The dynamic responses characteristics of colluvial landslide based on model test

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Abstract. Based on shaking table model test to study the colluvial landslide caused by Yushu earthquake, the deformation and instability process of the colluvial landslide under different earthquake components and intensities were studied, the dynamic response characteristics are analysed. The results show that the permanent deformation of colluvial landslide under the strong earthquake is one of the important factors causing geological disasters. The top of the landslide appears to have a series of tensile cracks and shear fractures at first, with the increasing of seismic intensity, those cracks develop from front to back gradually, the arc fissures in the middle of the slope develop continuously and lead to subsidence and the potential slip surface extends from shoulder to the slop toe. The peak ground acceleration (PGA) and earth pressure and acceleration Fourier spectra are found to increase with the increasing of the elevation and intensity, the effects of different lithology associations on the acceleration response rules also vary with the different excitation directions. PGA amplification factors present obvious non-linearity characteristics and the variation trend is inversely proportional to the intensity. The influence of vertical component of seismic on the PGA amplification factors of landslide is slightly greater than horizontal.

1. Introduction
The colluvial landslides are that the landslide occurs in the Quaternary and modern loose accumulation layers, it has some special characters of wide distribution range, large sliding body, strong damage and complicated mechanism [1-3]. The material composition, mechanical properties, human engineering influence and complex hydrogeological environment of the landslide are important factors influencing the specific landslide conditions, deformation and failure laws and dynamic response characteristics of such slopes [4]. With the rapid development of China's economy, the number of slumping accidents caused by the construction of airports, highways, high-rise houses and large-scale water conservancy projects have increased, the economic losses have increased significantly and posing a severe test for the western region which is dominated by colluvial deposits. In addition to the geological conditions of the landslide itself, the human engineering activities have gradually become the main cause of the instability of the landslide. Therefore, the dynamic response characteristics of colluvial landslide under the strong seismic dynamic load need to be studied urgently.

Dynamic response of slopes under earthquake loads has always been a hot issue in seismic engineering. At present, seismic response studies of landslides mainly focuses on the dynamic stability analysis and dynamic response mechanism [5-6]. Although the commonly used methods such as pseudo-
static method are widely used [7-8], it is considered in the aspects of spatial-temporal distribution and dynamic characteristics of seismic acceleration. In the course of application of slope and dam stability, it is slightly insufficient [9]. Despite the displacement discriminant method has undergone many years of development and adjustment [10-12], but it is more complex and there is a problem of time resources in view of the regional and group characteristics of accumulation landslides.

In recent years, physical simulation method has been widely used and developed rapidly in the study of the stability of accumulative slope, this method has the characteristics of advanced and stable equipment, convenient and efficient experiment, accurate and reliable results [13], and so on. The test results can better reflect the deformation and failure mechanism and seismic response characteristics of landslides under seismic loads, and provide important information for the analysis of seismic stability of slope. At present, the main physical simulation methods are mainly geocentrifuge and large-scale shaking table test. Centrifuge test is generally limited by size and vulnerable by boundary effect [14]. Large-scale shaking table test is an important means to study the stress-strain state, dynamic response law and frequency spectrum characteristics of landslides under earthquake. It is very helpful for the study of dynamic response characteristics, deformation and instability mechanism and prevention measures of landslides [15-19].

In this paper, a large-scale shaking table test is carried out to simulate the failure principle of the landslide in the 2# accumulation layer of the Yushu Airport Road Landslide Group in Qinghai Province under the action of seismic force, with the methods of analysis frequency spectrum, pressure and acceleration in the accumulation layer under the action of earthquake, emphatically discussed the ability of the slope to bear vibration load again after earthquake and the contribution of vertical seismic load to the stability of the slope, it provides some basic information for slope stability evaluation and treatment engineering design after earthquake.

