Microstructure Study on Intact Clay Behavior Subjected to Cyclic Principal Stress Rotation

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Abstract
A series of cyclic principal stress rotation tests were carried out on intact clay to model the influence of traffic loading. The microstructure of intact clay after the cyclic loading was captured by scanning electron microscope (SEM) technology. The SEM images were analyzed according to the fractal theory by the PCAS (particle and crack analysis system) quantitative testing technology. The influence of cyclic stress ratio and frequency on the dynamic behavior of intact clay was studied according to the variation of microstructure characteristic parameters before and after cyclic loading. The test result shown that the specimens failed with less number of cycles with higher stress ratio or lower frequency. The critical failure strain tended to increase with the increasing of cyclic stress ratio, but was almost the same with different frequencies. The scale, arrangement and pattern of pores of the specimens varied regularly with the increasing of cyclic stress ratio, while the influence of frequency was irregularly. The orientation of pores was consistent with the direction of shear band in general.

Keywords: Intact clay, Microstructure, Cyclic principal stress rotation, Scanning electron microscope

1 Introduction

Principal stress rotation (PSR) is a common loading path in geotechnical engineering, which can be induced by dynamic loadings such as earthquakes, vehicular traffic and ocean waves (Ishihara and Towhata 1983; Gräbe 2002). Great efforts have been made to study the effect of PSR on the soil strength-strain behavior in the past decades, for a more reliable prediction of the soil response in the practical design. Many test results have demonstrated that PSR has significant impact on the soil strength-strain behavior. Such as plastic strain, pore water pressure accumulation and non-coaxial behavior. The previous studies also have indicated that the designs without considering the effect of principal stress rotation may be unsafe (Yang and Yu 2006).

According to the components of soil material, the deformation mechanism of soil is dependent on the change of pores in the soil. In this study, the undrained behavior of intact clay subjected to cyclic principal stress rotation is investigated from the perspective of microstructure.
2 Test Apparatus, Sample Preparation and Test Procedures

An advanced automatic hollow cylinder apparatus was used in this paper. The axial load \( W \), torque \( M_T \), inner pressure \( p_i \) and outer pressure \( p_o \) can be controlled independently, and the frequency of torque and axial load can be applied up to 5Hz.

Intact clay blocks were taken from an excavation pit 4m below the ground surface in Hangzhou (China). The physical parameters of the studied clay are listed in Table 1.

<table>
<thead>
<tr>
<th>Unit weight ( \gamma/(kN/m^3) )</th>
<th>Void ratio ( e )</th>
<th>Water content ( w/% )</th>
<th>Specific gravity ( G_s )</th>
<th>Liquid limit ( \omega_L/% )</th>
<th>Plastic limit ( \omega_P/% )</th>
<th>Plastic index ( I_p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.8</td>
<td>1.15</td>
<td>43.3</td>
<td>2.68</td>
<td>49.8</td>
<td>22.8</td>
<td>27</td>
</tr>
</tbody>
</table>

Table 1 Soil parameters

The intact clay block was trimmed into a hollow cylinder sample by a special sample kit (Zhou et al. 2007), with an outer and inner diameters 100mm and 60mm respectively. The height of the sample is 200mm, which designed to minimize the end restriction.

The intact clay used in this research had high degree of saturation, hence a relatively small backpressure of 50kPa was applied to ensure a Skempton’s pore pressure coefficient, B, higher than 0.97 for all tests. The specimens were isotropically reconsolidated under an effective pressure of 150kPa after saturation. Considering the lower permeability, big sample size (much bigger than normal triaxial sample), and long drainage path, the consolidation was considered being finished when the drainage volume was less than 100mm\(^3\) per hour.

The microstructure analysis technique used in this paper was the system developed by Liu et. al (2011). The fractal theory was also used to the quantitative analyses of the SEM images. The system mainly contained two steps. The SEM images were binary processed to recognize the particles and pores at first. The images after binary processed were shown in Figures 1a, 2a and 3a, the black zone represents the soil particles and the white area was pores. Then, the images were vectored to get the results shown in Figures 1b, 2b and 3b, in these figures soil particles were in black, while the pores were in color. After the above processing, the microstructure factors of pores can be obtained.

