

A MICROSTRUCTURE EXAMINATION ON THE DYNAMIC RESIDUAL STRAIN OF LOESS

WANG Lanmin¹ YUAN Zhongxia² WANG Jun³

ABSTRACT

The loose structure of loess is well known, which is often linked to the water collapse and seismic settlement. In this paper, using SEM image analysis and dynamic test of collapsible loess, the authors examine the microstructure change of loess after dynamic triaxial test on seismic settlement of loess samples. The result indicates that the microstructure adjustment in loess when it is subjected to strong effect of dynamic stress is only limited to the pores with larger diameter. But at the same time, cementation and particle arrangement play an important role so that only certain portion of the largest pores collapsed or deformed to some extent. By cross-examination between loess samples before and after the tests, it is able to get some interesting clues on the microstructure change of loess under dynamic load. All the results could provide useful information for loess ground treatment aiming to eliminate or reduce settlement of loess ground under dynamic loading of strong earthquakes or heavy vehicles.

Keywords: Loess, Microstructure, Residual Strain, Dynamic Loading

INTRODUCTION

Chinese collapsible loess with its particle size mainly from 50 to 5 μ m is always a safety concern for engineers. Not only the water collapsibility is a problem, but also the larger amount of dynamic residual strain is a great challenge for seismic safety.

The dynamic characteristics of loess including the larger residual strain has been attributed to the unique microstructure of loess (ZHANG Z.Z, 1983, 1986), but as to the details of the microstructure change, there lacks enough evidence. However, many scholars in China propose a theory on the microstructure of loess. In this theory, it is believed that because the particles of loess are relatively small and light, which makes sedimentation of these particles prone to environment disturbance. As a result, loess particles usually connect each other at the points where they initially meet but may not be the stable connection position. This leaves loess with more pores and of which there is a kind of pore called “trellis pores” needs to be given special consideration. The “trellis pores” are those pores formed by several silt particles in a loop-like arrangement and its size is much larger than that of the silt particle composing the trellis pores. Because at least some of the particle connections are at a relatively unstable position, the effect of load can cause some of the pores collapse, consequentially, larger amount of residual strain develops (WANG, 2000, 2003).

This study is to provide some evidence for the above-mentioned assumption with dynamic triaxial test and SEM soil microstructure analysis.

METHODOLOGY

Dynamic Triaxial Test

¹. Professor, Lanzhou Institute of Seismology, China Earthquake Administration, Lanzhou, 730000, China

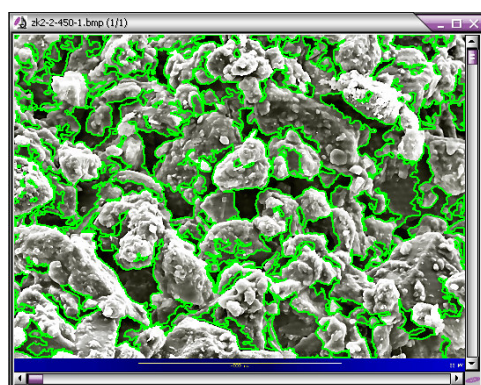
². Associate Professor, Ditto

³. Senior Engineer, Ditto

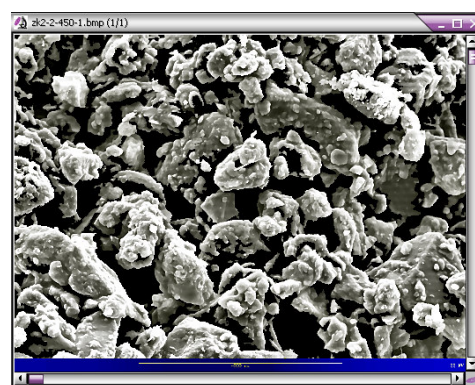
In Dynamic triaxial test, time history of ground motion acceleration obtained from seismic hazard analysis are applied on loess specimens to simulate earthquake effects. The time history of ground motion for each group of samples is based on the seismic hazard analysis on each of the sites because the present sites are located in two Chinese provinces, where there is different seismic hazard background (Parameters of ground motion see Table 3). The ground motion is further changed into dynamic stress loading on the specimens by up and down movement of a piston with the maximum value of dynamic stress at different level so that it can simulate the effects of earthquakes with different levels of intensity. Usually, four or five time histories of dynamic loading with different intensity levels are applied to each group of loess specimens in the test to get necessary data for making out a curve of seismic residual strain of loess versus dynamic stress.

