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# Amplification of thickness and topography of loess deposit on seismic ground motion and its seismic design methods

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## Abstract

The Loess Plateau in China is a region with the biggest thickness and most complicated topography of loess deposit in the world, where is affected by strong earthquakes frequently. The seismic amplification effects were discovered in the Plateau during the Wenchuan Ms8.0 earthquake and some other strong events. The field investigations, observations, and analyses indicated that large number of casualties and tremendous economic losses were caused not only by collapse and damage of houses with poor seismic performance, landslides, liquefaction and seismic subsidence, but also amplification effects of thickness and topography of loess deposit on seismic ground motion. In this paper, the characteristics of strong ground motion recorded in the region were analyzed; shaking table tests were performed and numerical analysis was carried out on amplification of thickness and slope of loess deposit on seismic ground motion. Moreover, we also developed site amplification factors of ground motion for seismic design of engineering projects on loess sites. The results showed that the amplification effects are more predominant with increase of thickness and slope of loess deposit. The ground motion may be amplified in seismic intensity by 1-2 degree, PGA by 1.1-2.2 times, and predominant period by 1.1-1.6 times respectively.

Keywords: Loess Plateau; Site effect; Deposit thickness; Topography; Shaking table tests

## 1. Introduction

The Loess Plateau is seated on the upper and middle stream of the Yellow River in northern China, covering an area of 440,000km<sup>2</sup> with the thickness of loess deposit ranging from several meters to more than 500 meters. The Plateau is one of the most tectonically active areas of the world and also one of the most seismically active regions (see Fig. 1). There were 367 earthquakes with magnitude greater than Ms5.0 occurred in the region from B.C. 78 to Dec. 31, 2016. Among them, there were 7 events with the magnitude no less than Ms8.0, 20 events with the magnitude between Ms7.0-7.9; and 71 events with the magnitude between Ms6.0-6.9. More than 1.4 million people were killed by the earthquakes in the region.

Along with “The Belt and Road” initiative practicing, a large number of construction projects and a large scale of urbanization have been carrying out in the Plateau and its adjacent area. However, site effects of loess deposit have not been well considered in seismic design of those projects due to lacking a systematic and quantitative study on it. Wang and Wu (2010, 2013) found that the amplifications of ground motion on loess deposits were remarkable and caused additional damages in the Plateau during the strong quakes in these areas [1,2]. In this paper, in order to study the amplification effect of loess thickness and topography on ground motion from far-field earthquakes, a field investigation, strong motion observation, shaking table tests and numerical analysis were overall carried out. Firstly, the

characteristics of seismic ground motion in the Plateau and its adjacent area were studied based on the investigations on the Wenchuan Ms8.0 earthquake and the Minxian-Zhangxian Ms6.6 earthquake, including field intensity evaluation, borehole exploration, and observation of temporary strong motion array. Secondly, shaking table tests and numerical analysis on amplification of thickness loess deposit were carried out. Thirdly, the curves of the amplification of PGA and characteristic period, at which the normalized seismic response spectrum curve begins to go down, versus thickness and slope of loess deposit were presented. Finally, the amplification factors of PGA and extended characteristic periods, which are characteristic periods increased by amplification effect, for different thickness and slope of loess deposit were proposed for a basis of seismic design in the Loess Plateau areas.

## **2. Phenomena of amplification of loess deposit**

The Wenchuan Ms8.0 earthquake in 2008 and the Minxian-Zhangxian Ms6.6 earthquake in 2013 caused enormous buildings, houses, and infrastructures collapsed or seriously damaged [1-3]. The Wenchuan Ms8.0 earthquake also triggered more than 12,000 landslides, collapses and mudflows, which dammed more than 30 quake lakes. During the two earthquakes, the phenomena of site effects on ground motion were remarkable both in the mountainous area of southeastern Gansu province and the Loess Plateau area within range of 200km to 670km away from the epicenter. In Haoping village on the top of a loess mountain, Longnan city of Gansu province, most all the houses collapsed due to an earthquake effect of VIII-IX degree intensity (Chinese seismic intensity) caused by amplification of loess mountain topography on ground motion, where is about 250km away from the epicenter of the Wenchuan earthquake (see Fig. 2). While all the houses in Liujiabu village with the same structure as those in Haoping village basically kept in good condition, where is 326m lower than Haoping village at nearly the foot of the mountain. The latter shown an less earthquake effect of VII degree. The other typical case shows a significant amplification effect of loess deposit thickness on ground motion. In Qingyang city, Gansu province, high reinforced concrete buildings, chimney, tombstones as well as dwelling caves in loess deposit were damaged by an earthquake effect of VII degree during the Wenchuan earthquake due to a remarkable amplification of thick loess deposit of about 300m on ground motion, where is 670km away from the epicenter of The Wenchuan earthquake (See Fig. 3). Even resonant effect of extended predominant period components made the damages more serious. The field investigation shown that in the mountainous areas, earthquake intensity on the top of mountains was higher than that at the foot of mountains by 1 degree at least. On a loess Yuan, which was one of typical topographies in Loess Plateau, a high table-like plain of thick loess deposit with abruptly descending edges, houses and buildings on the top of loess Yuan damaged seriously, even if where is located at more than 600 kilometers away from the epicenter. However, those at the valleys kept in good condition,

The Minxian-Zhangxian Ms6.6 earthquake is the largest one since the 1954 Shandan Ms7.2 earthquake occurred in Gansu province. The quake affected 13 counties, caused 95 persons dead, 2414 injured, 314,120 people homeless. The quake-hit area situates in the northeastern edge of the Tibetan Plateau, where is the transition region among the Gannan Plateau, Loess Plateau and Longnan mountain area. The landform there is quite complicated and dominated by mountains, gulleys and rivers valleys. The earthquake intensity in the meizoseismal area of 706 km<sup>2</sup> is VIII degree (the Chinese Seismic Intensity with 12 degree). Meanwhile, the area of intensity equal or greater than VI degree reaches up to 16432km<sup>2</sup>, which is larger than that caused by an earthquake with similar magnitude occurred in the other regions in general. In the area of VIII degree, the ground surface is covered by loose and thick loess deposit. The earthquake induced more than 600 landslides, collapses and seismic subsidence in loess deposit. During the quake, houses on the top of mountain damaged seriously. However, those at the valleys kept in good condition.

Dazhai Village in Pingliang City and Majiagou Village in Minxian City, Gansu Province are chosen as two typical loess sites for the Wenchuan earthquake damage investigation (see Fig. 4) and for the Minxian-Zhangxian earthquake damage investigation respectively (see Fig. 5). According to Wu et al. (2009) and Wang et al. (2013) [1,4], earthquake intensities on the top of mountains were higher than that at the foot of mountains by 1 or 2 degree due to the amplification effects of thick loess deposit on the top of loess Yuan or mountain.

### 3. Strong-motion data and site amplification in loess region

#### 3.1 Strong motion data in loess region

The National Strong Motion Observation Network System of China (NSMONS) was proceeded to build in 2007[5]. Geophysical Background Strong Motion Station Network and Lanzhou Early-warning Strong-Motion Station Network were constructed in 2013. These digital strong ground motion networks consist of 144 stations in loess region including province of Gansu, Shanxi, Shaanxi, Qinghai and Ningxia Autonomous Region (see Fig. 6). Since 2008, NSMONS has recorded more than 34 earthquakes with  $M_s > 3.0$  in loess region, including the Wenchuan  $M_s$  8.0 earthquake (Wenchuan EQ) and the Minxian-Zhangxian  $M_s$ 6.6 earthquake (Minzhang EQ). More than 900 time histories of strong-motion components from the main shocks of the two earthquakes and their aftershocks were recorded by NSMONS in loess region. The maximum peak ground acceleration in loess region is up to 185gal, recorded by the 62WUD station 306km away from the epicenter in Wenchuan EQ. The Minxian-Zhangxian  $M_s$ 6.6 earthquake occurred on the southern edge of the Loess Plateau. Ground motions from the main shock of the Minzhang EQ were observed at 64 stations and more than 270 time histories of strong motion components recorded by NSMONS, among which the maximum PGA is 177gal at the 62MXT station where is 17 km away from the epicenter [6,7].

