SEISMIC SUBSIDENCE OF LOESS INDUCED BY A SHORT DELAY BLASTING

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ABSTRACT :

As viewed from concept, seismic subsidence of loess is an abrupt settlement of soil due to earthquake loading in non-saturated and low moisture conditions. In laboratory testing, it has been proved that seismic subsidence of loess is an existing thing. There is nothing, however, to discover a convictive proof of loess seismic subsidence in before investigations of seismic hazards, because an earthquake is always so far that not enough energy to destroy the microstructure of loess and to induce seismic subsidence in a flat loess field. Here the authors introduce a field testing to observe the characteristics of loess seismic subsidence at a loess site (Q_3) by means of a series of explosion, or a short delay blasting, simulating an earthquake event. In order to understand the seismic subsidence of loess better, there are 140 observation points to be arranged in the testing field; at the same time, 4 observation points of different layer subsidence are placed near the center of the site, monitoring soil subsidence with the depth of 4m, 8m, 12m, and 16m respectively. Ground motion in the loess field caused by the explosions, otherwise, is recorded by 24 accelerographes. After the explosions, observation data shows that all points developed an obvious subsidence in the testing field. The maximum seismic subsidence of loess ground in testing site reaches 33mm approximately, and this point stands at the south of the field, whereas the maximum seismic subsidence of soils around the site attains to 26mm. It could be disclosed that, furthermore, just after explosion the seismic subsidence of loess is almost 50 percent to the maximum observation value of loess subsidence; that is to say, during the blasting process, seismic subsidence of loess increases rapidly. But in sequent stages, the development of loess subsidence becomes tardy and tardy. This development of seismic subsidence of loess fits an exponential function.

KEYWORDS: Loess, seismic subsidence, short delay blasting, landform, earthquake

1. INTRODUCTION

Loess is a particular kind of soil with porous structure and weak cohesion, depositing in different stages of the Quaternary. The compressibility of loess mass is low at natural moisture content as a result of a special microstructure (Miao Tiande, 2001). While water immerges, however, strength of loess mass will be reduced dramatically, which could make this soil collapse (Gao Guorui, 1980; Yang Yunlai, 1988; Rogers et al., 1994; and Feda, 1996). In China, there is the most widespread distribution, the thickest deposit and the most comprehensive topography of loess all over the world and area of loess reaches 640,000 km^2, in which collapsible loess area is about 500,000 km^2 (Wang Guolie et al., 2001). Furthermore, most loess area in China is also seismic region, where many strong earthquakes occurred. Under the effect of moderate or strong earthquakes, liquefaction or/and seismic subsidence of loess is easily induced.
As viewed from concept, seismic subsidence of loess is an abrupt settlement of soil due to earthquake loading in non-saturated and low moisture conditions. In laboratory testing, it has been proved that seismic subsidence of loess is an existing thing. There is nothing, however, to discover a convictive proof of loess seismic subsidence in before investigations of seismic hazards, because an earthquake is always so far that not enough energy to destroy the microstructure of loess and to induce seismic subsidence in a flat loess field. Here in order to understand the seismic subsidence of loess better, the authors introduce a field testing to observe the

characteristics of loess seismic subsidence at a loess site (Q_3) by means of a series of explosion, or a short delay blasting, simulating an earthquake event.

2. TESTING FIELD

After more than 2 years for selecting the right loess site (Q_3) to perform an in-situ test by means of a series of explosions, a short delay blasting, the testing field is located at the south of Lijiawan Ping near Lijiawan village of Gansu province, Northwestern China, with an altitude of 1803m.

2.1. Landform in the Field

A rough landform around the field is shown in Figure 1, where the area circled with dash-dash-dot-dot line is the test site and the area outlined with dash-dash-dot line is observation field. Having a flat topography, a proper thickness of collapsible loess deposit and a certain distance away from villages, this field is suitable to carry out the explosion testing on NSF along piles induced by seismic subsidence of loess ground.