SEM Sample Preparation and Image Analysis

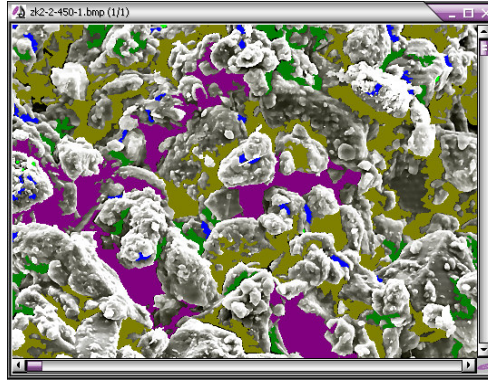
- 1) The original samples and samples after dynamic test are wind-dried
- 2) The dried samples are hand-broken into pieces and the relatively flat piece are chosen to be used in further preparation.
- 3) The small piece of sample with diameter range from 10 to 6mm are gilded with metal sputter under electric current of 20mA and vacuum pressure of 5×10^{-2} mm/Hg. The spraying process lasts 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 supporting 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.



(a) Pores delineation



(b) Pores are converted into objects



(c) Pores classification

Figure 1. Process of pores classification

- 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	Nature of Pores
A	4.5	$r \leq 2$	Micro-pores
B	28.3	$2 < r \leq 6$	Small pores
C	113.5	$6 < r \leq 12$	Inter-particle pores
D	708.9	$12 < r \leq 30$	Trellis pores
E	2835.7	$30 < r \leq 60$	Secondary holes, inter-particle block space

- 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 dynamic test.

RESIDUAL STRAIN OF LOESS SAMPLES

Four groups of samples are used to get the residual strain under different seismic intensity. The samples using in dynamic triaxial test is shown in Table 2. They are secured from four sites respectively in Shaanxi and Henan provinces. ZK1 to ZK3 are loess samples, while ZK4 is clay sample. The dynamic loading parameters are given in Table 3.

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

Sample Group	$\gamma_d/\text{KN/m}^3$	W/%	$S_r(\%)$	σ_{dmax}/KPa
ZK1	13.4 -13.8	12.47-13.65	24-27	66-149
ZK2	13.5-14.1	9.21-9.73	17-9-	72-145
ZK3	13.6-14.1	7.53-8.01	14-16	80.4-107.4
ZK4	15.3-15.5	19.83-20.62	44-47	131.8-208.5

**Table 3. Parameters of Ground Motion for Different Group of Samples
(With Exceedance probability of 10% within 50 years)**

Sample Group	Predominate Period/s	Duration/s	Corresponding Intensity
ZK1	0.50	20	VIII
ZK2	0.37	20	VII
ZK3	0.38	20	VIII
ZK4	0.27	20	VII

The development of residual strain under different maximum dynamic stress for different groups of samples is given in Figure 2. It can be seen that except for Group ZK4, all groups developed certain amount of residual strain during test. The most common feature of damage of samples is shown in Figure 3. Finally, because ZK4 did not show significant residual strain development, analysis on pores change would be only focused on the three other groups with residual strain.

