The micro-structure study on mechanical properties of Dredge fills

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Abstract

Mechanical tests and electron microscopy scanning tests were done and micro-structural parameters were quantitatively analyzed in order to study the essence of structural characteristics of Dredge Fills. After comparing the mechanical test results with the statistical results of microstructure parameters, it can be find that the transition stage of the stress-strain curve of dredge fill compression test is also the mutation stage of the curve of micro-structural parameters, and the same time, the micro-structural parameters of shear test soil samples under different axial strain were not linear variation with the axial strain increases and mutated in 10% to 15% axial strain. The analysis result shows that the structural mechanical properties of the dredge fill are subject to its microstructure, and mutation of mechanical test curve is a macroscopic manifestation of microscopic structure damage. The experimental results indicate that dredge fill has the basic mechanical properties of structural soil.

Keywords: Dredge Fills, structural constitution, microstructure, mechanical properties

1 Introduction

Currently, reclamation forms an effective way to develop land resources, dredge channels, and clean the coastal water environment. China has a coastline of 18,000km with rich tidal-flat resources amounting to some 22,000km^2 in area. Reclamation using hydraulic filled silty soil in the Shadow Sea is one of the main approaches used to explore land resources in the coastal areas of China. However, dredge fill, as a special type of artificial soil, is characterized by its strong structural properties. Due to its special engineering properties, a series of problems are usually encountered. Current research is mainly focused on the methods of treating dredge fill. However, more systematic studies [1], aimed at the relationships between the factors influencing structural properties, the structural strength of dredge fill, and its microstructure, are few in number.

Dredge fill from Zhengzhou, China is taken as the object of the current study. By means of mechanical and micro-structure testing in the laboratory, the variation of stress-strain and the microstructure of the dredge fill during consolidation and shearing processes is investigated. We also give a quantitative discussion of the mechanical properties of the structural dredge fill at the microscopic level.

2 The mechanical properties of structural dredge fill

The soil sample used in this study was taken 3m under the ground at a dredge-filled site in Zhengzhou, China. The Hydraulic fill ground opened in the early 1980s and was improved by vacuum preloading. The soil sample is mainly composed of clay particles and 78–99% of the total weight is made up of particles smaller than 75μm. The clay content of the mineral components is high; illite accounts for 30–37%, kaolinite for 9–10%, chorlite for 11–12%, and illite mixed layers for 42–45% of the total clay content.

To study the structural properties of the dredge fill, undisturbed and disturbed dredge soil samples are subjected to consolidation testing using a triaxial shear test and unaxial compression test, respectively. Figure 1 shows the e-LgP correlation curves of the undisturbed and disturbed samples obtained from these tests. From the figure, it can be seen that there is a distinctive structural yield stress in the dredge fill consolidation test. When the consolidation stress is about 112.5 kPa, a notable deflection is found in the test curve from the undisturbed sample. When the consolidation stress is less than 112.5 kPa, the compression test curve has the form expected from a strain softening type of soil. On the other hand, when the consolidation stress is greater than 112.5 kPa, the compression curve shows a variation characteristic of a strain hardening type. As the curve obtained in this test is characterized by typical properties of structural soil compression [1–3], Zhengzhou dredge fill is demonstrated to be a kind of structural soil.

The shear strength of the dredge fill is measured using a triaxial shear test. To evaluate the structural properties of the dredge fill, the undisturbed dredge fill sample and the reconstructed one are subjected to a consolidated, undrained triaxial test. The figure shows that the shear strength parameter of the undisturbed dredge fill sample is much greater than that of the reconstructed one. Also, the shear strength envelope of the undisturbed dredge soil sample is broken and a deflection occurs when the confining pressure exceeds 300 kPa. In contrast, the envelope of the reconstructed dredge fill is straight. All of these properties correspond to shear strength properties characteristic of structural soil [2, 3], which is indicative of the strong structural properties of the dredge fill.

