

Sensitivity Analysis of Seismic Response in Soft-Hard-Interlayer Slopes

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Abstract. In recent years, seismic disasters have captured worldwide attention and garnered extensive research efforts. A series of significant earthquake events, such as those in Haiti, Nepal, and Italy, have resulted in substantial loss of life and property damage. Of particular importance is the impact of earthquakes on slope stability, triggering slope loosening, landslides, and collapses, posing significant threats to both human lives and assets. Therefore, studying the seismic-induced dynamic response of slopes is of utmost importance. This study, employing the Flac3D finite difference method software, investigates the dynamic stability of soft-hard-interlayer slopes formed during the construction of mountainous highways under seismic influences. The study reveals that both acceleration and displacement responses exhibit significant elevation amplification effects. However, due to the higher compressive strength of hard soil layers, the restraining effect on soft soil layers is relatively weak, manifesting in a decreasing trend in certain specific locations. Consequently, acceleration response is lower in hard soil layers but higher in soft soil layers. The analysis of displacement and stress further reveals the influence of soil properties on slope response, with hard soil layers bearing greater stress within the slope. Additionally, the analysis of displacement and stress highlights that the displacement response in soft soil layers is more prominent compared to hard soil layers, and stress concentration phenomena are likely to occur at the toe of the slope. This study provides valuable reference and guidance for slope engineering, ensuring the safety of human lives and property.

Keywords: Seismic disasters, Slope stability, Soft-hard-interlayer slopes, Elevation Amplification Effects.

1. Introduction

With the recent upsurge globally in seismic activities, there arises a grave issue that threatens both life and property. Earthquakes, as natural disasters, possess potent suddenness and the capacity for destruction, potentially inducing substantial casualties and property damage in an exceedingly short span of time. Regions of traditionally high-risk, such as the circum-Pacific and Himalayan seismic zones, along with areas considered otherwise safe, such as Italy, Mexico and Nepal, have witnessed recurring incidents. The frequent incidence of earthquakes has drawn global attention and prompted intensive research on seismic hazards.

Over recent years, there have been many significant seismic events worldwide that have made a profound impact. For instance, the 2010 earthquake in Haiti, registering a magnitude of 7.0, resulted in approximately three hundred thousand casualties and widespread architectural collapse. Another grim instance is the 2015 earthquake in Nepal, which caused unprecedented human loss and financial destruction. The 2016 earthquake in Central Italy exacted the lives of 297 individuals, in addition to causing substantial damage to historic buildings.

Among these, earthquakes have a substantial impact on the stability of slopes. Seismic vibrations can cause deformation and damage to slope soils. Intense vibrations cause soil particles to rearrange, resulting in volume and deformative accumulation. These deformations and damages can lead to slope instability, triggering landslides or collapses.

Further, earthquakes can alter the mechanical properties of slope soil. Vibrations change the pore water pressure in the soil and alter its dynamic response characteristics. Increased pore water pressure reduces the soil's shear strength and slope stability. Moreover, earthquakes can change the friction angle of slope soil, compromising its ability to resist sliding and increasing the risk of landslides.

Seismic liquefaction also influences slope stability. Under the effect of a strong earthquake, groundwater-saturated fine-grained soil can lose its consolidating force due to increased pore water pressure, turning into a liquid state. This liquefaction reduces the soil's rigidity and shear strength, leading to an unstable slope. When liquefaction occurs near the slope area, the risk of slope damage is exacerbated.

Consequently, earthquakes wield a direct and significant influence on slope stability. In seismic risk areas, the monitoring and assessment of slope stability, coupled with implementation of corresponding engineering controls and management strategies, are paramount in mitigating and preempting disasters induced by earthquakes.