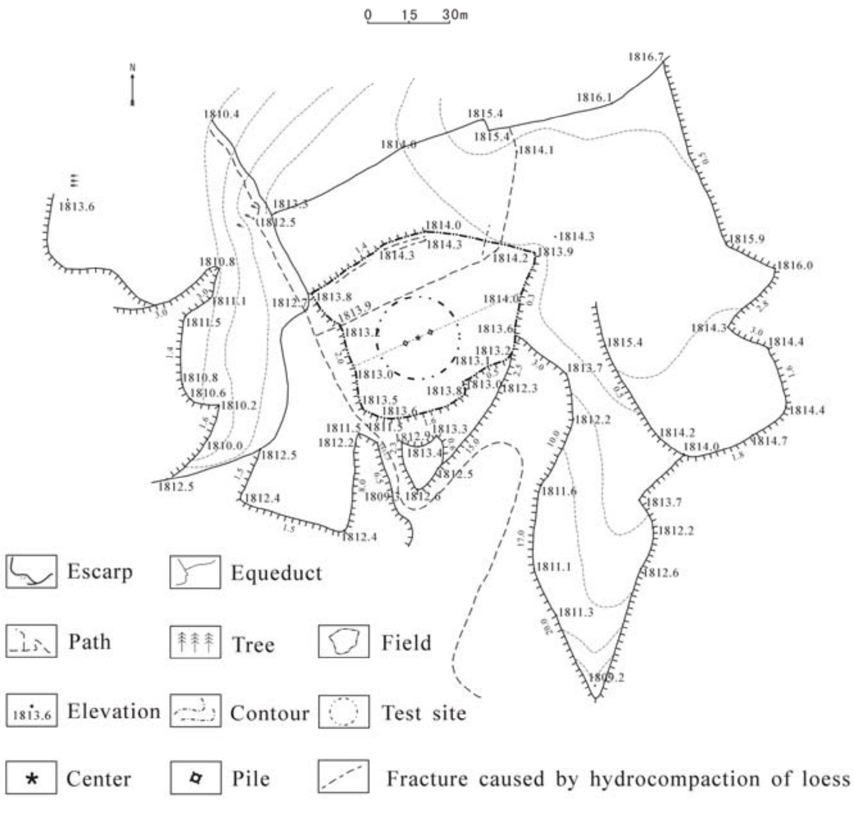


Figure 1 A rough drawing of landform around testing field

Sedimentary sequence of this field can be roughly seen at terrace’s basset. Data obtained by exploratory well, two hand digging holes both with a 28m depth, shows that from top to bottom there are four layers overlaying Tertiary red bed, including arable layer, seismic loess, redeposited loess, and pebble bed (Figure 2). With a buried depth of 1m and a 14m thickness, the upper loess layer has the typical physical characteristics of collapsible loess, i.e. loosen soil mass, high porosity, and great void ratio. In this layer, water content of soil ranges from 12% to 16% and slight clay particle is in sight at some position. The characteristics of redeposited loess, with a thickness of 13m, differs from its overlain soil by that water content of soil is roughly less than

10% and clay content is much more. Horizontal bedding, furthermore, is distinctly visible in this soil layer and it increases gradually with the depth.

