The method of adjusting design ground motion parameters of thick loess sites

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ABSTRACT

The Loess Plateau in China is a region with the largest thickness, the greatest area and the most complicated topography of continuous sedimentary loess deposit in the world, where earthquakes occurred frequently. The field investigations of Wenchuan earthquake and other strong events indicated that large number of casualties and tremendous economic losses were closely related to the amplification effects of thickness and topography of ground motion on loess deposit. In order to study the amplification of thickness on ground motion, the characteristics of strong ground motion in the region were analyzed; shaking table tests were performed and numerical analysis was carried out. The results showed that the amplification effects are predominant with increase of thickness of loess deposit. Finally, the adjustment factors of seismic ground motion were proposed for seismic design of engineering projects on loess sites.

Keywords: loess site, amplification effect, ground motion, seismic design, adjustment

1 INTRODUCTION

The Loess Plateau in China covers an area of 440,000km^2 with the thickness of loess deposit ranging from several meters to more than 500 meters, which is one of the most tectonically active areas of the world and also one of the most seismically active regions. There were 20 events with magnitude between Ms7.0-7.9 and 7 events with magnitude equal or greater than Ms8.0 occurred in the region from B.C. 78 to Dec. 31, 2016. More than 1.4 million people were killed by the earthquakes in the region. The field investigation shown that remarkable amplification of ground motion on thick loess sites was one of main causes for serious damage of houses, buildings and infrastructures.

At present, a lot of thick landfill sites and high terrace sites in the Loess Plateau were provided for a large-scale urbanization construction and “Belt and Road” infrastructure construction. The risk of which houses, buildings and infrastructures damage or collapse due to the site effect of ground motion amplification increases remarkably. However, site effects of seismic ground motion on loess deposit have not been well considered in seismic design of those projects due to lacking a systematic and quantitative study on it.

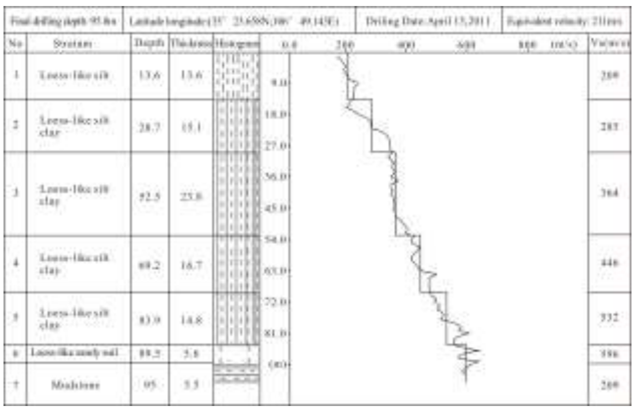
In this paper, the site amplification effects of seismic ground motion on loess deposit were studied based on the field investigations, shaking table tests and numerical analysis. Moreover, the site amplification factors of ground motion for seismic design consideration on loess sites were proposed. The amplification factors and characteristic periods to considering site effects of thickness of loess deposit may provide an important scientific and practical basis for the engineering seismic fortification in the loess areas.

2 PHENOMENA OF AMPLIFICATIONG OF LOESS DEPOSIT

Loess Yuan is a high table-like plain with 100-300 meters thick loess deposit and abruptly descending edges, which is one of three major types of landforms in the plateau. During the Wenchuan 8.0 earthquake in 2008, the houses and buildings on Loess Yuan abnormally damaged due to amplification of ground motion even if it is 500-700km away from the epicenter (Wang and Wu, 2010).

For example, 70% of houses in Dazhai Village was collapsed or seriously damaged by the Wenchuan earthquake, where is located on a Loess Yuan with about 100m loess deposit and more than 500km away from the epicenter (Fig.1). In Qingyang City, Gansu province, a high-rise building damaged on a Loess Yuan with about 200m loess deposit, where is 670km away from the epicenter (Fig. 2). According to Wu et al. (2012), the earthquake intensity might increase 1 degree due to the site effect of thick loess deposit.

(a) Seriously damaged houses in Dazhai Village.