In recent years, considerable achievements have been made in the study of dynamic response laws and stability analysis of slopes. For instance, Zhou Wei investigated the dynamic response of layered rock slopes under seismic loads (2023) [1]. Zhang Junwei explored the numerical simulation of soil slope response under seismic action with an infinite boundary (2023) [2]. Zhou Linlu researched slope stability and the effectiveness of remedial measures under seismic action (2023) [3]. A generic predictive model for earthquake-induced slope displacement based on finite element analysis was developed by Cho, Y. (2022) [4]. Wang Yongqiang analyzed the destruction of soil-rock composite slopes under seismic action (2022) [5]. Jun Feng focused on the dynamic response and failure evolution of low-angle interlayered soft and hard rock slope under seismic conditions (2022) [6]. Qi Xin conducted a stability analysis of soil-rock composite slopes under earthquake conditions (2021) [7]. Li Z researched earthquake response and post-earthquake stability assessment of submarine clay slopes (2022) [8]. Yang C published assessment of seismic landslide susceptibility of bedrock and overburden layer slope based on shaking table tests [9].

This article studies the dynamic stability of the soft and hard interlayer slopes formed in the construction of mountain highways under the effect of earthquakes. With three different slope profiles as backgrounds, numerical models of the slopes were established using the finite difference software Flac3D. The study examines the distribution patterns of acceleration, displacement, stress, and shear strain increments within the slopes under seismic action, aiming to identify locations prone to slope failure. The findings from this research will provide a theoretical basis and technical guidance for seismic reinforcement studies focused on slope stability.

2. Numerical model setup

2.1. Software Introduction

FLAC 3D (Fast Lagrangian Analysis of Continua in 3 Dimensions) is a numerical simulation software based on the finite difference method, used to simulate and analyze geological, geotechnical, and structural response problems in the field of rock and soil engineering. It can account for the nonlinear, deformable, and failure behaviors of soils and rocks, providing a powerful tool for studying and predicting the mechanical behavior and engineering response of geotechnical materials [10].

FLAC 3D finds significant research applications in geotechnical engineering, including underground engineering studies, rock mechanics research, and investigations on faults and seismic activities (Figure 1).

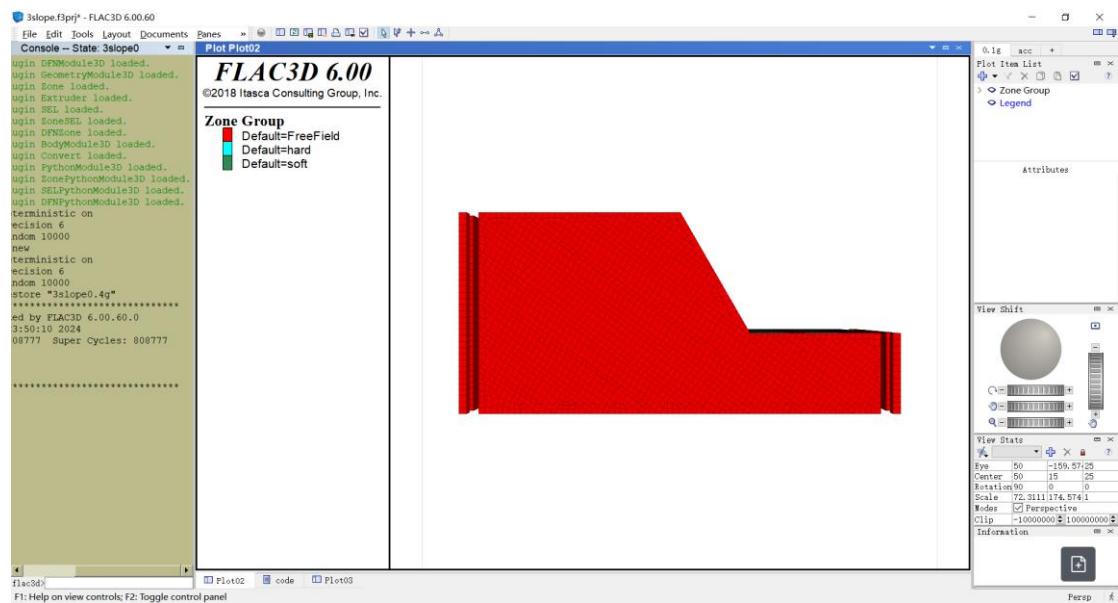


Figure 1. Flac 3D Model Diagram

2.2. Numerical Model Creation and Parameter Configuration

Table 1. Physical and mechanical properties of slopes

	group	Density/ Kg/m ³	Bulk/Pa	Shear/Pa	Cohesion/Pa	Internal friction angle	tension/Pa
1slope	hard	2500	2.5e9	1.2e9	500e3	30	0.1e5
	soft	2000	6e8	2.8e8	300e3	25	0.05e5
3slope	hard	2500	2.5e9	1.2e9	500e3	30	0.1e5
	soft	2000	6e8	2.8e8	300e3	25	0.05e5
2slope	hard	2500	2.5e9	1.2e9	500e3	30	0.1e5
	soft	2000	6e8	2.8e8	300e3	25	0.05e5

