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THE LIQUEFACTION POTENTIAL OF LOESS IN CHINA AND ITS PREVENTION

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SUMMARY

The recent field investigation and laboratory study show that loess has potentials of liquefaction and flow failure. In order to evaluate liquefaction potential of loess which appears extensively in Northern China and study its preventing methods, dynamic triaxial test, dynamic torsion shear test and in situ explosion test on saturated loess were performed. Based on the test data and the other relevant data on loess, the zoning maps of liquefaction with three probabilities of exceed in 50 years, 63%, 10% and 2%, for the famous Loess Plateau of China were compiled using GIS method. The study results are as follows: (1) Loess deposits of Q_4, Q_3 and Q_2^2 have predominant potentials of liquefaction and consequent deformation; (2) Zoning maps of liquefaction for the Loess Plateau of China may provided sub-zones of serious potential, moderate potential, slight potential and non potential of liquefaction; (3) The most effective treatment for loess ground against liquefaction is chemical treatment. Both dynamic tamping and compaction pile may improve liquefaction resistance of loess in some way, but they can not eliminate liquefaction potential of loess ground completely.

INTRODUCTION

Loess is a kind of soil deposit with weak cohesion and porous microstructure formed in the Quaternary period, which presents extensively in Northern China. Loess is prone to liquefaction under a certain condition. For example, the magnitude 8.5 Haiyuan Great Earthquake in China in 1920 caused liquefaction of loess deposits in Shibeiyuan. The soil deposits above the liquefied layer flowed forward for 1.5 km and destroyed a large village. Similar case occurred in 1989 in Tajikistan, when a 5.5 earthquake triggered liquefaction of loess layer. The mudflow formed during loess liquefaction buried a village and caused horrible disaster of 200 deaths[1]. Liquefaction of loess, however, is not only less well understood but also unique in many aspects when it is compared with liquefaction of sand [2].

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LABORATORY TESTS ON LOESS LIQUEFACTION

A commonly method for laboratory study on loess liquefaction is dynamic triaxial test. In such test, sinusoidal or irregular seismic loading is applied to saturated loess samples to observe the development of pore water pressure and residual strain in loess specimens. For the former, the equivalent cyclic times are used to simulate the actual effect of earthquake with different intensities. For the latter, because the recorded seismic ground motion is applied directly to the samples, it is more reliable as far as the simulating of earthquake ground motion is concerned.

The porous, weak cemented and water sensitive loess, however, pose a difficult problem for saturation of loess samples. The degree of saturation remains mostly around 85% to 95% after back pressure and water level difference seepage method is applied to saturate loess samples. If further measures are applied, to increase the degree of saturation of loess samples, however, there would be hardly any pore water pressure increase observed during the liquefaction test (Fig. 1), which implicates that the structure of loess samples were greatly changed to what can be called critical state of disintegration, sequentially, the structure collapse of loess prevent any obvious increase of pore water pressure [3].

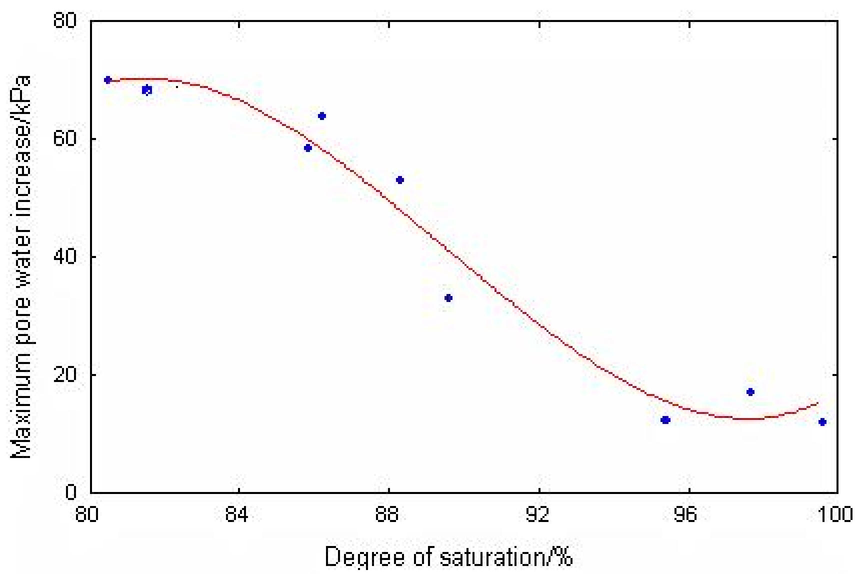


Fig. 1 The maximum pore water pressure increase versus degree of saturation of loess samples under an effective confining stress of 90 kPa.

A typical test result is given in Fig.2. It can be seen that there is clearly increase of pore water pressure and the development of residual strain is much large, which often reaches 12%. These are typical characteristics of loess liquefaction. In our study, the liquefaction of loess is divided into three stages according to the main characteristics of pore water pressure increase and residual strain development. As it is shown in Fig. 2, in the first stage, there found rapid increase of pore water pressure while the development of residual stain is modest. It is believed that in this stage, the skeleton of loess remains stable. The cyclic vibration causes the rising of pore water pressure, which is obviously observed. But the pore water pressure ratio under dynamic triaxial test, if it is compared with sand liquefaction, is relatively low, which often stands at around 0.4 to 0.8. In the second stage, things change a lot. That is, the development of pore water pressure is modest while the development of residual strain is very dramatic. It is found that in this stage, the water sensitive and weak cemented loess skeleton at least partially collapses under the effect of cyclic loading. The large deformation of loess prevents rapid development of pore water pressure. At the end of this stage, pore water pressure is at peak. In the third stage, the pore water pressure of loess sample remains stable while the rapid increase of residual strain continues. The accumulating of residual strain is often more than 10% for most samples we tested.

