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Criterions, Prediction and Prevention of Loess Liquefaction

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CRITERIONS, PREDICTION AND PREVENTION OF LOESS LIQUEFACTION

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ABSTRACT

Although loess liquefaction is not very common during earthquakes in Northwest of China, it is disastrous if it happens. Both study and valid evidence from Haiyuan 8.5 Earthquake in 1920 and Tajikistan 5.9 Earthquake in 1989 have proved that loess liquefaction could be very disastrous under certain conditions. In this paper, the criterions of loess liquefaction are discussed to show that unlike typical liquefaction of sand, loess which falls into the category of both silt clay and clayey silt has unique characteristics during liquefaction test. To predict liquefaction of loess, a simple method based on laboratory test and field evidences using GIS is proposed. The prediction results and corresponding measure have been adopted in Seismic Design Code for Buildings in Lanzhou Urban Area. Finally, recent approach of treatment of loess with chemicals methods is developed, which may have some application implication as an simple and feasible treatment method against liquefaction of loess.

INTRODUCTION

Loess is widely distributed in Northwest of China, where Loess Plateau, with 400,000 square kilometers, is the largest plateau of loess in the world. The plateau is covered by thick loess layer, which is from tens meters to more than 500 meters. Lanzhou, Gansu area, with completely developed loess layer and large deposit thickness, has been named as "the thickest loess sedimentation area in the world" and represents the typical geological characteristics of the loess layer in China.

For a long period, liquefaction of silt soils including loess is not recognized even if there were some study and it is often controversial. This attitude changed during 1990's. Loess liquefaction is not very common but surely observed during earthquakes in Northwest of China and other part of the world like Tajikistan and central states of Untied States (Ishihara, 1990; Hwang and Wang, 2000). During Haiyuan 8.5 Earthquake in 1920, Tajikistan 5.9 Earthquake in 1989 and much earlier, the New Madrid earthquake in 1811-1812, there were loess liquefaction which caused landslides of nearly horizontal layers and other types of geotechnical hazard. Villages were buried and hundreds of lives lost for the cases of China and Tajikistan. Investigation and records have shown that Haiyuan earthquake caused the rise of the underground water of nearly 4-5 meters, which led to liquefaction in Late Pleistocene(Q_3) loess layer at depth of 14-16m. The sliding distance reached a maximum of 1.5km of the super stratum along the hillside. Even 50 years later, the flow trace of the loess can still be identified in the field. In 1990, based on field investigation, an overall assessment of loess liquefaction were given by Bai et al. (Bai, 1990), since then there comes a great interest for loess liquefaction study. Wang Lanmin performed dynamic triaxial test of loess liquefaction and made inversion analyses of the three cases, which shows that the PGAs triggering loess liquefaction during the Haiyuan earthquake, New Madrid earthquake and Tajik earthquake are respectively around 380gal, 240gals and 150gals.

Liquefaction of loess is unique in many ways. First of all, it is a flow type of liquefaction. That is, under the effect of cyclic loading, the pore water pressure in loess rises, effective stress is down and large amount of residual strain develops, finally, loess loses its strength and became mud flow. The amount of residual strain as it is shown in dynamic test could easily be more than 10%, which is really huge. The loess sample after liquefaction test is very soft and cannot stand on itself without leaving for desiccation of certain amount of time. The shape of sample, which is a normal cylinder before liquefaction test, turns into a bulged form at the bottom (Fig.1). This indicates that loess samples turns into a mud flow due to liquefaction. An interesting feature of microstructure of loess after liquefaction test is the formation of many round holes, which do not observed in sample before test. The diameter of these round holes is from 60 to 200 micron(Fig.2). Because of its regular shape, it has to do with the pore water movement. We assume that there are two reasons for the formation of such round holes: 1. during the test there are collapse of microstructure which formed a larger pore, 2. the pore water movement using such holes as main channel, and thus they are also subjected to pore water pressure, which is homogenous, the homogenous pore water pressure caused these holes to have a round shape. This phenomenon also indicates that because of low permeability of loess, pore water movement is quite uneven at different parts of the sample, most of the pore water running through the channels composed with the round holes and channels connecting or around them.

Fig.1 Loess samples after liquefaction test

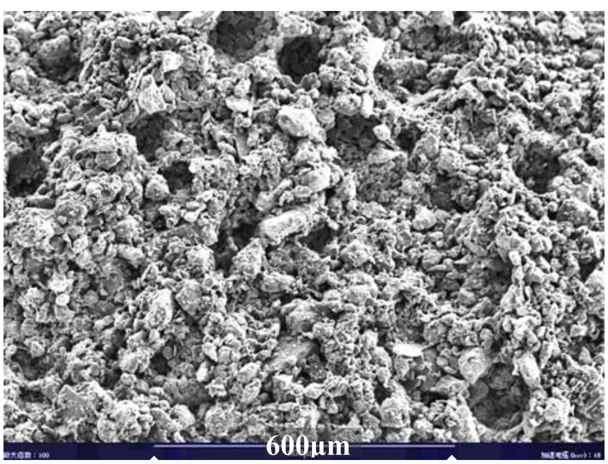


Fig.2 Microstructure of loess after liquefaction
(Magnification factor: 100)

There is a major difference between liquefaction of sand and that of loess. For sand liquefaction, it is the result of densification of sand structure which forced some portion of water move out from the skeleton and even rise up. But for loess, because of its low permeability, water cannot move as freely as it is in sand. As a result, the pore water pressure buildup applies shear stress to loess structure and causes it to collapse. The collapse and consequentially, the development of larger amount of residual strain are because f loess structure is porous with void ratio usually more than 1. During liquefaction, the pores were damaged and the particles rearranged to contact more closely each other.