In this study, three soft-hard interlayer slope profiles from a highway in the southwestern region of China are taken as the research objects. After appropriate generalization, a numerical model is established as shown in Figure 2. Each model consists of a soft-hard interlayer. The parameter configuration in numerical simulations is presented in Table 1.

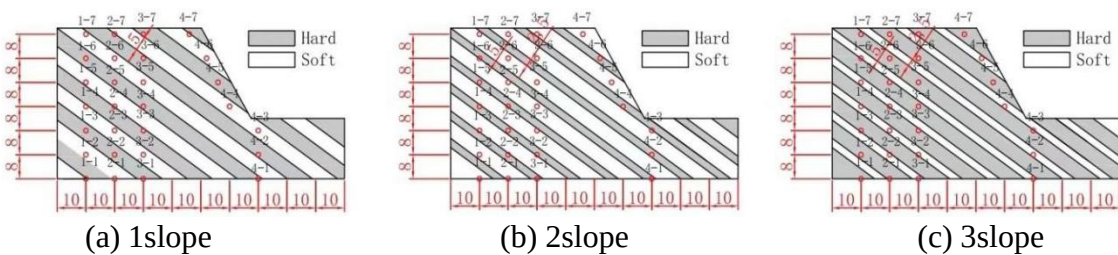


Figure 2. Calculation models for different interlayer

To investigate the distribution patterns of acceleration, displacement, stress, and shear strain increments within the internal slopes of different terrain under seismic effects, we employed the FLAC 3D software and conducted an analysis by assigning various monitoring points for each slope. The following descriptions pertain to three models:

The first model (as depicted in Figure 2(a)) consisted of five sets of monitoring points, numbered from 1-1 to 4-7, totaling 28 points. Seismic analysis was carried out on this model, and by monitoring these points, we obtained distribution patterns of acceleration, displacement, stress, and shear strain increments within the slopes under seismic effects.

The second model (as shown in Figure 2(b)) was equipped with four sets of monitoring points, numbered from 1-1 to 4-7, amounting to a total of 28 monitoring points. Similarly, seismic analysis

was conducted on this model, and dynamic variations within the internal slopes were recorded at these monitoring points.

The third model (as illustrated in Figure 2(c)) included five sets of monitoring points, numbered from 1-1 to 4-7, with a total of 28 monitoring points. Through seismic simulation, we recorded the distribution of parameters such as acceleration, displacement, stress, and shear strain increments within the internal slopes.

Through the analysis of these models, we can acquire insights into the response characteristics of different slope terrains under seismic effects. This knowledge is of utmost significance for understanding slope stability, predicting potential failure modes, as well as formulating appropriate supporting measures. The simulation and analysis results will serve as crucial reference data for design and decision-making in the field of geotechnical engineering.

3. Result analysis

3.1. Acceleration responses

For this dynamic analysis, we selected a seismic wave for loading. Figure 3 portrays the chosen seismic wave, with its main energy segment of 0-40 seconds serving as the input wave, with a specified maximum amplitude of 0.4g. Throughout the loading process, we gradually increased the input acceleration from 0.1g to 0.4g, aiming to examine the distribution patterns of response acceleration, displacement, and stress parameters within the internal slopes under varying input acceleration for different terrain types.