2. Shaking table test program

2.1. Shaking table system
The shaking table is a large horizontal-vertical two-way electric servo vibration table used by the Lanzhou Earthquake Engineering Key Laboratory of the China Earthquake Administration Lanzhou Institute of Seismology as shown in Fig. 1.
2.2. Test design

Table 1. Formatting sections, subsections and subsubsections.

| physical quantity | Resemblance Constant | Similarity coefficient |
|-------------------|-----------------------|------------------------|
| Size \( l \)      | \( C_l \)             | 100                    |
| Dense \( \rho \)   | \( C_\rho \)          | 1                      |
| Elastic Modulus \( E \) | \( C_E \) | 100                    |
| Cohesion \( c \)   | \( C_c \)             | 100                    |
| Internal friction angle \( \varphi \) | \( C_\varphi \) | 1                      |
| Stress \( \sigma \) | \( C_\sigma \) | 100                    |
| Strain \( \varepsilon \) | \( C_\varepsilon \) | 1                      |
| Acceleration \( a \) | \( C_a \) | 100                    |
| Displacement \( s \) | \( C_s \) | 100                    |

Table 2. Material properties.

| Soil layer       | Type    | Dense (kg·m\(^{-3}\)) | Elastic Modulus (MPa) | Cohesion (kPa) | Internal friction angle (°) | Poisson's ratio |
|------------------|---------|------------------------|-----------------------|----------------|-----------------------------|-----------------|
| Overburden layer | Prototype | 2000                   | 3400                  | 169.00         | 25.00                       | 0.30            |
|                  | Model   | 2050                   | 34                    | 1.75           | 30.00                       | 0.30            |
| Sliding layer    | Prototype | 1500                   | 1350                  | 5.00           | 19.00                       | 0.38            |
|                  | Model   | 1510                   | 13.5                  | 0.05           | 18.60                       | 0.36            |
| Bedrock          | Prototype | 2300                   | 5500                  | 4.00           | 40.00                       | 0.28            |
|                  | Model   | 2330                   | 55.00                 | 4.60           | 36.40                       | 0.35            |

This test prototype selects the 2# landslide of the Yushu Airport Road landslide group in Qinghai. This colluvial landslide caused by the earthquake. The inclination of slope is about 10° while longitudinal length of the landslide is about 317m and maximum width is about 482m and maximum thickness is 22.80m. It can be divided into overburden, sliding layer and bedrock three floors from top to bottom. The whole colluvial landslide is divided into two levels: the front and the rear, front stage is mainly distributed outside the diversion canal of Xihang Power Station and the elevation is between 3708 and 3735m, the front stage’s longitudinal length is about 85m and thickness of the sliding body is about 18m, volume of the sliding body is about 54.2×10\(^4\)m\(^3\).

In order to more accurately reflect the Seismic dynamic response of the landslide, it is especially important to establish a reasonable similarity theory and select the correct similar parameters. If the stacking slope is simplified to a linear elastic structure, the force relationship under static and dynamic forces can be expressed as:

\[
\sigma = f(F, \rho, g, \mu, E, l, c, \varphi)
\]

\[
\sigma = f(\mu, v, a, g, \rho, t, \omega, E, l)
\]

Where \( \sigma \) is stress (Pa), \( F \) is force (N), \( \rho \) is density (kg/m\(^3\)), \( g \) is gravity acceleration (m/s\(^2\)), \( \mu \) is Poisson's ratio, and \( E \) is elastic modulus (Pa), \( l \) is length (m), \( c \) is cohesion (Pa), \( \varphi \) is internal friction angle (°), \( u \) is displacement (m), \( v \) is velocity (m/s), \( a \) is acceleration (m/s\(^2\)), \( t \) is time (s), \( \omega \) is the frequency (Hz).

Combined with the relevant indicators of the vibrating table, the geometrical dimensions (\( C_l=100 \)), density (\( C_\rho=100 \)) and elastic modulus (\( C_E=100 \)) are taken as the basic dimensions. Use the dimensional analysis method and the \( \pi \) theorem calculation to determine the similar physical quantities of the model.
2.3. Model making

In order to study the ground motion response law of the landslide, the longitudinal profile of the model shown in Fig. 2-left is designed in combination with the similarity ratio. The model box adopts the rigid sealing model groove of the Key Laboratory of key laboratory of loess earthquake engineering, CEA (Fig. 2-right), the inner groove size is 3.0m × 1.5m × 1.14m and the transparent plexiglass plate is used on both sides of the model box to ensure that the damage of the broken model can be observed in real time. The model box is fixed by the high-strength bolt to ensure the stability of the vibration transmission and reduce the relative displacement of the table and the model box.