Site effects on ground motion can be analyzed with strong-motion observatory data. The Wenchuan EQ shows obvious topographical effects and far field effects which mean amplification effect of long period component of ground motion in the loess region far than 200km away from the epicenter. The effect of deposition thickness and topography on seismic ground motion is also remarkable in the quake-hit area shown by the Minzhang EQ. Here the effect of deposition thickness on ground motion was analyzed by the reference station method, and the effect of topographic factors on ground motion amplification was studied based on the records from temporary strong motion array [8,9].

#### 3.2 The effects of loess deposition thickness on ground motion

Based on the reference station method [10], the stations on bedrock and the stations on soil layer with the similar epicentral distance and azimuth were selected to evaluate the influence of the deposition thickness on the characteristics of ground motion. Since the stations on bedrock of NSMONS are very rare in loess area, 62WUD and 61YLT station were selected as the research sites for ground motion amplification. While 62WIX, 62ZHQ and 61TAY stations were used as the reference stations on bedrock sites, considering stations distribution, deposition thickness and recorded strong motion data. Strong ground motion data recorded in Wenchuan EQ and Minzhang EQ were selected to analyze site effects of the deposition thickness on ground motion. The seismic events, strong motion records and station information are shown in Table 1.

62WUD station is located in a valley of Bailongjiang river, where the thickness of loessial sediment is about 65m [8]. The 62WIX bedrock station near the 62WUD is located in a bedrock cave in Wenxian County, which is about 8 meters deep. However, the strong motion accelerograph is installed at 4 meters away from the cave entrance, of which the records can be considered as outcropping motion. The epicenter of Wenchuan EQ and the two stations are located in the same line. The distance between the two stations is about 55km. 62ZHQ bedrock station is located in Zhouqu County of Gannan Tibet autonomous district. It has almost same azimuth of 62ZHQ station during Minzhang EQ. The distance between the two stations is about 68Km. 61YLT station is located on the Loess Yuan of Guanzhong basin of Shaanxi Province. According to the results of the seismic microzonation project of Yangling County, the loess deposition thickness of 61YLT station is about 120 meters [11]. 61TAY station is located on the bedrock site of the northern foot of Qinling Mountains. The distance between 61YLT and 61TAY stations is 22Km. The relative locations of the epicenter of Wenchuan EQ and Minzhang EQ and the selected strong motion stations are shown in Fig. 7.

The ratio of PGA amplification of the stations on soil sites are listed in Table 1. The ratio of PGA and response spectra between the stations on soil sites and the reference stations on the bedrock were calculated. It is indicated schematically in Table 1 that the site amplification of 61YLT station with larger deposition thickness is higher than that of 62WUD during the main shocks of Wenchuan EQ and Minzhang EQ. As shown in Fig.8, the peak acceleration ratio

and response spectra ratio of 61YLT are 2.3~3 times of 62WUD. And the amplification of predominant period at 62WUD station is 0.3~1s, while the amplification range at 61YLT station is 1~4s. With the increase in deposition thickness, the predominant period of spectra ratio tends to be longer. For 61YLT station site, the Wenchuan EQ and MinzhangEQ are far-field earthquakes, epicentral distance is longer than 500km, site amplification effects of 61YLT in long periods were significantly higher than that of 62WUD.

### 3.3 The effects of loess topography on ground motion

After the Wenchuan earthquake, a temporary strong motion array consisting of three stations was installed near the Wenxian County town. Three observation stations were installed on the same deposit, but at different locations of a mountain: the bottom (N 32.94°, E 104.70°, altitude: 927 m), the middle (N 32.95°, E 104.67°, altitude: 960 m) and the top (N 32.94°, E 104.67°, altitude: 969 m) of the mountain (Fig. 9). From May 27 to June 28, 2008, 9 aftershocks were recorded by the temporary strong motion array [1,4]. Based on the strong motion observation data, the effect of mountainous topography on ground motion can be obtained. Table 2 presents the PGA values of 9 events at three stations and the amplification factors of PGA at the top and middle observation stations comparing to that at the bottom station. It shows that almost all the PGA at the top station are greater than that at the middle station, while the values at the middle station are all slightly greater than at bottom station, except for the event on June 5, 2008.

Based on the recorded strong motion data of Ms5.7 aftershock on May 21, 2008, average acceleration response spectrum (thin lines) of three observation stations and the top and middle observation station average response spectra ratio (thick lines) comparing to the bottom station were calculated shown in Fig. 10. It may be seen that both the PGAs increase and predominant periods tend to be longer with increase of the slope height. The ground motion amplification on the top station reached to the maximum value near the resonant frequency of the site. Due to the influence of rupture direction of the main shock on ground motion propagation, PGA of NS components were larger than the EW components, so were the response spectra.

## 4. Shaking table tests of the loess site amplification effect

During the Wenchuan earthquake in 2008, the seismic intensity of the Dazhai village of Pingliang City in Gansu province is as much as VII degree, which is one degree higher than that of the surrounding areas. However, the village is about 550 kilometers away from the epicenter. The previous study shows that the amplification effects of ground motion caused by thick loess deposit are the main cause of intensity anomaly [1,2]. In order to study further the quantitative amplification law of loess thickness on ground motion, shaking table tests were performed for loess models with different thickness under different seismic loadings in this paper.

### 4.1 Experimental equipment

The shaking table equipment of the Key Laboratory of Loess Earthquake Engineering, CEA was employed for the model tests. This equipment has a table with the size of 4m×6m, the maximum load of 25 ton, horizontal and vertical running directions, and driven by 24 servo motors. Its maximum acceleration, velocity and displacement is 1.7 g, 1.2m/s and ±50cm respectively. The regular waves and irregular waves can be inputted. The table effective frequency range is 0.1 Hz ~ 70 Hz. In order to reduce the boundary effect of the model tests, a laminar shear soil container with a size of 1.5 m × 1.5 m × 1.4 m was used in tests.

### 4.2 Similarity design and model parameters

Based on the loess deposit of Dazhai Village (Table 5), the generalized model of horizontal free field models with different loess thicknesses of 50m, 80m and 110m were established. There was a 20 meters thick mudstone layer beneath the loess layer. The geometric similarity ratio was determined as 100:1 according to the size of the shear soil container, the corresponding elastic modulus, density and other similar ratio were determined according to Lin Gao's elastic similarity rule [12] after the relevant literatures of Clough&Pirtz (1956) [13] and Kagawa (1978) [14], which are shown in table 3.

Based on the similitude, the loess thicknesses of tested prototypes were respectively designed to be 50cm, 80cm,



and 110cm, and the bottom layer was set up with 20cm thick mudstone. The mudstone of the model was made of cement, sand, red iron powder, clay and water according to the ratio of 1.22%, 56.25%, 33.75%, 1.88% and 6.75% of the material. The upper Overlying loess of the tested models was made by remodeling loess, barite powder, sawdust, water in accordance with 73%, 20%, 2%, 5%. The parameters of the prototype models were determined by laboratory tests shown in Table 4. Three models of loess sites with a total height of 70cm, 100cm and 130cm are made with the above-mentioned materials respectively. For each model, four sets of acceleration sensors with horizontal and vertical directions are amounted in different heights of the model shown in Fig. 11.

#### 4.3 Seismic wave and condition loading

The time histories of accelerations recorded in Wenxian county and Tangyu town were employed in the tests, where are respectively about 100 kilometers and 544 kilometers away from the epicenter during the main shock of the Wenchuan EQ. They are respectively called as Wenxian wave and Tangyu wave for short in the paper. The Wenxian wave has higher frequency spectral components and a stronger energy distribution in a frequency range from 0.1Hz to 23Hz with a predominant frequency of 3.67Hz. The energy of Tangyu wave is mainly concentrated in the lower frequency range with a predominant frequency of 0.5Hz (Fig.12). Due to the difficulty of quantifying radiation damping, the effect of radiation damping has not been taken into account in the shaking table tests.

According to the current seismic zoning map of China, the seismic design ground motion is generally between 0.05 and 0.3g in loess deposit region. In order to investigate the dynamic response characteristics of different loess deposit thickness sites under different loadings, three amplitudes of 50gal, 100gal and 200gals for the Tangyu and Wenxian waves were respectively applied from low to high intensity level during the tests.

