity at the bottom of the slope, the velocity outside the upper platform is greater than the velocity inside, and the velocity inside the lower platform is greater than the velocity outside. This provides a new perspective for understanding the dynamic response of highway foundation pit slope under seismic dynamics.

Keywords: Seismic Dynamic Action, Highway Slope, Response Distribution Reinforcement Measure.

1. Introducion

During the construction of expressways, a large number of cutting slopes are generated. The stability of slopes is the key factor in determining the safe construction and operation of the cutting. Since the 1960s [1], the number of geological disasters caused by slope excavation has increased drastically. The reason is that with the advancement of human living standards and the continuous development of technology, human demands for the material conditions of life are constantly escalating. To expand the scope of production and living activities, more comprehensive infrastructure needs to be established. With the leap-forward transformation of China's infrastructure from overall lagging behind, bottleneck constraints, basic alleviation to overall adaptation, remarkable achievements have been made in key infrastructure fields such as transportation, energy, and water conservancy. The velocity and scale are witnessed by all. Undoubtedly, the problems related to slope engineering brought about by project construction and resource development are also gradually increasing. The heights of the slopes are rather large, the quality requirements for slope engineering are high, coupled with the complexity of the geological environment and the active intraplate tectonic activities, numerous engineering accidents of slope instability and failure have emerged rapidly.

Some scholars have conducted research on the stability of road slopes under seismic effects. For instance, Chen Yonggang et al. [2] employed the UDEC discrete element software to simulate the displacement process of the Scavia counter-tilted slope model under bidirectional seismic impacts and analyzed the movement patterns of the blocks; Tang Hui et al. [3] through introducing the block cutting technology based on topological principles, fabricated the fractured rock slope model and examined the influence of the occurrence and distribution of joints on the safety factor of the slope; Kuang Yi et al. [4] conducted a comprehensive analysis on the dynamic stability of the slope based on FLAC3D, and analyzed the acceleration response, displacement response and yield response of the structural plane under seismic effects; Yin Xiaojun et al. [5] proposed a novel model for the sliding of loess slopes under seismic effects, offering a new reference for the seismic design of related slopes and the calculation of seismic landslide displacements; Zhang Huajin [6] by introducing methods and techniques such as Bayesian inference, selective ensemble learning, deep learning and D-S evidence theory, presented a data-driven approach for the stability analysis of rock slopes, providing a methodological basis and beneficial reference for the prevention and control of landslide disasters.

This paper utilizes the computing software UDEC to explore the vibration characteristics of slopes under seismic actions and the associated impacts such as displacement and velocity, and analyze the variation rule of the stability of slopes under seismic actions. It investigates the degrees of influence of parameters like slope height, slope angle and the inclination angle of the structural plane on the stability of slopes under seismic actions, and seeks the optimal combination of slope design parameters, laying a theoretical and practical foundation for the safety monitoring and disaster research of similar high-road slopes. Seeking the optimal combination of slope design parameters provides a new perspective and a more accurate evaluation method for understanding the dynamic response of highway foundation pit slope under seismic dynamics.

2. A brief introduction to the software

Based on dynamics, the discrete element method was proposed by Cundall A in 1971 and 1978 for the analysis of rock mass and soil mechanics. MAINI et al. improved the rigid body discrete element model and developed a deformable block and fractureable UDEC program.

The main difference between rock and rock mass lies in discontinuities in rock mass. These fracture networks lead to discontinuity, non-uniformity and anisotropy of rock mass. Discontinuities destroy the integrity of rock and reduce its strength. In engineering, the stability of rock mass [8] is mainly controlled by the strength of rock mass. Continuum analysis method has some limitations in dealing with the stability of rock mass, but non-continuum method (such as discrete element method) can reflect the structure of rock mass more truly and effectively, and accurately analyze its deformation characteristics and failure laws.