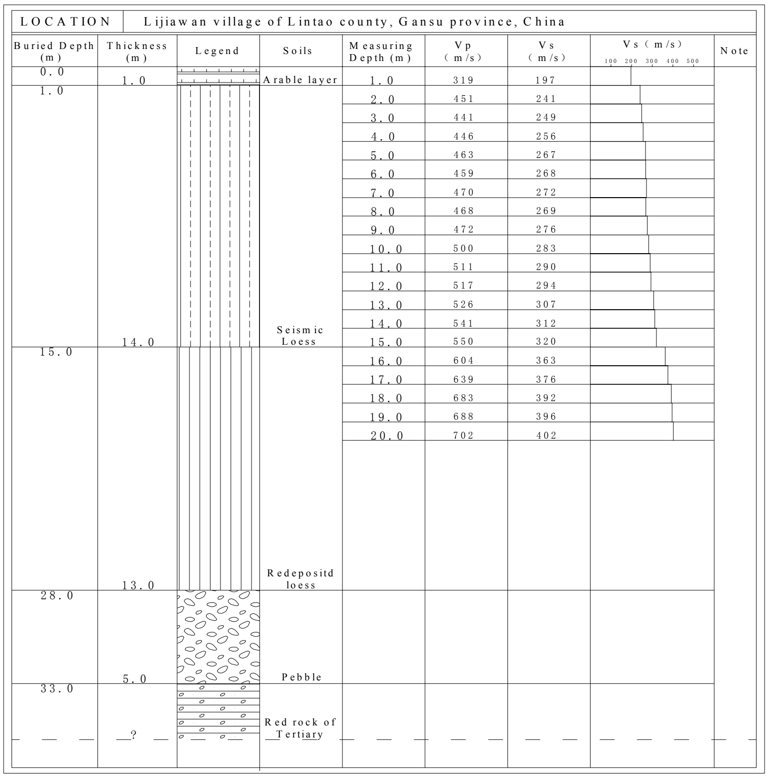


Figure 2 A column of strata profile in the observation field

2.2. Seismic Subsidence of Loess by a Laboratory Test

A laboratory testing data of loess seismic subsidence in the field are shown in Figure 3. The results markedly indicate that the loess above 15m has a more seismic subsidence than the soil mass below this depth.

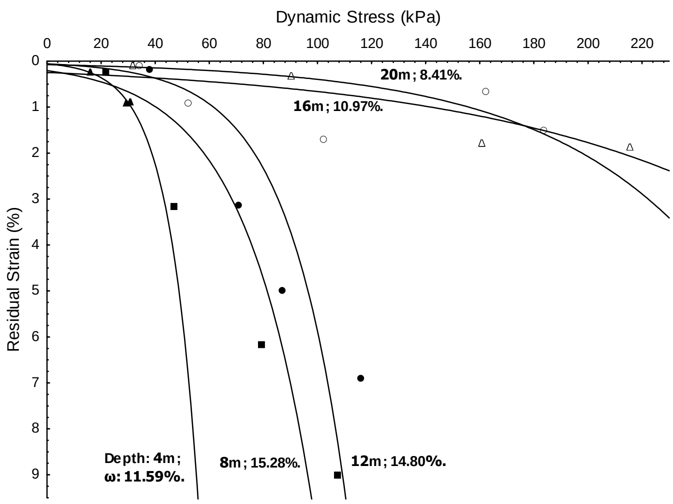


Figure 3 Characteristics of seismic subsidence of loess with different nature water content and depth

3. DESIGN FOR OBSERVATIONAL SYSTEMS AND EXPLOSION FOCUS

3.1. Observation Points of Loess Seismic Subsidence

For observation of loess seismic subsidence as shown in Figure 4, there are 97 points in test site and 43 points around the site. These points in the testing site are arranged by an equal-area method, with a point density of $0.16/m^2$, whereas observation points around the site are disposed along 8 directions with two different intervals of 2.5m and 3.5m (Figure 4). Furthermore, 4 observation points of different layer subsidence, which monitor soil subsidence with the depth of 4m, 8m, 12m, and 16m, are placed near the center of the site. Two fiducial marks, moreover, are situated at the east of the testing site with a distance of 220m from the center, following an azimuthal angle of 40°.