The slope model is 1000mm high and the slope is about 10°. The slope is divided into three layers: bedrock, overburden and sliding layer, each layer is layered and properly paved and compacted. The similar materials in each layer were prepared by mixing cement, quartz sand, bentonite, talcum powder, gypsum powder, glycerin and water. To better restore the physical and mechanical properties of the slope prototype, the specific proportion of the configuration was determined through relevant laboratory tests: the M15 cement mortar precast block was used in the bedrock layer, the material composition of the overburden was 70% sand, 0.5% bentonite, 26.5 % talcum powder and 3% water, the material composition of the sliding layer material is 80% sand, 2% gypsum powder, 5% talc powder, 10% glycerin and 3% water.

2.4. Sensor arrangement

There are 28 sensors arranged in different parts of the landslide including accelerometers and earth pressure sensor, the sensors layout is shown in Fig.3. Among them, 18 accelerometers are arranged in the colluvial landslide and the surface of the landslide, mainly distributed in the overburden, sliding layer and the interface. The earth pressure sensor is arranged at regular intervals along the contact surface. A total of 5 sets of 10 earth pressure sensors are arranged to measure the horizontal and vertical earth pressure response values.
2.5. Input waveform scheme

In order to better study the dynamic response of landslides under different seismic loads, the critical response law of landslides with significant deformation or instability is discussed, the loading conditions are loaded by applying seismic loads step by step. The waveform input by the test is a sine wave and EL Centro seismic wave, the input direction of the sine wave is horizontal (x-direction) and vertical (z-direction) and the EL Centro wave is horizontal (x-direction), vertical (z-direction), and coupled (XZ-direction) three types of input. According to the basic seismic intensity VII (PGA $a_x = 0.1g$, $a_z = 0.05g$), VIII ($a_x = 0.2g$, $a_z = 0.1g$), IX ($a_x = 0.4g$, $a_z = 0.2g$) stepwise loading, before each intensity loading used the sine wave for sweeping. In the final stage of the test, 1.0g and 1.5g are coupled to the EL Centro wave for the instability damage analysis of the landslide.

Since the seismic wave will change its spectral characteristics and propagation law to some extent after compression, it will have a greater impact on the experiment. Therefore, the shaking table experiment uses the original waveform as the input load. By enlarged or reduced the acceleration time-history curve to a certain extent, realize the seismic loads of different intensities to meet the experimental require.

3. Result analysis

3.1. Dynamic damage macroscopic characteristics

It can be seen from Fig. 5-a that when the intensity is VIII degrees ($a_x=0.1g$) there are three separation fractures appear at the top of the model, and an arc cracks has been found in the middle of the slopes, the other shear cracks appear along the slope face and gradually expand. Severe breakage at the foot of the overburden and the crushed area is about 0.26m², due to a serious sliding at the foot of the slope, the sinking of the slope foot is about 1cm.

When the seismic loads reach IX degree ($a_x=0.4g$) and X degree intensity ($a_x=1.0g$) (Fig. 5-b), the trailing edge crack of the landslide extended, new multiple transverse and longitudinal cracks appeared on the slope shoulder, some of the cracks are filled with broken particles of overburden. The arc-shaped
fissure damage in the slope middle is aggravated which widest part can reach about 7cm. Also, the shear fissure of the slope surface develops rapidly and limited by the diversion channel.

As shown in Figure 5-c, when the input seismic load increase to 1.5g, the fracture of the slope shoulder developed again. By the tensile stress some shoulder shear fissures developed to the middle and the arc-shaped fissure extends down to about 10 cm. The crack above the aqueducts is widened and the overburden is missing at the interface between the model and the model box. The settlement depth of the overburden from the bottom of aqueducts to slope foot increased, soil on surface was apparent completely broken and fragmented soil was basically piled up to the foot of the slope.