Since 1990's liquefaction of Loess has been an hot topic and on the front of scientific exploration. Wang L.M et al (1996, 1999) carried comprehensive study on the liquefaction characteristics of loess liquefaction and its mechanism. Also, sit explosion is applied to show that loess liquefaction is possible. Yang Zhenmao et al. (2004) studied the pore pressure increase characteristics and steady state strength. Yuan Zhongxia et al. (2004) studied on mechanism and discrimination criterion of loess liquefaction and regarded that loess liquefaction is a " flow type" and has large deformation. Liao Shengxiu, Chen Juhong (2007) using hard evidence from site, showed that long duration of mechanical vibration of pile driver caused liquefaction of loess field. Wang L.M et al. (2007) applied the research results into practices through drafted "Seismic Design Code for Buildings in Lanzhou Urban Area", which is the first local engineering specification for the discrimination and treatment of loess liquefaction.

The loess liquefaction is fall into the category of liquefaction of silt-clay mixtures as the term used by American scientists. Prakash et al. (1998) proved that PI and initial void ratio are two relatively independent parameters, which decide whether the loess could liquefies or not. And the age and structure decide the pattern of pore pressure increase during liquefaction. The development of pore pressure and strain during loess liquefaction are different from that of sand under the cyclic loading. Boulanger and Idriss (2006) divided the liquefaction behavior into "sand-like" and "clay-like". This through new light on study of liquefaction of loess and draw a clear line on problems and type of silt soils that were debatable as far as liquefaction is concerned.

Although liquefaction mechanism and behaviors of loess have been studied, there is also some no well established test procedures and criteria to assess liquefaction potential or treat loess ground for liquefaction. With the development of urbanization and agriculture irrigation, the area of saturated loess and loess with high water content has been enlarging. There is a very high probability to liquefy loess under the earthquake with certain intensity. So there is still urgent need to study loess liquefaction and clarify some of the filed where which it still not well accepted or recognized.

TEST OF LOESS LIQEFACTION

Most laboratory loess liquefaction tests have been done on the electromagnetic dynamic triaxial instrument in Lanzhou Institute of Seismology (LIS) before 2006. The instrument has some disadvantages, such as, lacking of back pressure for saturation, open-loop control and which makes the test process rather awkward sometimes.

The water head method was commonly used to saturate the loess. Because of the pore microstructure, weak cementation among particles and the hydraulic sensitivity of the loess, the air in the enclosed void is difficulty to discharge using water head saturation. Usually, the degree of saturation ranges from 0.8 to 0.9. Since 2006, LIS imported WF 12440 hollow cylinder apparatus which is also capable of dynamics triaxial test but with close-loop control and back pressure option. The laboratory research in this paper is mainly based on tests carried out on this test equipment.

The Method of Experiment

Firstly, using back pressure saturation method to saturate the loess, make the pore pressure water parameter B equal or more than 0.95. Afterwards, consolidate the loess isotropically or anisotropically. After the saturation and consolidation stages, the load is applied to the loess sample until it destroys. The behavior of the saturated loess are studied under different load, different consolidation ratio and different cell pressure. The applied load is 15, 20, 25kPa. The vibration wave is sinusoidal wave with 1Hz frequency.

Using WF12440 hollow cylinder torsional instrument as the test platform, the normal triaxial function of the WF12440 was used. The pneumatic actuators apply the pressure to the sample. Because the air can be compressed, when load is applied, the system can carry out feedback control and the load would not change greatly by the in-and-out air. The sample, put inside the triaxial cell which is filled with water, is protected isotropically by the water when loading. WF12440 can also dynamically control the back pressure axis, cell pressure axis and pore pressure axis and integrate control and data acquisition system. (shown in Fig.3)

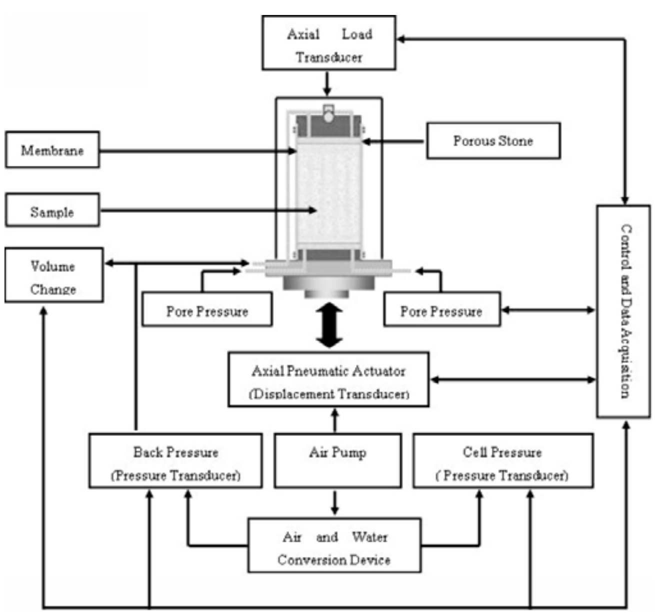


Fig. 3 Sketch of the structure of the hollow torsional apparatus

The test sample is the solid cylinder loess, with outer diameter 50mm and height 100mm. In order to compare the test results, the loess, which makes of the remolded samples, comes from the residue of the undisturbed loess. The test loess, excavated from underground 9m in Yuzhong, Lanzhou, is the typical Q_3 loess. Table 1 represents the basic physical parameters of the specimens and Fig.4 is the grain size distribution curve of Lanzhou loess.

Table 1 Basic physical parameters of the specimen

W (%)	ρ_d (g/cm^3)	Saturation (%)	LL	PL	PI
5.6-13.1	1.17-1.42	15.5-38.5	22.2	13.6	8.6

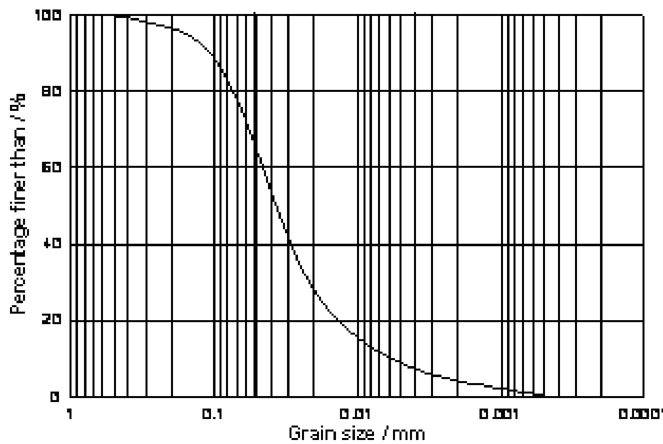


Fig.4 Grain size distribution curve of Lanzhou loess

The Result of Experiment

Saturation test. The water content plays an important role to the behavior of loess liquefaction. Therefore, to fully saturate the loess is the precondition for the saturated loess liquefaction test.