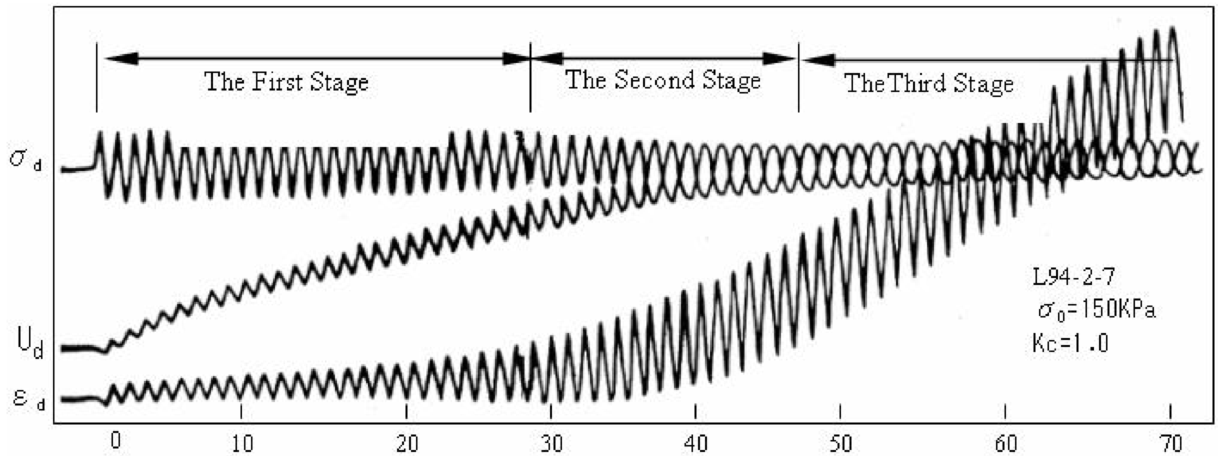


Fig. 2 Time histories of stress, strain and pore pressure recorded in the test.

Dynamic torsion test is another method to investigate loess liquefaction. The dynamic torsion test on remolded saturated loess samples the first author performed in Tokyo Denki University in Japan proves that loess has high potential of liquefaction (Fig. 3). The pore water pressure ratio of loess liquefaction reaches as high as 0.9, which is higher than those in our previous study using dynamic triaxial tests on undisturbed saturated samples. This is due to difference in microstructure between the remolded samples and undisturbed samples, which made the remolded samples to have higher degree of saturation than undisturbed sample before their microstructure damaged due to saturation. But, in any way, it is strong evidence that not only loess may liquefy but also its liquefaction potential is very high.

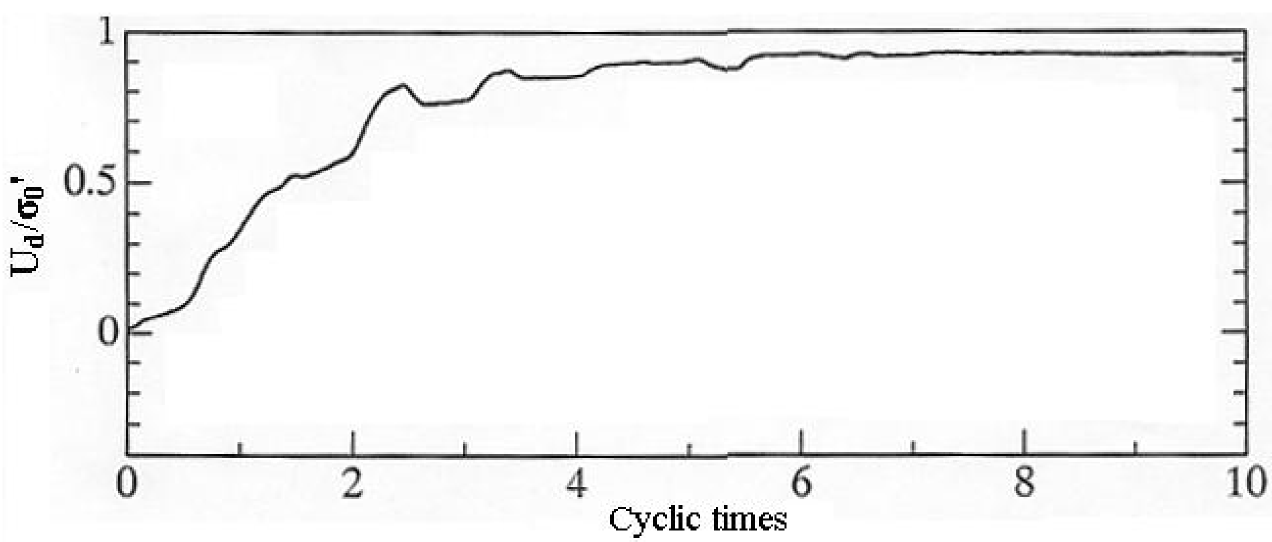


Fig. 3 Loess liquefaction under dynamic torsion test

So we know that one distinctive point for loess liquefaction is the development of large residual strain and low pore water pressure ratio. At the same time, the cyclic stress ratio, which is often used as an indicator of liquefaction resistance, of loess liquefaction stands mostly at around 0.2. This indicates that loess in Northwest China is prone to liquefaction if the ground is saturated with water or has high water content and earthquake intensity is above 7 degree in Chinese seismic intensity scale.