2.1 Cyclic Rotational Shear Test

Cyclic principal stress rotation with different cyclic frequencies and stress ratios were applied after consolidation. Many researchers had studied the cyclic triaxial tests with frequencies of 0.05Hz, 0.1Hz and 0.2Hz (Procter et al. 1984; Zhou et al. 2002; Chen et al. 2004; etc.). For the sake of comparison reason, the same cyclic loading frequencies were adopted in the present research, and the cyclic stress of 40kPa, 60kPa and 70kPa were chosen. Table 2 shows the test plan, in which \( p \) in the consolidation pressure.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Shear stress ( q=(\sigma_1-\sigma_3) )</th>
<th>Stress ratio ( R=q/p )</th>
<th>Frequency ( f )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series I</td>
<td>S1</td>
<td>40kPa</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td>60kPa</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>S3</td>
<td>70kPa</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>S4</td>
<td>60kPa</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>S5</td>
<td>60kPa</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Table 2 Test plan
2.2 Microstructure Test

The vacuum freeze-drying method was used to prepare the samples for SEM observation, so as to avoid the shrinkage of the samples caused by evaporation. The samples were frozen quickly at $-196^\circ C$ in the liquid nitrogen and then dried in vacuum at $-4^\circ C$ for 24 h. The dried clay samples were gold-plated to increase contrast between pores and soil particles, so that regions of light pixels represented soil particles and dark pixels represented pores. SEM images taken by Hitachi S-3500N scanning electron microscope were in grayscale mode with $1280 \times 1040$ pixels (equivalent to 94.1 $\mu m \times 76.5 \mu m$, 13.6 pixels/$\mu m$) and magnification $\times 2000$. The unit of both area and length is pixel in the images, which can be converted to physical true area and length. The SEM images of intact and specimens after cyclic loading are shown in Figures 1a and 1b, respectively. The corresponding binary image and vector image after processing are shown in Figure 2 and Figure 3 respectively.

![Figure 1 SEM images of samples](image1)
![Figure 2 Binary images results](image2)
![Figure 3 Vector graphics results](image3)
![Figure 4 Typical forms of shear band](image4)

Figure 1 SEM images of samples
(a) intact specimen (b) specimens after cyclic loading

Figure 2 Binary images results
(a) a

Figure 3 Vector graphics results
(a) a

Figure 4 Typical forms of shear band
(a) a

3 Test Results

3.1 Cyclic Rotational Shearing Behavior of Intact Clay

Figure 4 shows the typical failure form of intact clay after cyclic rotational shearing. Obvious shear band can be found in the middle part of the specimens. The shear band has a width of 3–5cm, and had an angle with the lateral direction. This is different from the shear band formed in specimen sheared with fixed principal stress direction carried out by Shen (2007).

The curves of axial strain versus cyclic number of specimens with different frequencies and stress ratios are given in Figure 5. It can be found that the axial strain increased slowly at the beginning stage. It accumulated with the increasing number of cycles. The axial strain increased abruptly when reached a certain number of cycles. Obvious shear band formed and the specimen failed. The specimen failed with less number of cycles when sheared with lower frequency or higher cyclic stress ratio. The strain at the turn point of the curve was defined as the threshold strain, this strain was relatively small. The threshold strain of intact clay increased with the increasing of cyclic shear stress ratio, while it was less influenced by the frequency.
3.2 Variation of Microstructure

3.2.1 Variation of Pore Size Distribution

The deformation of soil is dependent on the variation of the volume of pores, this associated with the variation of pore area in the SEM image. Figure 6 gives the distribution curves of pore accumulation of intact clay rotational sheared with different stress ratios and frequencies. The steeper curve represents more pore content in this scale range. It can be found that, before and after cyclic shear soil pores were mainly tiny pores. While, tiny pores increased due to the compression of large pores under cyclic loading.

Figure 7 shows the distribution of pores content within each scale of intact clay before and after cyclic loading. The proportion of small pores increased with the increasing of cyclic stress ratio and frequency, which means the higher cyclic stress level or frequency, the greater the degree of fragmentation of soil pores and particles, the more tiny pores were generated. In addition, with respect to the isotropic consolidation specimen, there were still some large pores after cyclic shearing. This indicates that, during cyclic loading process, some large pores were broken into small pores and a number of new large pores generated, this is the microscopic nature of shear band fold phenomenon.
3.2.2 Variation of Porosity Fractal Dimension Factor

The porosity fractal dimension factor is used to describe quantitative indicators the distribution of soil particle size, it can directly reflect changes in the pore scale. Figure 8 shows the variation of porosity fractal dimension factor of intact clay with different cyclic stress ratios and frequencies. It can be seen that, intact soil had the maximum value of porosity fractal dimension factor, and the degree of uniformity was worst. The isotropic consolidation specimen had the minimum value of porosity fractal dimension factor, the degree of uniformity was best. It means that under isotropic consolidation pressure, large pores broken into small ones, pore size became uniform. The value of porosity fractal dimension increased after cyclic shearing, and it increased with the increasing of cyclic stress ratio and frequency, the degree of pore uniformity reduced the porosity. This is consistent with result of the variation of pore size distribution shown above.

