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EFFECTS OF LOCAL GEOLOGY ON GROUND MOTION IN THE LANDSLIDE CONCENTRATED AREA CAUSED BY HAIYUAN M8.5 EARTHQUAKE IN 1920

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Abstract

As the direct inducement of all kinds of earthquake disasters, strong ground motion usually causes a large number of casualties and property losses through the form of building collapse, tsunami and earthquake landslide. In hilly region of Western China, the casualties from landslides triggered by strong earthquake could exceed a third of the total. The loess hilly region in the south of Ningxia， China， located on the Northwest edge of Qinghai-Tibet plateau, is a region with frequent seismic activities and the development of seismic geological disasters. According to historical records, there have been many strong earthquakes of magnitude 6 or above in the southern region of Ningxia, among which the Haiyuan earthquake of magnitude 8.5 in 1920 was the most recent one, which triggered a large number of loess landslides and caused heavy casualties. Especially in Xiji county and Jingning county, 80km away from the epicenter, the loess landslides triggered by the earthquake are distributed in clusters and densely. The geophysical investigation of landslide concentrated area shows that successive landslides are developed on loess hills with a gentle slope and cover thickness of about 10-40m. The soil layer on the side of successive landslides development on typical loess hills is thicker than the other side. Based on the calculation and analysis of the 2-D numerical model of the research site, it is concluded that the discrepancy of topography and overburden on both sides of the strip loess hill lead to different amplification effect of ground motion, which is one of the factors leading to the successive development of landslides on one of the hill side. A theoretical approach shows that regional geological conditions, such as continuous hilly slopes and loose overburden, seriously affect the distribution rules of ground motion in this area, and the unique hydrological environment promotes the cluster of loess landslides, which are concentrated in the areas with shallow groundwater level.

Keywords: earthquake ground motion, site effects, loess landslide, geophysical investigation, Haiyuan earthquake in 1920

1. Introduction

Many studies on seismic landslides show that the distribution pattern of landslides is mainly controlled by structural faults, so seismic landslides are distributed intensively in strips along the vicinity of seismic faults [1-2]. However, it is found that seismic landslide in loess region of Northwest China is not only related to the distribution of faults but also closely related to local site conditions [3-5]. For example, a profound earthquake in the loess region of China, 8.5-magnitude Haiyuan earthquake in 1920, formed several landslide dense areas within the seismic intensity of IX - XI, the area adjacent to Xiji and Jingning county in China is the most typical landslide concentrated area where large scale, clustered, and low sliding angle are the prominent characteristics of the seismic landslide. In 1995, Zhang et al [6] divided the seismic landslides in this area into three types: landslides caused by loess subsidence, landslides caused by loess liquefaction and landslides induced by strong ground motion. Since then, many researchers have classified the seismic landslides from different perspectives. Although researchers have different levels of understanding of the disaster mechanism of large-scale individual landslide, more and more studies have agreed that the dense development of landslide in this area is the result of multiple factors such as strong ground motion, vulnerability of loess, stratigraphic structure and topographic and geomorphic processes [7-8].

As the prime mover of earthquake damage, ground motion is affected by local topography, soil properties, rock structure and other factors, which can cause amplitude amplification and long-term duration increase in some frequency bands [9-10]. strong ground motion usually induces a large number of casualties and property losses through the form of building collapse, tsunami and earthquake landslide. The analysis of seismic damage and the records of strong ground motions have shown that the destructive seismic disasters in loess region are closely related to the amplification effect of strong ground motions, since loess with different geological ages and thicknesses cover on the surface of central and western China [11-12]. In this paper, the geological conditions and seismic site effect of dense development of landslide in Xiji county and Jingning county are comprehensively analyzed through field reconnaissance and numerical calculation.