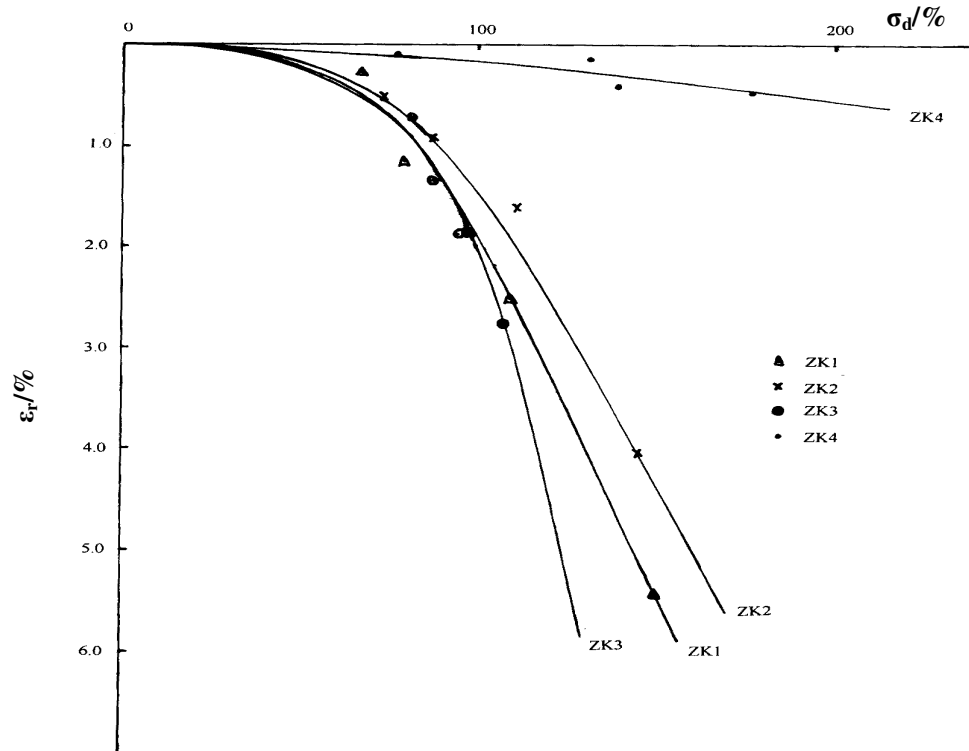


Figure 2. The Curves of Seismic Residual Strain Development for Different Groups of Samples

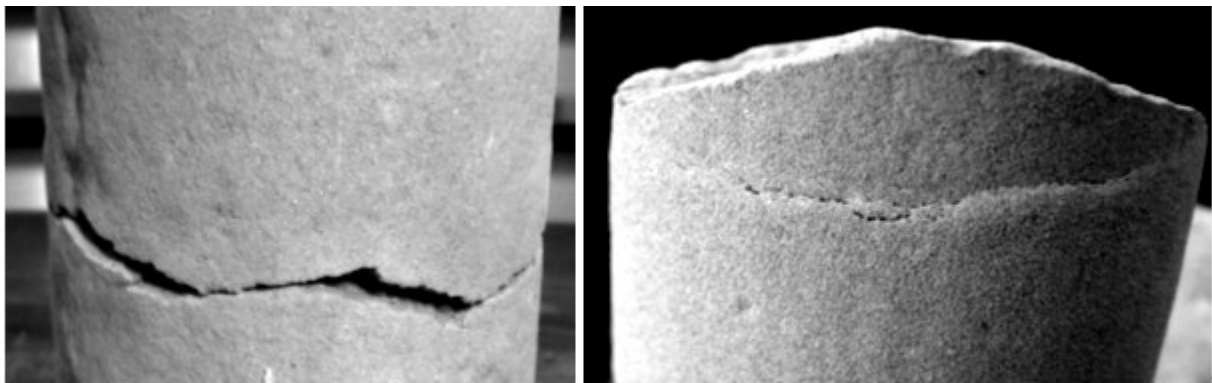


Figure 3. Damage to Samples of ZK1(Left) and ZK3(Right)

GENERAL DISCRIPTION OF SOIL SAMPLE AND THEIR MICROSTRUCTURE

1. ZK1

Samples of Group ZK1 are light grayish brown, relatively light and small holes of texture or organism cause can be identified with naked eyes. It has high sand content second only to sample group ZK3. It is sandy loess and easy to be broken with hand. Under low magnification factor of 100 (Figure 4), it can be found that there is a relatively high portion of single particles which are not cemented with

others. But the existence of mud-block-like particles means there is still cementation of certain degree.