In the test, back pressure saturation method was used to saturate the loess with initial low saturation degree. According to the equation of Skempton's, the pore water pressure parameter B:

$$B=\triangle U/\triangle\sigma_3 ,$$

$\triangle U$: increase of pore pressure,

$\triangle\sigma_3$: increase of cell pressure.

It is commonly known that if B is equal or more than 0.95, the soil is saturated. During the process of saturation, cell pressure and back pressure are increased to make the pore pressure raise. The pore water pressure parameter B is automatically checked by the computer to decide whether the full saturation is reached. As shown in Fig.5 the back pressure method can be used to make B reach 0.95, or the sample full saturation, and the height change of the sample is less than 0.5%.

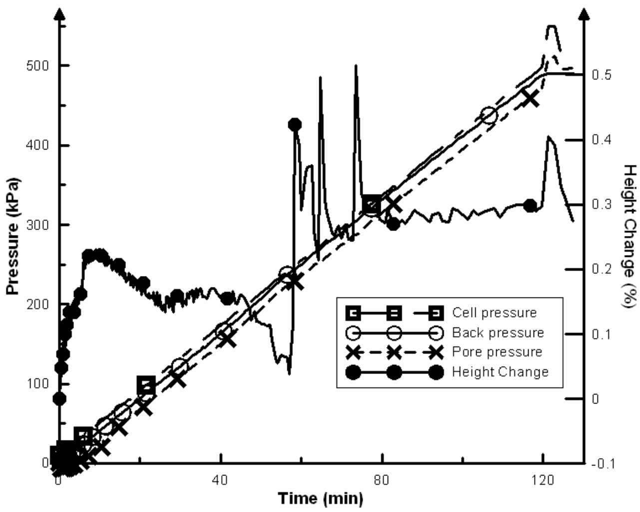
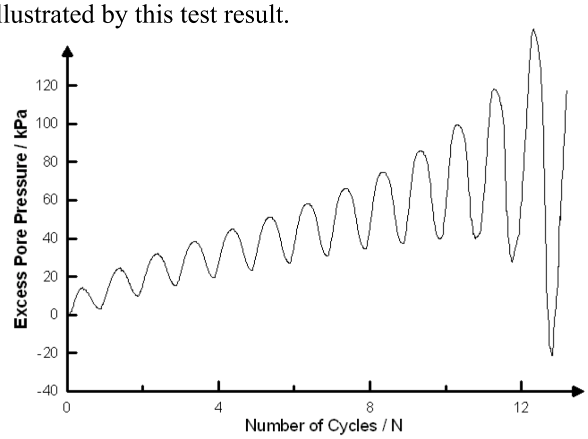
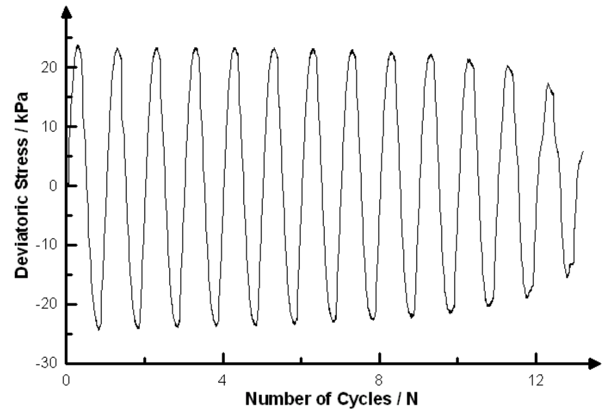


Fig. 5 Pressure development and length change curve of back pressure saturation method

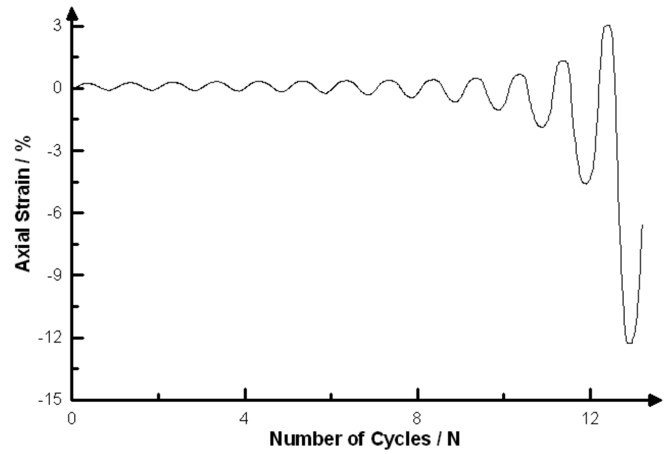
Vibration test. Fig.6 is development curve of the excess pore pressure, deviatoric stress and axial strain of undisturbed loess with loading cycles under the isotropically consolidation, effective consolidation pressure 130kPa and cyclic stress ratio 0.1. The cyclic stress ratio is the ratio of dynamic shear stress and effective consolidation; deviator stress is the difference between axial stress and cell stress. The following discussion is illustrated by this test result.