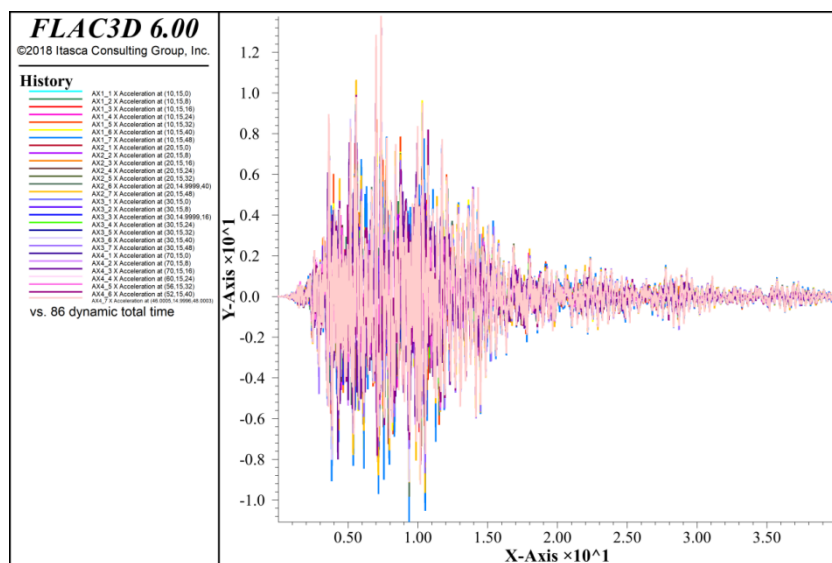
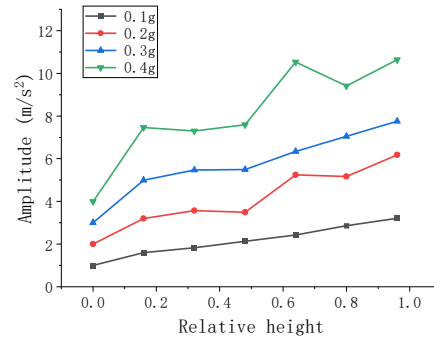
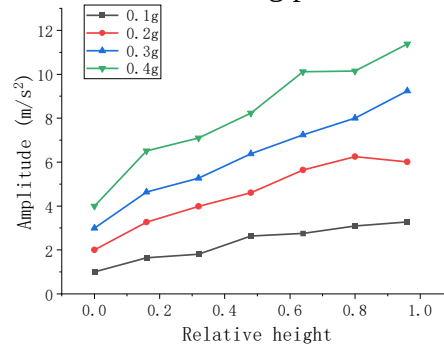


Figure 3. Seismic waves

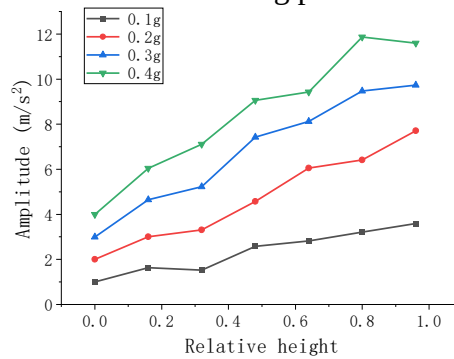
During the analysis of response acceleration, we observed the following patterns when incrementally inputting acceleration from 0.1g to 0.4g. By plotting the data and examining the point-line graph (see Figure 4(a)), we found that the response acceleration exhibited a gradual increase. Moreover, when investigating detection points 3-1 to 3-7 and 4-1 to 4-7 (as depicted in Figures 4(b) and 4(c)), we noticed that the highest acceleration response generally occurred at the positions with the highest elevation. The reason behind this phenomenon could be attributed to the reduced restraining forces at the uphill positions compared to other locations, resulting in less hindrance to the propagation of acceleration and consequently leading to higher acceleration magnitudes. Furthermore, through a comparative analysis of the three graphs, we observed that higher initial input accelerations corresponded to larger response accelerations.



