

# Failure Mechanism of Locked Slopes Under Seismic Loading Based on PFC2D

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**Abstract.** Due to the difficulty of accurately characterizing the discontinuous characteristics of the failure process of locked slopes using traditional continuous medium methods, and systematic analysis of slopes with geological locked structures is still insufficient. Therefore, this paper is based on the discrete element numerical simulation method, and this article simulates the deformation, crack propagation, and failure process of slopes under seismic waves, and studies the failure mechanism of locked slopes under seismic loads. Analyzed the velocity field, acceleration field, and crack propagation law of slopes under different frequencies and amplitudes. The research results indicate that the locked segment plays a key role in slope stability, and the rupture first starts from the locked segment (especially the lower end of the locked segment) and gradually extends to the slope surface, significantly affecting the failure mode and dynamic response of the slope; The larger the amplitude of earthquake load, the greater the range and severity of slope rupture; The frequency of seismic loads is generally negatively correlated with slope failure and dynamic response, with sudden changes occurring only when seismic waves resonate with the slope.

**Keywords:** Locked Type Slope, Locked Segment, Seismic Response, Failure Mechanism, Discrete Element Method.

## 1. Introduction

The locked segment type rock slope refers to the rock bridge segment with relatively good strength in its slip zone, and the rock bridge locking segment is the main controlling factor of the stability of rock slope. The study of the failure mechanism of the locked slope under the action of earthquake is helpful to understand the instability mechanism of the locked slope, and provides a scientific basis for the seismic design of slope engineering.

At present, the research on the failure mechanism of slope under earthquake has made some progress. Through theoretical analysis, numerical simulation and model test, scholars at home and abroad have conducted in-depth research on the dynamic response, failure mode and stability evaluation method [1] of slope. Through theoretical analysis [2] and derivation, the researchers established the dynamic response model of the slope under the action of earthquake, and analyzed the influence of factors such as the propagation characteristics of seismic wave [3], the damping characteristics of slope materials and natural frequency on the stability of the slope. The research found that when the seismic wave propagated in the slope, the stress state of the rock and soil mass of the slope would change instantaneously, thus affecting the stability of the slope; Through the indoor conventional physical experiment, wave velocity test, nuclear magnetic resonance test, point load test, uniaxial compression test, combined with the rock mass quality evaluation based on RMR value and GSI value, the Hoek Brown strength criterion is converted to the shear strength parameters  $c$  and  $\phi$  of dolomite rock mass [4], so as to obtain the evolution model of weak interlayer; By simulating the advantages of continuous discrete media with manifold element method [5], it is concluded that when the sliding bed is regarded as an elastic body, the dynamic response characteristics of the slope surface are significantly different due to the influence of seismic wave propagation inside the sliding bed, and the peak acceleration distribution on the sliding surface is 1.5~2 times larger than the input ground motion curve; Based on the forward modeling idea, the seismic response and impact disaster degree of a accumulation landslide are studied by using the particle flow method [6]. It is concluded that the deformation of the landslide starts from the front edge, and the

clavicular segment penetrates from front to back along the sliding surface, which has undergone four processes: traction loosening, overall acceleration, deceleration sliding, and complete static; By using the bottom friction test and numerical simulation method [7], the failure mechanism of bedding rock slope under the condition of different rock dip angle is compared and analyzed, and it is concluded that the failure mechanism of slope changes significantly with the different rock dip angle; The failure process of bedding rock slope was obtained based on the measurement point image tracking technology. The displacement results of characteristic points showed that the deformation and failure of bedding rock slope had obvious stages; Based on the discrete element numerical simulation method [8], the dynamic response law of soft hard interbedded bedding rock slope is revealed, and it is concluded that the amplification effect of soft rock on acceleration is more obvious under the action of earthquake.

By changing the amplitude, frequency and other factors of seismic wave, this paper studies the influence of natural frequency and amplitude of seismic wave on the dynamic response of slope. By comparing and monitoring the response at different positions, it studies the influence of locked segment on the failure mode and stability of slope, and systematically analyzes the dynamic response characteristics of locked slope under earthquake.