(a) Number of Cycles vs. Excess Pore Pressure



(b) Number of Cycles vs. Deviatoric Stress

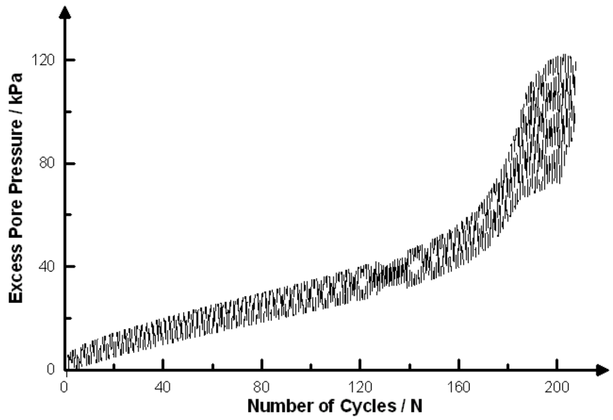


(c) Number of Cycles vs. Axial Strain

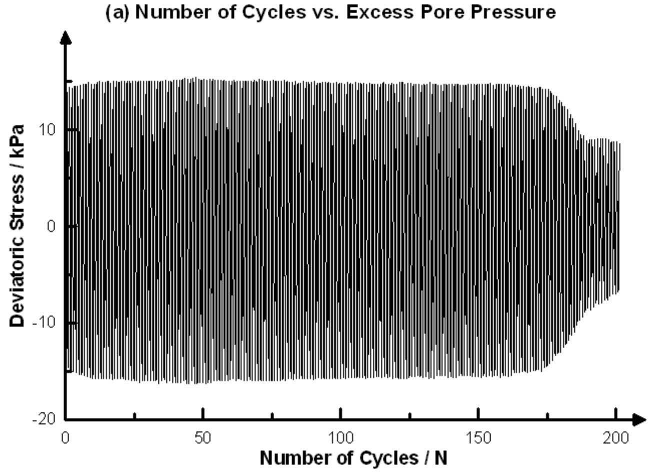
Fig.6 Development of excess pore pressure, deviatoric stress, axial strain of saturated undisturbed loess with loading cycles

Under the condition of isotropic consolidation, excess pore pressure can reach the effective consolidation pressure. The excess pore pressure increases slowly at the beginning; the excess pore pressure increases rapidly suddenly from 8 cycles until it reaches the effective consolidation pressure at 12 cycles. Simultaneously, the deviatoric stress decreases obviously and axial strain reaches 3%. After 12 cycles, the excess pore pressure has negative value, namely, the decrease of excess pore pressure. After that, the curve of excess pore pressure has some irregular fluctuation, the deviatoric stress decreases until zero and axial strain has big increase.

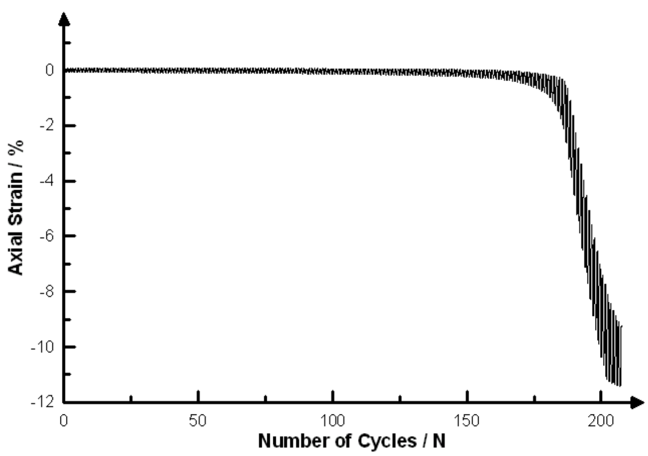
Figure 7 is development curve of the excess pore pressure, deviatoric stress and axial strain of remolded loess with loading cycles under the isotropically consolidation, effective consolidation pressure 120kPa and cyclic stress ratio 0.06.



(a) Number of Cycles vs. Excess Pore Pressure



(b) Number of Cycles vs. Deviatoric Stress



(c) Number of Cycles vs. Axial Strain

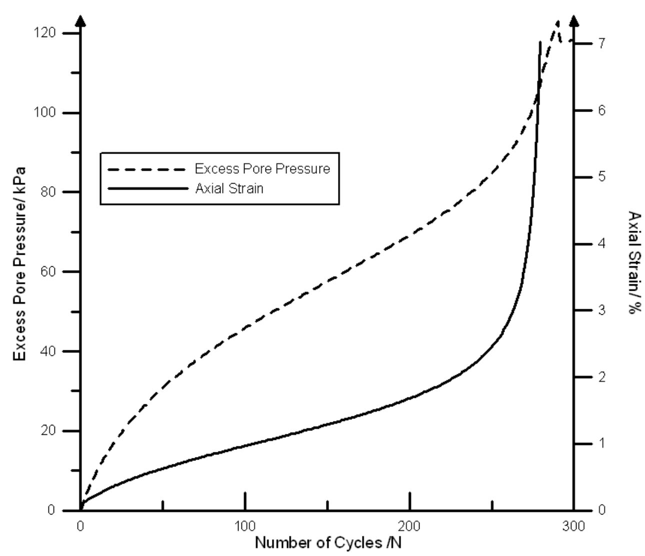
Fig.7 Development of excess pore pressure, deviatoric stress, axial strain of saturated remolded loess with loading cycles

The development curve of the excess pore pressure, deviatoric stress and axial strain of undisturbed loess and remolded loess is similar with loading cycles under the isotropic consolidation.

The reasons are as follows: No matter the loess is disturbed or not, the water is filled with the void at the beginning, and the dynamic settlement develops slowly. With the shearing of soil, the shear stress destroys the remaining cohesion among grains and makes them slip. The big particles draw together, the fine grains fill in the void and the loess has shear thinning and collapse settlement. With the damage of soil structure, the speed of dynamic settlement increases and the excess pore pressure increases largely. The decrease of the effective stress leads to the softening of the loess. The excess pore pressure accumulates until reaching effective consolidation pressure. Then the soil is destroyed.

The conclusion can be drawn: under the isotropic consolidation, the excess pore pressure of the saturated undisturbed and remolded loess can reaches the effective consolidation pressure. When the axial strain is less than 2%, the structure of the loess is relatively stable and the excess pore pressure increases continually; when the axial strain reaches 3%, the excess pore pressure increases obviously and the deviatoric stress decreases obviously; when the axial strain is more than 3%, the axial strain increases largely, the increase of the excess pore pressure is slow and can be negative value, and the soil is destroyed.

Figure 8 is development curve of the excess pore pressure, deviatoric stress and axial strain of undisturbed loess with loading cycles under the anisotropic consolidation. The effective consolidation pressure is 130kPa and the consolidation ratio is 1.2.