2. Landslide distribution characteristics of Haiyuan earthquake

On December 16, 1920, an 8.5-magnitude earthquake occurred on the Haiyuan fault zone at the Northeast edge of the Qinghai-Tibet plateau. The extreme seismic intensity of this earthquake is XI degree or above (China earthquake intensity table), The death toll from the earthquake stands at more than 230,000[6]. The massive and numerous landslides caused by strong motion, has become one of the most important factors in the loss of life and property and might cause more than a third of total casualties. Figure 1 shows the location of successive development of landslides induced by Haiyuan earthquake, Xiji-Jingning landslide area.

Seismic intensity distribution of Haiyuan earthquake (Fig.1) shows that the isoseismal line of intensity XI along the long axis of the seismic fault, is much longer than the length of the short axis, and the distribution area of isoseismal lines on both sides of the fault is not symmetrical. Although the Haiyuan earthquake fault is a sinistral strike-slip fault, it has a certain inclination angle and the fault generally inclines to the south and west. Therefore, in the south and west of the upper plate, the seismic damage is more serious and the attenuation of intensity is slower.

Characteristics of loess seismic landslide caused by Haiyuan earthquake are summarized: (1) Seismic landslides are concentrated along the river system in a few long and narrow areas, among them, the maximum seismic landslide density in the Lanni river basin in the southeast of the extreme earthquake area can reach 4.124 /km^2 [5]. (2) The initial slope of the concentrated area of seismic landslides is about 10° - 25°. There are more landslides developed on the gentle slope covered with low-strength and high-moisture loess than on the steeper mountain area. (3) Massive seismic landslides mainly shown as arm-chair shape, tongue shape and irregular multi-section arc shape in plane form, and the small-scale seismic landslides are mostly fan-shaped.