The dynamic response of a site is determined by the characteristics of the ground motion, the site characteristics and the coupling effect between them. In order to ensure that model tests would appear similar to the dynamic response of prototype, and Wenxian and Tangyu acceleration histories were compressed in a 10:1 ratio.

#### 4.4 Variation of site natural frequency characteristics

Transfer function is the expression of the dynamic characteristics of the vibration system in the frequency domain, which is determined by the dynamic characteristics of the system. Therefore, the model kinetic parameters can be calculated by the transfer function in shaking table model test [15]. If the acceleration time history of the bedrock surface under the loess layer is  $\ddot{u}_b$ , the relative acceleration of the j point on the loess layer surface is  $\ddot{u}_j = \ddot{u}_j - \ddot{u}_b$ , then the relative acceleration transfer function of j point is:

$$H_a(\omega, z_j) = \frac{G_{xy}(\omega, z_j)}{G_{xx}(\omega)}$$

(1)

where  $G_{xx}(\omega)$  is the self-power spectrum of  $\ddot{u}_b$ ,  $G_{xy}(\omega, z_j)$  is the mutual power spectrum of  $\ddot{u}_j$  and  $\ddot{u}_b$ ,  $\omega$  is wave frequency,  $z_j$  is the location of j point. The peak value of  $H_a(\omega, z_j)$  is the predominant frequency of the site.

It can be seen from Fig.13, the frequency spectrums of transfer function of different deposit thicknesses are significantly different. With increase of deposit thickness, the range of response spectrum becomes narrower, amplitude of the spectrum decreased in higher frequency section, and the predominant frequency of the site gradually shift to the lower section. For the loess thicknesses of 50cm, 80cm and 110cm, the predominant frequencies of the models are determined as 15.4Hz, 13.4Hz and 9.2Hz respectively from the three red curves of 50gals in Fig.13, in which the models have no damage. Because a similar design was done, the corresponding predominant period of simulated loess sites can be calculated as 0.65s, 0.75s and 1.08s respectively from the following formula:

$$T_p = \frac{C_t}{f_m} \quad (2)$$

Where  $T_p$  is the predominant period of prototype loess site,  $C_t$  is time similarity ratio,  $f_m$  is the predominant frequency

of model site. Fig.14a shows that the trend of the predominant period of simulated site through model test versus the thickness obtained by shaking table tests are basically close to that calculated by equivalent shear wave velocity. But their variation rules are different. The former almost changes linearly, while the latter has strong nonlinearity which can be expressed by the following formula:

$$T_p = 0.0002H^2 - 0.0182H + 1.1617 \quad (3)$$

here  $T_p$  is the predominant period of simulated loess site,  $H$  is its thickness.

It is also shown in Fig.14b that all the predominant periods of loess sites with different thicknesses increase with increase of the peak acceleration of loadings, which may become longer from 0.65s to 0.80s, 0.75s to 0.90s, 1.08s to 1.70s for different thicknesses of 50m, 80m, 110m under the loadings of 50gal, 100gal, and 200gals. This phenomenon may be attributed to cumulative damage of soil mass and deterioration of dynamic performance of soil, which can be expressed by the following formula:

$$T_p = a \times \ln(\text{PGA}) + b \quad (4)$$

here  $a$  and  $b$  are constants in the formula, PGA is peak acceleration of ground motion. From the formula (4), we can see that with the increase of PGA, some damage occurs to soil body. Correspondingly there is a nonlinear increase in the predominant period of loess site.

#### 4.5 Amplification effect of thickness

Taking the PGA values of bedrock surface as a base line value, the PGA amplification factor of the free field was calculated. The relationships between amplification factors and deposit thickness under dynamic loadings of Wenxian wave and Tangyu wave are presented in Fig.15. It shows that the variation patterns of amplification factors versus deposit thicknesses under different loading waves and the variation patterns of amplification factors versus peak accelerations with different deposit thicknesses are similar, which is that all amplification factors increase with increase of loess thickness and decrease with increase of peak acceleration. Generally speaking, when the thickness increases from 50m to 110m, the amplification factors increased from 1.52 to 2.34. However, the values of amplification factors of PGA were obviously different under different loading waves and different peak accelerations. The Wenxian wave with a wider spectrum had stronger PGA amplification effects than that of Tangyu wave. The decreasing of amplification factors with increasing of peak accelerations of loading might be due to damage of soil mass under stronger loadings.

These tested results verify that the phenomenon that earthquake intensity was amplified by 1 degree or more due to topography of loess mountains. For loess Yuan with thicknesses of 50m-110m, the peak acceleration of ground motion may increase to 1.52-2.34 times. The predominant period of ground motion may extend to 1.10-1.66 times. The resonant effect of high-rise buildings may be generated.

## 5. Numerical analysis on amplification of loess deposit

### 5.1 Geometric model and boundary conditions

In order to study systematically amplification effects of loess deposit, a numerical analysis was carried out to provide a quantitative basis for seismic design of engineering projects on loess sites. Loess is a nonlinear material, of which shear modulus decreases and damping ratio increases with the increase of shear strain. In this analysis, the methods proposed by Mei et al. (2010) and Wang et al. (2012) were employed for a two-dimension finite element dynamic analysis, considering characteristics of free-field soil and its nonlinearity [16,17]. By using an equivalent shear modulus and damping ratio instead of all the shear modulus and damping ratio under different strain amplitude in numerical calculation, thus the nonlinear dynamic calculation transforms into a linear problem. The elastic-plastic Drucker-Prager constitutive relation was used to describe the loess, the linear elastic model was used for bedrock, and the assumption of the plane strain was used by foundation. The infinite element boundary was adopted as the boundary condition while a viscous boundary was employed as the bottom condition to prevent the reflection effect of seismic

wave at the artificial boundary. The time history of acceleration was inputted in horizontal direction at the bottom of the model. The model parameters include the corresponding dynamic shear modulus, damping ratio, internal friction angle and cohesion of loess and bedrock were determined by laboratory dynamic triaxial tests (Table 5). There's no doubt soil damping ratio is very important to evaluate the amplification effects of loess deposition thickness.

The standard model was established for simulating the loess deposit of Dazhai village on a loess Yuan shown in Fig. 16, in which the calculated grid size is  $2.5\text{ m} \times 2.5\text{ m}$ . It can meet the requirement of accurate simulation for stable propagation of seismic waves in the model. The model parameters were set up based on Table 5. For purpose of comparison, five positions, A, B, C, D, E, were respectively chosen at the foot, middle, the top edge of the slope, as well as the two locations on the top of the slope respectively with 1 times and 5 times of the slope height away from the top edge.

### 5.2 Effect of slope

Given a fixed loess thickness of 50m, five cases with different mountain slopes of  $20^\circ$ ,  $30^\circ$ ,  $45^\circ$ ,  $60^\circ$  and  $70^\circ$  were analyzed for the model. The input seismic motions were horizontal acceleration time histories of EL-Centro, Wenxian and Tangyu waves (Fig. 17). The maximum value for its acceleration time-history were applied to  $70\text{cm/s}^2$ , that is the maximum value of intensity of frequently occurred earthquake, VIII degree, used in time-history analysis of ground motion according to “Code for Seismic Design of Buildings” of China [18].

The PGA values and amplifying factor at different locations of the loess deposit with different slope are shown in Figure 18 and Figure 19. The results indicate that slope effect is predominant. All the PGA values at the top are greater than that at the middle of the slope model, and the values at the middle are greater than those at the bottom. The PGA magnification of Site-A are between 1.1-1.3 times, and those for Site-B and Site-C are between 1.3-1.5 times and 1.5-2.0 times respectively. While the acceleration values on the top plain of the loess Yuan show a decreasing trend with the increasing of the distance away from the top edge of the Yuan. The PGA magnification of Site-D and Site-E are between 1.2-1.3 times and 1.1-1.2 times respectively. Fig. 18 also indicates that the amplification increases with increasing of the slope angle, and the loess mountain with a slope ranging from  $60^\circ$ - $70^\circ$  has the most significant amplification effects on seismic ground motion, which may increase PGA by an amplification factor of 2.