IN SITU TEST ON LOESS LIQUEFACTION

When the concept of loess liquefaction was firstly put forward by some experts including the first author of this paper, it raised controversy. One strong objection is that loess liquefaction is not witnessed in the numerous cases of earthquakes in loess area. The loess liquefaction during the 1920 Haiyuan Great Earthquake in China though can be clearly identified until the 1980s, does not convince some scholars because they held that the ground water table was too deep in the area and the phenomenon observed can be explained as ground flow in the direction of very gentle slope.

In order to examine the objectivity of loess liquefaction as well as the laboratory research results, artificial explosions with micro-interval were carried out to simulate the intensity and cyclic times of seismic ground motion. A field liquefaction test in saturated loess site under the explosive ground motion was performed in Lanzhou, China [4].

The saturated loess site is located in wind-laid Q_3 sandy silt deposit with the thickness of more than 15 meters. Table 1 presents its physical parameters of loess. Nine explosions with homogeneous time interval of 0.31 seconds were executed in soil deposit with the depth of 4.5 meters around the saturated loess site shown in Fig.4. The designed distances to explosive focus, explosive weights and PGA are listed in Table 2. Before the test, a sensor for measuring pore pressure and a three-component acceleration sensor for recording ground motion were put into the expected liquefaction layer in soil deposit. We also measured shear velocity in the loess layer and predominant period of ground tremor before the test, the values of which are respectively 326 m/s and 0.292 second.

Table 1 Physical parameters of the test site

W (%)	γ(kN/m^3)	e	P.L (%)	P.I	Gradation (%)		
					Clay	Silt	Sand
9-10	14.6-15.0	1.101	15.7	9.2	14.0	67.6	18.3

Table 2 The distances to explosive focus, explosive weight and PGA

Focus No.	1	2	3	4	5	6	7	8	9
Distance(m)	25.4	25.4	20.5	25.4	20.5	25.4	20.5	25.4	20.5
Weight (kg)	15	30	10	30	15	20	15	30	10
Expected PGA (gal)	242	347	274	347	242	281	242	347	274

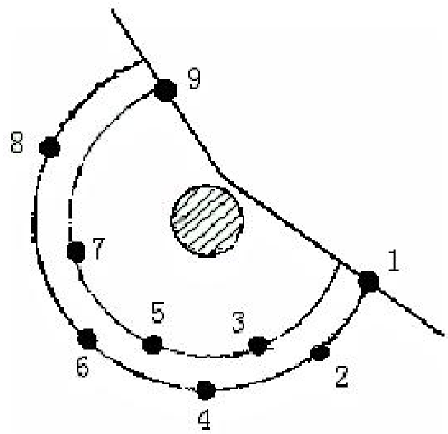


Fig. 4 The pattern of saturated site and explosive focuses

During the test, 3 components of ground motion, EW-component, NS-component and UD-component, were recorded. The important thing is that an obvious development process of pore pressure was observed in the expected liquefaction soil layer. Fig. 5 shows the EW-component of ground motion and Fig. 6 presents the time history of pore pressure development during the explosions. Table 3 and Table 4 are respectively the main parameters of these records.

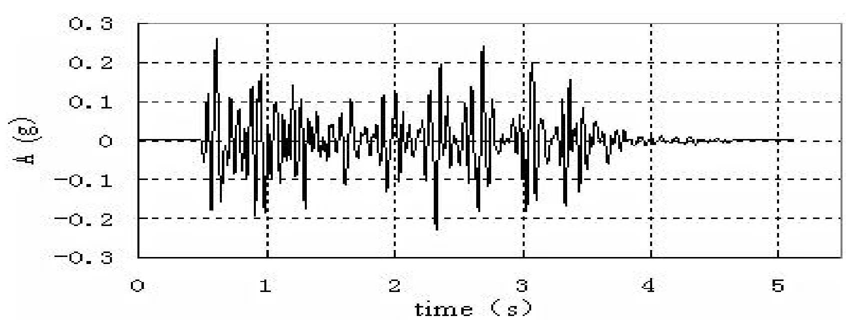


Fig. 5 EW-component of ground motion acceleration

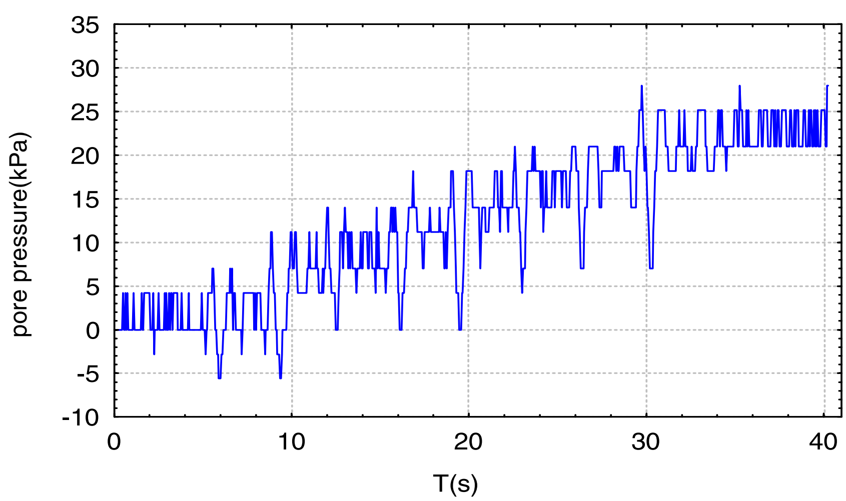


Fig. 6 Development of pore pressure during the explosions

Table 3 The main parameters of acceleration records of explosive ground motion

Component	Max. PGA (gal)	Effective cyclic times	Predominant frequency (Hz)	Duration (s)
EW	260.7	16	12.5	4.597
SN	180.9	14	8.6	4.350
UD	328.3	12	8.8	3.985

