

LOESS LIQUEFACTION: FROM THE POINT VIEW OF MICROSTRUCTURE

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ABSTRACT

The liquefaction of loess, identified not very long compared with that of sand, is believed to be influenced by and accompanied with microstructure adjustment. To understand the liquefaction of loess, especially, those unique phenomena during this process and its aftermath, it is necessary to give a check-up from the point view of microstructure. In this paper, SEM image before and after liquefaction test were used to analyze and study difference of microstructure of loess. It is found there are interesting changes for loess samples after liquefaction test, which reveal not only the pore water behavior but also the microstructure rearrangement during the process of liquefaction. On the one hand, excess pore water pressure created “water channel” in large size at the initial period of test and which is kept until the end of the test; on the other hand, the excess pore pressure applied on the close pores with larger size combined with the water erosion on the weak link among the particle composing the larger pores crushed the pores, thus changes the microstructure of loess to a great extent. The results presented will be helpful for better understanding of liquefaction of loess and could provide clues for further study.

Keywords: Liquefaction, Loess, Microstructure, Triaxial test

INTRODUCTION

Loess liquefaction was observed in 1920 Great Haiyuan Earthquake in China. The liquefaction of loess layer of a relatively level terrain caused large amount of landslide which buried a whole village. 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 inversion analysis was done, which shows that the PGA to trigger loess liquefaction is as low as around 150gal or intensity of VII in Chinese scale. While these studies improved the understanding of loess liquefaction greatly, there are still questions and uncertainties on it.

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 usually more than 10%, which is really huge. So 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

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strain are because firstly, loess structure is porous with void ratio usually more than 1, and secondly, there are mainly close pores filled with only air in loess structure. Because the saturation of loess is seldom larger than 95% using the head pressure saturation, mostly stands at 80% to 90%. When these air-filled and closed pores broken, water filled in and it prevents further ascending pore water pressure.

PORE WATER PRESSURE DEVELOPMENT DURING LOESS LIQUEFACTION

Figure 1 shows the pore water development of different loess samples during liquefaction tests. It can be found that pore water pressure rises quite quickly during initial liquefaction stage, especially when residual strain is less than 2%. This can be explained as following: 1) loess has much lower permeability of from 1×10^{-6} cm/s to 1×10^{-4} cm/s, which is only a small portion of permeability of fine sand, which stands at round 1×10^{-3} or larger. As a result, after cyclic loading, there will be a rapid rise of pore water pressure, since water cannot move in short times. 2) The critical value that causes structure damage is around 2%, after which, there will be significant damage to loess structure. At this stage, many air-filled pores collapse and water fills in, while there develops great amount of residual strain, the development of pore water pressure is rather slow. In almost all cases in figure 1, nearly 80% of overall pore water development reached, at the point where residual strain is about 2%. 3) After residual strain critical value of 2%, there observed rapid residual strain development while the increase of pore water pressure is very slow. As long as residual strain reaches 6%, there would be no pore water pressure development, which also marks the final stage of loess liquefaction. The rapid increase of residual strain must be associated with loess microstructure rearrangement.