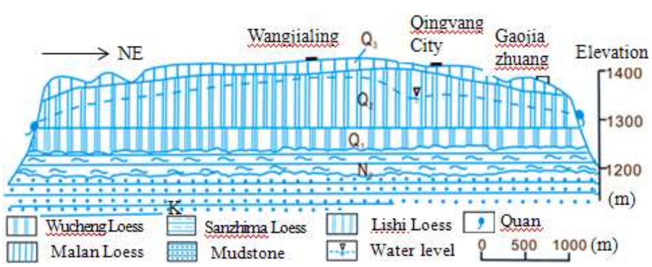


(b) Borehole geologic records and Vs data of Dazhai Village.

Fig. 1. Dazhai Village in Gansu province suffered Ⅶ degree damage by the Wenchuan 8.0 Earthquake, where more than 500km away from the epicenter.

(a) A 12-storey frame-shear wall building on a Loess Yuan with about 200m loess deposit.

(b) Damaged interior wall



(c) Hydrogeological profile of Dongzhi Yuan (Yang et al, 1982).

Fig. 2. Qingyang city in Gansu province suffered VI degree damage by the Wenchuan 8.0 Earthquake, where more than 670km away from the epicenter.

3 SHAKING TABLE TESTS OF AMPLIFICATION EFFECTIN THE LOESS SITE

3.1 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, and is driven by 24 servo motors. Its maximum acceleration, velocity and displacement is 1.7g, 1.2m/s and ±50cm respectively. A laminar shear soil container with a size of 1.5m×1.5m×1.4m was used in tests.

3.2 Similarity design and model parameters

Based on the loess deposit of Dazhai Village (Table 1), the generalized model of horizontal free field models with different loess thicknesses of 50m, 80m and 110m were established and 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 (2000) elastic similarity rule.

The loess thicknesses of tested models were respectively designed to be 50cm, 80cm, and 110cm, and the bottom layer was set up with 20cm thick mudstone. The parameters of the prototype and models were determined by laboratory tests shown in Table 2. For each model, four sets of acceleration sensors with horizontal and vertical directions are amounted in different heights of the model shown in Fig. 3.

3.3 Seismic wave and condition loading

The time histories of accelerations recorded in Tangyu town during the Wenchuan EQ were employed in the tests (Fig.4). Three amplitudes of 50gal, 100gal and 200gal were respectively applied from low to high intensity level during the tests.

3.4 Amplification effect of thickness

As fig.5 shown that all amplification factors increase with increase of loess thickness and decrease with increase of peak acceleration. When the thickness increases from 50 m to 110 m, the amplification factors increased from 1.52 to 2.34 and site predominant periods of ground motion may extend to 1.10-1.66 times.

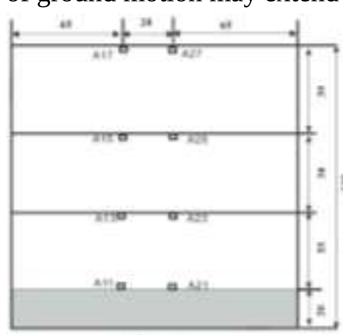


Fig. 3. Loess site model and sensors location.

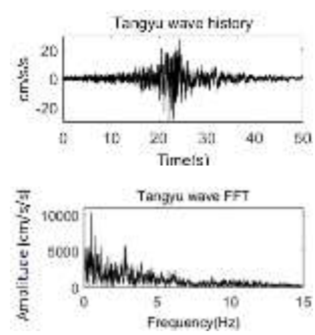


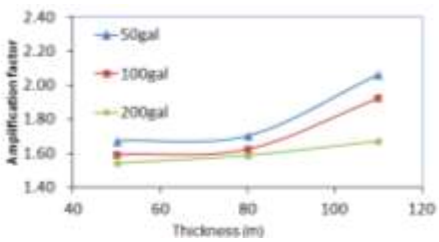
Fig. 4. Input seismic ground motion and its FFT spectrum.

Table 1. Soil layer classification and soil parameters of Dazhai Village.