Water absorbability test with one week gives a merely $2.6\pm0.2\%$ water absorbability rate, therefore, the pores in the samples is relatively larger compared with size of pores which contributes water absorbability.



Figure 4. ZK1 Sample SEM Image under Magnification Factor of 100

2. ZK2

Zk2 samples are light brown, relatively heavy, with clay content second only to ZK4 samples which makes the particles hold together well. Under magnification factor of 100, it shows a finer appearance compared with that of ZK1 samples (Figure 5). Hence, ZK2 samples have relatively higher structure strength if the effect of water content is excluded. The water absorbability of this group of sample is around 2.5%, which is similar to that of ZK1 samples.

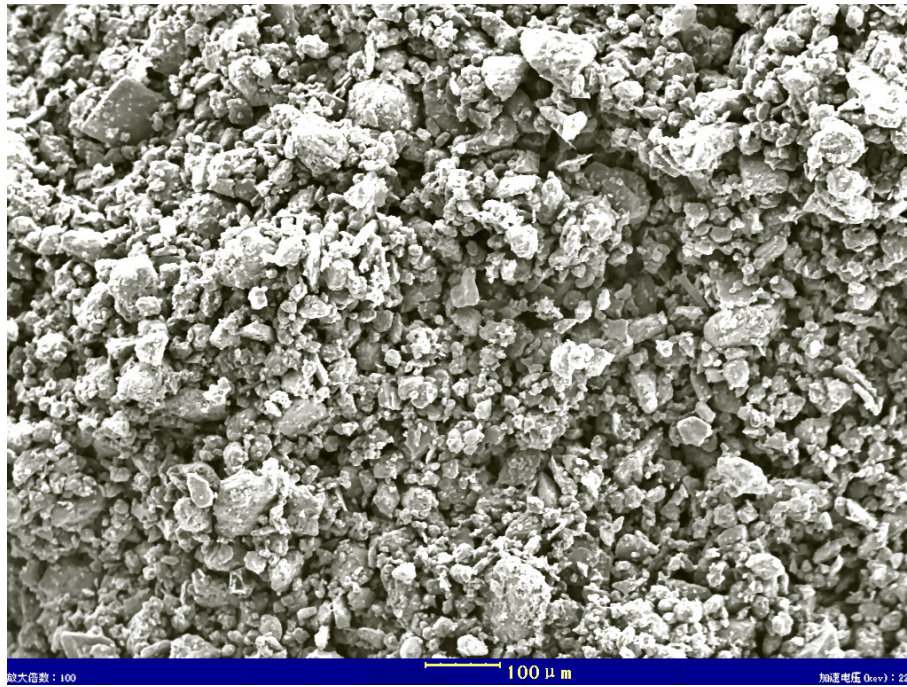


Figure 5. ZK2 Sample SEM Image under Magnification Factor of 100

3. ZK3

ZK3 samples are light grayish in color, easily to be hand-broken and when it is done many particles fall. ZK3 samples have the highest sand content of all four sample groups. Under magnification factor of 100, ZK3 sample has large amount of sand particle in singular form. And there are also loose and low cementation features presented (Figure 6). The water absorbability rate is $1.6 \pm 0.2\%$, which is the lowest of all sample groups. Because water absorbability is mainly determined by the content of small pore especially those with size less than 1 micron, this means that ZK3 samples have relatively larger pore sizes.