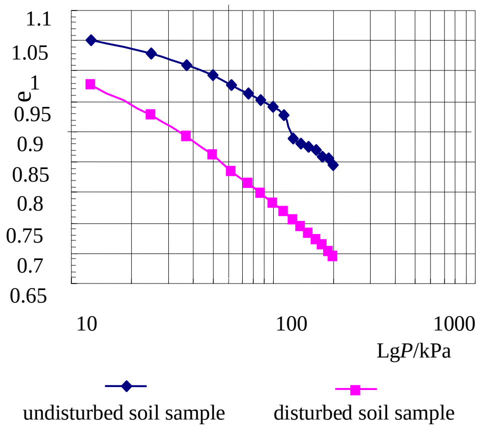


FIGURE 1 Contrast curve of hydraulic fill compression test between undisturbed soil sample and disturbed soil sample

3 The microstructure responses of the mechanical properties of structural dredge fill

Soil is a kind of porous continuum. The cause, size and appearance of pores at all levels directly influence the deformation and failure of the soil mass. A soil mass with an abundance of macropores is extremely unstable and is one of the root causes of soil deformation. Ceteris paribus, soils with a higher porosity are more liable to compressive deformation and shear failure, and thus lead to the destruction of upper buildings. Therefore, some emphasis on the pore characteristics [4] is necessary in the study of the microstructure of the dredge fill.

3.1 MICROSCOPIC TESTING AND METHODS OF STUDYING THE DREDGE FILL

3.1.1 Preparation of the soil sample

A set of compression tests was designed to investigate the rules governing the changes in the microstructure caused by the process of dredge fill compression. Soil samples are taken when the compression tests are stable. Then, vertical cross-sections of the soil sample are analysed using a scanning electron microscope (SEM). Figure 2 illustrates the method of making the soil sample via compression under different stresses. The shaded region in the figure is the scanning area.

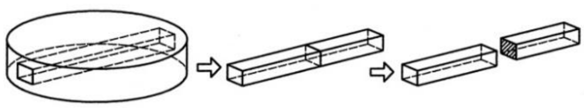


FIGURE 2 Soil samples for micro-structural testing after consolidation test

To investigate the rules governing the changes in the microstructure during shear failure of the dredge fill, a triaxial shear test sample is made from the same soil sample. A consolidated, undrained triaxial shear test with a confining pressure of 40 kPa is performed. The test ends when the axial strain reaches 5, 10, 15, and 20%, respectively. As shown in Figure 3, the tested soil sample is processed to be the soil sample of microstructure test during the shearing of the dredge fill.

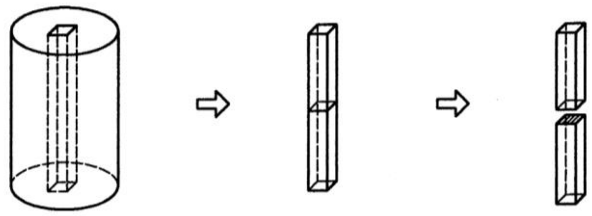


FIGURE 3 Soil samples for micro-structural testing after shear test

To observe the rules governing the changes in the microstructure in different positions after shear failure of the dredge fill, a triaxial shear test under a confining pressure of 300 kPa was performed. Then, a sample was taken after shear failure for microscopic analysis using SEM. A cross-section in parallel with the shear failure surface is of particular interest. The method used for making the soil sample is shown in Figure 4, where a shaded cylinder denotes the shear failure surface, and a shaded cuboid refers to the scanned cross-section.

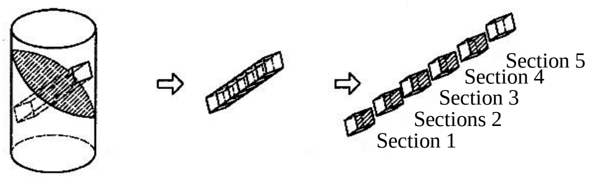


FIGURE 4 Soil samples for near shear failure surface

The dry soil sample is processed using a freeze-drying method. The vacuum freezing sampling instrument for investigating soil microstructure developed by the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences and the Tianjin Institute of Urban Construction was used for this purpose. The operating procedure is as follows. First, the undisturbed soil is sawn to produce a soil slice measuring 4mm×4mm×10mm using a thin steel wire. This is then put into isopentane (boiling point 140°C) and the isopentane vessel equipped with sample is placed into liquid nitrogen (boiling point 190°C). This causes the sample to be frozen so that the liquid in the soil is turned into non-crystallized ice without expansion. Finally, the soil sample is vacuum pumped at 50°C for over 15 hours to sublime out the non-crystallized ice in the soil directly. The procedure used thereby achieves the objective [6] that the soil sample is dried without deformation.