(a) Data from monitoring points 2-1 to 2-7



(b) Data from monitoring points 3-1 to 3-7



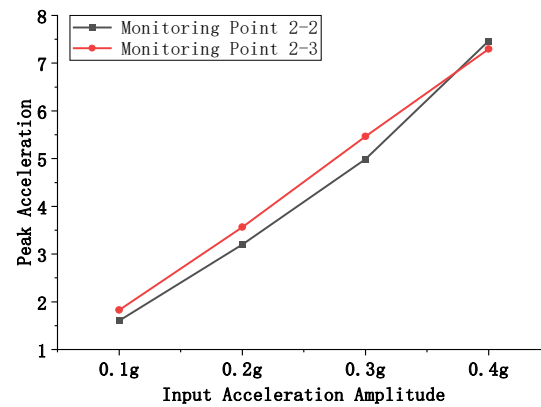
(c) Data from monitoring points 4 -1 to 4-7

Figure 4. Acceleration response of selected monitoring points

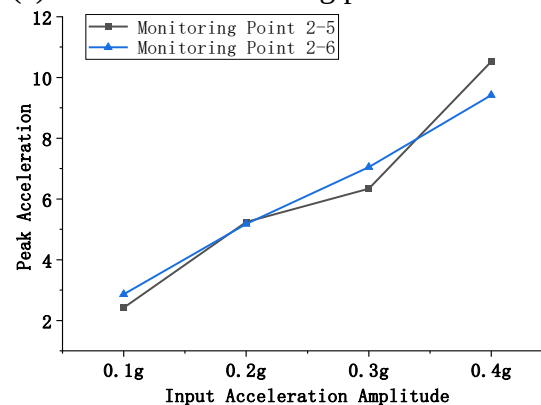
Based on the analysis of the acceleration response graph for the soft-hard interlayer slope, it is observed that the acceleration does not consistently increase with height. In fact, there are certain specific locations where a downward trend can be seen. For example, there are varying degrees of changes in acceleration between monitoring points 2-2 and 2-3 (Figure 5(a)), as well as between monitoring points 2-5 and 2-6 (Figure 5(b)).

Referring to the information in Figure 2, monitoring points 2-2 and 2-5 are located within the hard soil layer, while monitoring points 2-3 and 2-6 are within the soft soil layer. The differing levels of constraining forces within the soft-hard interlayer lead to variations in the propagation patterns of acceleration. It can be deduced that the hard soil layer, as compared to the soft soil layer, experiences higher stress under the same conditions. The tightly packed particle arrangement and higher density of the hard soil layer contribute to its greater ability to withstand compression, enabling it to bear larger external stresses without significant deformation or failure. In the hard soil layer, where the constraining forces are greater, the acceleration response is smaller. Conversely, in the soft soil layer with lower constraining forces, the acceleration response is larger.

Thus, monitoring points 2-2 and 2-5 in the hard soil layer exhibit relatively smaller acceleration, while monitoring points 2-3 and 2-6 in the soft soil layer display higher acceleration.



(a) Data from monitoring points 2-2 to 2-3



(b) Data from monitoring points 2-5 to 2-6

Figure 5. Acceleration response of selected monitoring points

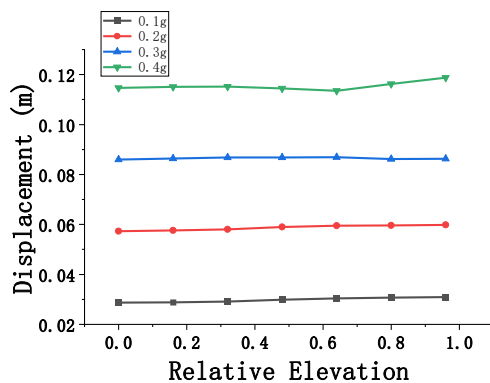
3.2. Displacement responses

During the gradual increase of loading acceleration from 0.1g to 0.4g, we conducted an analysis of the displacements on the soft-hard interlayer slope. The research results indicate a relationship between displacement response and the position of the soil layers.