Compared with the numerical analysis software of continuum method, UDEC has the following characteristics in numerical simulation of rock mass:

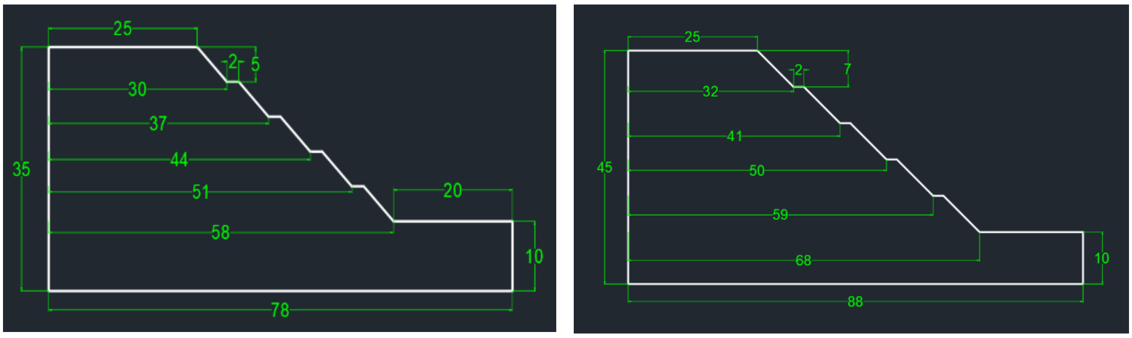
(1) Discrete block assembly is used to represent the rock mass structure and discontinuous plane is used as the boundary plane between the blocks to simulate the rock mass structure more truly.

(2) Allowing large displacement and rotation of the block along the discontinuity plane, and considering the slip and spalling of the block in calculation, the instability failure process of the rock mass can be better demonstrated.

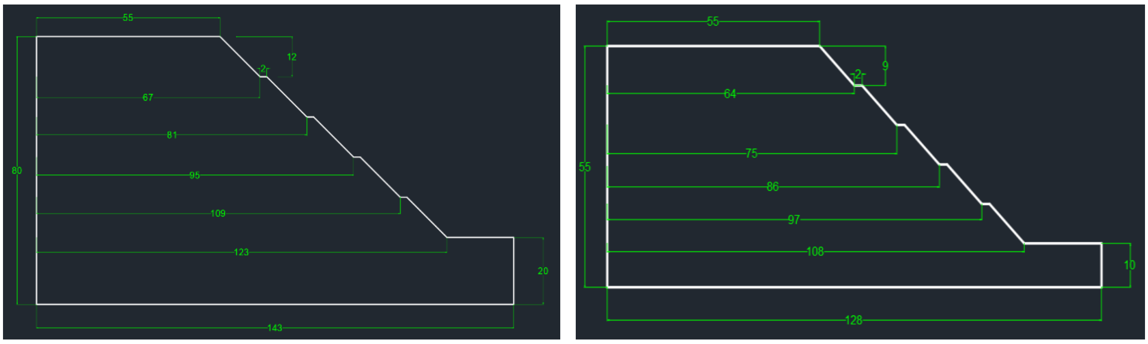
(3) In the calculation process, the new contact surface is automatically identified, and the crack expansion and development of joint fissure in rock mass are simulated.

3. Setup of the simulated slope model

The establishment of different ideal stepped rock slope models is shown in the Figure 1. (The units in the following pictures are m.)



(a) (b)



(c) (d)

Figure 1. Different ideal stepped rock slope models.

Table 1. Slope length, width and grading height

	a	b	c	d
slope height (m)	35	45	80	55
slope width (m)	78	88	143	128
stepped height (m)	5	7	12	9

Model rock physical and mechanical parameters: mass density was 2500 kg/m^3, shear elasticity was 2.6 GPa, bulk modulus was 4.9 GPa

The static instability of the fractured rock slope is simulated by reducing the structural surface mechanics index. The static instability under gravity and the dynamic instability under seismic disturbance are respectively simulated and analyzed. In the dynamic stability analysis, a harmonic shear wave with peak acceleration of 0.10g is selected as the ground motion load input from the bottom of the model. At the same time, viscous boundaries are set on the left and right sides and the bottom of the slope model, and local damping is adopted, and the local damping coefficient is 0.005.

The numerical analysis of the dynamic response of layered rock slope under earthquake action takes the generalized prototype of the physical model slope as the research object, and establishes a two-dimensional simplified numerical calculation model (as shown in Figure 1) in which the side slope angles are all 45°. In the numerical simulation, molar Coulomb criterion is adopted for the constitutive relation of the slope block. The left and right boundary of the numerical model is fixed with X-axis displacement, the bottom surface is fixed with Y-axis displacement, and the top surface is treated as a free surface.