3.1.2 Microstructure imaging

Scanning electron microscopy is one of the most important tools currently used to investigate clay soil microstructure. This is because it is capable of producing excellent images at various levels of magnification, has wide view, high resolution and images may be stereoscopic. In addition, they can be used to directly image rough surfaces with large fluctuations. SEM is regarded as the only method of microstructure testing that can directly observe the distribution and contact relationship between particles.

SEM's working principal involves secondary electron imaging. That is, the image is produced point by point in a temporal and spatial sequence and displayed on the kinescope of an external microscope. Due to the porosity and desiccation of the soil sample and its poor electrical conductivity, the sample is treated with gold spray before imaging by the SEM. This prevents generation of a discharge by the bombardment from the electron beam used in the scanning process. To ensure high image definition, the typical structure cell can first be found using high magnification. Then, the magnification is gradually reduced [7, 8] until the SEM magnification of ×2000 is selected. In this way, a more ideal statistical law could be invoked for use in this research.

3.1.3 Microstructure parameter selection and their physical meaning

Considering that moisture content has a great effect on the mechanical properties of the dredge fill, the space taken up by moisture needs some emphasis. This is illustrated by the distribution of pores in the microscopic images. Therefore, the pores are chosen to be the object of a quantitative study of the soil microstructure. Based on the above experimental conditions, dredge fill samples are scanned using SEM and quantitative statistical analysis is carried out on the pores in the sample. Five pore microstructure parameters [9, 10] are selected for consideration.

1) *Equivalent diameter*: Defined as the diameter of a circle with area equivalent to the pore area, which is an important parameter to illustrate the size and properties of the pores. All pores are statistically included and averaged.

2) *Pore number*: The number of pores in a microscopic image can directly illustrate the pore size, the distribution, and contact relationship of the soil particles.

3) *Pore perimeter*: This is equal to the sum of the boundary lengths of all the pores. It shows the contact area between pores and particles, and indirectly indicates the size, appearance, and regularity of the pores.

4) *Pore morphology ratio*: This is the ratio of the major and minor axes of the pore. The higher the ratio, the more 'strip-like' is the pore. If the ratio is close to 1, the pore is more likely to be a square or circle.

5) *Pore roundness*: This is another parameter representing pore morphology. The further its value is from 1, the more irregular the pore is. The closer its value is to 1, the more like a circle the pore becomes (when its value is 1, the pore turns into a standard circle).

3.1.4 Acquisition of the microstructure parameters

The above microstructure parameters are mainly obtained for dredge fill samples by analyzing the pores in the SEM images using the 'Field and Feature' measuring tool modules in Leica Qwin. The parameters express the morphology and distribution features of the pores during the deformation of the dredge fill from different aspects.

3.2 MICROSTRUCTURE RESPONSE TO THE COMPRESSIVE PROPERTIES OF STRUCTURAL DREDGE FILL

3.2.1 The response to compression

Figure 6 displays vertical cross-section SEM images of soil samples used in compression tests at different consolidation pressures. In general, all the images show a plate stack structure. When the consolidation stress is less than 100 kPa, the arrangement of the particles is relatively loose with a line-area contact relationship. The pore directionality is indistinct. When the consolidation stress is in the 100-125 kPa range, the particle arrangement is much looser with line-area and area-area contact. The whole structure is presented as a plate frame structure or a laminated bracket structure. When the consolidation stress exceeds 125 kPa, fine particles are arranged gradually closer with smaller pores, poorer pore directionality, and a main line-area contact relationship. The change in the microstructure demonstrates that the dredge fill has experienced structure failure and the formation of new structures during the consolidation process. The result is in good agreement with the compression test curve.