## 2. Method

Particle Flow Code in 2 Dimensions (PFC<sup>2D</sup>) is a two-dimensional particle flow numerical simulation software based on discrete element method (DEM). It studies the mechanical behavior and failure process of complex media (such as rock and soil) by simulating the interaction of circular particles. This study analyzes the amplification effect of slope acceleration and stress concentration phenomenon in the locked segment by applying dynamic loads (seismic waves). A "three-stage" [9] locked type rock slope foundation model was constructed using PFC<sup>2D</sup>. The slope model is shown in Figure 1. DFN (Discrete Fracture Network) method was used to implant potential sliding surfaces to construct the locked segment, with lengths of 50m and 90m and inclinations of 170° and 105°, respectively. The characteristics were reflected by assigning lower mechanical parameters.

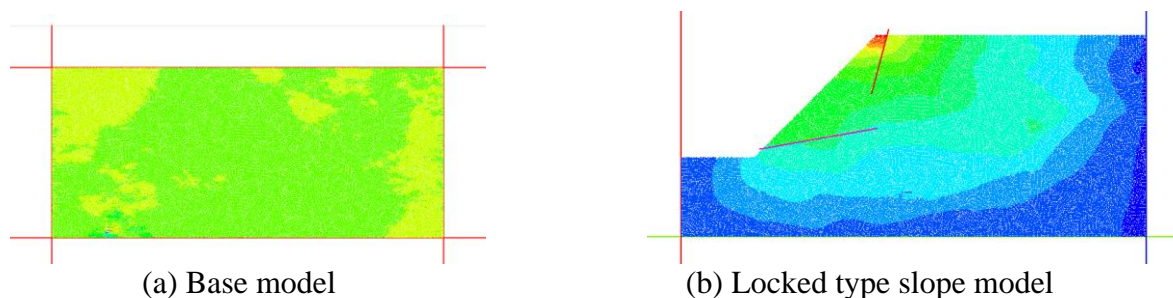
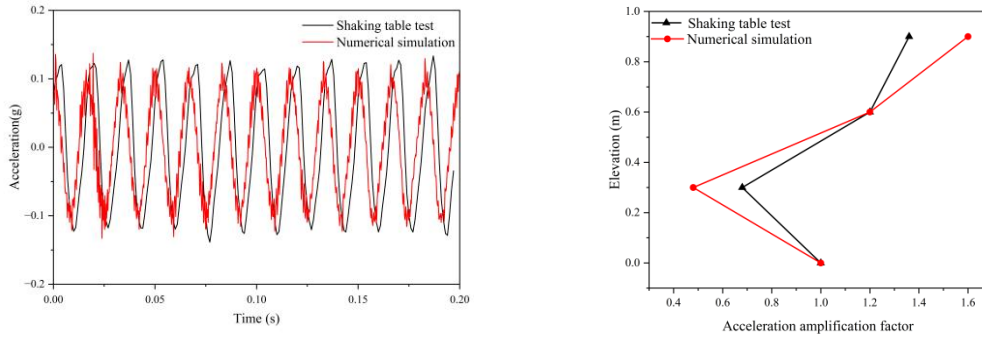


Figure 1. Locked type slope modeling process

## 3. Parameter verification

This study systematically verified the micro parameters of the Particle Flow Model (PFC<sup>2D</sup>) through vibration table test data to ensure the accuracy of the numerical model. The verification results show that the simulation results have a high degree of agreement with the vibration table test data [10] in terms of acceleration time history curve and acceleration amplification factor, which proves the rationality of the selected micro parameter combination. The comparison of model simulation results and vibration table experimental data is shown in Figure 2.



(a) Time history acceleration comparison (b) Magnification factor comparison

**Figure 2.** Comparison of model simulation results and vibration table experimental data

The final micro parameter combination of the model was determined. The Microscopic parameters of slope model is shown in Table 1.