Table 4 The main parameters of recorded pore pressure

Max. pore pressure (kPa)	Pore pressure ratio	Settlement(cm)	Residual strain (%)
21	0.328	3	0.43

Before the explosive test, dynamic triaxial test of liquefaction on undisturbed saturated samples secured from the test site was performed under a sinusoidal loading with a frequency of 1 Hz. After the explosion test, dynamic triaxial test on the same group of samples was carried out under dynamic loading of both the time history of explosive ground motion and equivalent sinusoidal waves with different frequences. The test results are presented in Table 5.

Table 5 Laboratory test results of liquefaction

Dynamic loading	σ_0' (kPa)	σ_d (kPa)	$\sigma_d / 2\sigma_0'$	U_d / σ_0'	MPGA(gal)	¦Å (%)	N_f
Sinusoidal loading (1Hz)	64	28.1	0.20	0.391	139	12.2	12
Sinusoidal loading (10Hz)	64	22.3	0.17	0.391	118	1.05	30
Sinusoidal loading (12.5Hz)	64	16.8	0.13	0.334	90	3.09	30
Explosive loading (EW)	64	33.5	0.25	0.436	174	0.49	16
Explosive loading (EW)	64	37.7	0.294	0.539	294	0.85	16

From the above-mentioned test results, we found that the explosions induced a predominant development of pore pressure and a residual strain of 0.43%. The saturated loess layer liquefied partly. The minimum PGA triggering the liquefaction figured out from laboratory test is less than that from the field explosion test. However, the laboratory test results under sinusoidal loading with the frequency similar to the predominant frequency of explosive loading is more close to the field explosive test results, especially for the laboratory test under the explosive loading. Similarly, the frequency of loading has an obvious effect on residual strain. For the loadings with the same wave, the higher the frequency is, the less the residual strain develops. Therefore, as long as using the same time history of loading, laboratory dynamic triaxial test can be used to predict liquefaction of loess site. Such a result will be partial to safety although there is a deviation probably coming from the differences between soil samples and site soil or in restrained condition between the two kinds of test.

MECHANISM OF LOESS LIQUEFACTION

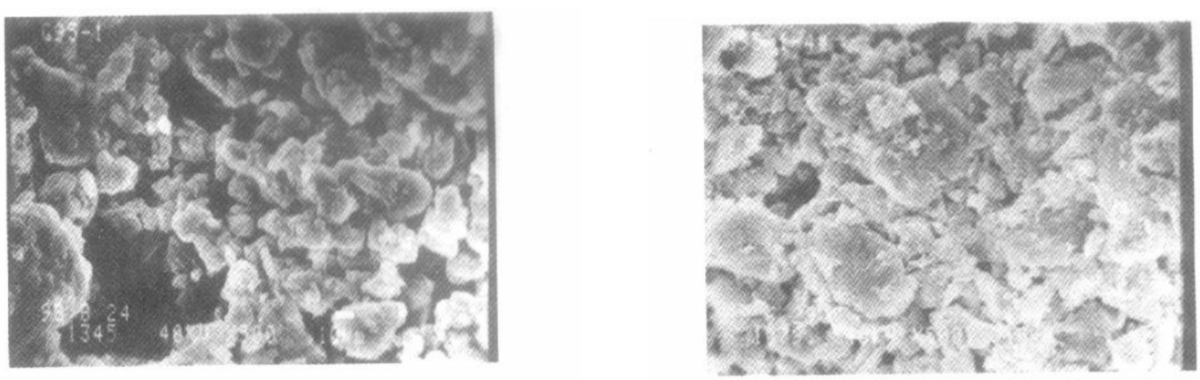
The mechanism of loess liquefaction is not completely the same as that of sand liquefaction. Using microstructure and hydraulic chemical evidences, we can explain why the mechanism of loess liquefaction is different from that of sand liquefaction. In the microstructure of saturated loess, middle and large pores are filled with water. But a portion of small pores and most of mini-pores do not. Easily dissolvable salt

(NaCl£¬KCl£¬Na_2SO_4 and Na_2CO_3) and dissolvable salt ($CaSO_4$) dissolves or partly dissolves in loess when meet with water, which has certain effect on the stability of loess microstructure. At the beginning of loading, the microstructure basically remains stable. Strain is largely elastic and pore pressure develop rapidly (Fig.2) With increase of cyclic times, dissolvable salt continues to melt (Table 6), which causes microstructure of loess lose its strength, as a result, some of the large and middle pores collapses (Fig.7). Silt particles fall into the space of the damaged pores. The pore volume decreases. Consequently, pore pressure rises and effective stress decreases. On the other hand, dissolution of salts damaged middle and large pores. Thus, some water enters the pores that were filled with air previously and the pore water pressure disperses to some extent. This is why pore pressure ratio cannot reaches 1.0.