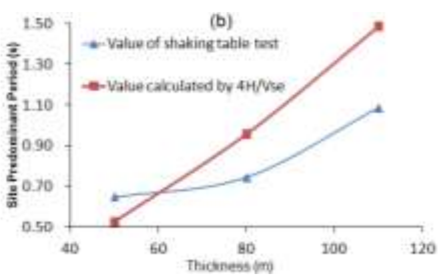
Soil layer	Density (g/cm^3)	Thickness (m)	Velocity of shear wave (Vs) (m/s)	Modulus of elasticity (Mpa)	Damping ratio	Poisson ratio
Loess-like silty clay	1.46	14	227	19.56	0.15	0.30
Silty clay	1.46	15	274	28.50	0.15	0.30
Silty clay	1.48	26	379	55.27	0.15	0.30
Silty clay	1.48	14	461	81.78	0.15	0.30
Silty clay	1.49	15	523	105.96	0.15	0.30
Mudstone	1.80	16	571	126.31	0.15	0.30

Table 2. Material parameters of prototype model.

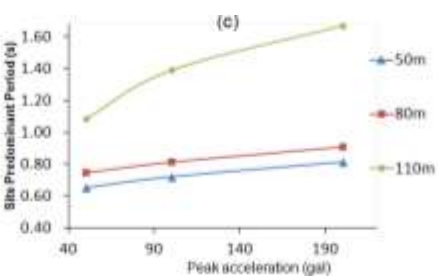
Material		Density (g/cm3)	Modulus of Elasticity(MPa)	Poisson ratio
Loess	Prototype	1.46~1.48	19.60~80.80	0.30
	Model	1.46	0.60	0.30
Mudstone	Prototype	1.80	126.00	0.30
	Model	1.80	1.20	0.30



(a) Amplification factors versus thickness.



(b) Variation of characteristic period with thickness.



(c) Variation of characteristic period with PGA.

Fig. 5. Variation of the amplification factors and the predominant period of loess site.

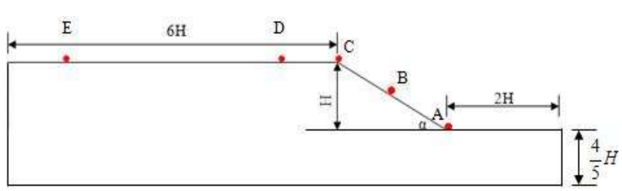


Fig. 6. The standard loess slope geometric model of finite element analysis.

4 NUMERICAL ANALYSIS ON AMPLIFICATION OF LOESS DEPOSIT

4.1 Geometric model and boundary conditions

In order to study systematically amplification effects of loess deposit, a numerical analysis was carried out to provide a basis for seismic design of engineering projects on loess sites. The methods proposed by Wang and Mei (2012) were employed for a two-dimension finite element dynamic analysis, considering characteristics of free-field soil and its nonlinearity. The elastic-plastic 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 standard model was established for simulating the loess sites of Dazhai village and Qingyang finance bureau shown in Fig. 6, the model parameters were set up based on Table 1 and Table 3.

4.2 Effect of loess thickness

In order to evaluate the amplification effect of loess thickness on ground motion, simulations were performed on the 2-D models of loess site with different thickness of loess deposit, which are 20 m, 40 m, 60 m, 80 m, 100 m, 120 m, 160 m, 200 m, and 240 m, respectively. When PGA is 0.05g, the amplification factor on seismic ground motion from 1.1 at 20 m to 1.6 at 240 m (Table 4), However, with the increase of PGA, the amplification factors gradually decrease and its become 1 at 0.4g.

In addition, we calculated the characteristic periods of response spectrum according to "Specification of Seismic Design for Highway Engineering" of China (2013). The characteristic period gets longer from 0.55s to 0.75s with the increase of the loess thickness shown in Table 5.

5 ADJUSTMENT OF SEISMIC DESIGN PARAMETERS BY AMPLIFICATION EFFECT OF LOESS SITE

Based on the field investigation and numerical analysis results, a method of taking the amplification effects of loess thickness on ground motion into account in seismic design of buildings and infrastructure on loess sites was proposed in this paper shown as Table 4 and Table 5 respectively, which was partly verified by shaking table tests. It can be seen that the amplification factor in each zone of design PGA increases with increase of loess thickness and decreases with increase of design PGA. The maximum factor may be 1.6. Moreover, characteristic periods in each design PGA zone extend from 0.54 to 0.75 with increase of loess thickness.