The maximum side length of the unit is 0.5m. In the process of numerical calculation, the models self-weight is analyzed first, and the stress obtained under the action of gravity is taken as the initial stress condition, and then the dynamic load is applied. The frequency of the dynamic load applied in numerical calculation is 10Hz, the duration is 0.5s, and the amplitude is 0.1g. In the process of numerical calculation, the models self-weight is analyzed first, and the stress obtained under the action of gravity is taken as the initial stress condition, and then the dynamic load is applied. The numerical calculation of the applied dynamic load is a sine wave with a frequency of 10Hz and an amplitude of 1, and 3000 cycles are performed.

4. Result analysis

4.1. Analysis of maximum stress before and after earthquake

Seismic activities [9] have significant influence on the stress state of underground rock mass. May lead to the destruction and fracture of underground rock mass, may lead to the collapse and collapse of underground rock mass, poses a threat to underground engineering, underground facilities and the development and utilization of groundwater resources. In addition, the change of stress state of the underground rock mass caused by the seismic activities may cause the sliding and displacement of the underground rock mass, and then lead to geological disasters such as slope landslide and rock collapse. These disasters may pose a threat to the safety of nearby people and property. So it is very important to study the stress distribution before and after earthquake.

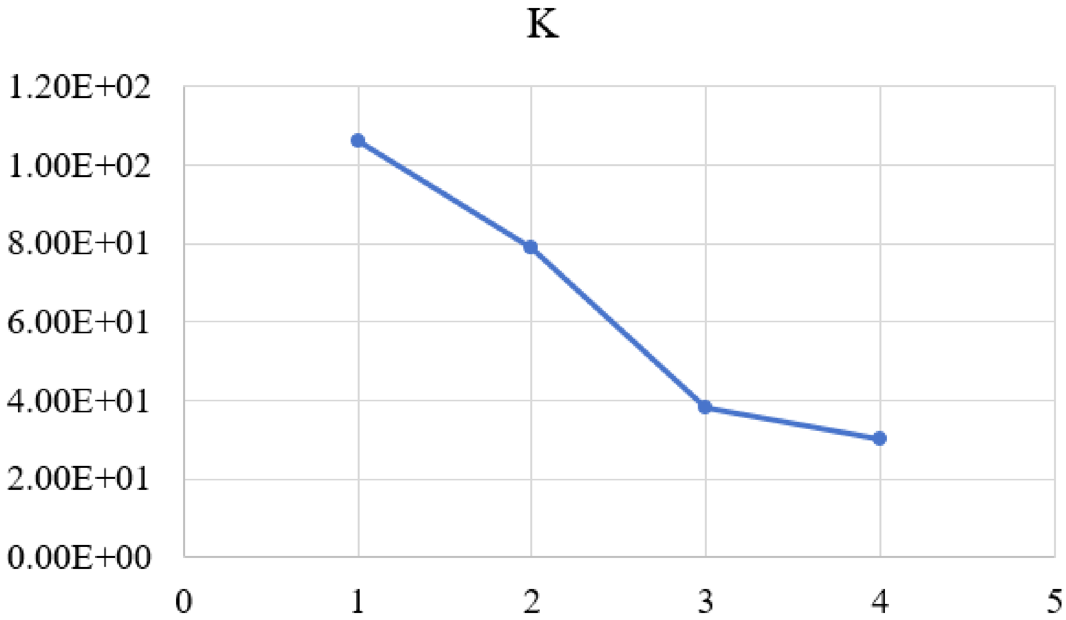


Figure 2. Variation of stress amplification factor K of different slope models before and after earthquake.

In udec700 finite element analysis software, four different slopes are simulated under static and dynamic states respectively, and the maximum stress before and after earthquake of each group of slopes is obtained after processing the data. In order to more clearly compare the influence of each slope before and after the earthquake, the amplification factor K is defined, that is, the maximum stress of the slope after the earthquake is compared with the maximum stress of the slope before the earthquake, and the relationship diagram is drawn Figure 2.