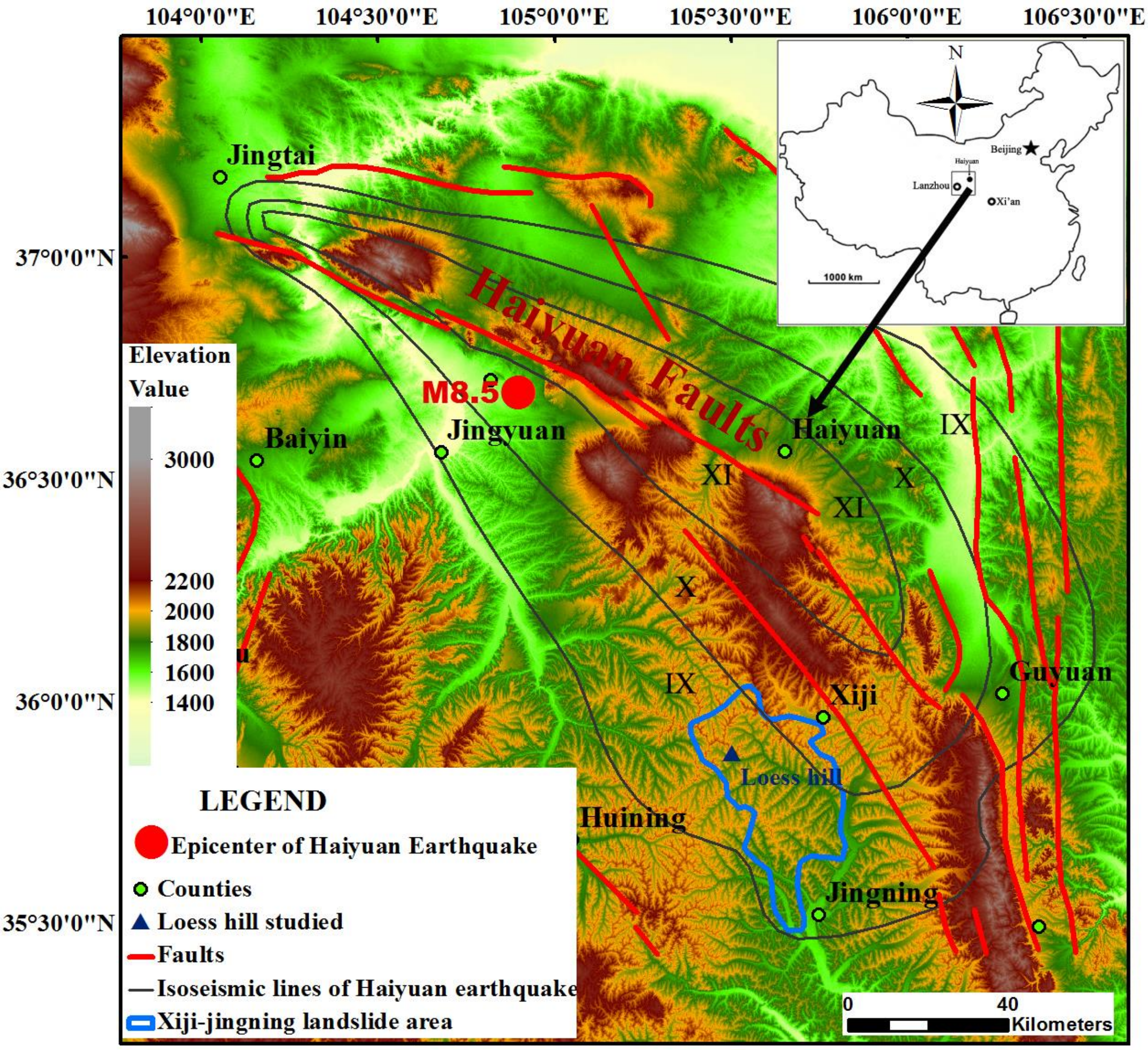


Fig.1 –Location of Seismic intensity and dense area of seismic landslides induced by Haiyuan 8.5 earthquake.

Macroscopical difference of earthquake damages is not only affected by the source mechanism but also related to the geological conditions on both sides of the faults zone. Seismic intensity of landslide dense area of Haiyuan earthquake is basically located in the IX region, according to the seismic wave attenuation theory, the intensity of bedrock in the IX region should not be stronger than near the epicenter. However, the number and density of landslide in the IX area were the highest, while those in the X and XI areas are lower. Local geological conditions such as gully topography and loose loess cover may be the main reasons for this phenomenon. The northeast part of the extreme earthquake area covered with a thin layer of soil, is mainly semi-desert low mountains and hills, gradually transiting to the flat semi-desert steppe. In the southwest of the extreme earthquake area, the front of loess terrace and hilly slope area covered with thick and loose loess, show high intensity seismic damage where landslides block rivers and form many dammed lakes. The research on earthquake damage shows that the strong ground motion is the main inducement of structural damage and geological disaster, and the geological and topographic conditions have significant influence on the ground motion in the earthquake area. The topography, soil properties, rock structure and other factors of the dense area of Haiyuan earthquake landslides determine that the seismic response of the area also has regional characteristics.

3. Numerical simulation of ground motion effect

It is found that the initial slopes of landslide concentrated area of Haiyuan earthquake are less than 20° (relatively gentle topography), and the underlying strata covered with loess about 10-40m are mudstones or sandstones formed in the Tertiary. Due to a significant impact on the ground motion from geological and topographic conditions, seismic response characteristics of the Xiji-Jingning landslide area is determined by local topography, soil properties and stratigraphic structure. In this paper, a strip loess hill with successive landslides development in one side (Fig.2) was selected and local area overlying layer thickness and wave velocities were investigated through shallow seismic exploration and microtremor test. Following is the 2D finite element analysis of the cross section of the loess hill.

Fig.2 – Loess hill with successive landslides development in one side

3.1 Finite element model-2D

In order to find out the influence of irregular topography and strata structure on the seismic ground motion of the loess hill, a 2D finite element model (Fig. 3) is established based on the cross section of the loess hill where the microtremor test was taken (Fig.2). The key part of the model is 870 m long and 103 m high, the angles of the slope on both sides were 17° and 13°. The thickness of the overburden is about 17m on the left side of the model, and on the right side, it increases gradually from 17 m to 40 m. The material parameters of the model are shown in Table 1.