**Table 1.** Microscopic parameters of slope model

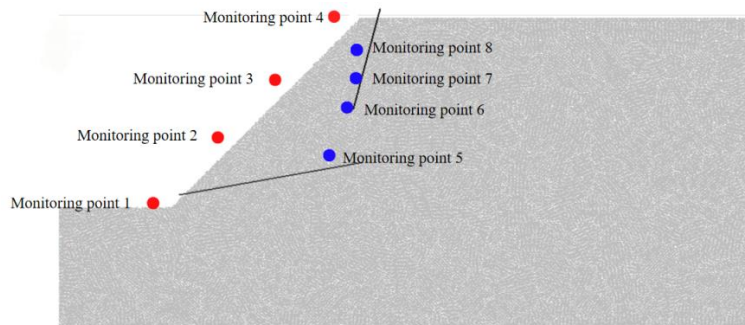
Parameter	Parameter values					
Geometric parameters of the model	Width (m)			Height (m)		
	347			120		
Particle parameters	Particle radius range (m)		Particle density (kg/m <sup>3</sup> )		Porosity	
	Minimum radius	Maximum radius	2.7×10 <sup>3</sup>		0.12	
	0.4	0.45				
Contact parameters	Particle to surface contact (Linear contact model)	Elastic modulus (GPa)	Stiffness ratio	Coefficient of friction	Linear	
		60	1.5	0.4	1	
	Particle to particle contact (Parallel cementation model)	Elastic modulus (GPa)	stiffness ratio	Adhesive modulus of elasticity (GPa)	Bonding stiffness ratio	Linear
		26.9	1.5	26.9	1.5	
		Adhesive tensile strength (MPa)	Adhesive friction angle (°)	Coefficient of friction	Cohesive force of bonding (MPa)	
	Particles and Cracks (Flat joint model)	20	20°	0.4	15	
		Friction angle (°)	c Kpa (Pa)	Coefficient of friction	Tensile strength (Pa)	
15	900	0.2	500			

#### 4. Simulation

Harmonic seismic waves are applied to the bottom edge of the model, and the amplitude (0.1g, 0.2g, 0.3g, 0.4g, 0.5g) and frequency (3hz, 5hz, 7hz, 9hz) of the seismic waves are sequentially changed to explore the sensitivity of seismic wave parameters to slope dynamic response. After each simulation, the displacement, velocity, acceleration, and crack propagation characteristics of the slope are recorded in detail, and the distribution pattern of the deformation concentration zone is analyzed through visualization methods.

In order to study the impact of the locked segment on the slope and compare and analyze the dynamic response mode at the locked segment, four monitoring points are uniformly distributed on

the slope surface, and four points are selected at the upper and lower locked segments to facilitate the comparison of abnormal changes at the locked segment. The Distribution of monitoring point locations is shown in Figure 3.