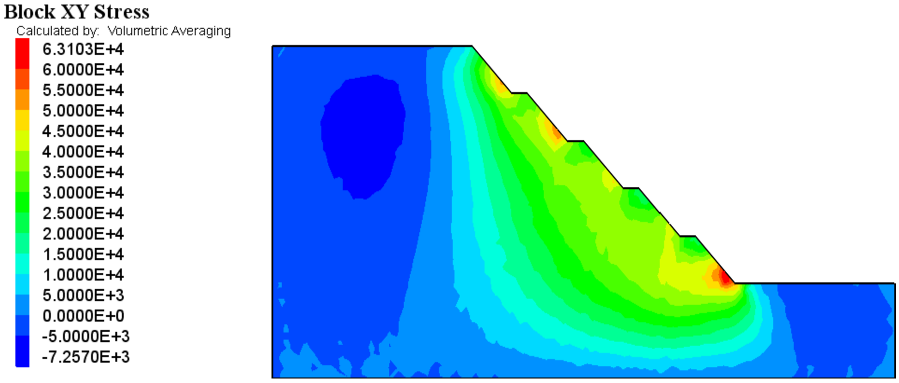
According to Figure 2, the stress amplification factor K of different slopes before and after the earthquake is greater than 1, and it is found that the stress after the earthquake is greater than the stress before the earthquake. Before the earthquake, there may be stress relaxation in the tectonic stress field, but the stress value may increase after the earthquake. This change of stress directly affects the intensity and distribution of ground motion

Moreover, with the increase of the slope height, the stress amplification factor K before and after the earthquake gradually decreases, that is, the higher the slope is, the multiple of the slope stress increase after the earthquake is smaller than that of the slope with a smaller slope height.

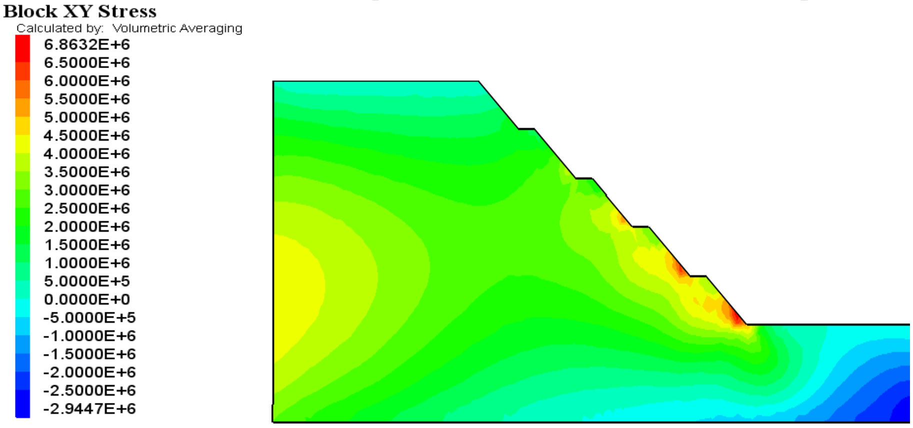
4.2. Stress distribution cloud map before and after earthquake

In order to understand the variation law of the internal stress of slope under the action of seismic dynamics, so as to effectively prevent and control the problem of slope instability caused by earthquake, it is very important to study the stress distribution cloud map of slope before and after earthquake.

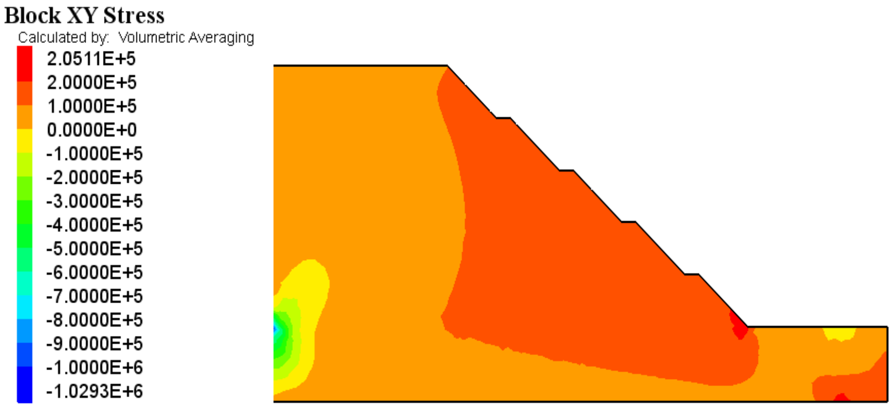
The stress distribution cloud maps of model 1 and model 2 before and after the earthquake obtained by simulation are shown in the figure below.