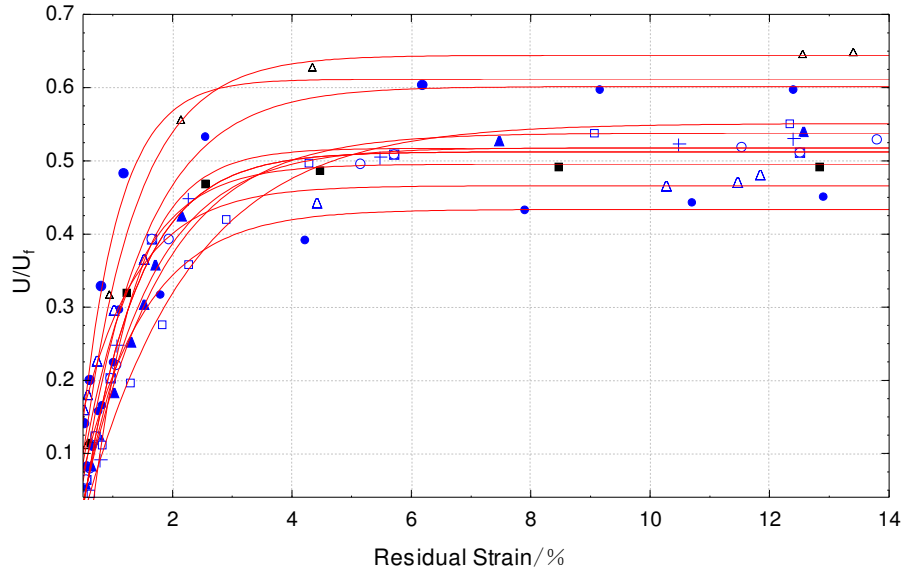


Figure 1. Pore water pressure

Based on Figure 1, the pore water development of saturated loess during liquefaction can be fitted with formula (1).

$$U_r = A - B * e^{C * (-\varepsilon_r)} \quad (1)$$

where U_r is U / σ'_0 , is pore water pressure ratio, namely U / σ'_0 , and ε_r is residual strain, A, B and C are test parameters.

Since $\lim U_r = A$, then A is in fact the ultimate pore water pressure ratio. Further analysis also shows that parameter B is closely related to A as Figure 2 shows.

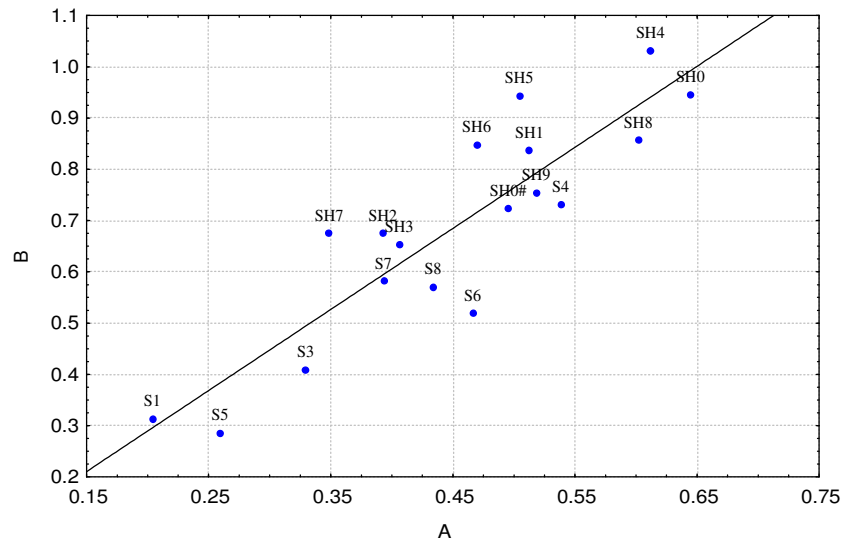


Figure 2. Linear fitting of relationship between parameter A and B

The fitting coefficient is 0.88, even the data in figure 2 are from two different group of samples. The implication of this is that when the ultimate pore water pressure is higher, the increase of pore water pressure is quicker. So this is just a case of natural cause.

Hence A represents the ultimate pore water pressure; further analysis is done to reveal the factors that influence it the most. It is found that the higher the dynamic stress, the higher the pore water pressure would be. Similar results also got by Anubhav and K. Rao (2001). The effect of dry density is positive. Because loess with a compacted will endure stronger dynamic effect, thus there would be a higher pore water pressure.