Table 6 Variation of ion concentration in pore water before /after liquefaction

Ion	Cl^-	NO_2^-	NO_3^-	SO_4^{2-}	Na^+	K^+	Ca^+	Mg^+
Water for saturation (ppm)	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
1 H.S.B.L. (ppm)	124	<0.5	<0.5	2202	111	6	449	207
1 H.S.A.L. (ppm)	608	208	435	3900	570	10	830	250
Long time S.B.L. (ppm)	117	2.0	0	2057	80	4.8	375	243
Long time S.A.L. (ppm)	149	2.1	1.2	3716	122	8.2	723	408

Abbreviations: A- after, B- before, H- hour, L- liquefaction, S- saturation.



(a) Before liquefaction **(b) After liquefaction**

Fig. 7 Microstructure of a loess specimen before and after liquefaction

CONDITIONS FOR LOESS LIQUEFACTION

Based on field investigation and laboratory study, the conditions for loess liquefaction are summarized as following:

1) Site conditions

Based on the liquefaction occurred in several earthquakes, it is found that loess liquefaction can only be possible if 1. The loess stratum is younger than Q_2^2 in geological time, which is especially Q_3 and Q4 and 2. The ground water table is shallow (usually <10m. But just before an earthquake, the ground water table can raise some, which is the case for the liquefaction in 1920 Haiyuan Great Earthquake.) or there is water source.

2) Physical indices conditions

Laboratory study on Q_3 loess from Lanzhou shows that if the water content of loess is above the plastic limit, liquefaction or partially liquefaction of loess can be observed. The higher the water content is, the higher the pore water pressure ratio would be (Fig. 8).

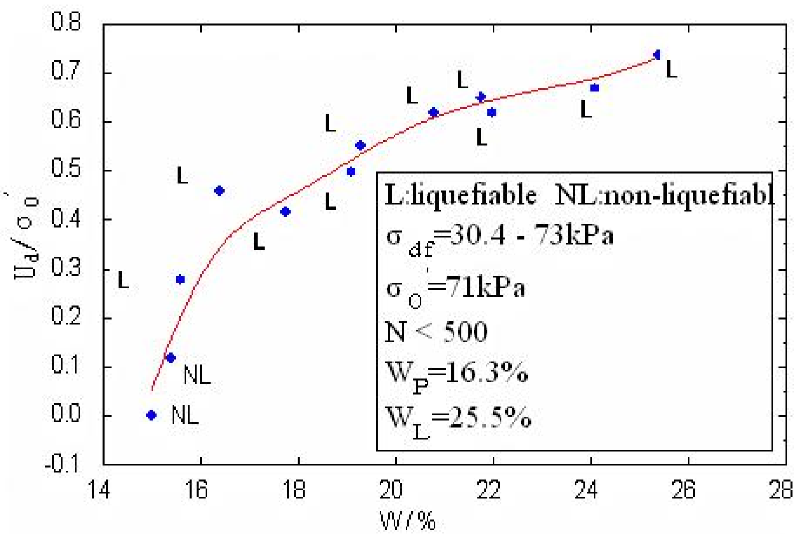


Fig. 8 Influence of water content on loess liquefaction

Plastic index, which is closely related with the grading of loess, also affects the liquefaction of loess [5]. Based on laboratory tests on remolded loess specimens by Prof. Prakash of U.S, it is revealed that when plastic index (I_p) below 4, the cyclic stress ratio decreases with increase of I_p. , but when it is above 4, the cyclic stress ratio increases with increase of I_p (Fig.9). When I_p>15, there will no liquefaction potential for loess under seismic intensity less than IX degree.

Dry density of loess can affect loess liquefaction. Generally speaking, the higher the dry density is, the more the cyclic times for loess liquefaction would be. But this is not a very clear-cut situation because water content is also a major factor that affects loess liquefaction.

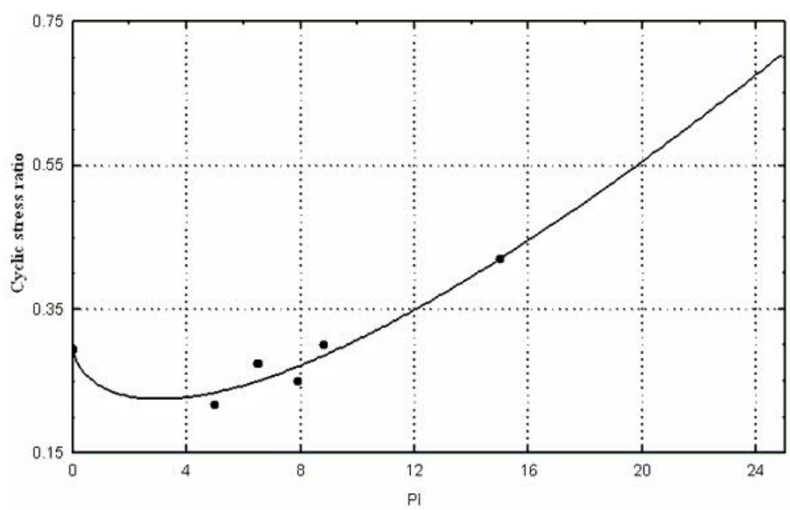


Fig. 9 The influence of plastic index on stress ratio of liquefaction (Prakash S. 1998)

3) Ground motion conditions

Our study shows that low intensity seismic ground motion will not cause loess liquefaction. The minimum acceleration of ground motion to trigger loess liquefaction is 100gal or VII degree in seismic intensity scale. But for loess with different silt content, the PGA for triggering liquefaction is different. The high the silt content is, the less the critical PGA would be (Fig. 10).