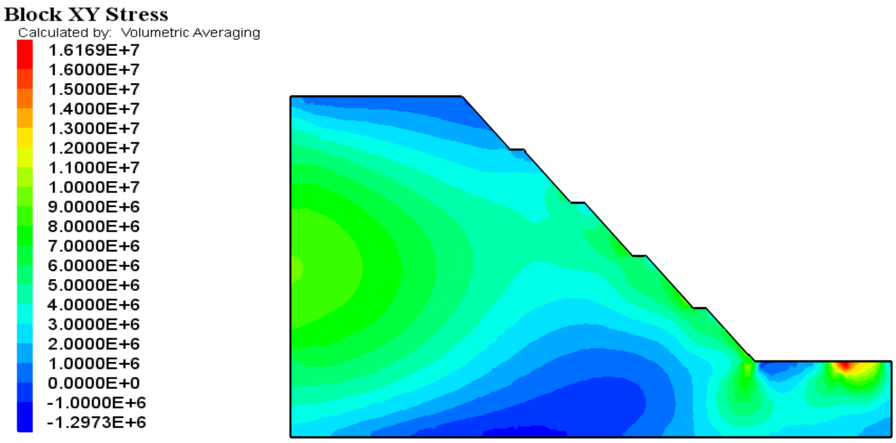
(a) Model 1 Pre-earthquake stress distribution cloud map.



(b) Model 1 Post-earthquake stress distribution cloud map.



(c) Model 2 Pre-earthquake stress distribution cloud map



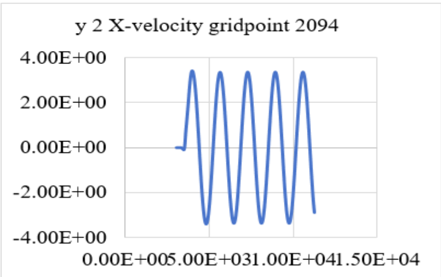
(d) Model 2 Post-earthquake stress distribution cloud map

Figure 3. Model 1 and Model 2 stress state distribution cloud map before and after the earthquake.

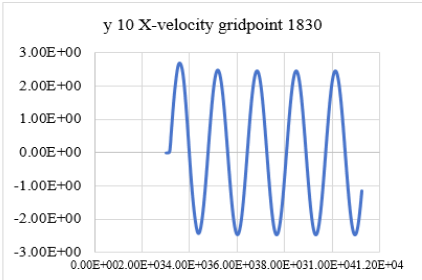
It can be seen from Figure 3 that the stress distribution of the model with a lower slope height before and after the earthquake is mainly concentrated at the foot of the slope platform, and the maximum stress before and after the earthquake does not change much compared with that before the earthquake. The slope with higher height is in the state of larger gravity distribution before the earthquake, but the stress distribution at each inflection point of the slope is smaller than that at other places after the earthquake.

4.3. Slope velocity analysis after earthquake

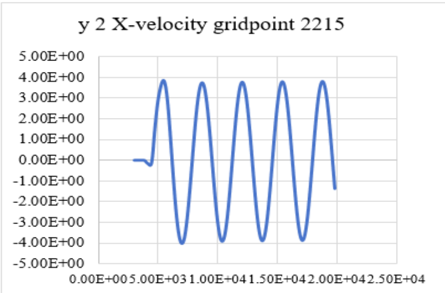
In order to understand the influence mechanism of earthquake on slope stability [10], and to provide scientific basis for slope design, reinforcement and early warning, so as to effectively prevent and control the slope instability caused by earthquake, it is of great significance to study the velocity time history of slope before and after earthquake. The following is the velocity time history diagram of the top and bottom of the slope model based on the simulation results.



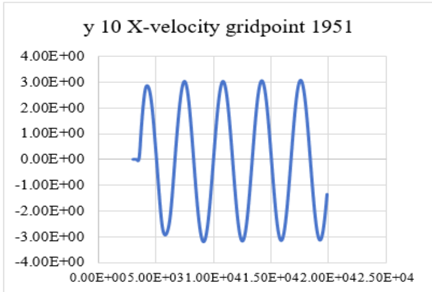
(a) Model 1 Top time-history of velocity.



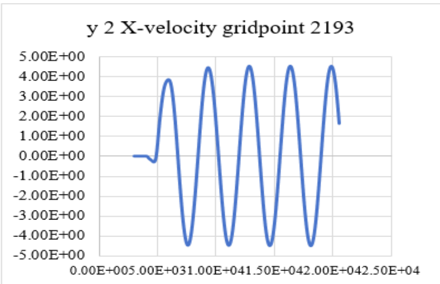
(b) Model 1 Bottom time-history of velocity.