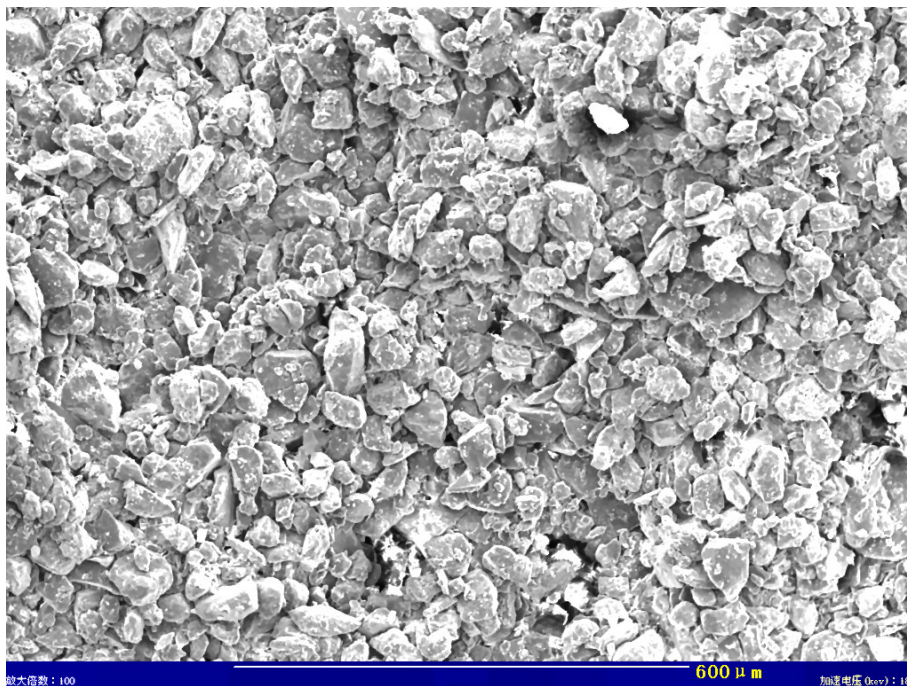


Figure 6. ZK3 Sample SEM Image under Magnification Factor of 100

4. ZK4

ZK4 samples are brown. The dried samples are very strong and cannot be hand-broken easily. Furthermore, the cross-section of broken sample is uneven, and sometimes salt can be seen. Salt test by boiling found that it has a soluble salt content of 2.5%, which is fairly high for loess. Some remnants of plants are also found. As a result, some of the pores found at low magnification factor are of organism cause, which may be large. ZK4 samples have water absorbability rate of $6.6\% \pm 0.1$, which is the highest of all sample groups and indicates that ZK4 samples have higher content of pores with size less than 1 micron.

Under magnification factor of 100, ZK4 samples have sharply different appearance compared with other groups (Figure 7). There hardly any singular particle exists. It is dense and well cemented. The nearly round shape of a few large pores can be identified means that they are rather results of organism activities than of being original. ZK4 samples are also heavy. Since it has the highest clay content and compact, no wonder there is no obvious residual strain developed even under the maximum dynamic stress of 200KPa.