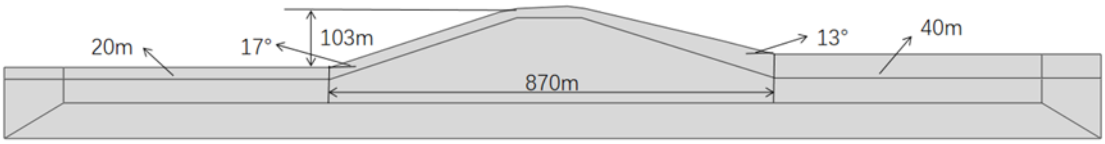


Fig. 3 – 2D-Finite element model of loess hill

Table 1 – Material parameters of the theoretical model

Lithology	Density (kg/m^3)	Elastic modulus (MPa)	Poisson's ratio	Cohesion value (KPa)	Angle of internal friction (°)
Loess	1500	160	0.3	40	25
Rock	2700	6500	0.25	-	-

Due to the finite element method has a finite calculation area, the method combining finite element and infinite element is selected to solve the boundary problem in dynamic analysis to avoid the reflection of seismic waves on the artificial boundary. The elastic model and the mohr-coulomb plastic model were selected for the constitutive relation, where the elastic model was suitable for the linear elastic element type, based on Hooke's law, and the parameters included Young's modulus and Poisson's ratio (Table 1).

3.2 Seismic wave input

When the magnitude 8.5 Haiyuan earthquake occurred in 1920, the epicenter of this study area was about 80km away, and the fault distance was about 30-40km, but no seismic records were obtained at that time. So, according to the consideration of magnitude and epicenter distance, the seismic records of Wenchuan 8.0 earthquake in 2008, with epicenter distance of about 80-90km are selected as the input seismic waves, which are Zhonghe wave obtained at the heading wall and Maoxian wave obtained at the hanging wall. During the calculation, the relationship between the mesh size of the model and the wavelength of the input seismic wave should be coordinated. The input seismic waves are processed by band pass filtering from 0.01 to 10Hz for the sake of the accuracy of the calculation, and the PGA of Zhonghe wave is $0.5m/s^2$, that of Maoxian wave is $2.8m/s^2$(Fig.4).