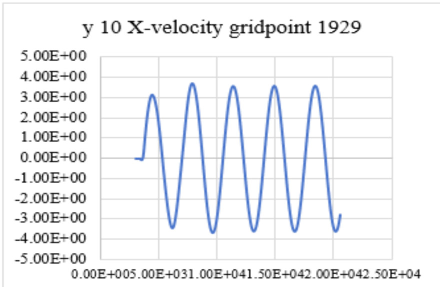
(c) Model 2 Top time-history of velocity.



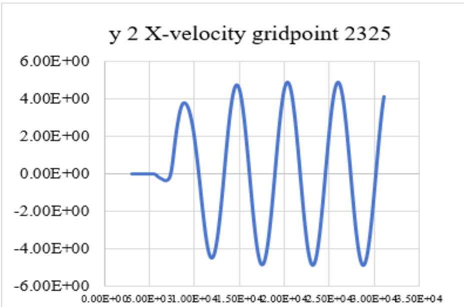
(d) Model 2 Bottom time-history of velocity.



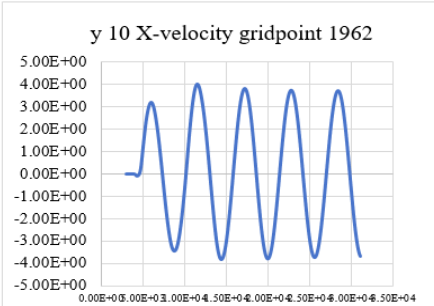
(e) Model 3 Top time-history of velocity.



(f) Model 3 Bottom time-history of velocity.



(g) Model 4 Top time-history of velocity.



(h) Model 4 Bottom time-history of velocity.

Figure 4 Model 1 to Model 4 top and bottom time-history of velocity.

It can be seen from Figure 4 that the velocity at the top of the slope is greater than the velocity at the bottom of the slope. For engineering construction, it is necessary to pay more attention to the damage at the top of the slope. For example, for model 1, the velocity at the top is 3.41m/s and the velocity at the bottom is 2.71m/s, and the velocity at the top is 1.26 times that at the bottom. Similarly, for model 2, 3, 4, top and bottom velocitys and top and bottom velocitys are shown in Figure 4. As the slope height increases, the ratio of top to bottom velocity gradually decreases. The dynamic response of slope is influenced by the coupling of terrain size and seismic wave length. The topographic effect of the slope can lead to the amplification or attenuation of seismic waves, thus affecting the velocity distribution.

Table 2. Model 1 to Model 4 Top velocity,
bottom velocity, and top velocity to bottom velocity ratio.

	Model 1	Model 2	Model 3	Model 4
Top velocity(m/s)	3.41	4.01	4.54	4.92
Bottom velocity(m/s)	2.71	3.20	3.71	4.03
Top velocity to bottom velocity ratio	1.26	1.25	1.22	1.22

It can be seen from Table 2 that the bottom velocities of the four models are all greater than those of the bottom velocities of the models. Therefore, the protection of the top slopes should be emphasized in engineering construction.

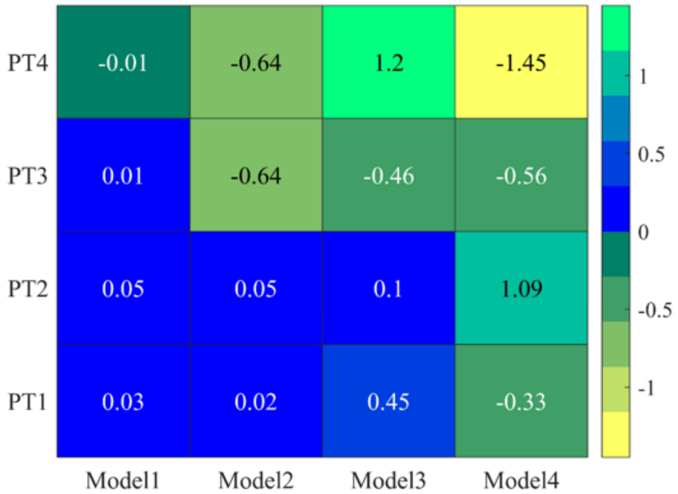


Figure 5. The difference between external velocity and internal velocity
at monitoring points from platform 1 to platform 4 of different slope models.

For the upper platform, that is, platform 4 and platform 3, the external velocity is less than the internal velocity; for the lower platform, that is, platform 2 and platform 1, the external velocity is greater than the internal velocity. Therefore, the key monitoring part of the upper platform is on the inside of the platform, and the key monitoring part of the lower platform is on the outside of the platform.