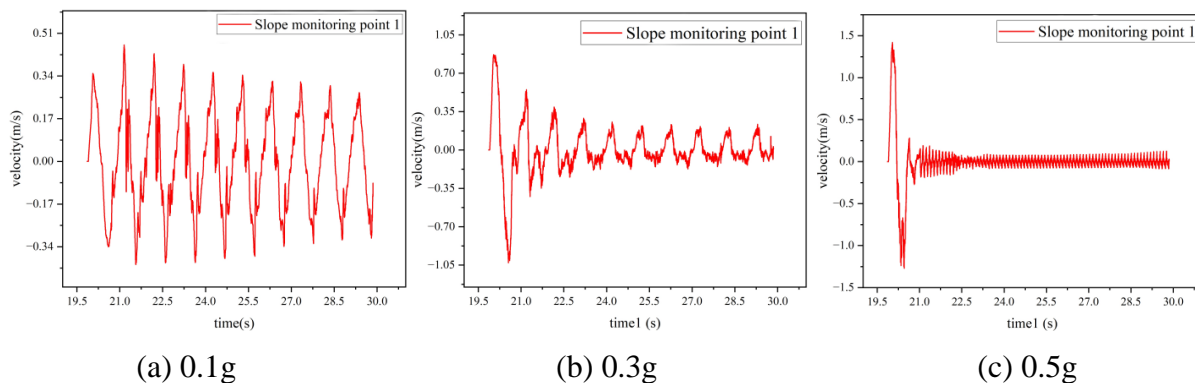


**Figure 3.** Distribution of monitoring point locations

#### 4.1. Observing the damage law of slope caused by seismic wave amplitude

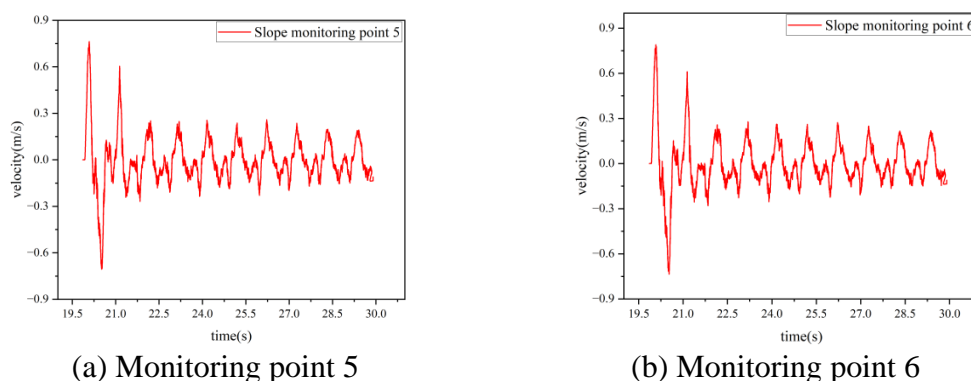
Firstly, by applying seismic waves with a frequency of 1 Hz but different amplitudes (0.1g - 0.5g) to the slope, and observing the changes and characteristics of cracks, monitoring point velocities, and accelerations, the frequency of the seismic waves is determined.

(1) The peak speed is positively correlated with the input amplitude. The Velocity variation curve of monitoring point 1 when seismic waves of the same frequency but different amplitudes are applied is shown in Figure 4.



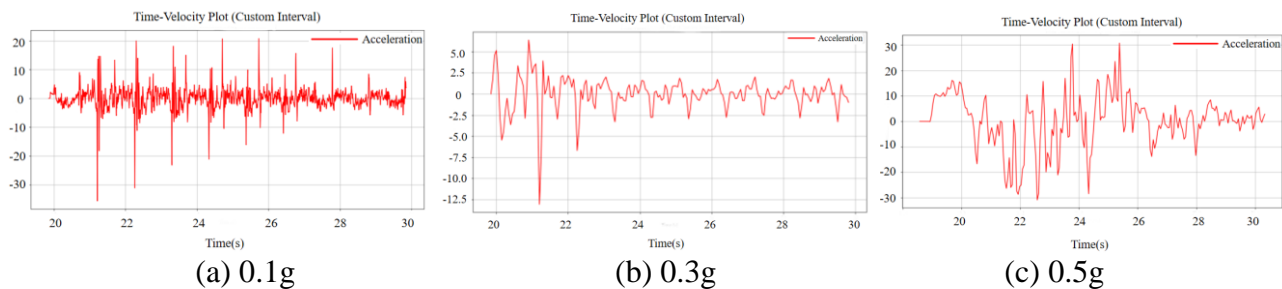
**Figure 4.** Velocity variation curve of monitoring point 1 when seismic waves of the same frequency but different amplitudes are applied

(2) The velocity response of the monitoring points on the locked segment is more severe than that on the slope. This indicates that the locked segment, as a stress concentration segment, which has an amplifying effect on seismic energy. The Velocity variation curves of monitoring points at different locations when a seismic wave with an amplitude of 0.4g is applied is shown in Figure 5.