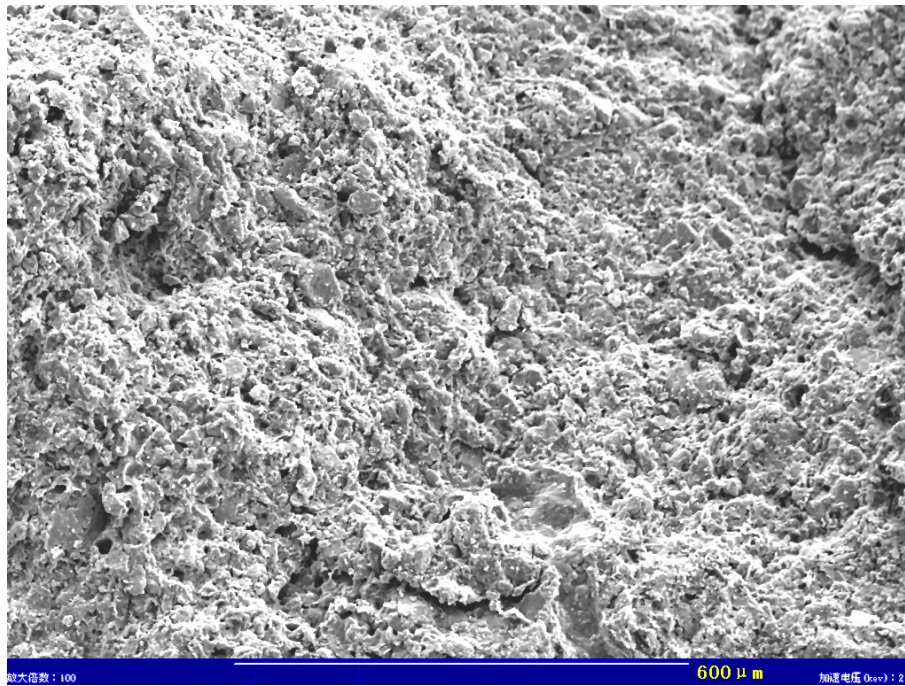


Figure 6. ZK4 Sample SEM Image under Magnification Factor of 100

MICROSTRUCTURE ANALYSIS

The microstructure analysis is carried out through calculating the accumulative area of each class of pores in samples before and after dynamic test. Then they are compared to get the idea what the change is. But it should be noted that pores of Class A may not be used for analysis. This is because Class A pores are too small to be fully identified. The data of Class A pores is still used for the purpose of statistic convenience, but will not take into consideration in later study.

Under all circumstance, significant changes of accumulative area of pores are observed (Figure 7 to 9, Samples with “#” indicating that they are samples after dynamic test. In order to reduce the chance of bias, two images are analyzed for sample both before and after dynamic test, one sample is represented with two bars.). But for different groups of samples, there are some differences in their

change. For ZK1, the reduction of accumulative area is primarily pore group D and to some extent C. For ZK2 and ZK3 the reduction of accumulative area is primarily pore group E. For ZK2 there is also slight reduction in group D.

