Study on dynamic response of slope under near-fault pulse-like ground motion

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Abstract. Compared with far-field ground motion, the most significant feature of near-fault pulse-like ground motion is the long-period, large-scale velocity pulse. This paper proves through statistical analysis that near-fault pulse-like ground motion is an important cause of slope damage and landslide. And use numerical simulation software FLAC3D to establish a homogeneous rock slope model, select near-fault ground motions with velocity pulses and non-pulse near-fault ground motions, and use an improved energy method to identify and extract the selected near-fault ground motions. The dynamic response of the slope under the action of near-fault ground motions with and without velocity pulses is comparatively studied, and the dynamic response law of the slope under the original records, pulse records, and residual records of pulse-like ground motions is explored. The research results show that the near-fault ground motions with velocity pulses can cause a greater dynamic response than ground motions without velocity pulses. There is an elevation magnification effect in the PGA distribution of the slope horizontally. The shorter-duration pulse record can cause a larger dynamic response, and the PGA magnification factor under the effect of the residual record is smaller than the original record. The velocity pulse strengthens the earthquake damage to the slope, and the slope produces a stronger dynamic response.

1. Introduction

The near-fault ground motion is different from the far-field ground motion. Researchers began to understand the near-fault pulsed ground motion in the last century. Infield investigation, it was found that the structure near the fault often suffered more serious damage. Housner et al. (1958) studied the seismic records of Port Hueneme in the United States. This is the first time that a single-pulse strong seismic record has been recorded. Through analysis, it is found that almost all the energy in the earthquake is concentrated in one pulse, which is believed to be the main reason for the serious damage to the structure. Bolt et al. (1971) analyzed the San Fernando seismic records in the United States, and the results showed that the near-fault pulsed ground motion would cause more serious damage to the structure compared with the ordinary ground motion. Bertero et al. (1978) reviewed and studied the existing near-fault ground motion and pointed out the main characteristics of high-amplitude and long-period acceleration pulse near-fault ground motion, which would cause devastating damage to buildings. After realizing the great destructivity of near-fault ground motion, a large number of scholars began to conduct in-depth research on the characteristics of such ground motion. Somerville et al. (1993;1997) studied the effects of the directional effect of rupture on the duration and amplitude of ground motion and found that the propagation velocity and direction of fault rupture jointly affect the velocity pulse. In addition, medium and long-period structures are more vulnerable to damage under the action of near-fault pulse ground motion. Bray et al. (2004) studied
near-fault ground motions with forwarding directionality and proposed an empirical relationship between PGV and velocity pulse period. It is believed that the energy of ground motion is mainly concentrated in a narrow period band centered on the pulse period.

In general, the existing studies have mostly focused on the formation mechanism of near-fault pulse-like ground motions, the identification and extraction of pulses, the law of attenuation of ground motions, and the impact on dams, base isolation structures, building structures, and bridge structures. However, it rarely involves the slip mechanism of a landslide caused by near-fault pulse-like ground motions and the influence on the dynamic response of the slope. However, a large number of facts have proved that the ground motion in the near-fault area can cause more damage to the slope body than the far-field ground motion. For example, the 2008 Wenchuan earthquake (MS=8.0) induced dozens of giant landslides with a scale greater than $1 \times 10^6$ m$^3$, including the Daguangbao landslide in Anxian County, the largest landslide in history (Huang et al. 2008). The landslide disaster induced by the Wenchuan earthquake caused more than 20,000 casualties, and the economic losses caused accounted for more than one-third of the total losses. Therefore, studying the special properties of near-fault pulse-like ground motions and their impact on slope dynamic response will provide a theoretical basis and technical support for solving the problem of slope dynamic disaster prevention. The research purpose of this paper is to explore that the velocity pulse in the near-fault pulse-like ground motion is the main factor that causes the slope instability and affects the dynamic response, and analyzes the dynamic response law of the slope under the pulse-like ground motion.