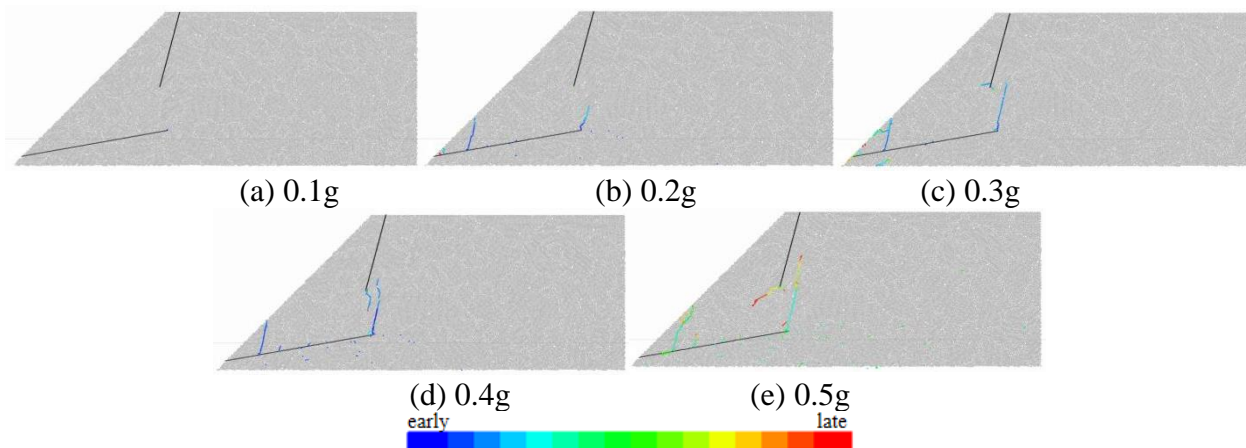
**Figure 5.** Velocity variation curves of monitoring points at different locations when a seismic wave with an amplitude of 0.4g is applied

(3) The acceleration response exhibits nonlinear growth with increasing amplitude. The Acceleration variation curve of monitoring point 1 when seismic waves of the same frequency but different amplitudes are applied is shown in Figure 6.



**Figure 6.** Acceleration variation curve of monitoring point 1 when seismic waves of the same frequency but different amplitudes are applied

(4) As the amplitude of the earthquake wave increases (0.1g to 0.5g), the extension range and degree of damage of the crack significantly increase, and the crack spreads from the lower end of the locked segment. The Crack variation when seismic waves of the same frequency but different amplitudes are applied is shown in Figure 7.