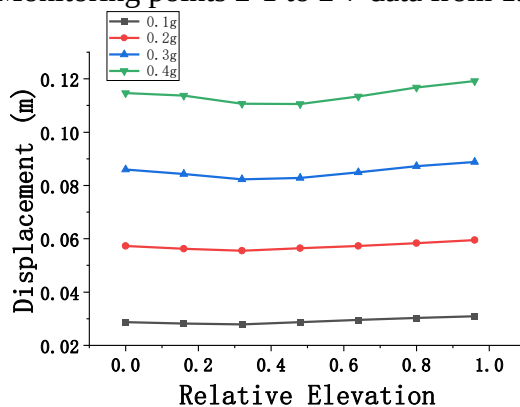
After plotting the data analysis graphs for observation points 2-1 to 2-7 on the three interlayer slopes, it can be observed that all three slopes exhibit a decreasing followed by increasing trend, with 2slope (Figure 6(b)) slope showing the most pronounced trend. Further examination of the three models reveals that observation points 2-1, 2-5, 2-6, and 2-7 are located within the soft soil layer, while observation points 2-2, 2-3, and 2-4 are situated within the hard soil layer. These observations indicate a difference in the influence of soft and hard soil layers on displacement response, with the displacement response in the soft soil layer being more significant compared to that in the hard soil layer.

The reason for this difference lies in the greater constraint provided by the hard soil layer. Due to its higher stiffness and strength, the hard soil layer exhibits greater rigidity and resistance to deformation, enabling it to better withstand the effects of external loads and exert stronger constraints on the surrounding soil mass. In contrast, the soft soil layer has lower stiffness and higher deformability, leading to larger deformations under external loading and thus resulting in a relatively greater displacement response.

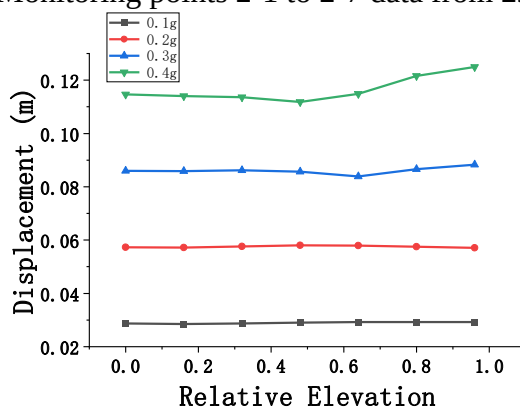
Therefore, the displacement response in the soft soil layer is more significant compared to the hard soil layer when subjected to external loading effects.



(a) Monitoring points 2-1 to 2-7 data from 1slope



(b) Monitoring points 2-1 to 2-7 data from 2slope



(c) Monitoring points 2-1 to 2-7 data from 3slope

Figure 6. Displacement response of selected monitoring points in three slopes

By examining the diagram, it can be inferred that an increase in input acceleration leads to an increase in displacement response. Furthermore, across the three charts, it is worth noting that the displacement response tends to reach its maximum value at the highest point.

Upon further analysis, disregarding the influence of different soil layers on the displacement response, it is observed that the displacement gradually amplifies during the upward process until reaching its peak. For instance, monitoring points 2-5, 2-6, and 2-7 in the soft soil layer of the 2nd slope (as depicted in Figure 7) exhibit an increasing trend in displacement response. Similarly, the same trend is observed in points 2-5, 2-6, and 2-7 of the 3rd slope (as shown in Figure 8). This elevation amplification effect can be attributed to the disparity in interlayer constraints.

Specifically, the upper layer at the top provides relatively less constraint to the displacement, while the lower soil layers face greater confinement. As a result of this constraint force, the lower soil layers transmit external loads gradually to the upper layers, causing a gradual increase in displacement response of the upper soil mass. This elevation amplification effect reaches its peak when the displacement response reaches its maximum value.