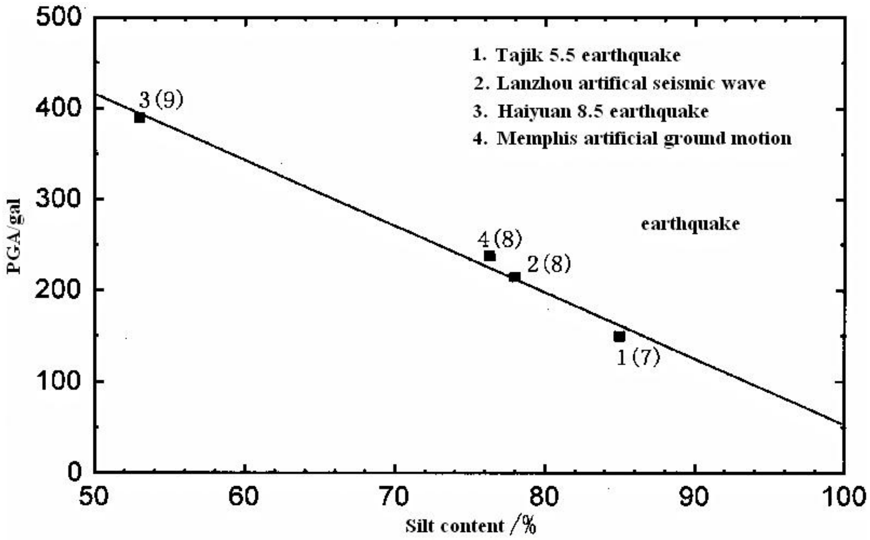


Fig. 10 The effect of silt content on the critical PGA of triggering loess liquefaction (Number in bracket is seismic intensity)

ZONING LOESS LIQUEFACTION USING GIS

One of the practical methods for loess liquefaction prevents in region level is liquefaction zoning. In zoning, loess is classified into several level of liquefaction potential. With this map, necessary measures can be taken to avoid liquefaction of loess ground of buildings.

The authors proposed methods for loess liquefaction at three levels[6]. For the liquefaction at regional level such as Loess Plateau in China, the macro-level of zonation should be applied. In this method of loess liquefaction zonation, the factors taken into consideration are faults, ground motion, type of loess, regional underground water table. Liquefaction zonation under seismic ground motion with different exceedance probabilities is quite useful, because it can be incorporated with seismic codes where ground motion with different exceedance probabilities is often available at regional level.

Fig. 11, Fig. 12 and Fig. 13are respectively the zonation maps of liquefaction potential of loess in Loess Plateau region under the effect of ground motion with exceedance probabilities (EP) of 2%, 10% and 63.5% in 50 years.

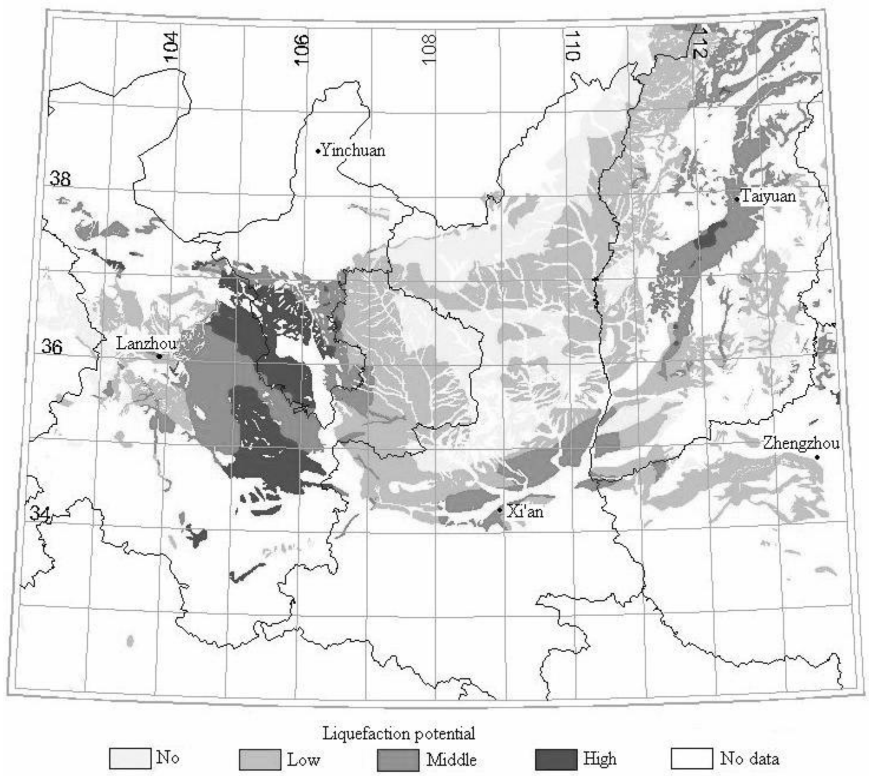


Fig. 11 Liquefaction zonation for Loess Plateau with EP of 2% in 50 years.