(a) Number of Cycles vs. Excess Pore Pressure & Axial Strain

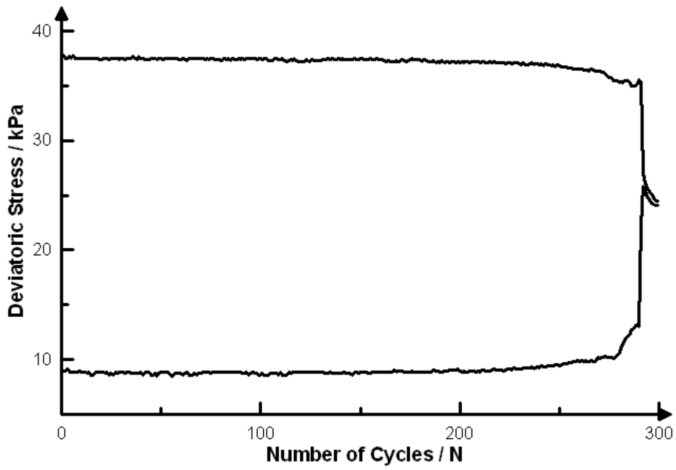


Fig.8 Development of excess pore pressure, deviatoric stress, axial strain of saturated undisturbed loess under the anisotropic consolidation

In Fig.8, 3% axial strain occurs before the biggest value of excess pore pressure. Before 3% axial strain, the axial strain and excess pore pressure increase slowly; after 3% axial strain, the excess pore pressure still increases slowly and the axial strain increases largely. The excess pore pressure reaches the biggest value, i.e., 124kPa and the axial strain is 28%. The sample is destroyed and the deviatoric stress does not apply tension load and compression load at 290 cycles.

The conclusion is drawn: The excess pore pressure can not reach the consolidation pressure when the loess liquefied after anisotropic consolidation. For a cyclic loading, the changes of the excess pore pressure can increase or decrease. Only when one cycle finishes, the excess pore pressure can have a pure increase. When the excess pore pressure accumulates to a certain level, it can reach the effective consolidation pressure, i.e., instant liquefaction. Under isotropic consolidation, the instant liquefaction occurs when the deviatoric stress reaches zero. While under anisotropic consolidation, the deviatoric stress can be divides into two parts: one is deviatoric stress applied during consolidation; another is axial stress applied during vibration. The vibration causes the volume of voids decrease. The water in the voids can not discharge in time, which leads to the increase of the excess pore pressure, sharp decrease of the effective stress applied on the soil skeleton. The loss of the soil strength makes the application of the outer axial stress impossible. While another part stress, deviatoric stress applied during consolidation has been applied to the sample all the time. When the deviatoric stress reaches the deviatoric consolidation stress, the soil has been liquefied. It means that the excess pore pressure can never reach the effective consolidation pressure because of the presence of the deviatoric consolidation stress.

CRITERIA OF LOESS LIQEFACTION

For the saturated loess, because of the decrease of the effective stress, the axial strain increases largely to reach 3% and more, while the excess pore pressure is difficult to reach the effective consolidation pressure. Wang Lanmin et al. (2003) pointed out that 3% is the value of the axial strain of the structural damage for loess. Although the 3% axial strain can occur before or after the initial liquefaction, the change of the axial strain is relatively same and the increase of the excess pore pressure is different from the different samples.

Based on the study of the behavior of the undisturbed and remolded loess, the criteria for the discrimination liquefaction are given:

under the isotropic consolidation,

$$\varepsilon_d \geq 3\% \ , \ \frac{u_d}{u_f} \geq 0.4 \ ;$$

$$\frac{u_d}{u_f} = 1$$

The one of these two criteria, which firstly reaches, would be adopted.

under the anisotropic consolidation,

$$\varepsilon_d \geq 3\% \ , \ \frac{u_d}{u_f} \geq 0.2 \, .$$

The criteria above are used to plot Fig.9. At last 1/3 number of cycles, all axial strain reach 3% and after that they increase largely.

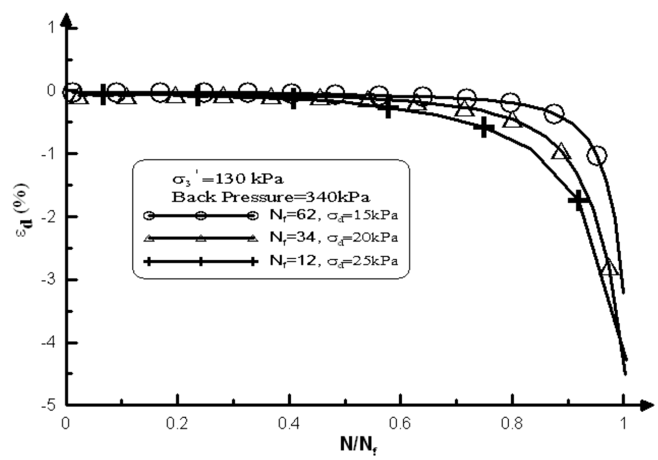


Fig.9 Cycles ratio vs. axial strain of saturated undisturbed loess under the isotropic consolidation

Compared with the criteria proposed by Wang Lanmin (2003) and Duan Ruwen (1990) , the criteria in this paper emphasize 3% axial strain. As discussed above, 3% axial strain is the structural damage value of the loess. And the raise of the pore pressure ratio has great connection with the saturation degree.

The loess saturation degree of liquefaction tests done by Wang Lanmin (2003) is no more than 80%. Because the measurement of excess pore pressure is influenced by many factors, such as saturation method, the accuracy of the instrument. The present criteria are more practical.

PREDICTION AND MICROZONATION OF LOESSLIQUEFACTION

Factors affect loess liquefaction

PGA is an important factor that triggers loess liquefaction. According to Wang (1996), the PGA of loess liquefaction in Haiyuan Earthquake and Tajikistan Earthquake is respectively 385gal and 150gal. Based on the test result, the minimum ground motion to induce loess liquefaction is 130, or VII degree in Chinese seismic intensity scale, which is approximately identify with MMI scale. So PGA should be used as a basic input for the prediction of loess liquefaction.