LOESS MICROSTRUCTURE CAUSED BY LIQUEFACTION

SEM Sample Preparation and Image Analysis

- 1) The original samples and samples after dynamic test are wind-dried
- 2) The dried samples are hand-broken into pieces and the relatively flat pieces are chosen to be used in further preparation.
- 3) The small piece of sample with diameter range from 10 to 6mm are gilded with metal sputter under electric current of 20mA and vacuum pressure of 5×10^{-2} mm/Hg, the spraying process last for around 8 minutes to make the soil surface covers with a thin layer of aurum atoms. The good electric conductivity of soil sample is vital for SEM observation
- 4) The sprayed samples are left in the air for up to 1 hour for cooling.
- 5) The soil samples are then placed into SEM chamber for observation.
- 6) During SEM observation, two or three times of magnification are selected to get a complete picture of the microstructure of loess samples. However, it is found that for loess the ideal magnification factor for analysis is from 300 to 600. If the magnification factor chosen is too small or too big, it would not be able to get the most important information on pores. Because if it is too small, the pores which have changed would not be observed or it is hard to identify the pores, if it is too big, though the small sized pore can be well identified, the pores assumed to be the cause of residual deformation would be missed. But the image under small magnification of around 100 and under high magnification factor of 800 can still be useful as reference.
- 7) Image analysis is done with Image-pro Plus, a software support interactive analysis of images.

- 8) The pores are delineated with a semi-automatic approach which supported by Image-Pro Plus and then converted into objects which is ready for analysis.
- 9) A classification of pores and their nature are given in Table 1. For simplicity, circular shape is assumed to get the equivalent diameter of the pores so as to be associated with pores classification and discussion of their nature already existed in Chinese literature.

Table 1. Pore classification and their nature

Pore Group	Area / μm^2	Diameter / μm
A	4.5	$r \leq 2$
B	28.3	$2 < r \leq 6$
C	113.5	$6 < r \leq 12$
D	708.9	$12 < r \leq 30$
E	2835.7	$30 < r \leq 60$

- 10) Using the aforementioned pore classification, the total area of each group of pores is accumulated and a histogram is plotted using the result of each samples.
- 11) The pore group area distribution of sample with and without dynamic test is compared in the last stage to get the information on what happened during the liquefaction test.

Microstructure Change of loess samples during liquefaction test

The physical indices and test condition of samples used in the microstructure analysis test are listed in Table 2.

Table 2. Physical Indices of Samples and Applied Maximum Dynamic Stress

Sample	$\gamma_d/\text{KN/m}^3$	σ_d/KPa	Sr (%)	Cyclic stress ratio
YZK1-4	13.9	66.7	90.95	0.573
YZK2-4	14.1	55.8	87.92	0.702
YZK3-3	14.0	84.7	86.05	0.760

Generally features of sample deformation and microstructure at low magnification factor are shown in Figure 3.



(a) Sample after liquefaction test



(b) Microstructure feature after liquefaction (Magnification factor 100)

Figure 3. Typical change of loess sample after liquefaction test

As it has been shown clearly, there are significant changes of both the sample and its microstructure. What is more, these phenomena are common for loess liquefaction tests. 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. 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. 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 means 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.

Using SEM image under magnification factor of 450, microstructure analysis is done for samples before and after liquefaction test. The samples with “#” are that after liquefaction test. Each sample analysis using two SEM images under the same magnification factors respectively for both samples before and after test. The changes of microstructure for threes couples of samples are shown by Figure 4 to 6.