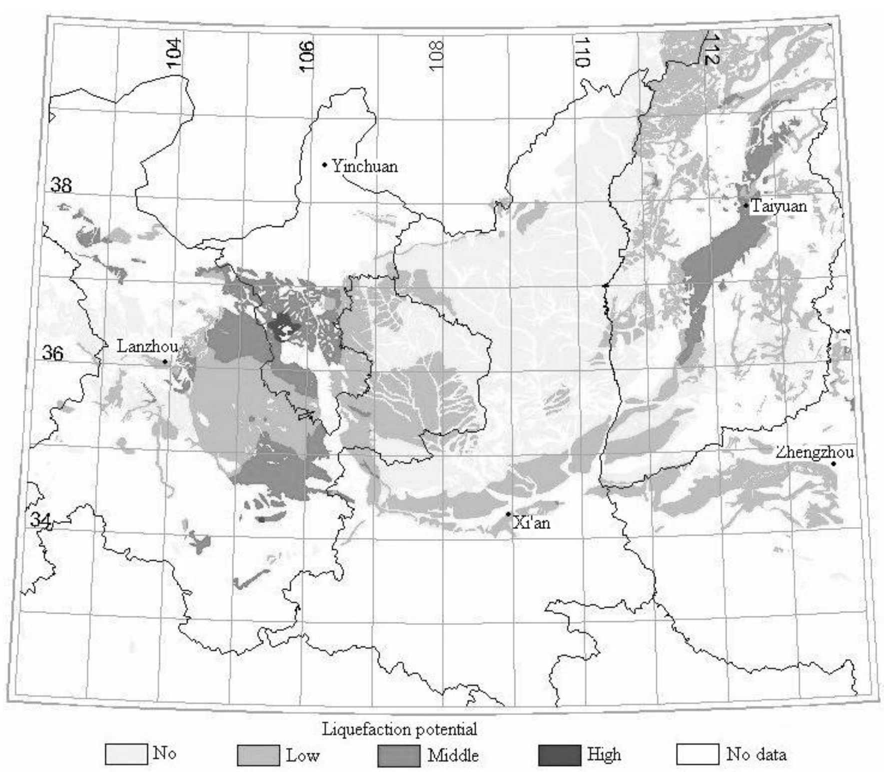


Fig. 12 Liquefaction zonation for Loess Plateau with EP of 10% in 50 years.

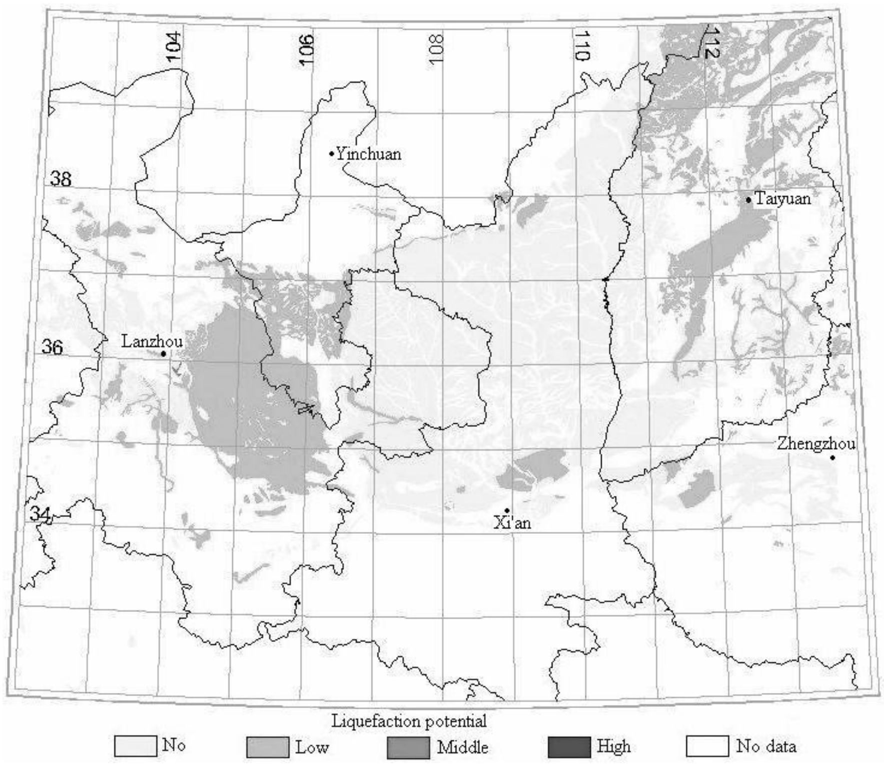


Fig. 13 Liquefaction zonation for Loess Plateau with EP of 63.5% in 50 years.

Table 7 is a summary of the zoning maps. It can be found that under a strong earthquake with return period of 475 or longer will caused serious liquefaction in many parts of Loess Plateau. But under earthquake with return period of about 50 years, liquefaction can be prevented for general purpose constructions with ground treatment because most cases will be slight liquefaction.

Table 7 Proportion of areas with different potentials of liquefaction in the Loess Plateau of China

Probability of exceed in 50 yeas	Non liquefaction	Slight liquefaction	Moderate liquefaction	Serious liquefaction
2%	17.2%	47.9%	23.4%	11.5%
10%	38.6%	39.9%	20.9%	0.6%
63%	61.9%	38.1%	~0%	0%

TREATMENT AGAINST LIQUEFACTION OF LOESS GROUND

Treatment against liquefaction of loess ground proved to be a hard nut to be cracked. Unlike the seismic settlement caused by the loose structure of loess, liquefaction is determined mostly by the gradation and weaken cemented skeleton of loess, which is often very hard to deal with.

There are two ways to prevent loess liquefaction. The first is to keep the external conditions such as underground water table and ground motion in a safe range, which will not trigger loess liquefaction. This is easier to be done if the property owner have enough freedom to select a site where the building or infrastructure to be constructed. The seismic isolation will be very useful in this case, too. But in an area of high seismic intensity and the land is limited to allow the property owner to select an ideal seismic resistance site, then the second way of reducing loess liquefaction potential by change the soil property of loess has to be considered. There is no practical proof of ground treatment effectiveness for loess liquefaction so far. Our study is based on laboratory study. The compaction treatment like dynamic tamping or compaction pile can reduce the liquefaction potential of loess to some extent (Fig. 14). But since these treatments only increase the relative density of loess, it can not eliminate the liquefaction potential of loess completely.