Based on study, as rule of thumb, intensity no more than VI is given a factor of 0, to indicate that there is no probability for loess liquefaction under such condition. For intensity higher than VI, it gives relative factor of 2, 4 and 5 to differentiate potential of liquefaction under seismic intensity of VII, VIII and IX respectively. Seismic intensity of ever larger are not take into consideration, because in Chinese seismic design code and seismic ground motion map, the maximum intensity is IX.

Besides PGA, loess liquefaction is affected mainly by factor such as plastic index (I_p) and ground water table. Through comparison study on liquefaction potential of loess, it is found that there is clear evidence that I_p has significant impact on loess liquefaction. The lower I_p is, the higher the liquefaction potential would be. For loess with I_p larger than 12, it would not liquefy under usually conditions even with high seismic intensity.

Density is also a factor contributing to liquefaction of loess, though it may not so significant compared with plastic index. Even under higher density achieved using dynamic compact. Loess liquefaction is still possible as laboratory test have shown. This is largely due to lack of cementation and also it is not possible to achieve too high density for porous loess. But in terms of liquefaction stress ratio (or cyclic stress ratio), the effect of density is also important. With higher density, the liquefaction stress ratio raised to make it harder to liquefy. In Figure 1, the liquefaction stress of loess samples before and after treatment with dynamic compaction is tested. Clearly, for loess after treatment, it has higher liquefaction stress ratio with average of about 0.26 compared with an average of merely 0.13 for loess sample before treatment. But liquefaction of loess samples used in the study is still low due to the low plastic index of only 8.

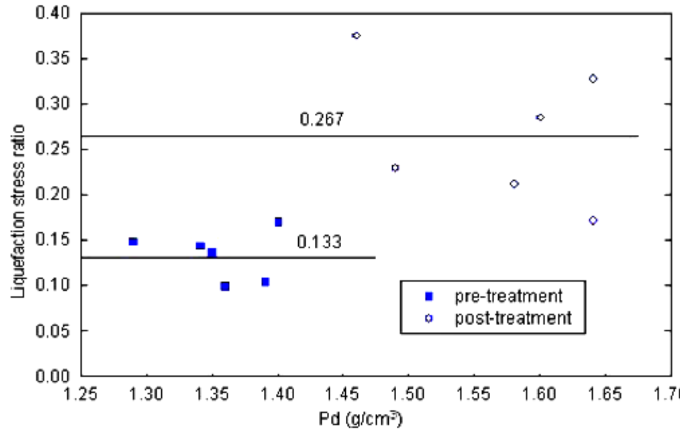


Fig.10 Effect of dry density on liquefaction stress ratio of loess

The ground table, which closely associated with saturation of loess, is also an important exterior factor. It is handy to use for prediction of liquefaction and has been used as an index in "Seismic Design code for buildings" in China for long times.

For urban area of Lanzhou, the ground water table data is obtained using nearly one hundred of borehole log data (Fig.11). The ground water table is largely distributed in a patter that is parallel to the Yellow River. Apart from the river, the ground water table rises. The deepest of the ground table is found on the 4th terrace of Yellow River. Naturally, the area with shallow ground water table should be given higher potential of liquefaction.

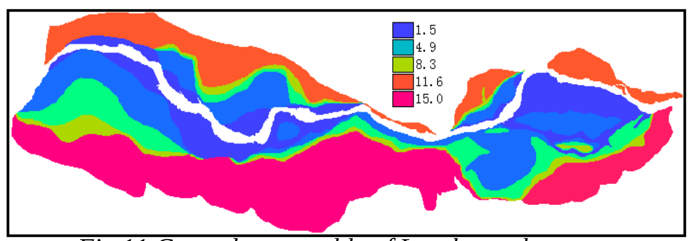


Fig.11 Ground water table of Lanzhou urban area

Finally, there comes the depth of foundation. If the loess layer is very deep, it is unlike to affect the safety of building. So depth of foundation is taken as reference for liquefaction evaluation in seismic design code.

The Compilation of Code for seismic design of buildings in Lanzhou Urban Area

The urban area of Lanzhou expands very quickly. The land of thick loess layer and some small patches of land in hilly areas are now developed or to be developed soon. Under the circumstance, the national "Code for Seismic Design of buildings (GB50011-2001)" does not reflect adequately all problems concerning seismic safety in Lanzhou. In 2006, the Provincial Department of Construction entrusted Provincial Committee on Architecture Sciences and Lanzhou Institute to draft new code for seismic design of buildings for Lanzhou Urban Area (Lanzhou Code). Most of the content on seismic structure design was drafted by Committee on Architectural Sciences; the provisions on seismic hazard and ground classification were undertaken by Lanzhou Institute of Seismology,CEA.

The notion of performance-based design was incorporated in a cautious way. That is, although performance based recommendations are made for ground treatment for buildings of different importance under different geotechnical seismic hazard setting, no such recommendation were made for structure design.

The research results by Lanzhou Institute of Seismology since 1980 to update were overall reviewed and simplified for practical application. The provisions wordings were made to be both practical and have enough safety margins.

In Chinese Code for Seismic Design of Buildings (GB5011-2001), buildings were classified into 4 groups from Group 1 to 4 with lower seismic design standard in order. The Group 1 buildings are not included due to the fact that their high seismic design standard almost always needs special study on site condition and seismic hazard. In drafted Code for seismic design of building in Lanzhou urban area, mainly it concerns with buildings of Group 2 and 3. For Group 4, it is not necessary to change the status quo, because Group 4 buildings only need adopt seismic design standard based on local seismic hazard level according to national seismic hazard map, and it allows some flexibility for lower level of seismic design as long as it is seen as proper.

The endeavor cost months of compilation and discussion of scores of experts. After the completion of the first daft, it is reviewed twice by experts and engineers from a wide spectrum in the field of civil engineering and urban development. At last, “Code for seismic design of buildings in Lanzhou urban area (DB62/T25-3037-2007)” were ratified and put into practice at the beginning of 2007.

Criteria for non-liquefaction loess in Lanzhou Code

Based on our study, the criteria for non-liquefaction loess in SDCLUA are as follows:

1. Saturated loess with age older than middle of Quaternary period (Q_2).
2. Degree of saturation less than 60%.
3. Saturated loess with I_p>12%, Clay content >15%
4. Meet one of the following conditions:
   1) $d_u > 5 + d_b$
   2) $d_w > 4 + d_b$
   3) $d_u + d_w > 9 + 2d_b$

In the above, d_u is thickness of non-liquefaction overlay, d_w is ground water table, d_b is depth of foundation.