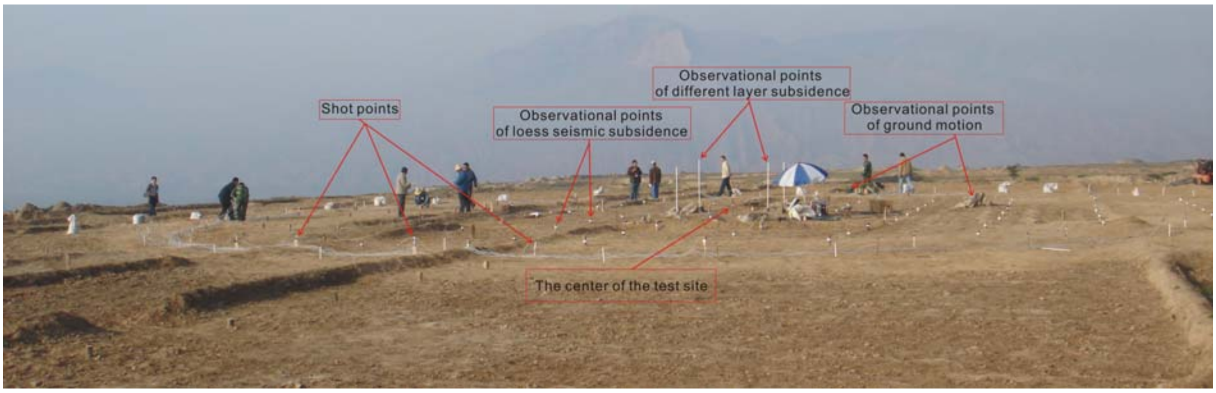


Figure 4 Details of field, test site, and all kinds of observation point

3.2. Observation Points of Ground Motion

In Figure 4, there are 24 observation points of ground motion caused by explosions, including 11 points in test site and 6 points around the site along the direction of E-W and S-N respectively. Then other 6 points scatters in the east of test site to understand attenuation of ground motion, with a 20m interval and the first point with a distance of 40m from the center, following an azimuthal angle of 80.5°. And the last observation point of ground motion is located at the position with a 110m distance from the center of the test site and along an azimuthal angle of 333°.

3.3. Design of the Explosion Focus

As corresponding points of explosives plotted on the field surface, the 30 shot points, with an interval of 3.14m and each depth of 23m, are disposed along a circularity, whose diameter is 30m and centre is situated at the center of the test site.
For the expected peak acceleration of around 450gal, which could generate an obvious seismic subsidence of loess in the field, 40kg middle-power explosive is filled in the bottom of each explosion well, estimated by the following equation,

$$a = \kappa\left(\frac{\sqrt[3]{Q}}{R}\right)^{\alpha}$$

where Q is the mass of explosive, kg; R is the spatial distance between explosive and observation point, m; a is the peak acceleration of ground motion induced by explosion, m/s^2; and κ and α are the attenuation coefficient

of explosion earthquake, here taking the two values with 90 and 1.55 respectively (Wang Lanmin, 2003).
After explosive-filling completely, each well is adequately backfilled. As shown in Figure 7, during blasting process each shot detonates two explosives at the same time, which are symmetrical against the centre of testing site. There are three kinds of delay time, 655ms, 705ms and 760ms, to be selected for the short delay blasting, and combining the delay time after each shot, expected duration of ground motion should reach 10.7s.

4. CHARACTERISTICS OF LOESS SEISMIC SUBSIDENCE IN THE FIELD

4.1. Distribution of Loess Seismic Subsidence in the Field

After explosion, there is not any ground fracture to be discovered in testing field. However, observation data shows that all points developed an obvious subsidence in the test site. During the whole period of this field testing, minimum and maximum seismic subsidence of loess ground in testing site is about 13mm and 33mm, and the maximum point stands at the south of the field. On the other hand, maximum seismic subsidence of soils around the site reaches 26mm, whereas minimum seismic subsidence in this region is about 0mm. As shown in Figure 5, seismic subsidence of loess in the field decreases from the south to the north. Furthermore, loess subsidence in testing site is distinctly greater than subsidence outside the loess site, and development of loess subsidence in the former region is more rapid.