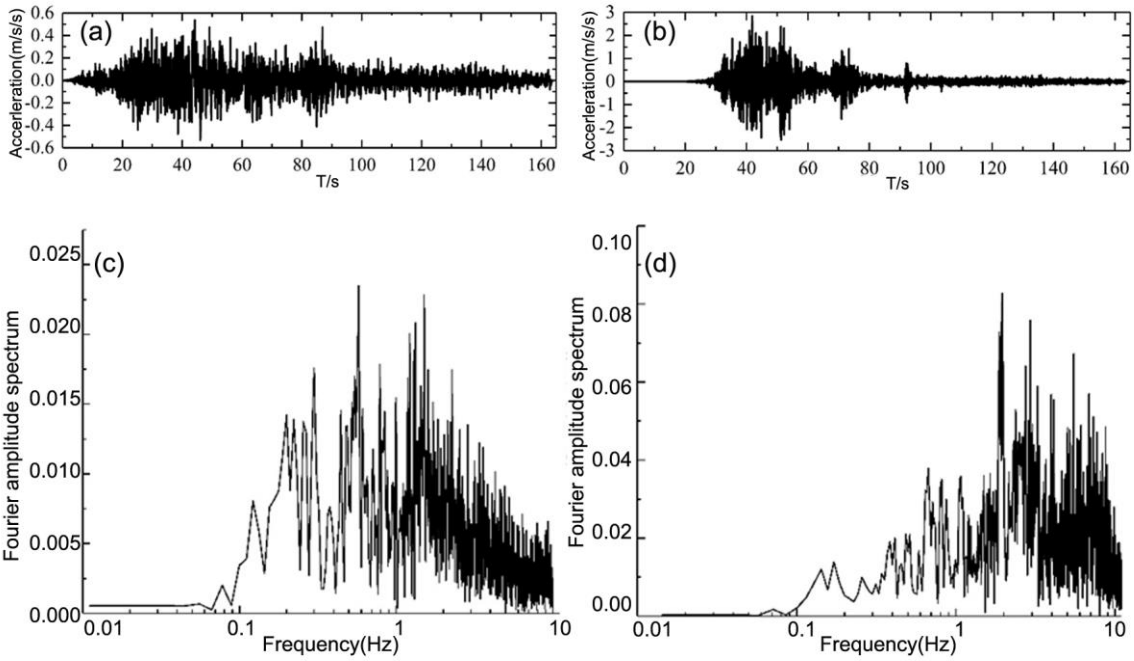


Fig. 4 – Time history and Fourier amplitude spectra of input seismic waves

(a) Time history of Zhonghe wave. (b) Time history of Maoxian wave.

(c) Fourier amplitude spectra of Zhonghe wave. (d) Fourier amplitude spectra of Maoxian wave.

3.3 Results of calculation

The time-history of ground motion at each point on the loess hill is obtained through the model calculation. Fig.6 shows the variation curves of PGA, factor of PGA amplification, PGV and PGD of ground motion at points with different soil thickness and topographic elevation on the transverse section of the loess hill. As the PGA of the input wave increases, so does the PGA of the surface (Fig.5(a)). Due to the dynamic nonlinearity of soil mass, when seismic waves with large amplitude are input, the amplification factor of PGA of surface is significantly reduced (Fig.5 (b)). The PGA on both sides of the ridge increases gradually with the increase of terrain elevation, and the larger value is not on the ridge, but on the shoulders on either side of the ridge. In fact, the maximum value of the loess hill appears on the right shoulder of the hill.

Although the slope on the right side is gentler than that on the left side, the PGA, PGV and PGD of the ground motion of the right shoulder show more significant amplification on account of the combined effect of the topography and the thicker loess (Fig.5 (a) (c) (d)). The maximum permanent displacement (Fig.6) appeared both on the right side, is 0.03m and 0.56m respectively under the action of two seismic waves. As a matter of fact, there were indeed a series of large and successive landslides on the right of the hill (Fig.2). it is concluded that the discrepancy of topography and overburden on both sides of the strip loess hill lead to different amplification effect of ground motion, which is one of the factors leading to the successive development of landslides on one of the hill side.