For loess site meet the above condition, liquefaction will not be considered in seismic design.

Loess liquefaction Zonation for Lanzhou Urban Area

Liquefaction map were compiled for seismic hazard with exceeding probability of 10% and 2% within 50 years (Fig.12 & 13). The liquefaction potential zonation is mainly based on ground water table, plastic index and PGA.

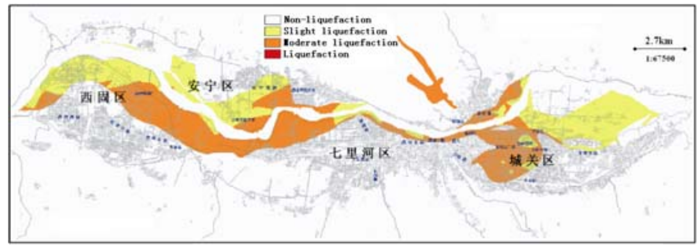


Fig.12 Loess liquefaction map under exceeding probability of 10% within 50 years for Lanzhou urban area

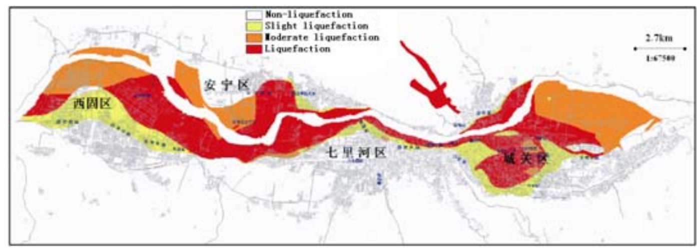


Fig.13 Loess liquefaction map under exceeding probability of 2% within 50 years for Lanzhou urban area

For high rising G2 buildings and G3 buildings above height limit, if they are located in area of modest liquefaction in 10% exceeding probability map or area of liquefaction in 2% exceeding probability map, laboratory test on liquefaction is recommended. In order to minimize liquefaction effect, recommendations on ground treatment and structure measures are listed in Table 3.

Table 2 Recommendations for loess liquefaction treatment

Grade of liquefaction		Slight liquefaction	Moderate Liquefaction	Serious Liquefaction
Ground treatment		1.Vibration compaction or replacement; 2.Dyanmic compaction gravel pile 3.Pile foundation under liquefaction layer		
Ground treatment standard and structure measures	HG2	Partially liquefaction settlement elimination	Completely/Partially liquefaction settlement elimination	Completely liquefaction settlement elimination
	HG3-A	-	Foundation and structure need treatment or higher standard design	Completely/Partially liquefaction settlement elimination, Foundation and structure need treatment
Pile foundation measures	HG2	-	Structure measures required	Take account NSF, structure measure needed
	HG3-A	-	Structure measures required	Take account NSF, structure measure needed

PREVENTION OF LOESS LIQUEFACTION

The existing experimental studies have shown that micro-structural characteristics of the original loess porosity determines the value and nature of the structural strength of skeleton, which eventually determines the strength of loess in the formation and structure of the process of re-compression level. Micro-structural characteristics of the engineering properties of loess is important. It can be found through the micro-structure of a new index for damage analysis parameters, but also for the loess non-linear analysis of the mechanical properties provide a new method for the loess region of the causes and prevention of earthquake damage to provide theoretical basis.

Formed in dry climate and not well consolidated due to its silt particle and porous structure, loess in Lanzhou has microstructure with "trellis pores", which is the result of metastable contacts of a chain of silt particles (Fig.14). The weak cementation and low plastics index, makes saturated Lanzhou loess easily liquefied under relatively low triggering PGA.

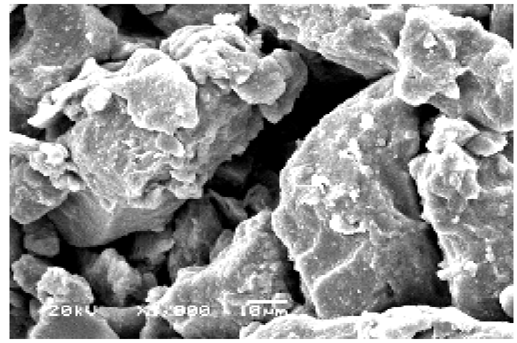


Fig.14 Microstructure of Lanzhou loess

The compaction treatment of saturated loess is not very effective for the purpose of liquefaction resistance. Because it can not alter the weak cementation and most of the microstructure to substantially reduce liquefaction potential. Non-hazard chemical treatment is more effective since it can improve cementation of loess, and the chemicals are easy to add to the saturated loess using proper method. Thus we have studied a new type of acid chemical modification, which is environment friendly and low cost.

Principle

Manual alter the microstructure of loess so that the cementation could be improved and skeleton as a whole strengthened. To do this, some chemical should be added which will react with chemical content of soil and produce material that will act as better cement in loess microstructure. The result is slight change of soil chemical content which will not produce negative impact. But with the chemical cementation material, it forms bond between larger particles.

The design is to use phosphoric acid and other weak acid to acidify loess, replace its microstructure with calcium carbonate as weak cement and a metastable trellis pores. At the same time, other salts added to form new type of chemical bonds, such as boron-bridge bond, phosphorus-oxygen bond, hydrogen bond, etc. Also filler is added to adjust the particle size ratio, so as to modify gradation of loess. The double purpose treatment would be more effect to reduce liquefaction potential. This is possible because formed in semi-arid or arid climate; there is more alkaline salt such as $CaCO_3$, $Fe2O_3$, $CaSiO_3$ etc. since the low moisture content can not produce hydrogen-bonded aggregate. So, the weak acid can be treated to generate high intensity cementation, there may be many hydrated salts, the typical reaction such as chemical formula (1) and (2).

$$SiO_2+CaCO_3+H^+=CaSiO_3 \cdot H_2O+CO_2 \quad (1)$$
$$Fe_2O_3+6H^++3H_2O=2Fe(OH)_3 \cdot 3H_2O \quad (2)$$

Discussion

Figure 15 is the microstructure of loess treat with acid chemical method. Due to light calcium ingredients are added to form floccule particles show in the boxes(Fig.2). Spectrum analysis showed that the content is change clearly. After cementation of particles except for the added element of Ca addition, due to eluviations effects had more Zn, Fe, S, K and other elements of deposition, these elements of the content than increase more than the original loess samples. The increase indicates that generation the scheduled hydration salts.