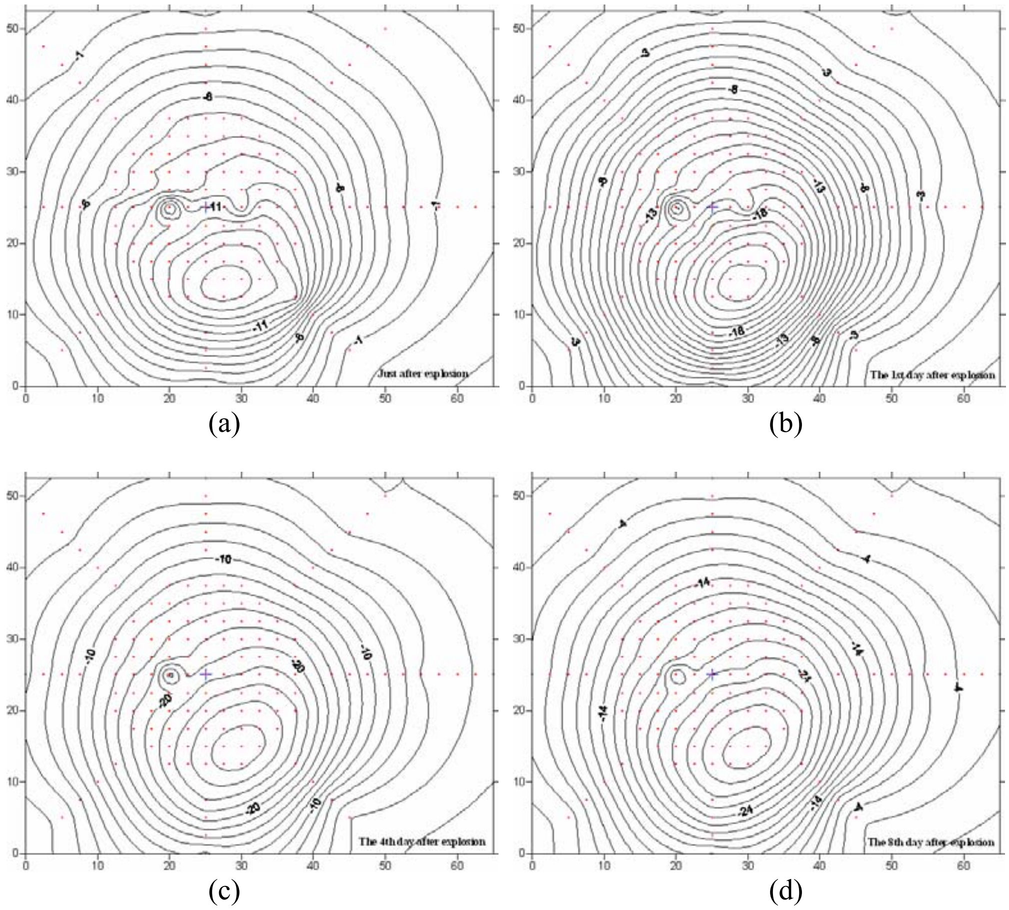
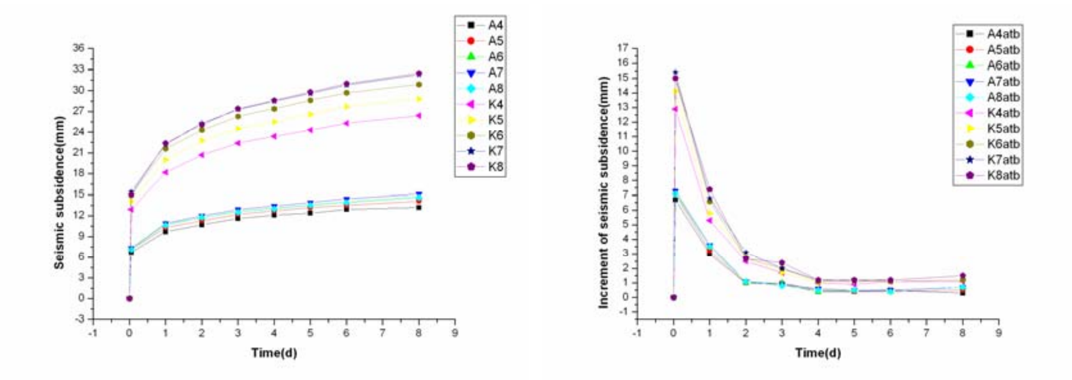


Figure 5 Isoline map of seismic subsidence of loess: (a) just after explosion, (b) the 1st day, (c) the 4th day, and (d) the 8th day, where the dots express the observation points of loess subsidence, and the cross is the center and subsidence unit is mm

4.2. Development of Seismic Subsidence with Time in the Loess Field

From the Figure 6(a) and Table 1, it could be disclosed that just after explosion the seismic subsidence of loess is almost 50 percent to the maximum observation value of loess subsidence. That is to say, during the blasting process, seismic subsidence of loess increases rapidly.