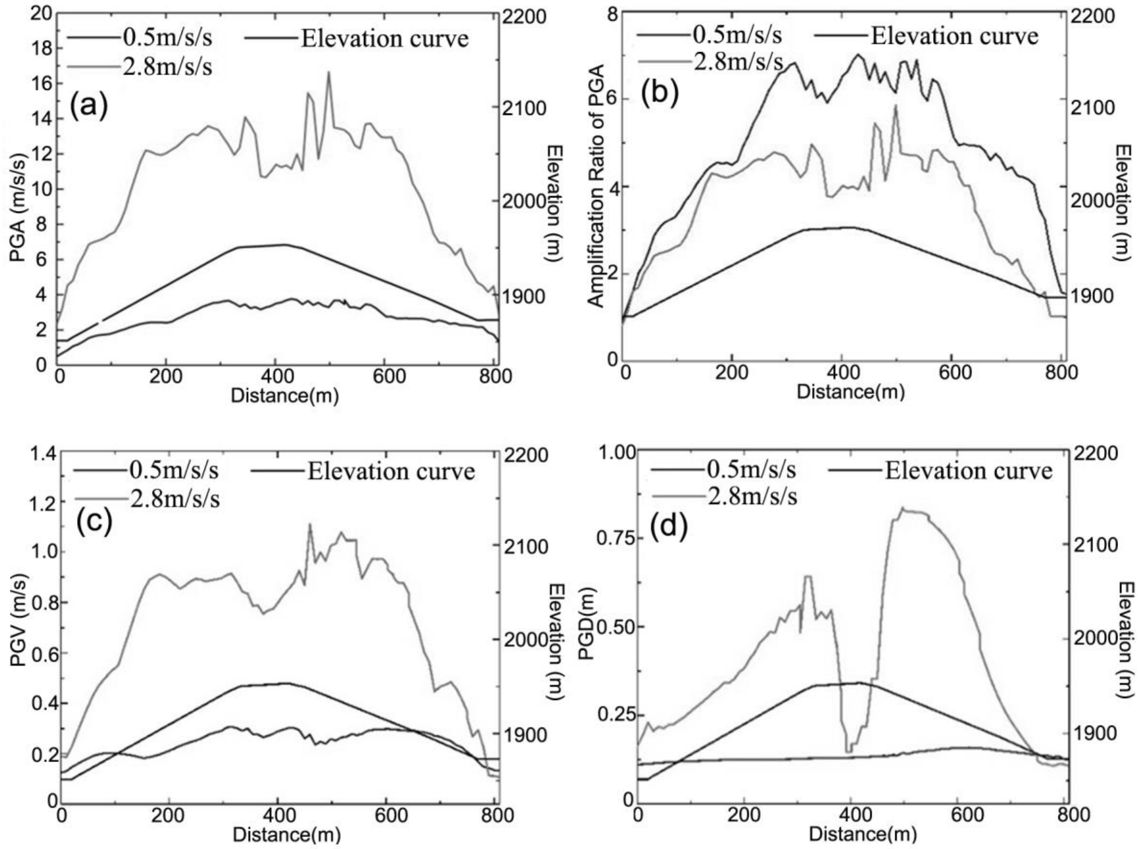
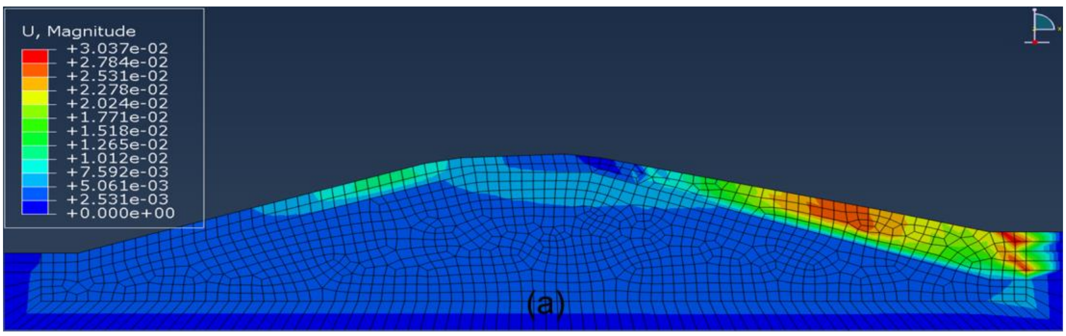


Fig.5 – Variation of ground motion parameters in cross section of loess hill

(a) Variation of PGA. (b) Variation of Amplification ratio of PGA.