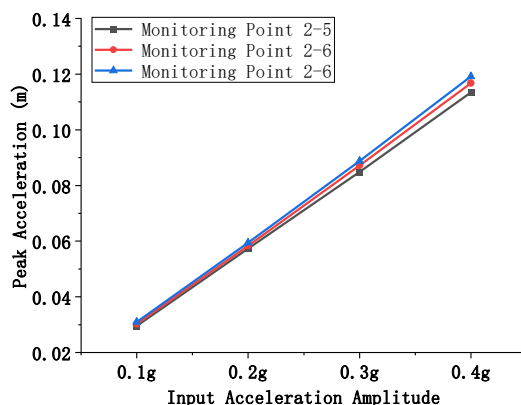


Figure 7. Data from monitoring points 2-5 to 2-7 from 2slope

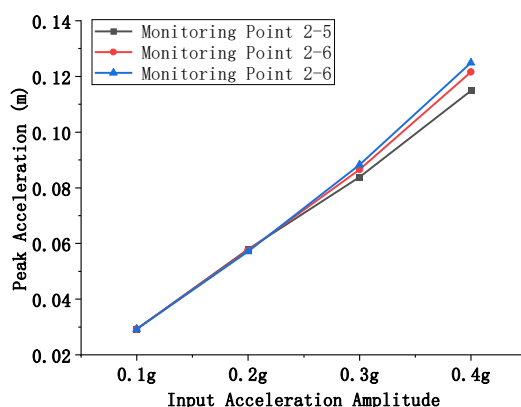


Figure 8. Data from monitoring points 2-5 to 2-7 from 3slope

3.3. Stress analysis

When the loading acceleration gradually increases from 0.1g to 0.4g, stress analysis of the slope reveals the following patterns:

In the diagram, it can be observed that the curves corresponding to monitoring points 2-7 to 2-2 (as shown in Figure 9(b)) exhibit a gradual upward trend. This indicates that as the depth of the observed strata increases, the stress also increases. This phenomenon arises due to the increased soil constraint, where enhanced confinement leads to a gradual increment in stress.

Upon closer examination of the graph, particularly between monitoring points 2-2 and 2-1 (as depicted in Figure 9(b)), a significant reduction in stress is observed. Referring to the model in figure one, we can ascertain that monitoring point 2-2 lies within the hard soil layer, while monitoring point 2-1 lies within the soft soil layer. The transfer of stress from the hard soil layer to the soft soil layer results in a sharp decrease in stress. This discrepancy is attributed to the reduced confinement in the soil mass causing a decrease in stress.

Specifically, the hard soil layer, due to its higher stiffness and strength, has the ability to provide greater constraint against the transfer of external loads. However, when the load propagates to the soft soil layer, the lower stiffness of the soft soil layer leads to relatively lesser confinement. Therefore, along the propagation path from monitoring point 2-2 to 2-1, stress diminishes significantly as a consequence of reduced confinement. This also explains why, despite an overall increasing trend, there are fluctuations between monitoring points 3slope2-7 and 2-1 (as shown in Figure 9(a)).