3.2. Magnification coefficient variation law

The PGA amplification factor different elevations of overburden layer and sliding layer under horizontal component of seismic wave is shown in Fig. 6-a. PGA amplification factor on overburden layer shows obvious amplification effect with the increase of elevation. Soft lithology of sliding zone makes it absorb certain seismic energy; therefore, the energy is consumed continuously in the process of propagation of sliding zone, which shows that the amplification factor decreases continuously along elevation and varies in the range of 1.0-1.2. The PGA amplification factor obtained from the measured points on the contact surface shows similar variation law under different intensity. From the foot to shoulder of the landslide, the factor shows a trend of first increasing and then decreasing. It is presumed that the contact surface is affected by two layers of soil, when the relative shear displacement occurs between the layers in the course of vibration, the acceleration measured by the sensor will change abruptly and the amplification factors changes abruptly also. Compared with the variation of the magnification factors in layers, the vertical arrangement measured points of the landslide can better reflect the variation law of the magnification factor in different layers. From Fig. 6-a-IV and 8-a-V, the overall magnification factor of the landslide decreases first and then increases at both shoulder and foot of the slope, which is closely related to the lithological composition of the landslide. When seismic waves propagate along the bottom to the surface, the magnification factor decreases in sliding layer, but when they propagate to the overlying stratum, the magnification factor decreases.

For the study of seismic dynamic response, just because the damage caused by vertical component of seismic wave is less than horizontal component, most numerical simulations or physical experiments focus on the influence of horizontal seismic component on the research object, but vertical seismic force may also be an important inducement for building damage and geological hazards. From Fig.6-b, it can be seen that there are some different laws between the magnification factor under vertical seismic load and the horizontal seismic load.

The magnification factors of overburden layer under vertical seismic loads of different intensities have basically the same law. The magnification factors of overburden layer increase from the foot of slope to the shoulder. The magnification factors at the shoulder decrease when the input seismic wave peak $a_c=0.1g$ and $0.2g$, affected by the transverse tension cracks and slip at the back edge of slope. The amplification factor in sliding layer basically remains unchanged along the elevation, but under the vertical load of $0.2g$, the amplification factor from the measured point A2-2 to the A8-1 shows a negative correlation with the elevation. But the magnification factors of each measured point on the contact surface are positively correlated with the elevation. Vertical observation points at the foot and shoulder showed that first decreases and then increases in the process of propagation from bottom to top, which is the same as the input horizontal load, indicating that the weak layer has a certain absorption effect on seismic wave.

In summary, both horizontal and vertical seismic loads have the effect of acceleration amplification factor increasing with elevation. The variation law of amplification factor in different elevations are different and there is a phenomenon of weakening in sliding layer. The amplification factor decreases regularly with the increase of input seismic load. Compared with the horizontal seismic load, the maximum magnification factor of the colluvial landslide under vertical is much larger, and the acceleration response in the sliding zone is larger than that on the slope surface. Although all of them have elevation amplification effect, the amplification factor under vertical load does not have the
characteristics mainly reflected in the slope surface likes horizontal loads, mainly reflected insides. From fig. 6-b, it is shown that the accumulative landslide has a strong absorption effect on the vertical component of seismic wave.

3.3. Spectrum analysis

As shown in Fig. 7, taking the data measured by A6-5 sensor on the slope surface as an example, the Fourier spectra of acceleration under horizontal and vertical seismic loads of different intensities are studied.

Under horizontal seismic load, as shown in Fig. 7-a, there are two main frequency bands in the spectrum line. The Fourier value is amplified in different degrees in the frequency band. The predominant frequency of the colluvial landslide is mainly concentrated in 0-5Hz and 12-16Hz and then rapidly attenuates under horizontal seismic loads. The Fourier spectrum has a significant difference between vertical and horizontal seismic loads (Fig. 9-b). Under vertical loads, the dominant frequency is relatively concentrated in higher frequency bands. After the seismic wave propagates to the slope surface, the predominant frequencies are distributed in the frequency bands of 0-5Hz and 8-12Hz. Whether horizontal or vertical loads, with the increase of input PGA, the amplitude increases in varying degrees and the high-frequency components are more abundant.

Taking the measured data of A7-1, A7-3, A7-4 and A7-5 vertically arranged at the back of the colluvial landslide under the IX degrees loads as an example, the change characteristics of the colluvial landslide along the elevation Fourier spectrum are studied.