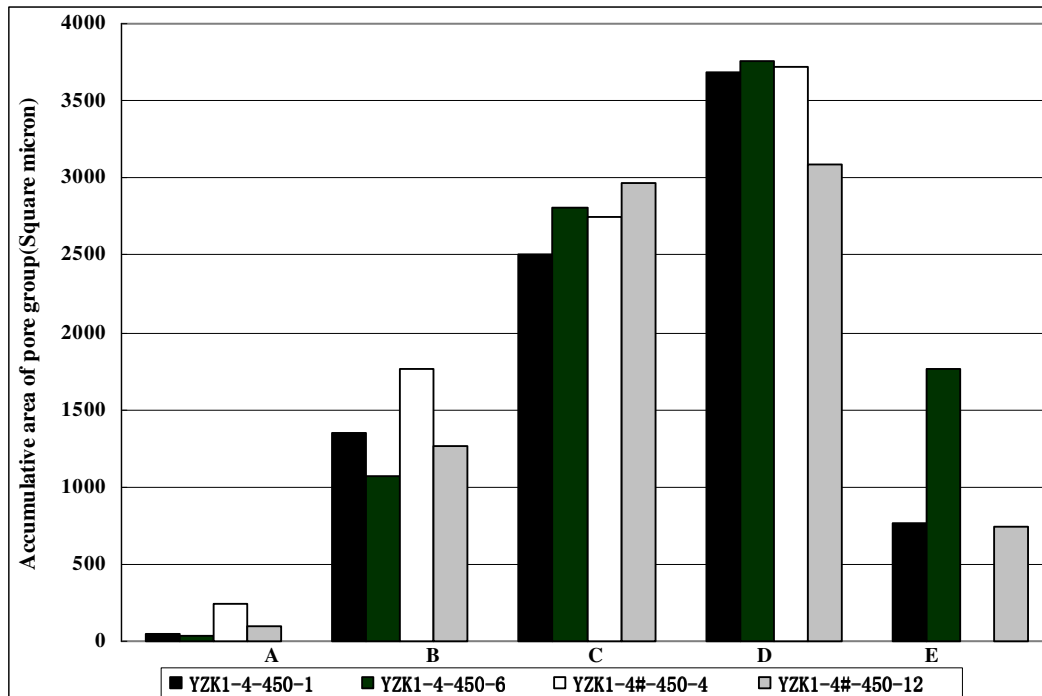


Figure 4. Accumulative Pore Area Before and After liquefaction Test for YZK1-4

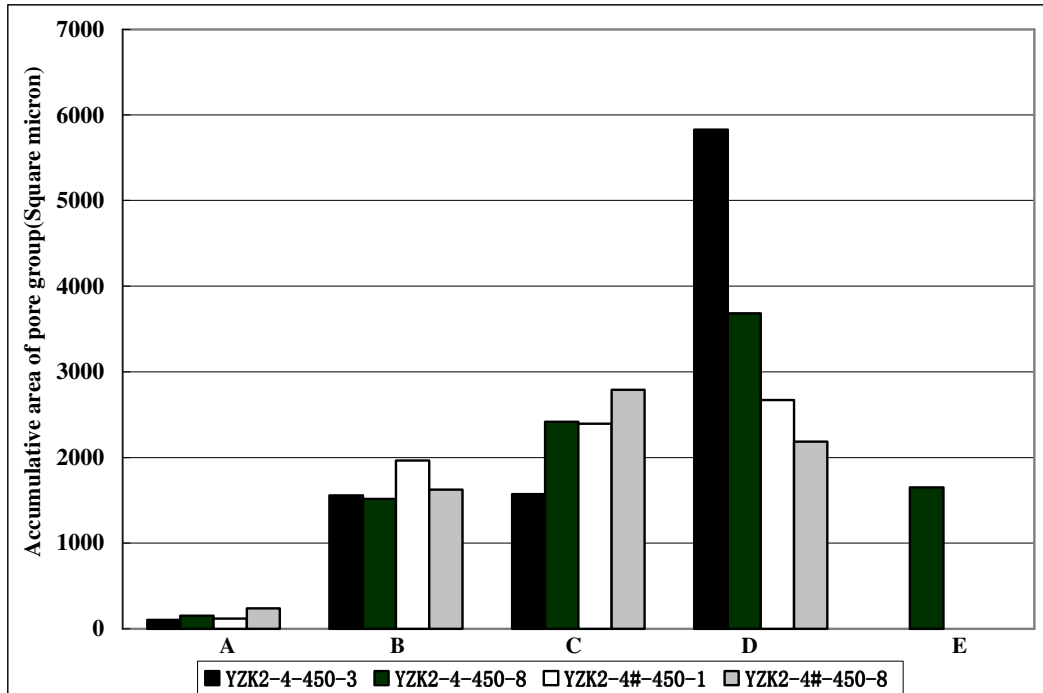


Figure 5. Accumulative Pore Area Before and After liquefaction Test for YZK2-4

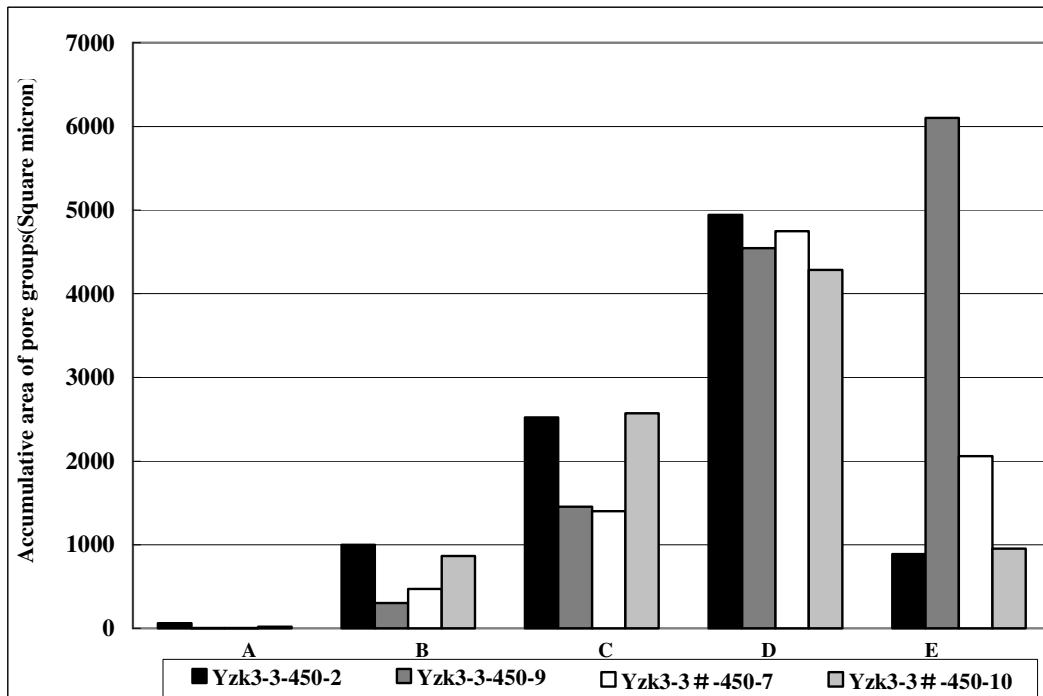


Figure 6. Accumulative Pore Area Before and After liquefaction Test for YZK3-3

In all three cases, there is significantly loss of pores with largest size. It is always that group E more likely to be broken. At the other end, the pores with small size show signs of increase to some extent. In case of YZK2-4, both group E and D experienced great loss. For the rest two samples, the loss of pores of group D is less significant, though there clearly a trend of pore decrease.

It should be noted that since the statistic nature of the study, there must be more than one SEM image of loess microstructure analyzed to get reasonable conclusion.

CONCLUSIONS

Loess liquefaction is a flow type of liquefaction which is characterized by low pore water ratio large residual strain. This is because of the loose structure of loess which begin to collapse and water fill in the many closed pore formerly filled with air.

The development of pore water pressure is mainly during the stage of residual strain less than 2%. Usually, over 80% of pore water increase would be reached compared with ultimate pore water pressure increase. If residual strain is more than 2%, loess structure would be at least partly destroyed and there begin rapid development of residual strain while pore water pressure increase is very slow. When residual strain reaches around 6%, there would be no significant further pore water increase.

Using SEM image analysis, the microstructure rearrangement, mainly broken of large pores is observed. This can explain the development of large amount of residual strain and relatively low pore water ratio of loess liquefaction.

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