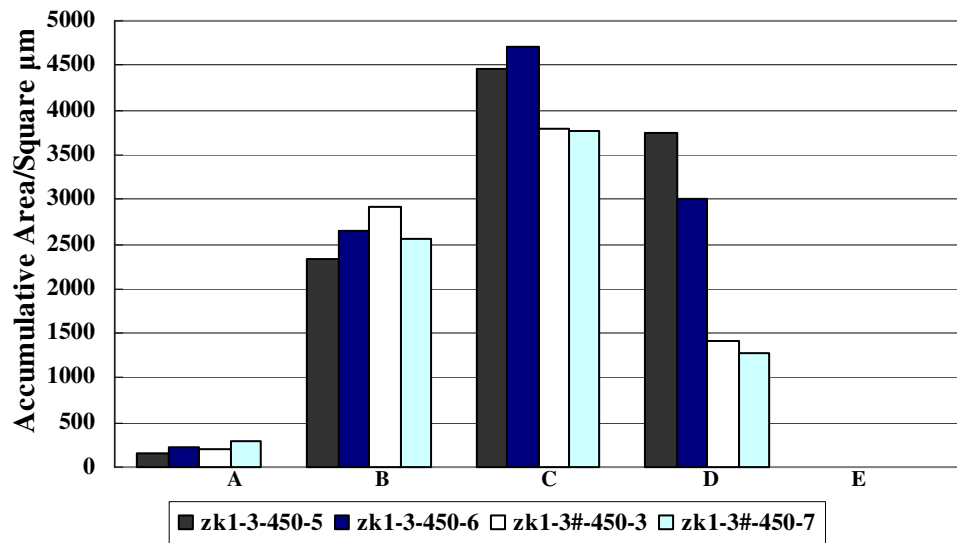


Figure 7. Accumulative Pore Area Before and After Dynamic Test for ZK1

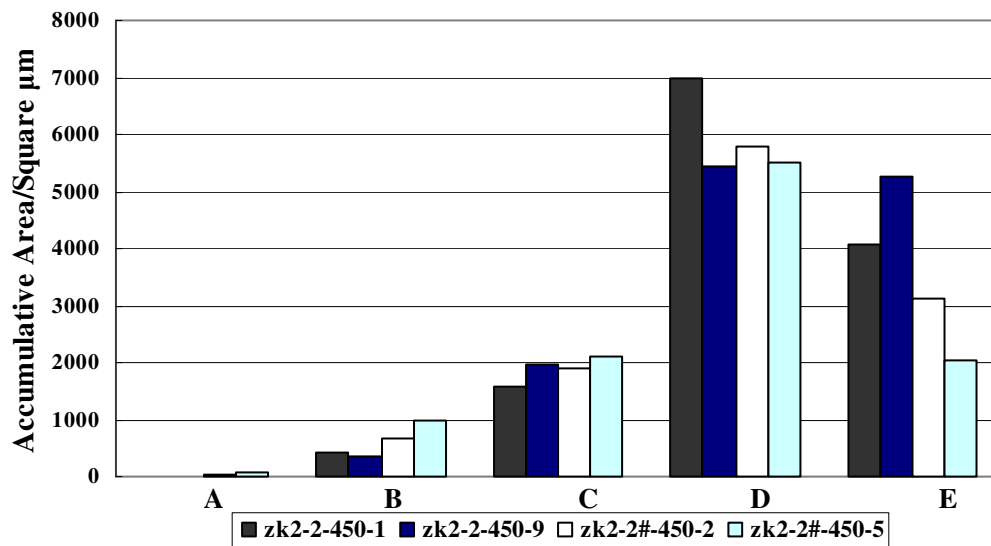


Figure 8. Accumulative Pore Area Before and After Dynamic Test for ZK2

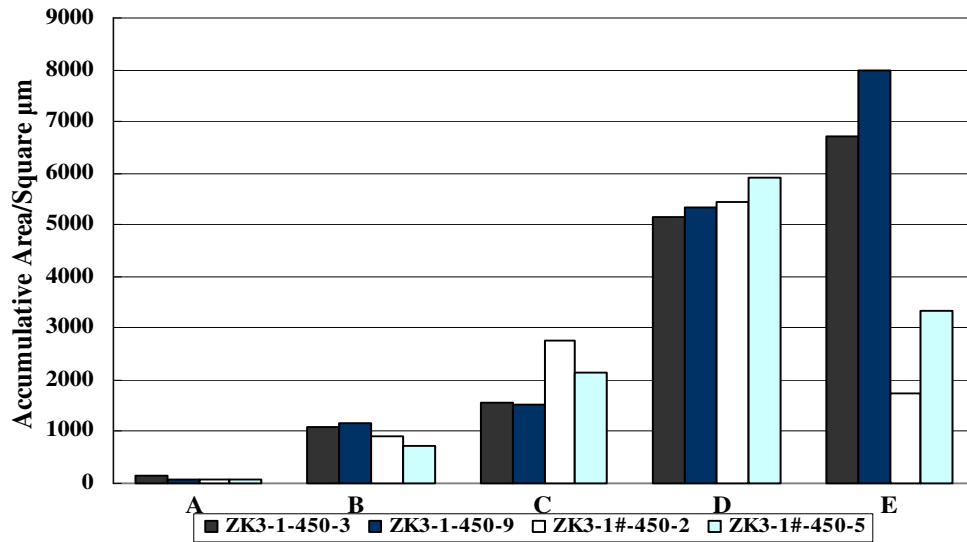


Figure 9. Accumulative Pore Area Before and After Dynamic Test for ZK3

Except for pore group A, which should not be considered as aforementioned, there is also slight increase of the pores with smaller size, especially in case of ZK2. This means, while it is always those pores with the largest or second to largest pores is broken, there is also increase of pores at the lower end of size. So it is clear now that when loess is subjected to strong dynamic stress, the broken of largest pores due to its weaken contact, are always the main source of residual strain. To some extent, pores with size next to the largest may also play a role, but this is uncommon. On the other hand, when the largest pores are broken, pores with smaller size are also formed at the same time, which leads to increase of pores with smaller size.

In order to show a relationship between the reduction of accumulative area of larger pores and residual strain development, sum of pore area loess calculated by the total area pores of two larger group of pores before test minus that of after test. Then pore area loss sum ~ residual strain chart are made as Figure 10. Generally speaking, the more loss of accumulative area of larger pores, the larger the residual strain would be. This is just as common wisdom suggests.