2. Fault effect of Landslide

To study the sliding mechanism of near-fault pulse-type ground motions and their influence on the dynamic response of slopes, 13 seismic events with detailed fault plane data were collected and sorted out. The 13 earthquake events triggered a total of 271,028 landslides, of which 197,481 were triggered by the Wenchuan earthquake, accounting for 72.9% of the total landslides. To avoid the Wenchuan earthquake landslide data from having too much influence in the analysis, the landslide fault distances of all the earthquakes that excluded the Wenchuan earthquake (Figure 1(a)) and the Wenchuan earthquake (Figure 1(b)) were statistically analyzed. The result of Figure 1(b) shows that about 74.4% of the landslides in the Wenchuan earthquake landslide data occurred within 20 km from the fault, and nearly 84% of the remaining seismic events after the Wenchuan earthquake were excluded are distributed within 20 km from the fault. Moreover, the number of landslides and the growth rate of landslide areas gradually decrease with the increase of the fault distance. What is more remarkable is that nearly 90% of the landslides with an area greater than 100,000 m$^2$ induced by the Wenchuan earthquake occurred within 20 km of the fault. The results are sufficient to show that a large number of landslides occur in near-fault areas, and near-fault ground motions often have velocity pulses. Therefore, it is reasonable to believe that near-fault pulse-type ground motions are an important cause of slope damage and landslides.

Figure 1. Fault distance distribution of landslides of different areas: a. All earthquakes except the
Wenchuan earthquake; b. the Wenchuan earthquake

3. Numerical simulation of slope dynamic response

3.1 Slope model
The purpose of this research is to explore the law of near-fault pulse-like ground motions affecting the dynamic response of slopes and does not involve specific slope prototypes. Therefore, a homogeneous rock slope model was designed in the simulation. Assuming that the rock mass is continuously homogeneous and isotropic, the model adopts the Mohr-Coulomb constitutive relationship, the material parameters refer to "Engineering Geology Handbook" (Fourth Edition), and the rock mass mechanical parameters are shown in Table 1.

| Density ρ(kg/m³) | Elastic modulus E(Gpa) | Friction angle φ(°) | Cohesive force c(kPa) | Extension strength(MPa) | Poisson ratio μ |
|------------------|------------------------|---------------------|-----------------------|------------------------|----------------|
| 2500             | 50                     | 40                  | 610                   | 5                      | 0.36           |

According to suggestions in the literature of Zheng et al. (2002), taking the slope height as an example, the distance from the toe of the slope to the leading edge of the slope is 1.5h, the distance from the shoulder to the back edge of the slope is 2.5h, and the total height of the upper and lower boundaries is not less than 2h. This paper refers to this standard and extends it appropriately. The total length of the model is 1400m, the slope height is 160m and the slope Angle is 45°. Grid size According to the research results of Kuhlemeyer et al. (1973), the maximum grid size Δl must be less than 1/10~1/8 of the shortest wavelength of the loaded wave. According to the calculation, the maximum grid size set as 6m can meet the requirements of calculation accuracy. Six monitoring points were arranged on the slope, respectively J1, J2, J3, J4, J5, J6. Taking the slope height as a reference, the relative heights were 1, 0.8, 0.6, 0.4, 0.2, 0. The slope model is shown in Figure 2.

Built-in commands are used to generate 2D and 1D grids around the model to produce free-field boundaries. Static boundary conditions are used at the bottom of the model, and stress time history is used for load input. The selection of damping and its numerical value is a complicated problem, but it is not the main purpose of this study. Therefore, local damping is selected in the calculation, which can save the calculation time on the premise of ensuring the calculation accuracy. According to the experience, the local damping coefficient is set as 0.157 in the dynamic calculation in this paper.

![Figure 2. Slope model](image)

3.2 Ground motion selection
The selection of near-fault pulse-like ground motions involves the identification and extraction of velocity pulses. This paper adopts the energy-based pulse recognition extraction method of Chang et al. (2016). This method improves Baker’s recognition method. The standard pulse mathematical model is used to fit the seismic velocity time history, and the least square method is used to analyze the pulse data.