Microstructure of the modified sample is shown as Fig. 15. There particles of clay cement produced a transparent material. In Fig.3b, the energy spectrum of the modified samples, the content of these elements have increased than the original soil samples as Fig.3a.

Cementation material elements of spectrum analysis showed, the box part of the micro-structure of about 2 μm clay aggregates show the iron content of up to 74%, far more than other elements, while Ca, K, Al and other elements of content also increased significantly. Confirm the preceding analysis, as phosphoric acid leaching, leaching does have a lot of post-hydration salts, barium salts and added together to form a collection of hydrated minerals embedded in silt particles, play a significant cementation effect. To be sure that in the borate modification of raw materials, and indeed between the depositions of particles formed the cementation material.

After cementation of particles except for the added element of Ca addition, due to eluviations effects had more Zn, Fe, S, K and other elements of deposition. These elements increases compared with that of the original loess samples. The increase indicates that generation the scheduled hydration salts.

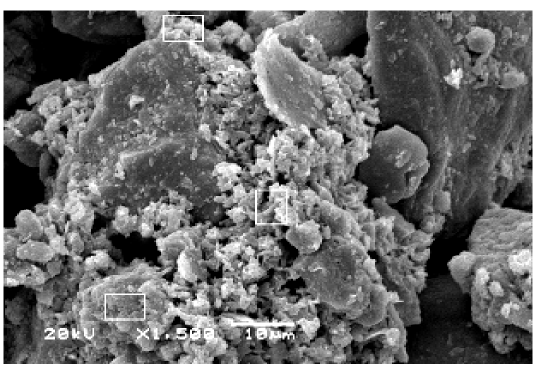
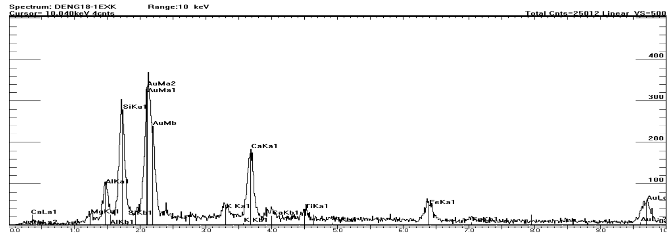
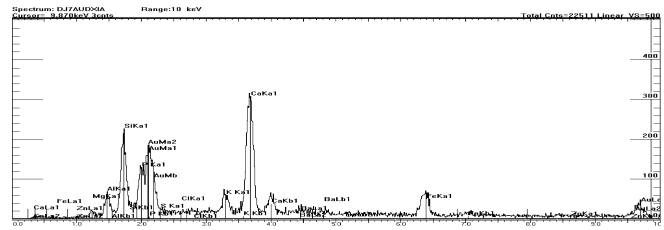


Fig.15 Microstructure of Acid-modified Lanzhou loess



3(a)



3(b)

Fig.3 Energy spectrum of loess sample(a) and acid modified loess sample

At the same time, dynamic triaxial test preformed for the loess samples, even under dynamic stress of 200 kPa, the residual strain decreased from 6.7% for the untreated sample to 0.75% for acid modified samples. This would improve loess ground to meet most of the standard for seismic safety. So the filling material does play a certain role in the cementation, and the cementation material of floc particles dispersed enhanced cementation force, greatly reducing the impracticable holes.

CONCLUSIONS

1. By applying back pressure, the degree of saturation of loess can be improved for laboratory test. Pore pressure parameter B can be more that 0.95, viz., the loess is fully saturated when the structure is not destroyed.

2. Under isotropic consolidation, pore pressure of the loess could reach the effective consolidation pressure and a strain of 3% could occur before or after the initial liquefaction. Under anisotropic consolidation, pore pressure of the undisturbed and remolded loess can not reach the effective consolidation pressure and a strain of 3% can only appear before the largest pore pressure value. The axial strain and pore pressure increase slowly before the strain of 3%, afterwards, the axial strain increases rapidly and the pore pressure does not change too much.

3. Based on the liquefaction criteria proposed in previous studies, loess liquefaction criteria are concluded as follows: for isotropic consolidation, adopt the firstly reached one between two criteria: strain reaches 3% and pore pressure ratio is not less than 0.4; the pore pressure ratio reaches 1. For anisotropic consolidation, strain reaches 3% and pore pressure ratio is not less than 0.2.

4. Liquefaction of loess in ground is mainly affected by external factors such as ground motion intensity, ground water table and depth of foundation and internal factors such as plastic index, density and degree of saturation. An evaluation incorporating these factors can produce a fairly could zonation map for prediction of loess liquefaction.

5. By introduce the notion of performance-based design in a careful manner, codes on loess liquefaction is included in newly compiled "Code for seismic design of buildings for Lanzhou urban area", which marks a major step toward application of research achievement on loess liquefaction for practical purpose.

6. By acid-modified chemical modification techniques of artificial reshaping ways to change the nature of the loess structure, reducing its residual deformation coefficient, can effectively enhance and improve the loess samples of the structural strength, thus significantly reducing the pores between particles and improve the distribution of the pore, reducing pore water suction between the particles, reducing soil liquefaction capacity, finally prevent the occurrence of liquefaction.

7. According to the micro-structural analysis, the acidic modification loess technologies, modification effect is good, deal with by low-cost and also has the advantages of simple to apple. The effect of anti-liquefaction is obvious. It has no chemical toxicity of filling materials, and also play a role that the adding phosphate can adjust the loess pH. That such acid-modified loess can also to prevent loess compaction and craze, subsequent layers without prejudice to the continuation of farming as well as can not cause environmental pollution.

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