Under the horizontal seismic load (Fig. 8a), with the seismic wave propagating from bottom to top, the acceleration Fourier spectrum curve obviously appears two main frequency bands: 0-10Hz and 12-16Hz. With the increase of elevation, the predominant frequency band basically remains unchanged, amplitude gradually increases, and the high frequency component gradually increases. On the contrary, under the vertical seismic load (Fig. 8b), the acceleration Fourier spectrum curve of the colluvial landslide model has no obvious change either in amplitude or predominant frequency. It can be seen that the horizontal component of seismic wave has a greater impact on the dynamic stability of the landslide, while the vertical component has a smaller impact.
From the spectrum analysis, it can be concluded that the amplitude of acceleration Fourier spectrum of landslide is positively correlated with the elevation under the same intensity seismic wave loading; the input seismic load intensity also has a great influence on the amplitude and frequency band distribution of acceleration Fourier spectrum, and the amplitude of Fourier spectrum is positively correlated with it; the horizontal component of seismic wave is more effective than the vertical on the predominant frequency of landslide.

![Acceleration Fourier spectra along different intensities in the colluvial slope](image1)

(a) Under the horizontal seismic component  
(b) Under the vertical seismic component

Figure 7. Acceleration Fourier spectra along different intensities in the colluvial slope

![Acceleration Fourier spectra along different elevations in the colluvial slope](image2)

(a) Under the horizontal seismic component  
(b) Under the vertical seismic component

Figure 8. Acceleration Fourier spectra along different elevations in the colluvial slope

### 3.4. Dynamic earth pressure analysis

As shown in Fig. 9-a, when horizontal seismic load is applied, the earth pressure shows that increases gradually from the foot to the upper side along the contact surface, reaching the maximum at the rear edge 5-1, and then decreases at the contact surface of the back edge, showing a general non-linear law with small ends and large middle ends. Under the influence of vertical seismic load (Fig. 9-b), the variation of pressure curve from the foot to the contact plane shows a trend of first decreasing and then increasing, and the maximum value of peak earth pressure appears at 6-1 of the back edge of landslide.

Under horizontal and vertical seismic loads, the dynamic earth pressure peaks of each measuring point generally increase with the increase of input seismic loads, but the whole shows non-uniformity, and the horizontal dynamic earth pressure and vertical dynamic earth pressure peaks are basically close.
Figure 9. Response mechanism of seismic earth pressure with different excitation

4. Conclusion

By carrying out large-scale shaking table model tests, the dynamic response characteristics and failure mechanism of colluvial landslide under different seismic components are analysed, and the ability of slope to bear vibration load again after earthquake is discussed. The following conclusions are drawn:

1. Under the action of seismic load, the first through-slot crack and shear cracks occur in the slope shoulder. With the intensities increase, the cracks gradually expand and develop downward along the slope surface. The arc cracks gradually develop in the middle of the slope body and cause subsidence. Crushing at the slope foot is serious which has a great influence on the stability of the landslide.

2. Under the action of the horizontal and vertical components of seismic waves, the acceleration amplification effect shows typical non-linear characteristics along the elevation, and is negatively correlated with the seismic intensity. The magnification effect of landslide on the vertical components of seismic waves is larger than that in the horizontal.

3. The material composition and combination characteristics of landslides have an important influence on the propagation of seismic waves in slope. The soft soil layer has obvious absorption effect on seismic wave; the overlying layer has strong amplification effect on the horizontal component of seismic wave, but it is not obvious when input vertical component; the colluvial landslide has stronger absorption effect on the vertical component of seismic wave under extremely high seismic load.

4. Acceleration Fourier spectrum amplitude of colluvial landslide is positively correlated with elevation and ground motion intensity; the high frequency part is more abundant with the intensity increase; the horizontal component of seismic wave has greater influence on the landslide predominant frequency.

5. The dynamic earth pressure gauge of colluvial landslide shows non-uniformity. The peak value of earth pressure under horizontal and vertical components is proportional to the seismic intensity, and the peak value of horizontal and vertical dynamic earth pressure is close to each other.

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