(c) Variation of PGV. (d) Variation of PGD



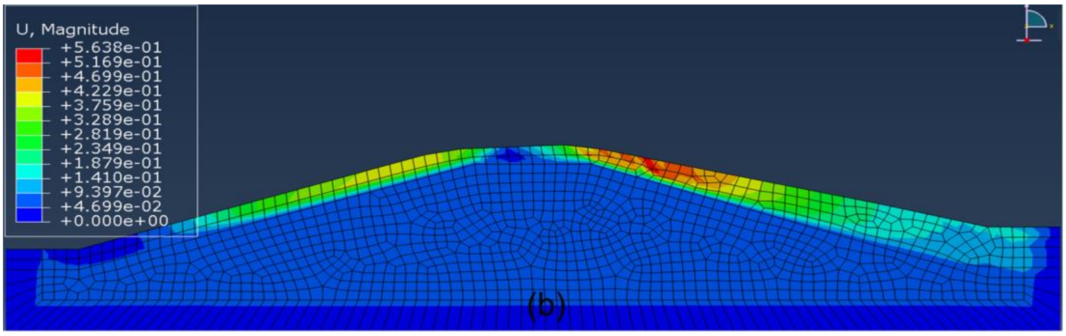


Fig.6 – Permanent displacement (Unit-m) of the model under the action of two seismic waves. (a) Input Zhonghe wave. (b) Input Maoxian wave.

4. Discussion and conclusion

Xiji-Jingning loess hilly region is located in the northwest edge of Qinghai-Tibet plateau. According to historical records, there have been many strong earthquakes of magnitude 6 or above in the region, the most recent of which was the 8.5-magnitude Haiyuan earthquake in China in 1920, which triggered massive loess landslides and caused heavy casualties. Especially in Xiji and Jingning counties, the large-scale loess landslides triggered by the earthquake are densely distributed in certain areas. It has been proved that this porous and weakly consolidated quaternary sediment of loess may aggravate the earthquake disaster in loess region, loess landslide which destroyed villages and roads and formed dammed lakes, is the main form of geotechnical earthquake disaster. Except Ningxia Haiyuan 8.5 earthquake, many other strong earthquakes, such as 1556 Shanxi Huaxian earthquake of magnitude 8, 1654 Gansu Tianshui south 8 earthquake, 1718 Gansu Tongwei earthquake of magnitude 7 above, 2013 Gansu Min-Zhang 6.6 earthquake et al occurred in the loess area, causing serious geotechnical seimic disaster and loss of life and property. It is believed that most of the loess landslides induced by earthquake are caused by the combined amplification of local site velocity structure and topographic factors. Therefore, it is necessary to make a clear understanding of the characteristics and mechanism of seismic damage in loess regions with strong neotectonic movement for engineering construction and disaster assessment.

The following conclusions are obtained through the above research:

(1) Due to the difference between the physical properties of the loose overburden and the underlying hard rock strata, ground motion amplification will be caused, which is called stratigraphic site effect. Amplification of ground motion caused by the local irregular terrain is generally called the topography site effect. The surface of the study area is generally covered with thick loose loess layer of late pleistocene, and there are relatively hard tertiary mudstone and sandstone strata below. The surface morphology is dominated by loess hills and valley terraces. Variation of ground motion in Haiyuan earthquake landslide concentrated area is determined by the topography, geotechnical properties, soil structure and other conditions.The seismic amplification of the surface is intensified by the combination of the stratigraphic site effect and the topographic site effect, and increases the power to trigger the seismic landslide

(2) The typical loess hill selected in this paper is a strip ridge with different slope angles on both sides and uneven thickness of loess soil. Numerical calculation shows that the shape of the loess hill base and the thickness of its loose overburden can amplify the ground motion in different frequency bands. At the same time, the real earthquake landslide also developed in the thick side of the soil layer. There is no doubt that ground motion amplification is one of the reasons for the massive and successive landslide on one side of the mountain.

(3) In addition to the impact of fault rupture mechanism and attenuation distance, the ground motion in the dense area of Xiji-Jingning landslides is largely related to the amplification effect of ground motion field caused by topography, soil properties and velocity structure. Based on the comprehensive study, it is

concluded that the regional geological conditions such as hilly slopes and loose surface overburden affect the distribution rules of surface ground motion in this area, while the unique hydrological environment promotes the loess landslides to be clustered together, and the seismic landslides mainly develop along the river system and develop in the narrow and long area with shallow underground water level.

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