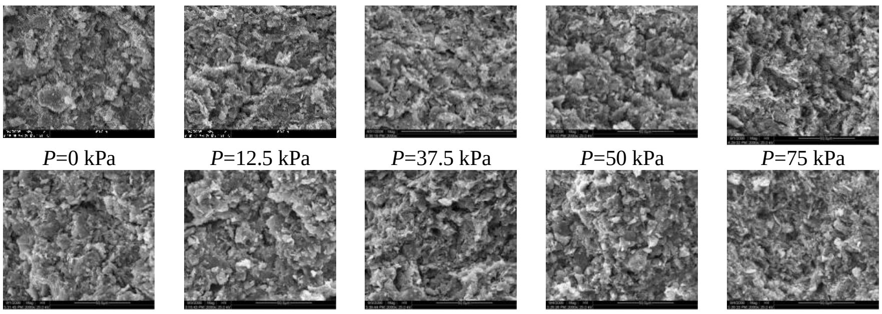


FIGURE 6 The SEM images of compressed soil samples under different consolidation stress

3.2.2 Microstructure parameter variation during compressive deformation and its meaning

Figure 7 shows microstructure parameter variation curves accompanying dredge fill consolidation.

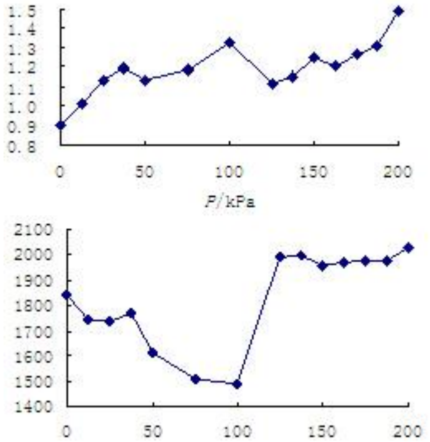


FIGURE 7 The micro-structure parameter curve of compressed soil samples under different consolidation stress

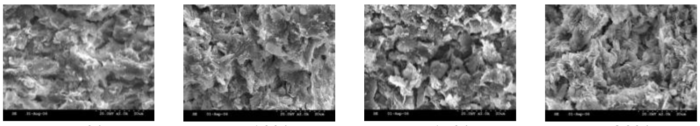
It can be seen that when the consolidation stress is less than 100 kPa, an increase in consolidation stress causes an increase in pore equivalent diameter, pore morphology ratio and pore roundness. At the same time, pore number and pore perimeter decrease. Further, when the consolidation stress exceeds 100 kPa, all the pore structure parameters change abruptly. When the consolidation stress exceeds 125 kPa, a further increase in consolidation stress causes an increase in pore equivalent diameter, pore morphology ratio and pore roundness. Also, the pore number and pore perimeter decrease.

Comparing the pore microstructure curves with the consolidation test curves, it is readily found that the turn phase of the stress-strain curve coincides with the mutation phase of the microstructure variation curve. This illustrates that the change in mechanical properties of the soil is essentially caused by the variation in the microstructure [11, 12].

3.3 THE MICROSTRUCTURE RESPONSES TO THE SHEAR RESISTANCE PROPERTIES OF STRUCTURAL DREDGE FILL

3.3.1 The response to shear processes in the microstructure images

Figure 8 shows SEM images of shear tested soil samples when the axial strain is set to 5, 10, 15, and 20%. Comparing the 5% and 10% axial strain images, the compactness of the particle arrangement of the soil sample when the axial strain is 10% is seen to be higher than that when the axial strain is 5%. Furthermore, both images show little difference in their structure as a whole, which indicates that the dredge fill structure is not damaged during shear deformation when the axial strain is less than 10%. Next, the 10% and 15% axial strain images are compared. The resulting comparison shows that each present notable variations in the structure as a whole. The soil sample has a flocculated microstructure when the axial strain is 10%, while at 15% axial strain there is a plate frame structure. Moreover, with an increase in axial strain, the arrangement of particles and aggregates becomes closer, and trellis pores partially occur. This shows that the whole structure of the soil sample has been damaged through a process of structural failure, and shear dilatation occurs. When the axial strain is 20%, the whole structure turns into a flocculated structure again, which a new structure is resulting from shear failure.