For model 1 to model 4, the gradient height of the slope increases, and the difference between the inner and outer angular velocities becomes larger and larger, indicating that the higher the slope, the more obvious the velocity growth of each platform. For platform 4, from model 1 to model 4, the velocity differences are -0.01, -0.64, -1.2, and -1.45 respectively, indicating that the velocity differences between platforms are increasing.

5. Conclusions

(1) The stress amplification factor K of different slopes before and after the earthquake is greater than 1, and it is found that the stress after the earthquake is greater than the stress before the

earthquake. Before the earthquake, there may be stress relaxation in the tectonic stress field, but the stress value may increase after the earthquake. This change of stress directly affects the intensity and distribution of ground motion.

(2) The stress distribution of the model with low slope height before and after the earthquake is mainly concentrated at the slope foot, while the stress distribution at the slope foot after the earthquake is smaller than that at other places.

(3) Under dynamic action, the velocity at the top of the slope is greater than that at the bottom of the slope, and the ratio of the velocity between the top and the bottom decreases with the increase of the slope height. The dynamic response of slope is influenced by the coupling of terrain size and seismic wave length. The topographic effect of the slope can lead to the amplification or attenuation of seismic waves, thus affecting the velocity distribution.

(4) The external velocity of the dynamic action is greater than the internal velocity, so the key part of the monitoring of the upper platform in the project is on the inside of the platform, and the key part of the monitoring of the lower platform is on the outside of the platform.

According to the above conclusions, the seismic reinforcement measures of cutting slopes can be increased in the future to deal with the hazards of earthquakes. In engineering, the intensity and direction of ground motion can be predicted by monitoring the stress change inside the platform, so that protective measures can be taken in advance. In engineering reinforcement, the change of stress before and after the earthquake should be considered, and corresponding reinforcement measures should be taken, such as increasing anchor frame beam and soil nailing. Especially the inner corners of the steps are areas of stress concentration, which are prone to cracking and damage. These areas should be reinforced with emphasis.

References

[1] A Ziwei. Study on the Stability Analysis and Influencing Factors of Anti-dumping Layered Rock Slope [D]. Xi'an University of Technology, 2023. DOI:10.27398/d.cnki.gxalu.2023.001317

[2] Chen Yonggang, Tang Hua, and Qin Yuqiao. Study on the Dynamic Failure Mode and Zoning of Anti-dumping Slope Based on the Discrete Element Method [J]. Journal of Henan Urban Construction Institute, 2024, 33(01):64-71+95. DOI:10.14140/j.cnki.hncjxb.2024.01.009

[3] Tang Hui, Zhong Wanbo, and Jiang Jie. The Influence of Joint Fracture Distribution and Occurrence on the Stability Analysis of High and Steep Slope [J]. Engineering Technology Research, 2021, 6(15): 46-48+140. DOI: 10.19537/j.cnki.2096-2789.2021.15.017

[4] Kuang Yi, Qiu Shibo, Chen Yixin, et al. Dynamic stability analysis of slope under earthquake action based on FLAC3D [J]. Water Resources Planning and Design, 2023, (05): 61-69

[5] Yin Xiaojun, WANG Lanmin. Study on dynamic sliding displacement of loess slope under earthquake [J]. Earthquake Engineering Journal,2022,44(05):1067-1073.DOI:10.20000/j.1000-0844.20201018001

[6] Zhang Huajin. Research on Data-Driven Analysis Method for Rock Slope Stability [D]. Kunming University of Science and Technology, 2023. DOI: 10.27200/d.cnki.gkmlu.2023.000051

[7] Munjiza A, Smoljanović H, Živaljić N, et al. Structural applications of the combined finite–discrete element method[J]. Computational particle mechanics, 2020, 7: 1029-1046.

[8] Basahel H, Mitri H. Application of rock mass classification systems to rock slope stability assessment: a case study. J Rock Mech Geotech Eng 9 (6): 993–1009[J]. 2017.

[9] Zakaria M T, Muztaza N M, Omar M R, et al. Stability analysis of geotechnical properties of slopes by seismic waves [J]. Maejo International Journal of Science & Technology, 2022, 16(2).

[10] Zhou L, Su L, Wang Z, et al. Slope Stability and Effectiveness of Treatment Measures during Earthquake [J]. Sustainability, 2023, 15(6): 5309.