### 5.3 Effect of loess thickness

In order to evaluate the effect of loess thickness on amplification, simulations were performed on the 2-D models with a slope of  $45^\circ$  and different thickness of loess deposit, which are 20m, 40m, 60m, 80m, 100m, 120m, 160m, 200m, and 240m, respectively. The input seismic ground motion was the horizontal acceleration time history of Wenxian wave as shown in Fig. 17(b).

The PGA values at points A through E corresponding to nine different thicknesses of loess deposit are presented in Figure 20 and Figure 21. All the PGA values at the top are greater than that at the middle of the slope model, and the values at the middle are greater than those at the bottom. The acceleration values show the decreasing trend with the increasing of the distance away from the top of mountain edge. The PGA magnification of Site-A are between 1.1-1.2 times, and those for Site-B, Site-C, Site-D and Site-E are between 1.2-1.6, 1.5-2.1, 1.1-1.5 and 1.1-1.2 times respectively. Because slope edge effect dominates at point Site-A, Site-B and Site-C, and the PGA value at Site-D is similar to that at Site-B. Consequently, the Site-E has so smaller amplification effect of slope that it can be ignored in seismic design. Therefore, we only study the influence of loess deposit thickness on ground motion at Site-E.

At the same time, we calculated the characteristic periods of response spectrum according to the “Specification of Seismic Design for Highway Engineering” of China [19]. The characteristic periods get longer with the increase of the loess deposit thickness shown in Table 7. Here the effect of soil thickness on the characteristic periods of the site is focused on. Based on the research results discussed above, a method of taking the amplification effects of characteristic period of thickness of loess deposit on ground motion into consideration in seismic design of buildings and infrastructures on loess sites has been developed. The characteristic period gets longer from 0.55s to 0.70s with the increase of the loess deposit thickness.



## 6. Suggestions of seismic design method

Based on the above-mentioned field investigation, ground motion observation, shaking table tests and numerical analysis results, a method of taking the amplification effects of both thickness and topography of loess deposit on ground motion into account in seismic design of buildings and infrastructures on loess sites has been developed.

As can be seen from Fig. 22a, the amplification factors of PGA from different sources basically increase with the increase of loess thickness. Taking into account the observed values of the site (from Table 1 and Table 2, the average of PGA amplification factor between 32m and 120m, the model test values and numerical calculation values, the design values of PGA amplification factor between 30m and 120m is obtained. The design values with the other thicknesses of loess are mainly based on numerical calculation values. In order to facilitate the engineering application, finally, the PGA amplification design values with different thicknesses of loess deposit are proposed in Table 7. Correspondingly, the site characterization period between 40 to 80 meters was figured out based on model test values and numerical calculations in Table 7. After 80 meters, the difference between the model test value and the numerical calculation is quite large. Considering the scale effect of the test model, the characteristic period of the site between 80 to 120 meters is mainly calculated based on the trend of 40 to 80 and the numerical analysis result.

For buildings on the top of loess mountains, the site effects on ground motion and influence of seismic landslides should be considered. The buildings should be set back with a certain distance from the slope top edge, which should be at least 5 times of the height of slope away from the top edge of the mountain for avoiding both significant amplification effect of ground motion and influence of landslides. If the buildings could not meet the required safety distance, the amplification effect of ground motion has to be taken into account in seismic design. In this case, the horizontal earthquake influence coefficient for seismic design is proposed to be adjusted by multiplying an amplifying factor presented in Table 6 according to the site conditions of loess slope shown as Figures 15 and Figures 16. Thus, the PGA amplifying factors of  $20^{\circ}$ - $30^{\circ}$  are 1.1-1.3, and those for  $30^{\circ}$ - $45^{\circ}$ ,  $45^{\circ}$ - $60^{\circ}$  and  $60^{\circ}$ - $70^{\circ}$  are 1.3-1.5, 1.5-1.7, and 1.7-2.0 respectively. For important buildings at the top and foot of loess mountains, seismic safety evaluation for construction sites should be carried out.

For the loess site with a deposit thicker than 20m without topographic influence, the amplification effects of ground motion should be considered and the horizontal earthquake influence coefficient for seismic design should be adjusted by multiplying an amplifying factor according to the thickness of loess layer shown as Table 7. Thus, the PGA amplifying factors of 20-40m are 1.2, and those for 40-60m, 60-90m, 90-120m, 120-180m, 180-240m and more than 240m are 1.4, 1.6, 1.8, 1.9, 2.0 and 2.2 respectively. And the characteristic periods of different loess deposit thickness are shown as Table 7. The characteristic period of 20-40m are 0.55s, and those for 40-60m, 60-90m, 90-120m, 120-180m, 180-240m and more than 240m are 0.63s, 0.68s, 0.72s, 0.73s, 0.74s and 0.75s respectively.

In the current Chinese national code, “Code for Seismic Design of Buildings” (GB50011-2010, 2016 Version) [20], there is no special regulation on site effect of loess sites on ground motion. In the code, a regulation on amplification factor of 1.1-1.6 of topography and extended characteristic period of 0.45-0.65s for Sites III and 0.65-0.90s for Sites IV based on both thickness and shear wave velocity on ground motion are set only for general thick and soft soil sites and a special study for a specific loess site is required to be carried out. However, loess sites are usually classified as Sites II or III based on its shear wave velocity and thickness, rather than Sites IV. That is to say, only the extended characteristic period of 0.45s-0.65s can be considered. The current code of Gansu province, “Specification for Seismic Design of Buildings” (DB62/T25-3055-2011) [20] has adopted the research achievement present by the authors. In the code, the amplification factors of thickness of loess sites without topography influence are taken as 1.1, 1.2 and 1.3 corresponding to the loess thickness of 50-100m, 100-200, and  $\geq 200$ m. Buildings on the top of loess mountains and at the foot of loess mountains should be set back respectively at least 5 times of the height of slope away from the top edge of the mountain and 1.5-2.5 from the foot of loess mountains for avoiding both significant amplification effect of ground motion and influence of landslides. Although both the current national and provincial codes have considered the site effect in a certain extent, the related technical regulations underestimated the amplification effect of thickness and

topography of loess deposit. Therefore, the more reasonable and accurate amplification factors of PGA and extended characteristic periods should be considered based on the further research achievements in loess site effect.

## 7. Conclusions

The above-mentioned research results show that the site effect of deposit thickness and topography of loess sites in the Loess Plateau of China on ground motion is remarkable, which not only amplifies peak ground acceleration, but also extends predominant periods of ground motion. Due to an effect of topography of a loess mountain, an earthquake intensity on the top of the loess mountain may increase by 1-2 degree than that at the foot of the mountain. The effect of loess thickness on ground motion may amplify PGA by 1.1-2.2 times of the value at rock base, and extend the predominant period by 1.1-1.6 times of the value at rock base. It is the significant site effect that caused houses collapsed at the villages on the mountains and high reinforced concrete buildings, chimneys and dwelling caves in loess deposit damaged abnormally on very thick loess sites, where is more than 600km far away from the epicenter of The Wenchuan 8.0 earthquake.

Synthetically Considering the above-mentioned research results and the site classification in Loess Plateau, a method of taking the PGA amplification and predominant period extension into account of seismic design was proposed, by which the site effect may be considered with an amplification factor of PGA ranging from 1.1 to 2.2 and a series of extended characteristic periods of 0.55s-0.75s for different thickness and slope angles of loess deposit. Thus, the site effects of far field strong earthquakes on ground motion in the Loess Plateau, especially in the loess Yuan and mountains, can be more quantitatively and reasonably estimated.

However, only the phenomenon of remarkable site effect of deposit thickness and topography of loess sites in the Loess Plateau of China on ground motion and its evaluation method were studied in this paper. More papers supplementing this paper in discussing the associated mechanisms in field observation, model tests and numerical analyses, more logically in detail individually, are expected to come out later.

## Acknowledgments

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**Table1**

Earthquake events, site information and acceleration data of selected strong motion stations.