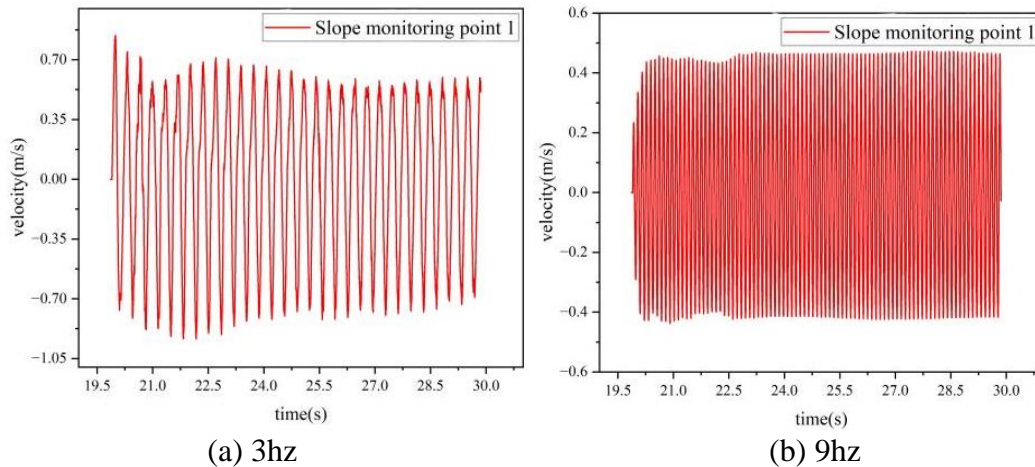


**Figure 7.** Crack variation when seismic waves of the same frequency but different amplitudes are applied

#### 4.2. Observing the damage law of slope caused by seismic wave frequency

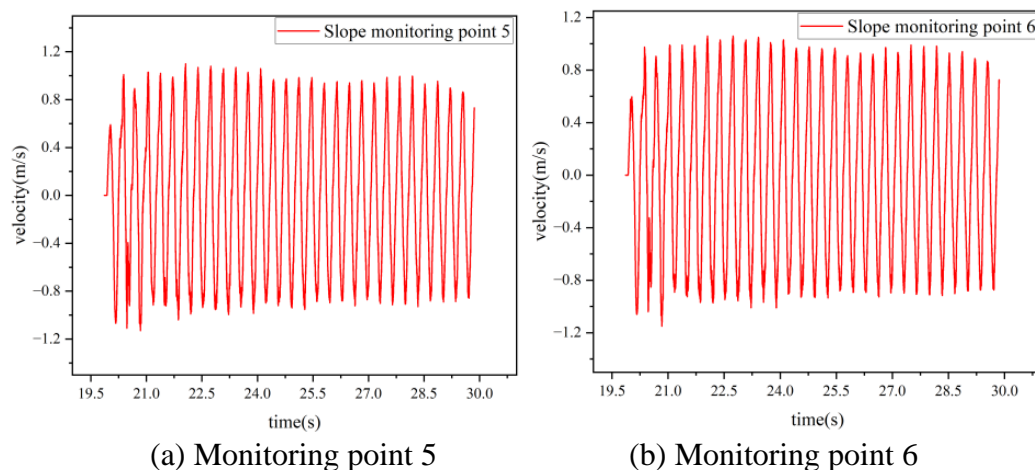
The influence of seismic wave frequency on the slope was studied by applying seismic waves of the same 0.6g but different amplitudes (3hz - 9hz) to the slope, and observing the changes and characteristics of cracks, monitoring point velocity, and acceleration.

(1) The speed response is generally negatively correlated with the input frequency, except for the load that is consistent with the natural frequency of the slope, where the dynamic response is more significant. The Velocity variation curve of monitoring point 1 when seismic waves of the same amplitude but different frequencies are applied is shown in Figure 8.



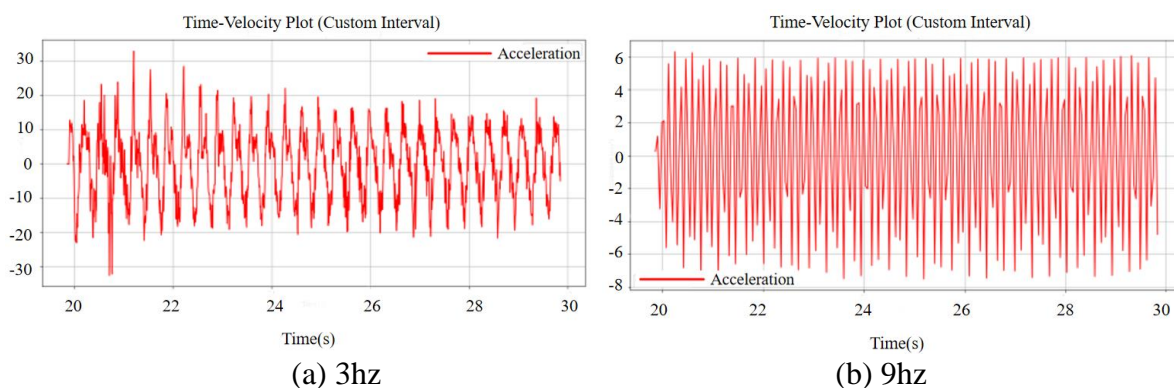
**Figure 8.** Velocity variation curve of monitoring point 1 when seismic waves of the same amplitude but different frequencies are applied

(2) The speed response of the monitoring point in the locked segment is higher than that of the slope at all frequencies. The Velocity variation curves of monitoring points at different locations when seismic waves with a frequency of 3Hz are applied is shown in Figure 9.