Greater dynamic shear stress or higher frequency result the greater degree of pore broken and the more generation of small pores. On the other hand, pores also merged to form a number of large pores, resulting in the size of the gap increased. In addition, the value of porosity fractal dimension factor was more influenced by the cyclic stress ratio than the frequency, which was associated with the critical failure strain level.

3.2.3 Variation of Pore Arrangement

The probability entropy of pores of intact clay before and after shearing is shown in Figure 9. The values of intact and isotropic consolidation specimens were relatively larger, all higher than 0.98. Indicating that, the pore arrangement of both specimens was arbitrarily, there was no obvious directionality. Since the arrangement of intact soil particles was arbitrarily, from the macro perspective, intact clay showed high compression performance at low pressure, which was the microscopic structural nature of intact soil. The pore orientation and ordering of specimen after cyclic shearing were better than that of intact clay. Higher cyclic stress ratio resulted the lower probability entropy and the better ordering, but the ordering of pores arrangement had no good relation with the variation of frequency.
Rose diagrams show the distribution of the number of pores in all directions. The rose diagrams of clay specimens before and after shearing are shown in Figure 10. It can be seen, the distribution of pores of intact and isotropic consolidated samples was more evenly with no obvious directionality. After shearing the arrangement of pores became orientation and regularity. With the increase of cyclic stress ratio, the pore distribution was concentrated in one certain direction, the orientation became significant. The influence of frequency on the arrangement of pore was not obvious. This is because the larger dynamic shear stress produced greater kinetic energy for the particles’ displacement and rotation, and the position of the majority of particles occurred adjustment, result the better orientation of the particles and pores. When the dynamic shear stress was smaller, the kinetic energy for the particles’ displacement and rotation was low, only a portion of the particles’ position occurred adjustment, it was relatively difficult to move the large particles and its orientation was relatively poor. Arrangement of pores and particles visible by moving a greater impact shear stress, less affected by the frequency, which is consistent with the law of entropy obtained by the probability above. So the arrangement of particles was influenced more by shear stress than by the frequency.

3.2.4 Variation of Pore Form

Figure 11 shows the average pore form factor curves of specimens before and after cyclic loading. The average pore form factor of the isotropic consolidation and sheared specimens increased when compared with intact clay. And it tended to increase with the increasing of cyclic stress ratio. While the average pore form factor was substantially the same at different frequencies. This indicates that, the pore form was greatly affected by cyclic shear stress, while less affected by frequency.
Figure 12 shows the distribution of pore shape factor, the distribution curves of pore shape factor moved to the right after cyclic shearing, the content of pores with large shape factor increased resulting in an average shape factor increased. This means that, the pore shape became smooth as small pore increased after cyclic shearing.

3.2.5 Pore Fractal Dimension Factor

Figure 13 shows the pore fractal dimension factor curves of clay sheared with various cyclic stress ratio and frequencies. It can be seen that, the pore fractal dimension factor of isotropic consolidated specimen was the lowest, which had minimum pore complex. After cyclic loading, the pore fractal dimension factor increased, it indicates that there are trends of soil compaction particles were constantly flipped, slipped, crushed, and the complexity of the pore structure increased. In addition, the fractal dimension factor decreased with the increasing of cyclic stress ratio, but with no significant change in frequency, this coincides with the variation of the average shape factor.

![Figure 13 Pore fractal dimension](image)

4 Conclusion

A series of cyclic principal stress rotational shearing tests were carried out on the Hangzhou intact clay in this study. The variation of microstructure of the intact and sheared clay was studied in particular. The following conclusion can be obtained.

Under cyclic principal stress rotational shearing, specimen failed with less number of cycles when sheared with higher stress ratio or lower frequency. The specimen failed with relatively low level of strain less than 1%. Obvious shear band formed when specimens failed.

Macroscopic deformation behavior of intact clay under cyclic rotational shearing had closely relationship with the variation of microstructure. Under the cyclic shearing pores broken and grown, which was the microscopic nature of shear band fold phenomenon. The arrangement direction of majority pores in the shear band zone consistent with the direction of the shear band.

The cyclic shear stress level had more significant influence on the macroscopic deformation and microstructure variation than the loading frequency. The critical failure strain of specimens increased with the increasing of shear stress ratio, correspondingly microscopic pore structure characteristics also showed good regularity. Higher cyclic stress ratio resulting larger porosity fractal dimension factor, lower degree porosity homogenization, lower probability entropy, higher degree of pore ordering; the increases of average shape factor, the reduction of fractal dimensionality, pore shape becomes smooth and the reduction of complexity.

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References