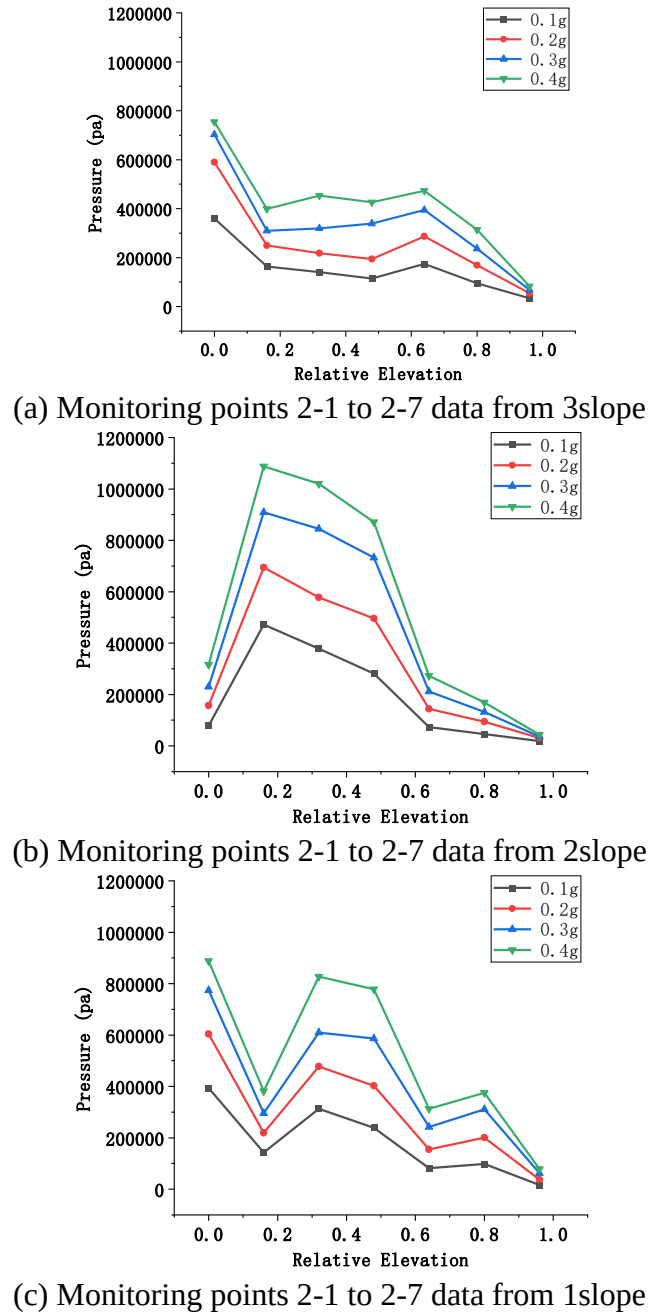


Figure 9. Stress distribution at selected monitoring points

Based on the diagram, it is evident that stress concentration may occur at the toe of the slope. By plotting the data histogram for monitoring points 4-3, 4-4, and 4-5 (as depicted in Figure 9(b)), a sharp increase in stress can be observed at monitoring point 4-4. This phenomenon arises due to the uneven distribution of stress resulting from the geometric shape of the soil layers and changes in boundary conditions, leading to stress concentration.

Stress concentration can potentially cause deformation and failure of the soil, thereby increasing the risk to slope stability. Hence, in the design of slope engineering projects, special attention needs to be given to the toe of the slope. Appropriate measures should be taken, such as reinforcing the soil or implementing suitable slope stabilization techniques, to mitigate the potential risks associated with stress concentration.

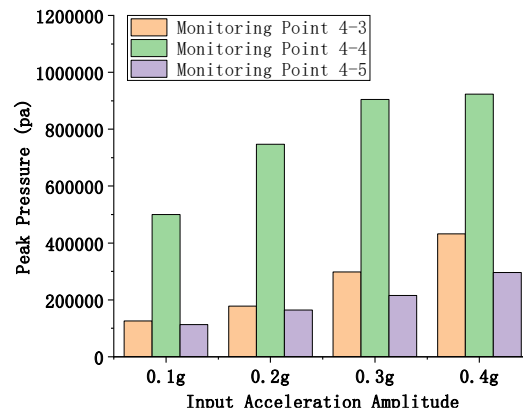


Figure 10. Bar chart presenting the data analysis of monitoring points 4-3 to 4-5

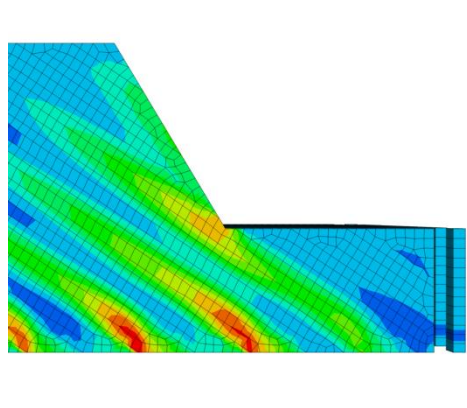


Figure 11. The stress distribution along the slope

4. Conclusion

- 1) The greater the initial input acceleration, the larger the response acceleration and displacement.
- 2) Response acceleration and displacement exhibit a phenomenon of elevation amplification.
- 3) Acceleration response and displacement response are influenced by the soil properties. Under seismic waves, the response ratio is more prominent in soft soil compared to hard soil.
- 4) Under the same conditions, hard soil can withstand greater pressure. During seismic waves, hard soil demonstrates higher stiffness and deformation resistance.
- 5) The properties of the soil have a significant impact on stress propagation, and under the influence of seismic waves, the effect of soil properties on stress propagation is greater than the impact caused by changes in the height of the slope.
- 6) The position of the toe of the slope experiences stress concentration under the influence of seismic waves.
- 7) By studying the dynamic response patterns of layered slopes with differing soil properties under seismic waves, it provides a theoretical foundation for understanding slope stability, predicting soil failure modes, and conducting research on slope support systems.

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