Earthquake	Ms	Type	Station Code	Thickness (m)	Distance from epicenter(km)	Azimuth (°)	PGA/Gal			Ratio of PGA	
							EW	NS	UD	EW	NS
Wenchuan Earthquake	8.0	R.S.	62WIX	0	245	28.3	142.6	141.1	131.9	1.3	1.2
		A.S.	62WUD	65	306	27.7	184.8	163.9	108.6		
		R.S.	61TAY	0	544	48.7	19	29.4	26.8	4.1	3.2
		A.S.	61YLT	120	572	48.2	77.2	93.8	27.5		
MinZhang Earthquake	6.6	R.S.	62ZHQ	0	80	168.9	14.1	15.7	11.8	2.1	1.1
		A.S.	62WUD	65	147	150.7	28.7	16.3	0.5		
		R.S.	61TAY	0	401	93.1	1.5	2.4	1.7	5.0	3.5
		A.S.	61YLT	120	422	96.2	7.5	8.3	3.1		

R.S.---Reference Station; A.S.---Amplification Station

**Table2**

Recorded events from the temporary strong ground motion array.

Date	Ms	Epicenter distance (Km)	Bottom station -B(gal)			Middle tation -M(gal)			Top Station -T(gal)			M/G			T/G		
			EW	NS	UD	EW	NS	UD	EW	NS	UD	EW	NS	UD	EW	NS	UD
			5/27/2008	5.7	88	51.2	61.5	44.5	54.2	67.6	48.9	46.3	105.6	51.7	1.1	1.1	1.1
6/05/2008	5.0	78	21.6	25.7	27.1	22.7	22.6	23.8	18.8	29.5	26.4	1.1	0.9	0.9	0.9	1.1	1.0
6/07/2008	4.3	83	5.3	5.4	6.1	6.3	8.8	6.2	8.1	14.7	7.2	1.2	1.6	1.0	1.5	2.7	1.2
6/08/2008	4.7	63	20.6	16.4	14.5	18.9	17.6	16.7	15.4	24.8	18.0	0.9	1.1	1.2	0.7	1.5	1.2
6/17/2008	4.5	87	5.7	6.6	5.4	6.8	8.2	9.7	7.6	13.0	7.9	1.2	1.2	1.8	1.3	2.0	1.5
6/19/2008	4.4	78	9.8	10.2	7.3	12.7	14.2	11.0	12.7	24.5	1.6	1.3	1.4	1.5	1.3	2.4	0.2
6/22/2008	4.2	84	9.0	6.7	7.8	8.3	7.8	8.8	13.6	12.1	6.0	0.9	1.2	1.1	1.5	1.8	0.8
6/23/2008	4.1	72	6.0	4.8	6.6	5.8	5.6	6.3	6.9	8.2	5.3	1.0	1.2	1.0	1.2	1.7	0.8
6/28/2008	4.8	136	10.1	5.7	9.4	13.4	10.2	9.5	11.0	10.9	10.1	1.3	1.8	1.0	1.1	1.9	1.1

**Table 3**

Similarity relations of model.

Physical quantity	Similarity relation	Similarity constant	remark
Geometric dimension(L)	$C_L=100$	100	Control quantity
Density( $\rho$ )	$C_\rho=1$	1	Control quantity
Acceleration(a)	$C_a=1$	1	Control quantity
Elastic modulus(E)	$C_E= C_L C_\rho$	100	
Poisson ratio	$C_\mu=1$	1	
Time(t)	$C_t=\sqrt{C_L}$	10	

**Table 4** Material parameters of prototype model.

material		Density $\rho(g/cm^3)$	Modulus of Elasticity(MPa)	Poisson ratio
loess	Prototype	1.46~1.48	19.6~80.8	0.3
	Model	1.46	0.6	0.3
Mudstone	Prototype	1.80	126	0.3
	Model	1.80	1.2	0.3

**Table 5**

Soil layer classification and soil parameters of Dazhai village

Soil layer	Density (g/cm <sup>3</sup> )	Thickness (m)	Velocity of shear wave (Vs) (m/s)	Modulus of elasticity (Mpa)	Damping ratio	Poisson ratio
Loess-like silty clay	1.46	14	227	19.56	0.15	0.3
Silty clay	1.46	15	274	28.5	0.15	0.3
Silty clay	1.48	26	379	55.27	0.15	0.3
Silty clay	1.48	14	461	81.78	0.15	0.3
Silty clay	1.49	15	523	105.96	0.15	0.3
Mudstone	1.8	16	571	126.31	0.15	0.3

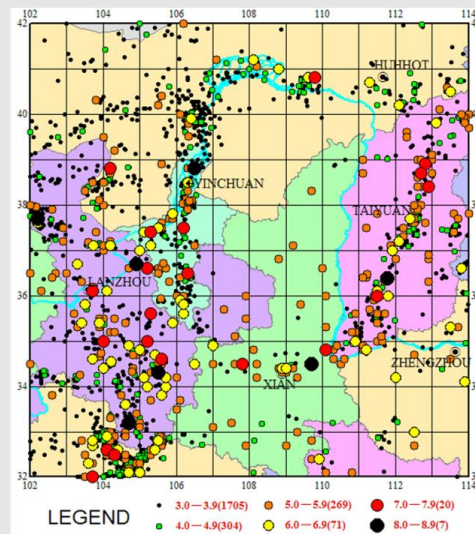
**Table 6**

Amplifying factor with loess slope effects

Slope (50m high)	20°~30°	30°~45°	45°~60°	60°~70°
PGA amplifying factor	1.1-1.3	1.3-1.5	1.5-1.7	1.7-2.0

**Table 7**Proposed amplifying factors of horizontal earthquake influence coefficient (PGA) and characteristic period (T<sub>g</sub>)

Thickness ΔH(m)	20≤ΔH<40	40≤ΔH<60	60≤ΔH<90	90≤ΔH<120	120≤ΔH<180	180≤ΔH<240	240≤ΔH
PGA amplifying factor	1.2	1.4	1.6	1.8	1.9	2.0	2.2
T <sub>g</sub> (s)	0.55	0.63	0.68	0.72	0.73	0.74	0.75



**Fig. 1.** Regional epicenters of earthquakes ( $M \geq 3$ ) in loess region of west China. (Seismicity: In years B.C. 78 ~ 2016 Dec. 31, except data for 3.0~3.9 and 4.0~4.9 in the recent 51 years.)



(a) The loess mountain



(b) Destroyed Haoping village on the top



(c) Liujiabu village in good condition at 326m lower location



**Fig.2.** Amplification effects of topography of a loess mountain in Longnan City, Gansu province 250 km away from the epicenter of Wenchuan 8.0 Earthquake in 2008.



(a) A 12-stories reinforced concrete building on thick loess site. (b) Damaged walls in the building. (c) Damaged tombstones and chimney in the city.

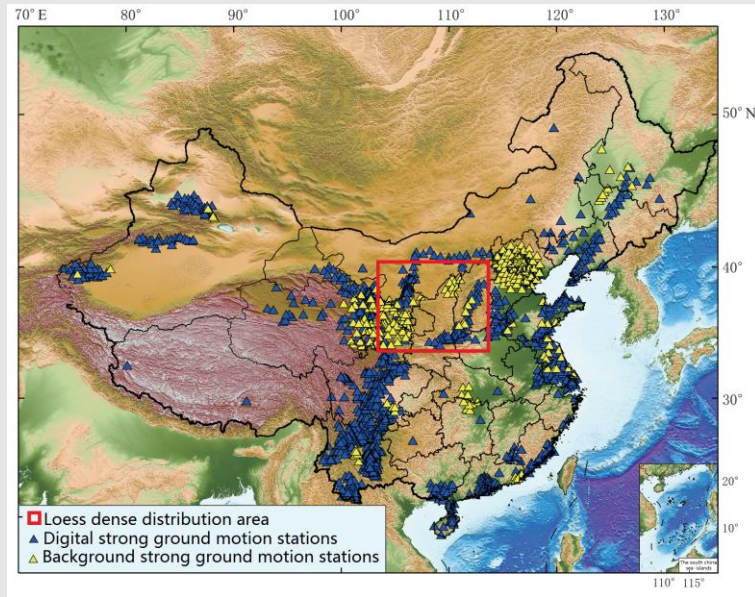
**Fig.3.** Amplification effects of thickness of loess deposit of about 300m in Qingyang city, Gansu province with a distance of 670km away from the epicenter of Wenchuan 8.0 Earthquake in 2008.