(a) (b)

Figure 6 Developing process of seismic subsidence of loess with time, where A4~A8 and K4~K8 express the northmost and the southmost observation points respectively, and A4atb expresses the increment of loess subsidence at point A4 during one day

Table 1 Statistical results of ratio between loess seismic subsidence just after explosion and the end of observation

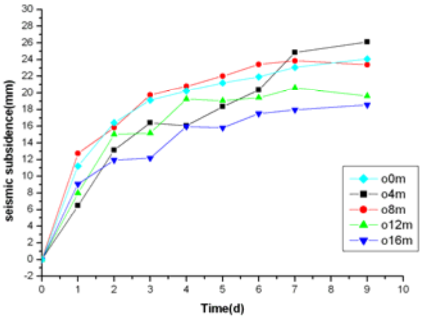
Observation Points of Subsidence	Average Seismic Subsidence (mm)		Ratio of after to end (%)	Observation Points of Subsidence	Average Seismic Subsidence (mm)		Ratio of after to end (%)
	Just after explosion	The end of observation			Just after explosion	The end of observation	
A (A4~A8)	7.10	14.32	49.6	1 (D1~H1)	7.69	15.55	49.5
B (B3~B9)	7.45	16.29	45.7	2 (C2~I2)	8.66	17.75	48.8
C (C2~C10)	8.11	17.93	45.2	3 (B3~J3)	9.41	19.42	48.5
D (D1~D11)	8.58	19.23	44.6	4 (A4~K4)	10.41	21.34	48.8
E (E1~E11)	8.82	20.54	42.9	5 (A5~K5)	10.62	22.30	47.6
F (F1~F11)	10.64	22.80	46.7	6 (A6~K6)	11.17	23.89	46.8
G (G1~G11)	11.28	24.27	46.5	7 (A7~K7)	11.43	24.82	46.1
H (H1~H11)	12.16	26.00	46.8	8 (A8~K8)	11.30	25.19	44.9
I (I2~I10)	13.36	28.10	47.5	9 (B9~J9)	11.48	25.76	44.6
J (J3~J9)	14.25	29.69	48.0	10 (C10~I10)	11.00	25.28	43.5
K (K4~K8)	14.50	30.18	48.0	11 (D11~H11)	10.25	24.25	42.3
Average subsidence ratio of after to end covered all observation points in the test site (%)							~46.5

After explosions, however, development of loess subsidence becomes slow and slow. Curves of seismic subsidence versus time as shown in Figure 6(a) indicate that development of seismic subsidence submits an exponential function. Figure 6(b) shows a result about increment development of loess seismic subsidence with time. This variation characteristic of settlement increment is similar to the developing process of seismic subsidence and it could be distinctly discovered that those observation points with more seismic subsidence likely have a higher increasing rate of settlement than other points.

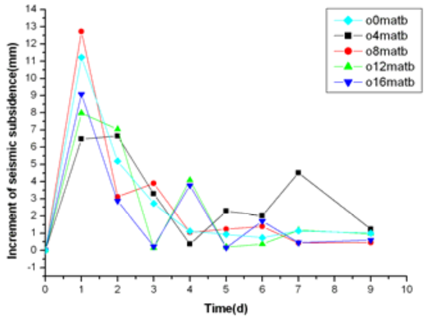
Moreover, while seismic subsidence of non-saturated loess is generated, its developing process for soil mass at different position desponds on the local landform. This result could be detected by combining Figure 5 and Figure 1.

4.3. Seismic subsidence of loess layers at different depth

Differences of loess seismic subsidence at the two depths of 0m and 8m in testing field are not distinct. Settlement of soil layer at the depth of 16m is the least one. At the depth of 12m, seismic subsidence of loess is intermediate between layers with depth of 8m and 16m. Developing process of loess seismic subsidence at the 4m depth is instable and its magnitude experiences a least start and a supreme end (Figure 7).