In the numerical calculation, the representative Imperial Valley, ChiChi, and Kobe seismic waves were selected. Each seismic wave was filtered and baseline corrected before input. The MATLAB
program developed by Chang et al. (2016) is used to identify and extract the selected ground motions. The three extracted seismic records are the original ground motion, residual ground motion, and the extracted pulse ground motion, which are named Original, Residual, and Pulse for the convenience of analysis. To compare the difference between near-fault pulse-like ground motions and non-pulse ground motions, three near-fault non-pulse ground motions in the same seismic event were selected for comparison. The corresponding time history diagram is shown in Figure 3 and Figure 4, and the seismic record information is shown in Table 2.

**Table 2. The seismic record information**

| Earthquake,year | Station | M  | PGA(g) | PGV(cm/s) | PGD(cm) | Rrup(km) | Mechanism     |
|-----------------|---------|----|--------|-----------|---------|----------|---------------|
| EQ1             | Imperial Valley-06,1979 | Chihuahua | 6.53   | 0.216     | 5.086   | 2.533    | 7.29          | strike slip   |
| EQ2             | Kobe, Japan,1995 | Amagasaki      | 6.9    | 0.276     | 33.574  | 26.610   | 11.34         | strike slip   |
| EQ3             | Chi-Chi, Taiwan,1999 | TCU089         | 7.62   | 0.353     | 34.987  | 18.681   | 9.00          | Reverse Oblique |
| EQ4             | Imperial Valley-06,1979 | Holtville Post Office | 6.53   | 0.258     | 9.853   | 5.624    | 7.5           | strike slip   |
| EQ5             | Kobe, Japan,1995 | Port Island (0 m) | 6.9    | 0.289     | 51.139  | 30.723   | 3.31          | strike slip   |
| EQ6             | Chi-Chi, Taiwan,1999 | TCU101          | 7.62   | 0.212     | 76.81   | 15.99    | 2.11          | Reverse Oblique |

**Figure 3. Acceleration time history of near-fault non-pulse ground motion**

**Figure 4. Acceleration time history of near-fault pulse-like ground motion**

### 4 Slope dynamic response
Many scholars have done a lot of research on the dynamic response of slopes through model tests and numerical simulations. The research results of Xu (2008), Liu (2015), Jia (2018) show that the dynamic response of slopes has elevation effects and trending effects., this paper focuses on
comparing vibration around the component influence on dynamic response, so choose the strongest acceleration response on the surface of the slope are analyzed. According to the research results of Qi (2003), the dimensionless acceleration amplification factor is introduced as an analysis index, which is defined as the ratio of the peak acceleration of the seismic dynamic response of the slope to the peak acceleration of the slope toe.

![Figure 5. PGA amplification factor comparison](image)

The six seismic records were input into the slope model to calculate their PGA amplification coefficient, and the results are shown in Fig. 5. The results in Fig. 5 show that both pulse-like and non-pulse ground motions will present an obvious elevation amplification effect after acting on the slope, that is, the amplification coefficient of PGA will gradually increase with the increase of the slope height and reach the maximum value at the top of the slope. In addition, the PGA amplification coefficient increased slowly when the slope height was below 0.5 times but increased rapidly when the slope height was above 0.5 times. This is consistent with the results of shaking table tests conducted by Xu (2008), Yang (2012), Li (2019), and Su (2021). The reason for this is that as seismic waves spread up more and more close to the slope shoulder, seismic wave on the slope shoulder attachment complex refraction and reflection phenomenon, the resulting seismic waves overlap, and the upper slope under the constraints of smaller and smaller, the slope shoulder attachment are two airport surface, slope, and slope under the effect of coupling, PGA in the upper slope present more intense amplification effect. Especially for the three ground motions of EQ3, EQ4, and EQ5, there is a large increase near 0.2 times the slope height, and then the PGA amplification factor declines rapidly. According to the research results of Xu (2008); Fan (2015), it can be inferred that the reason is that the large PGA seismic load acts on the slope, the slope damping ratio increases, the natural vibration frequency decreases, and the slope produce cracks under a large earthquake amplitude, and the rock structure is destroyed. The rock and soil particles become loose, the filtering effect is enhanced, and the material has a certain vibration isolation effect. In addition, as the amplitude increases, the frictional energy dissipation between rock and soil materials increases, which is also an important reason for the reduction of the PGA amplification factor.