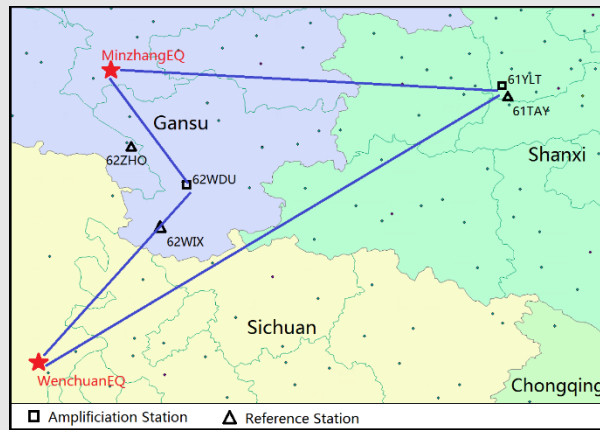
**Fig. 4.** The topography (left), the Dazhai Loess Mountain (middle) and damaged houses in Dazhai Village (right), Pingliang City, Gansu province



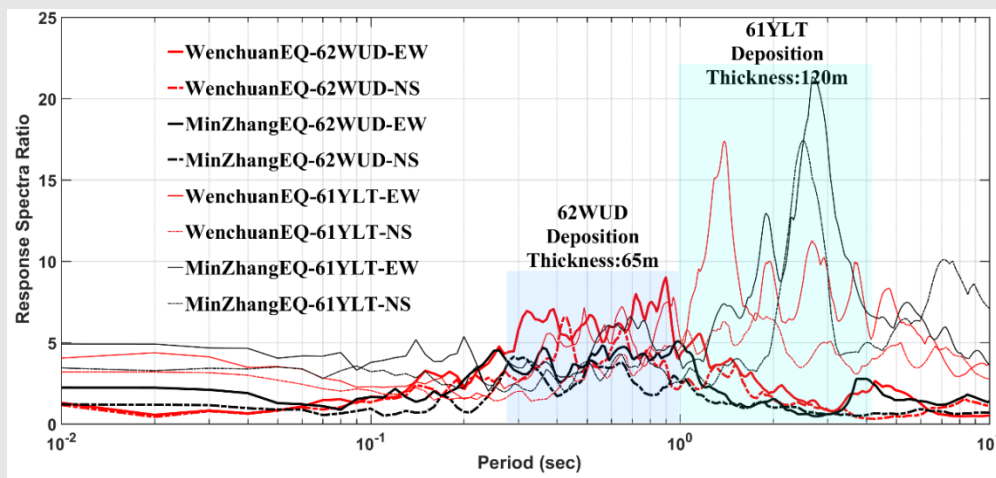
**Fig. 5.** The topography (left), seriously damaged houses in Majiagou Village (middle) and slightly damaged houses in Xinglin Village (right), Minxian Town, Gansu province



**Fig.6.** Chinese Digital Strong Ground Motion Networks (modified from Wen et al, 2016). The blue and yellow triangles represent the digital and background strong motion stations, respectively.



**Fig.7.** Locations of the mainshock of the 2008 Wenchuan and 2013 Minzhang earthquakes and the selected strong motion stations



**Fig.8.** The ratio of PGA and response spectra between soil amplification station and rock reference station

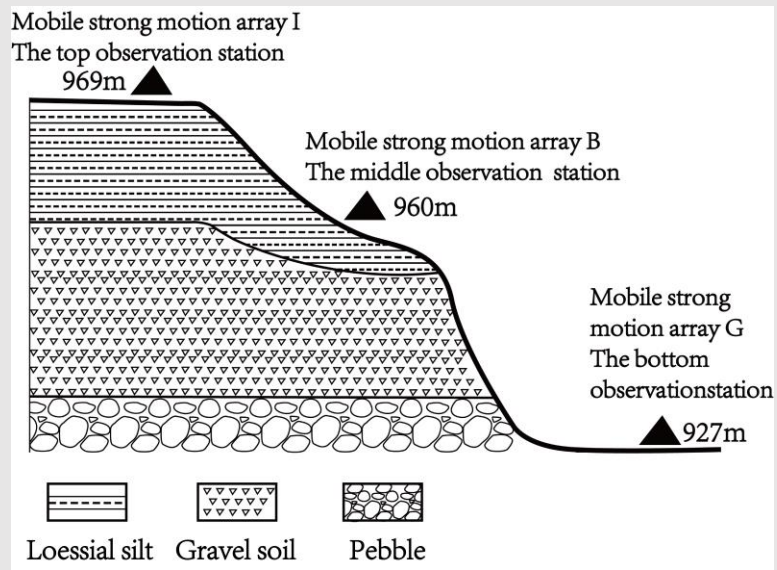


Fig.9. Temporary strong motion array near the Wenxian County

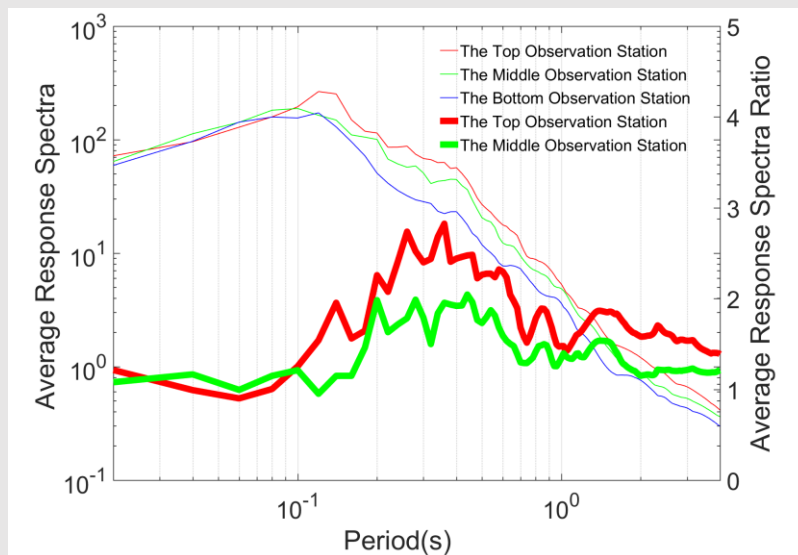


Fig.10. Average response spectra (thin line) and average response spectra ratio (thick line)