(a)



(b)

Figure 7 Variation of (a) seismic subsidence, and (b) settlement increment of loess layer with different depth, loess seismic subsidence at 0m represented by observation data of the center point on field surface

Theoretically, observation data of loess seismic subsidence at field surface represents total settlement of soil layers, whereas subsidence of soil layer at different depth shows its contribution to the total settlement. In Figure 7, subsidence contribution of top-soil to total settlement is evidently less than under-soil, i.e. the soil layer beneath the buried depth of 16m; this reveals that subsidence capability of topsoil is not induced completely by the short delay blasting and seismic subsidence of topsoil could take place again while seismic shock is enough strong, because laboratory data shows that seismic subsidence of soil mass between depths of 1m and 15m should be greater than other soil layer (Figure 3).

5. CONCLUSION

After the short delay blasting, there is not any visible ground fracture in the field. However, field testing data shows that all observation points experience an obvious settlement in the test site. The distribution of loess seismic subsidence in testing field desponds on a few factors, such as field landform, physical property of soil, and seismic loading etc. Observation data describes an asymmetric distribution of loess seismic subsidence in the field. As shown in Figure 1, there is an escarp with a drop height of 15m and south soil mass in testing field has more freedom for settlement certainly. Ignoring the variation of physical property of loess mass and seismic loading at different position in testing field, furthermore, this distribution characteristic is probably due to the landform around the field. Consequently, the maximum seismic subsidence of loess occurs within the southern field and it reaches the value of 33mm, nevertheless much less than a general loess settlement by soaking.
Actual peak acceleration of ground motion recorded during this field testing is much stronger than expected value designed by an above-mentioned empirical formula. This discrepancy could help to improve our understanding on evaluation of peak acceleration induced by explosions. Observation data of seismic subsidence indicates that loess failure caused by explosions differs from that by earthquake predominantly. According to a laboratory coefficient of loess seismic subsidence, total subsidence of loess layer with a buried

depth between 1m and 15m could reach 50cm approximately while field intensity degree exceeding Ⅷ, estimated by a layerwise summation method. The real average seismic subsidence of loess field is about 22mm and by this subsidence field intensity degree merely reaches Ⅶ, whereas the degree is up to Ⅷ based on acceleration of ground motion caused by explosions.

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REFERENCES

Gao Guorui. (1980). Microstructure and collapsibility of loss in China. *Science in China* **23(12):** 1203-1208.

Lei Xiangyi. (1987). Pore type and collapsibility of loess in China. *Science in China (Series B)* **17(12):** 1309-1316.

Liu Dongsheng. (1985). Loess and environment. Science Press, Beijing.

Wang Guolie, Ming Wenshan. (2001). Water immerging, deformation and engineering techniques of collapsible loess. Luo Yusheng, Wang Guolie ed. Engineering and research on collapsible loess. China Architecture and Building Press, Beijing, 21-32.

Wang Lanmin, Deng Jin, Huang Yuan. (2007). Quantitative analysis of microstructure of loess seismic subsidence. *Chinese Journal of Rock Mechanics and Engineering* **26(Supp.1):** 3025-3031.

Wang Lanmin, Liu Hongmei, Li Lan, et al. (2000). Laboratory study on mechanism and behaviors of saturated loess liquefaction. *Chinese Journal of Geotechnical Engineering* **22(1):** 89-94.

Wang Lanmin, SHI Yucheng, LIU Xu, et al. (2002). Loess dynamics. Earthquake Press, Beijing.

Xie Dingyi, Qi Jilin, Zhang Zhenzhong. (2000). A constitutive laws considering soil structure properties. *China Civil Engineering Journal* **33(4):** 35-41.

Xu Zhangjian, Lin Zaiguan, Zhang Maosheng. (2007). Loess in China and loess landslides. *Chinese Journal of Rock Mechanics and Engineering* **26(7):** 1297-1312.

Zhang Zhenzhong. (1999). Prediction of seismic hazard of loess. Earthquake Press, Beijing.

Zhang Zhenzhong, Duan Ruwen. (1987). Study on seismic subsidence and seismic hazards of loess. *Northwest Seismological Journal* **9(Supp.):** 63-69.