To further study how the velocity pulse affects the dynamic response of the slope, the extracted pulse record (Pulse), the residual seismic record (Residual), and the original record (Original) are loaded onto the slope, and the first letter of the calculation results of each record is marked in Figure 6. The results show that under the action of pulse record and residual record, the PGA magnification factor also exhibits an elevation magnification effect. The result of Fig 6(b) shows that the PGA magnification factor is larger in the middle and lower part of the slope, while the middle and upper part is smaller. The reason is the same as the above. The analysis of the paper is consistent, when the PGA amplitude is large, the slope may have cracks, the propagation of seismic waves is blocked, and the slope still exhibits a certain vibration isolation effect. The results of Fig 6(a) and Fig 6(c) show that
the dynamic response of the slope under the effect of the residual record is smaller than the original record. Based on the above analysis, it can be concluded that the pulse record strengthens the dynamic response of the slope, and the slope will be seriously damaged when the pulse amplitude is large.

Since Bertero et al. (1971) discovered velocity pulses from the observation data of the San Fernando earthquake, a large number of scholars have studied near-fault ground motions. Kalkan et al. (2012) found that near-fault velocity pulsed ground motions will cause steel structures to bear most of the energy in a short time and are more likely to suffer damage. Maniatakis et al. (2008) summarized and analyzed the characteristics of near-fault strong earthquake records in multiple areas, and found that the construction engineering structure in the near-fault area, even if the earthquake magnitude is lower than 6, will be severely damaged. In addition, the huge damage effect of near-fault pulse-type ground motions on structures was verified in the 1994 Northridge earthquake in the United States and the 1995 Kobe earthquake in Japan (Somerville et al. 1997). In addition, in the 1992 Landers Earthquake in the United States, the Chichi Earthquake in Taiwan in 1999, and the Wenchuan Earthquake in 2008, a large number of observational data showed that 95% of landslides occurred within 10 kilometers of the fault. Near-fault pulse-type ground motions have caused great damage to the slope (Liu et al. 2006; Huang et al. 2009; Huang et al. 2013; Parker et al. 2010). A large number of on-site observation results are in good agreement with the numerical simulation results in this paper, which is sufficient to show that the pulse characteristics of pulse-like ground motions are an important reason for affecting the dynamic response of slopes.

Figure 6. PGA amplification factor under the action of three components of pulse-like ground motion. (a) EQ4;(b)EQ5;(c)EQ6

5 Conclusions
In this paper, through statistical analysis and numerical simulation, the impact of pulse-like ground motion on the dynamic response of slopes is studied, and the following conclusions are obtained:

(1) According to the statistical analysis of 271,028 landslides triggered by 13 earthquake events,
nearly 74.4% and 84% of landslides occurred within 20km from the fault of the Wenchuan earthquake and after excluding the Wenchuan earthquake, respectively. The results prove that the near-fault ground motion is more likely to induce landslide than the far-field ground motion, and the near-fault ground motion with velocity pulse is an important cause of slope failure.

(2) The numerical simulation results based on FLAC3D show that, compared with the non-pulsed near-fault ground motion, the pulsed near-fault ground motion can cause the greater dynamic response of the slope, and the PAG amplification coefficient increases faster in the middle and upper part of the slope, and the PGA amplification coefficient reaches the maximum at the top of the slope, with the maximum value of 1.5.

(3) The ground motion recorded by pulse will cause a larger dynamic response of the slope, while the PGA amplification coefficient under the action of the residual records is smaller than that of the original records. The existence of the velocity pulse strengthens the damaging effect of the ground motion on the slope and makes the slope produce a stronger dynamic response.

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