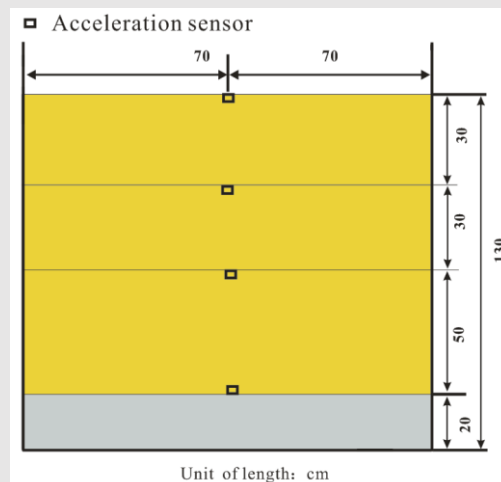


Fig.11. Loess site model and sensors location

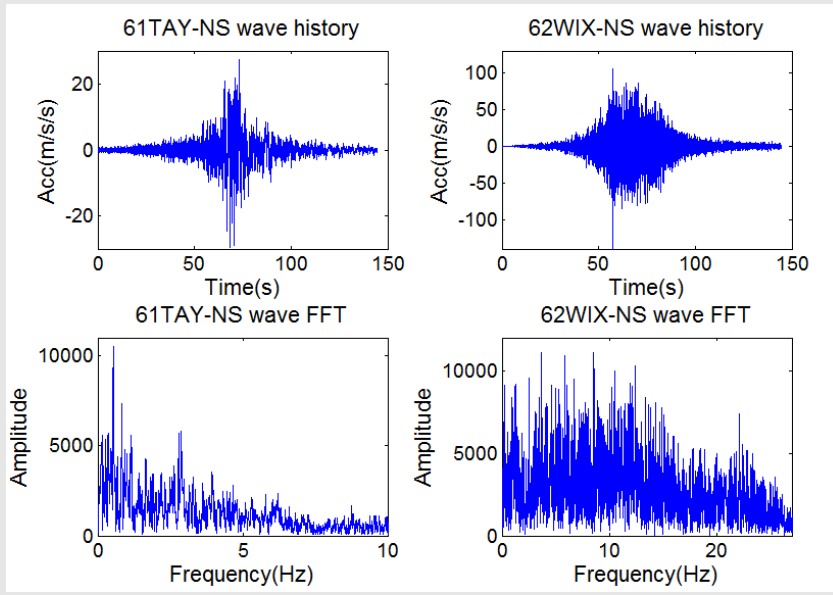


Fig.12 Input seismic ground motions and its FFT Spectrum

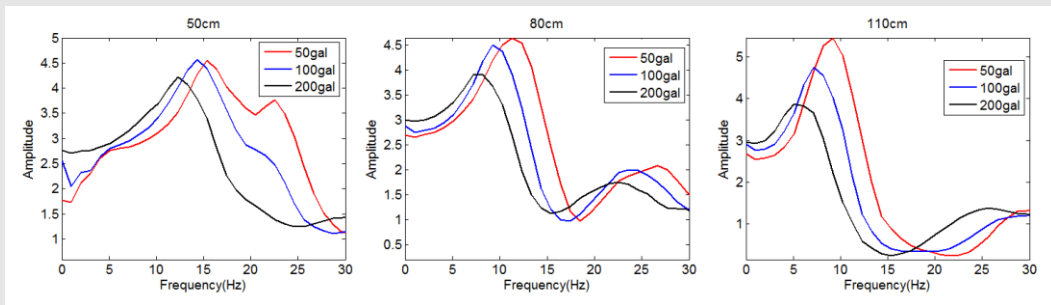


Fig.13. Transfer function frequency spectrum of acceleration of ground surface of the model

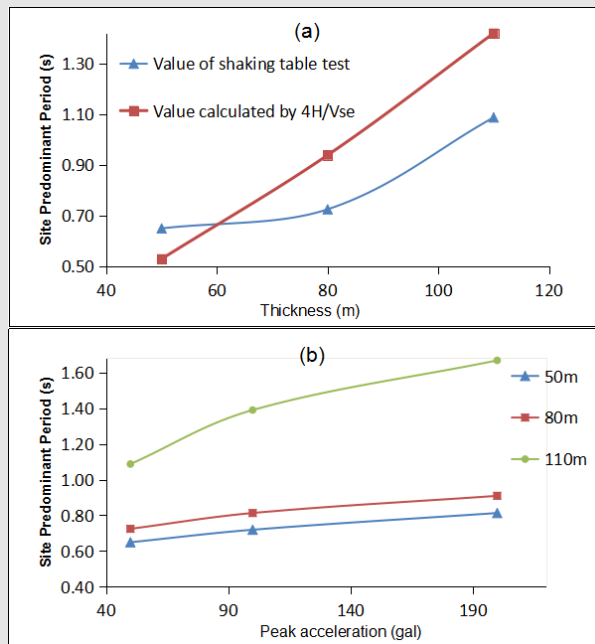


Fig.14. Variation of the predominant period of loess site; (a) different thickness, (b) different peak acceleration.



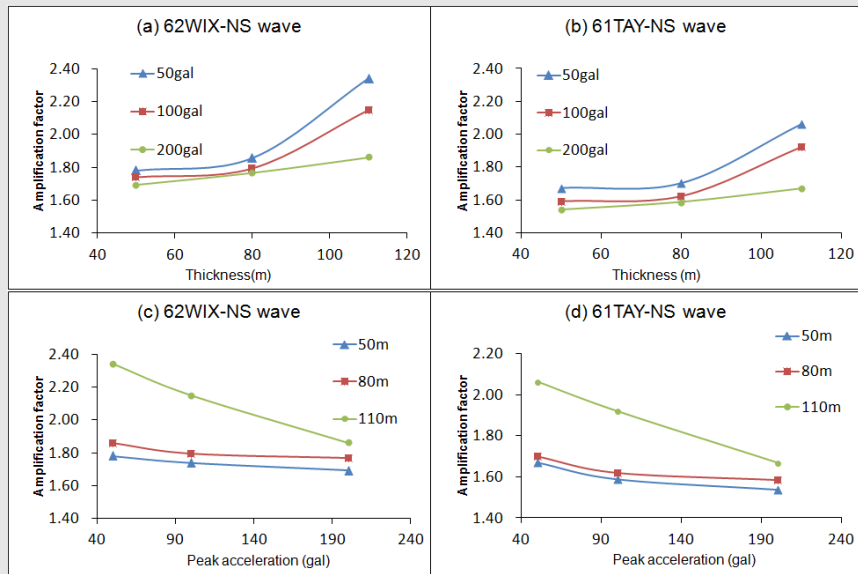


Fig.15. Variation of PGA amplification factors with different thicknesses and under different peak accelerations.

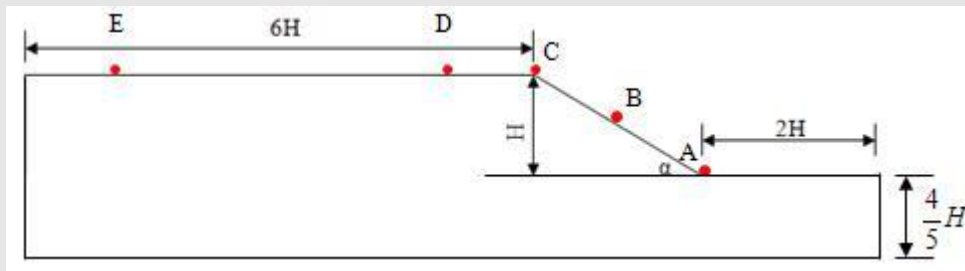


Fig.16. The standard model of finite element model analysis

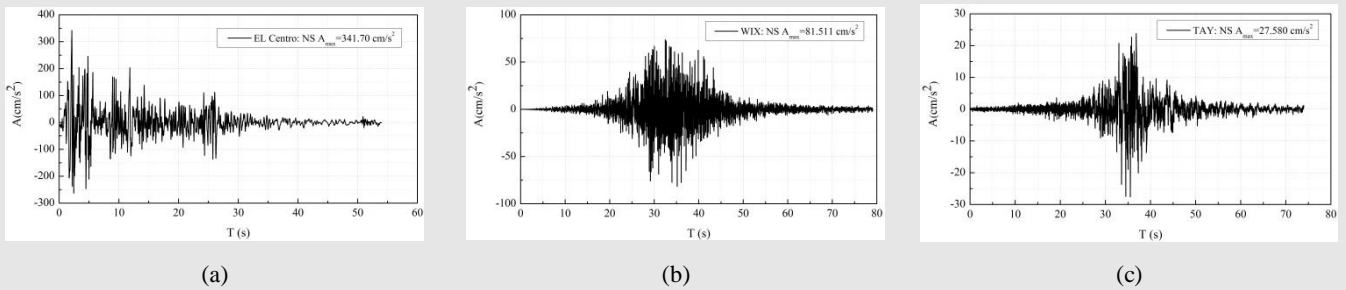


Fig.17. The horizontal acceleration time histories of (a) EL Centro; (b) Wenxian wave and (c) Tangyu wave during the Wenchuan 8.0 earthquake in 2008;

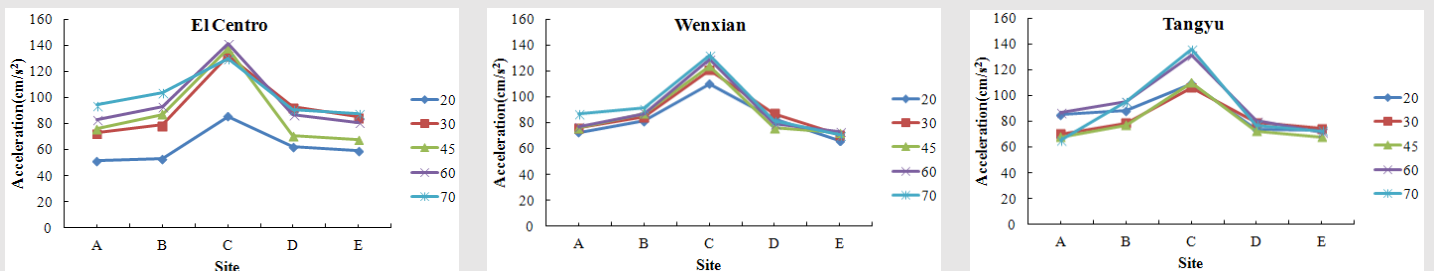


Fig.18. PGA at different locations of the loss deposit with different slope gradients.