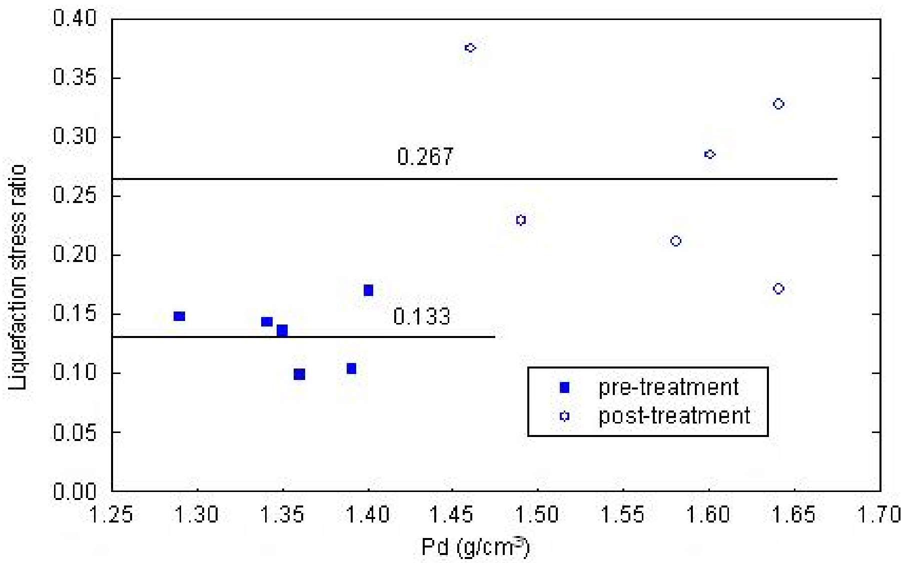


Fig.14 Stress ratio versus dry density before/after compaction piles treatment (at 5m depth)

Our study shows that the most effective method to eliminating the liquefaction potential of loess ground is to alter the soil structure with chemical grouting. Within the effective treatment depth, the cementation of loess structure is strengthened greatly. In laboratory test, there is only elastic strain and very small amount of elastic pore pressure increase observed even if very strong dynamic stress is applied (Fig.15). Therefore, chemical grouting can be used to treat loess ground for seismic safety.

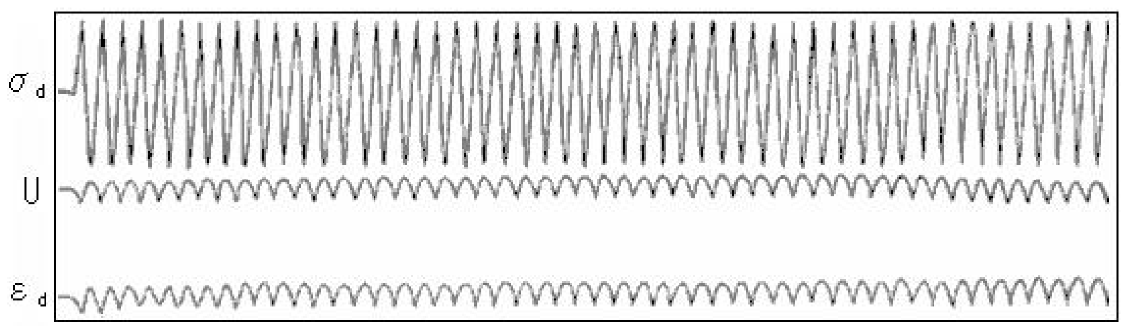


Fig.15 Time histories of stress, pore pressure and strain during liquefaction test of loess sample after chemical treatment

CONCLUSION

1. Both laboratory and in situ tests show that loess from Q_3 to Q_4 in Northwestern China is liquefiable under the proper underground water table condition. And the PGA triggering loess liquefaction is quite low. So the liquefaction problem in loess site should be paid attention to.

2. The mechanism of loess liquefaction is unique in sense that it develops large amount of residual strain while the pore water pressure increase is limited to 0.4 to 0.8 mostly under dynamic triaxial test. This is caused by the porous and weak cemented structure of loess and its water sensitivity. The soil skeleton of saturated loess is vulnerable if pore water increase reaches to certain extent.
3. The factors affect loess liquefaction is site condition (geological time when loess formed and underground water table), physical indices (largely plastic index and water content of undisturbed loess, to a less extent, dry density) and intensity of ground motion.
4. Based on GIS, zoning maps on loess liquefaction in Loess Plateau in China are provided for seismic ground motion with different exceedance probabilities within 50 years. These results show that under a strong earthquake with return period of 475 or more, the liquefaction problem can be serious for many parts of Loess Plateau. But under the effect of earthquake with return period of around 50 years, the liquefaction is slight.
5. Treatment of loess liquefaction remains to be a challenge. Property owner can opt for either the methods to change the external conditions that induce loess liquefaction or the methods to change the soil properties to improve the liquefaction resistance of loess. The former, however, may not be possible if the land available is limited or sometimes trying to reduce the underground water table in site is impractical. For the latter, the compaction treatments for loess ground can improve liquefaction resistance to some extent, but they are not very effective to eliminate liquefaction potential of loess. Chemical grouting is very effective by altering the soil structure of loess with effective treatment depth. Therefore, for sites with high standard for safety, chemical treatment can be applied.

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