The numerical calculation results were compared with the site II given by the current National Standard for Seismic Ground Motion Parameters Zonation Map of China (CEA, 2015) (Fig.7). Both the amplification factors and the characteristic periods of the loess sites on ground motion are larger than the values of the general sites (Site II) of the current codes. Obviously, the current code underestimated the amplification effect of loess sites on ground motion. Therefore, the method of adjusting design ground motion parameters based on Table 4 and Table 5 should be adopted for seismic design of engineering projects in thick loess sites.

Table 3. Soil layer classification and soil parameters of Qingyang finance bureau.

Soil layer	Density (g/cm^3)	Thickness (m)	Velocity of shear wave (Vs) (m/s)	Modulus of elasticity (Mpa)	Damping ratio	Poisson ratio
Loess-like silty clay	1.43	12	210	59	0.11	0.32
Loess-like silty clay	1.62	40	369	72	0.14	0.34
Loess-like silty clay	1.74	45	433	94	0.12	0.35
Loess-like silty clay	1.86	48	469	156	0.11	0.37
Mudstone	2.20	15	535	200	0.10	0.20

Table 4. PGA regulation factor Fa on loess site E (Reference A).

Thickness/m	20	40	60	80	100	120	160	200	≥240
≤0.05g	1.1	1.2	1.3	1.3	1.3	1.4	1.4	1.5	1.6
0.10g	1.1	1.1	1.2	1.2	1.2	1.3	1.3	1.4	1.4
0.15g	1.05	1.05	1.1	1.1	1.1	1.2	1.2	1.2	1.2
0.20g	1	1.05	1.05	1.05	1.05	1.1	1.1	1.1	1.1
0.30g	1	1	1	1	1	1	1.05	1.05	1.05
≥0.40g	1	1	1	1	1	1	1	1	1

Table 5. Characteristic period on loess site E (Reference A).

Thickness/m	20	40	60	80	100	120	160	200	≥240
≤0.05g	0.54	0.63	0.69	0.7	0.7	0.7	0.7	0.7	0.75
0.10g	0.55	0.64	0.69	0.7	0.7	0.7	0.7	0.7	0.75
0.15g	0.57	0.65	0.69	0.7	0.7	0.7	0.7	0.7	0.75
0.20g	0.59	0.67	0.69	0.7	0.7	0.7	0.7	0.75	0.75
0.30g	0.61	0.68	0.7	0.7	0.7	0.7	0.7	0.75	0.75
≥0.40g	0.63	0.69	0.7	0.7	0.7	0.7	0.7	0.75	0.75

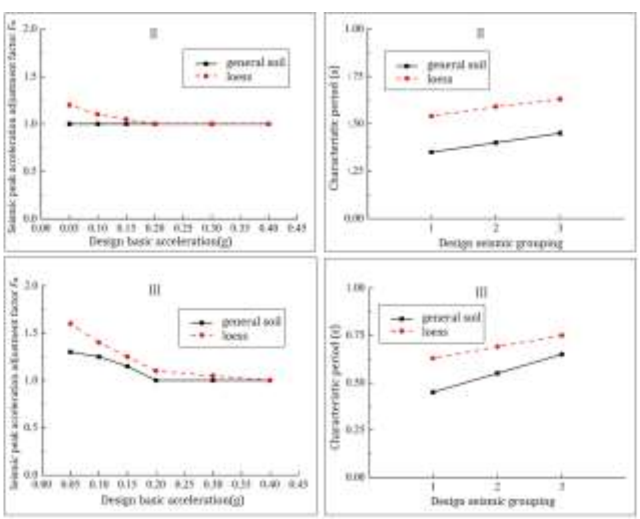


Fig. 7. The Adjustment factor of seismic acceleration and characteristic period between loess site and general site.

6 CONCLUSIONS

The site effect of thickness of loess deposit on ground motion is remarkable, which not only amplify peak ground acceleration, but also extends predominant periods of ground motion.

Synthetically Considering the above-mentioned research results and the site classification in Loess Plateau, adjusting factors of PGA ranging from 1.1 to 1.6 and a series of extended characteristic periods of 0.55s-0.75s were proposed for seismic design.

Special ground motion observation arrays should be set up for the further quantitative study on site effect in the Loess Plateau area, to examine the current preliminary method and make seismic design more reasonable and reliable.

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