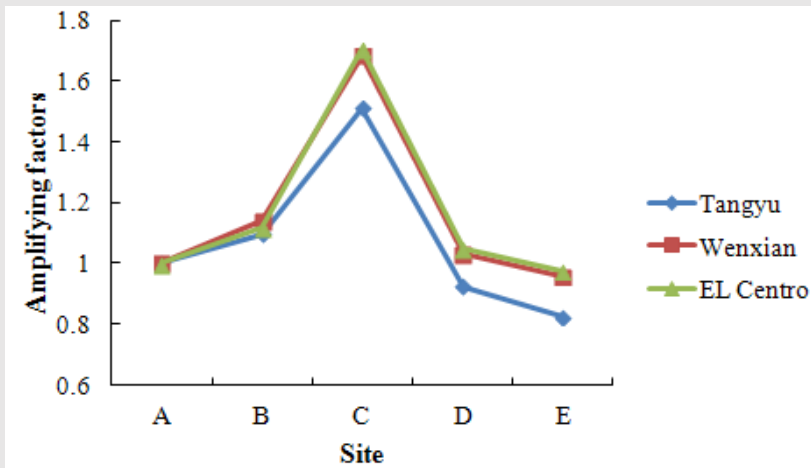


Fig. 19 PGA amplifying factor at different locations of the loess deposit with a slope of 60°.

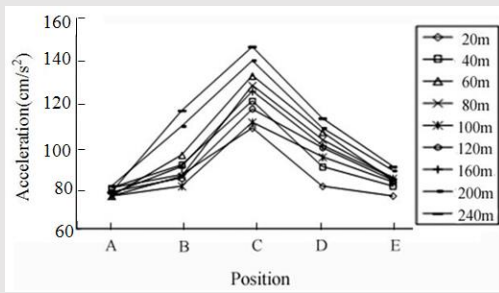


Fig.20 PGA at different locations of the loess deposit with different thicknesses.

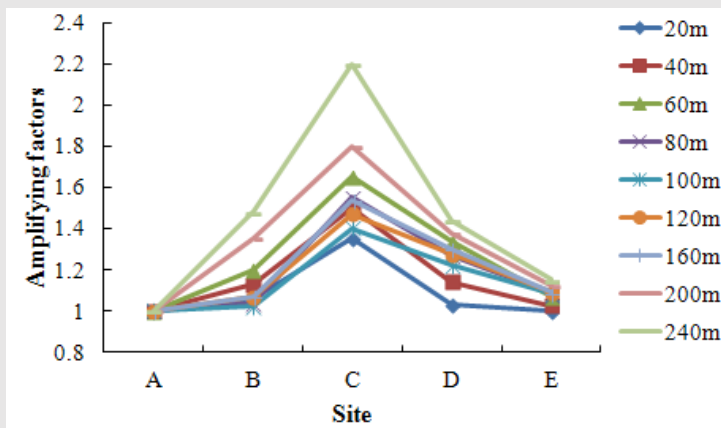
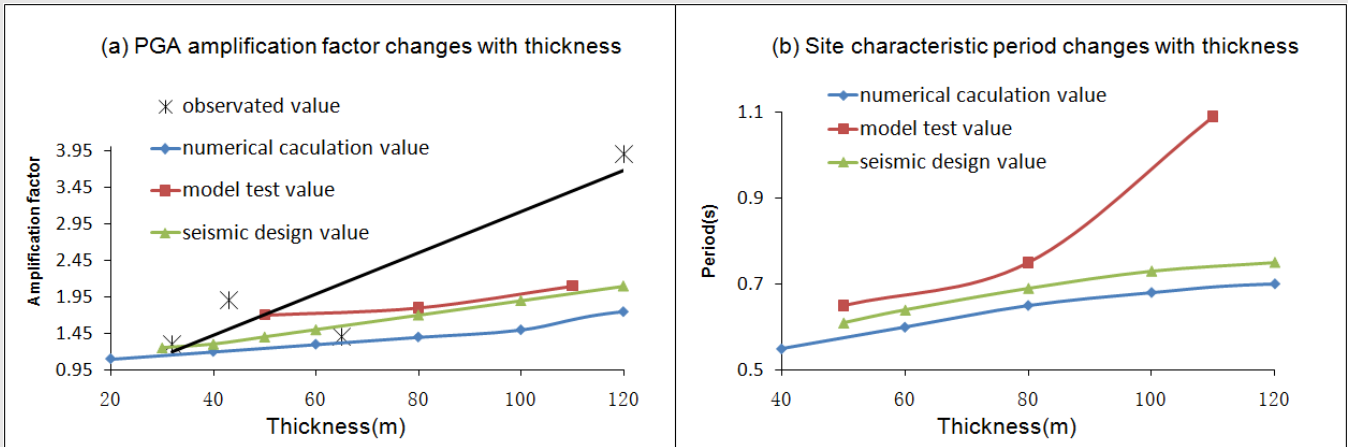
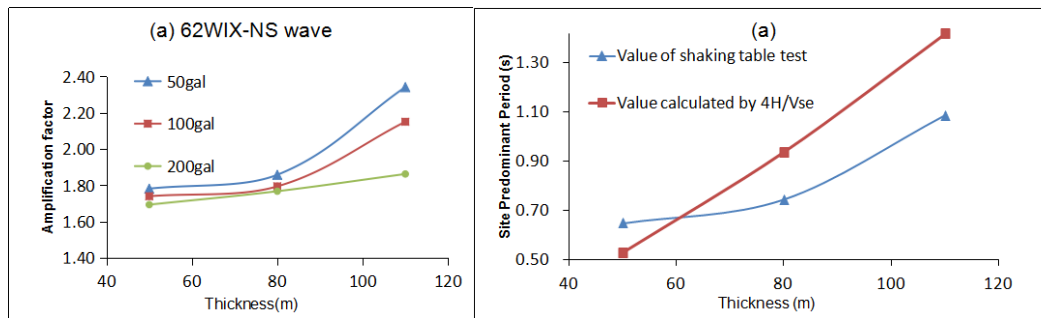


Fig. 21 PGA amplifying factor at different locations of the loess deposit with different thicknesses.

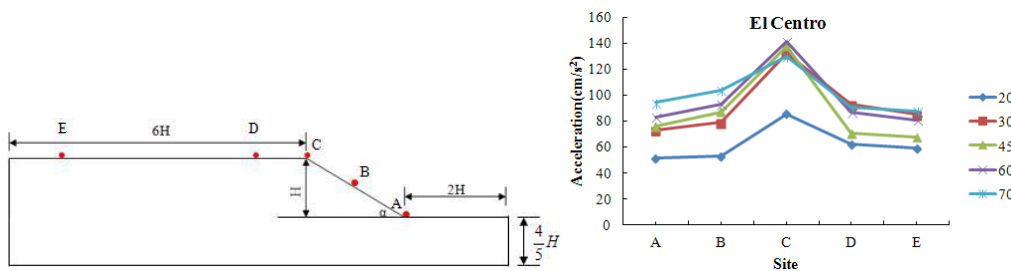


**Fig. 22** Amplification factor and site characteristic period change with soil thickness

## Graphical Abstract



Both the peak accelerations of ground motion and site predominant period increase with increasing of loess thickness respectively by 1.7-2.34 times and 1.10-1.66 times.



The peak accelerations of ground motions are amplified at different sites of a loess "Yuan", a high table-like plain with abruptly descending edges, with different slope gradients ranging from  $20^\circ$  to  $70^\circ$  in a thickness of 50m loess deposit.