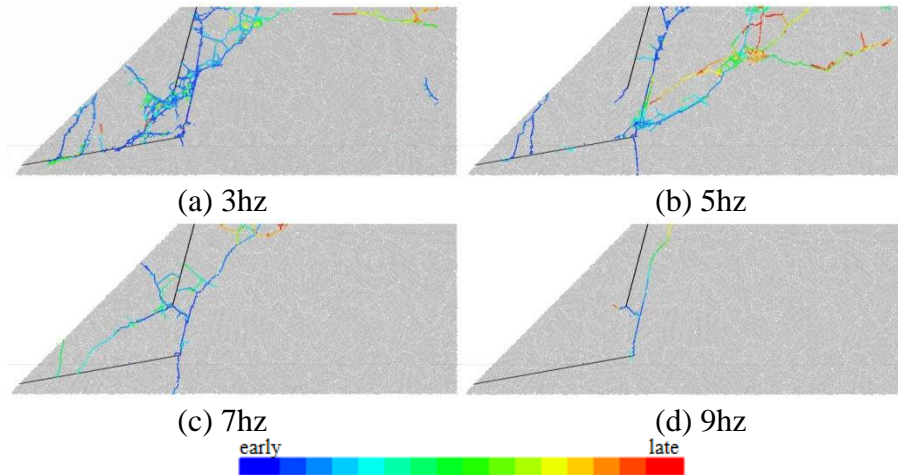
**Figure 9.** Velocity variation curves of monitoring points at different locations when seismic waves with a frequency of 3Hz are applied

(3) The acceleration response is negatively correlated with the input frequency. The Acceleration variation curve of monitoring point 1 when seismic waves of the same amplitude but different frequencies are applied is shown in Figure 10.



**Figure 10.** Acceleration variation curve of monitoring point 1 when seismic waves of the same amplitude but different frequencies are applied

(4) The rupture range is generally negatively correlated with frequency, except for the maximum rupture range when the seismic wave resonates with the slope, but the locked segment is always the source of rupture. The Crack variation when seismic waves of the same amplitude but different frequencies are applied is shown in Figure 11.



**Figure 11.** Crack variation when seismic waves of the same amplitude but different frequencies are applied

## 5. Conclusion

In this study, the dynamic response and failure mechanism of locked slope under seismic load are analyzed by PFC2D system. The results show that:

(1) Velocity field analysis: The velocity and acceleration responses are generally negatively correlated with the input frequency and positively correlated with the input amplitude, with the exception of the maximum dynamic response when the input seismic wave and slope resonance occur.

(2) Crack propagation characteristics: When the seismic wave resonates with the slope, the fracture range is the largest, the low frequency induces the penetrating failure, and the high frequency causes the small fragmentation, but the locked segment is always the origin of the rupture. The crack range is positively correlated with the seismic wave amplitude, and the crack shape is similar under the action of seismic waves of different amplitudes, and the seismic wave amplitude does not change the failure mode of the slope.

(3) The influence of locked segment on slope stability: The deformation concentration zone is mainly distributed at the locked segment, and this area is the initial rupture zone under seismic wave load and exhibits significant velocity changes. This indicates that the locked segment is a deformation concentration zone under seismic loads.

Through the above analysis, this study reveals the complex influence mechanism of seismic wave parameters on the dynamic response of locked slope, and concludes that the locked slope plays a key role in slope stability. The research results can provide micromechanical basis for seismic design of slope in seismic area, and highlight the unique value of particle flow method in complex geotechnical engineering problems. The discussion emphasized the important role of numerical simulation in revealing the seismic failure mechanism of slope, and laid the foundation for the development of seismic design theory based on micro mechanical mechanism.

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