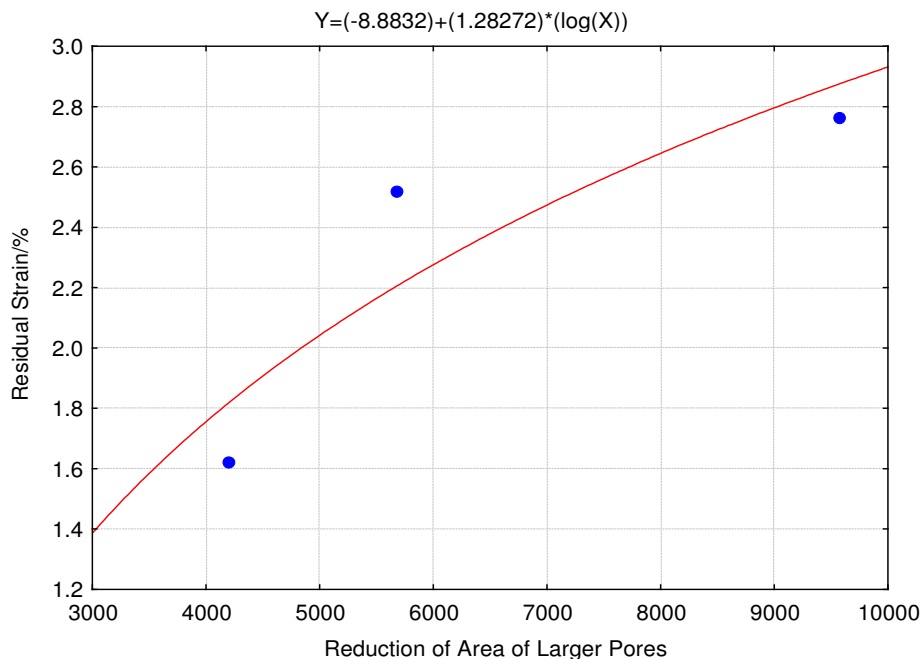


Figure 10. Residual Strain versus Reduction of Accumulative Area of Larger Pores

CONCLUSIONS

This study shows that:

1. The development of residual strain in loess is due to the collapse of large pores, mainly trellis pores formed by several silt particles, where at least some of the contacts between silt particles are unstable. In terms of size, it is always those largest pores collapse first, under some circumstance, pores with size second to largest size group may also collapse, but this is rare or less influential.
2. The more loss of the accumulative area of pores with larger size, the larger the residual strain under dynamic load would be.
3. It is also found that the water absorbability test can provide some information on the content of pores with very small size, which are called micro-pores and with diameter of less than 1 micron. The more the micro-pores is, the higher the water absorbability rate would be.

The fact that large residual strain development is caused by collapse of larger pores can be used in practice to assessment the deformation potential of loess.

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