ε=5% ε=10% ε=15% ε=20%

FIGURE 8 The SEM picture of soil sample after the sheer test under the different strain

3.3.2 Parameter variation during the shear process and interpretation

Figure 9 displays curves showing the variation in the microstructure parameters of the dredge fill in the shear tests. In the figure, as axial strain increases the variation in the parameters is not always linear; it changes abruptly when the axial strain is 10–15%. This shows that the structural properties of the dredge fill change during the shear failure process. When the axial strain is less than 10%, the shear process is manifested as 3D compression, gas compression and moisture migration into the pores. Moisture is gradually taken up in the pores and approaches saturation. This moisture migration enables the connection of different parts of the pores, and some particles concentrate on aggregates or the skeleton. This results in the single pore volume increasing and reduced pore regularity. Also, variation in the microstructure parameters include: reduction in pore number and an increase in equivalent area, pore morphology ratio and pore roundness. When the axial strain is 10–15%, shear stress exceeds the structural strength of the dredge fill and shear failure occurs in parts of the aggregates. This leads to an increase in pore number and pore perimeter and a decrease in equivalent area. However, the segmentation of pores improves the pore regularity in the microscopic images and thus the morphology ratio and roundness are reduced. When the axial strain is greater than 15%, the shearing process is characterized by triaxial compression, along with an increase in pore perimeter and equivalent area.

Under the shearing effect, pores are more irregular and their roundness and morphology ratio increase.

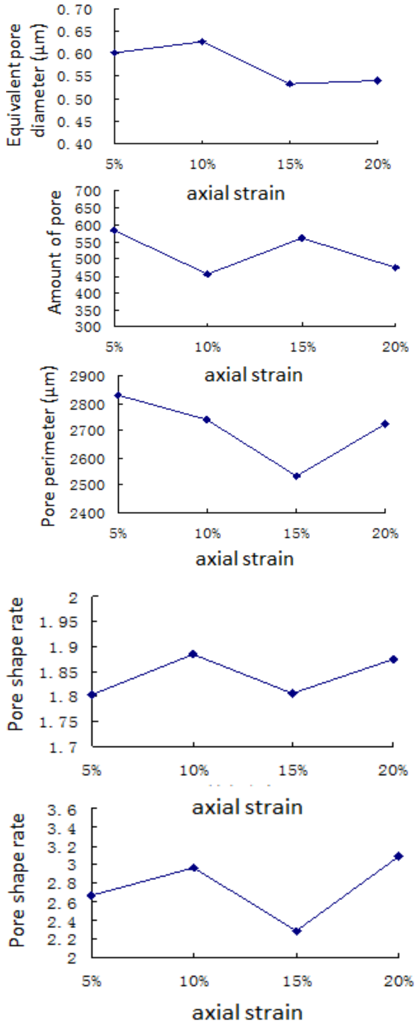


FIGURE 9 The micro-structure parameter curve of shear test soil samples of different axial strain

3.4 MICROSTRUCTURE RESPONSE FOR THE SHEAR FAILURE OF STRUCTURAL DREDGE FILL

3.4.1 The response to shear failure in microstructure images

Comparing the five images, it is seen that the morphology of sections 1 and 5 are similar. Likewise, the morphology of sections 2 and 4 are similar. Furthermore, analysis of the morphology indicates that sections 1 and 5 display macropore development and a flocculated structure as a whole. Also, the particles' contact relationship is generally line-area. The pore development in sections 2 and 4 is inferior to those in sections 1 and 5. Furthermore, their particle arrangement is closer with visible signs of shear cracking; the particle contact relationship represents a coexistence of line-area and area-area contacts. Section 3 is completely different in microstructure morphology from the other four sections. It shows a laminated support structure on the whole and there is an extremely notable directional alignment of flaky minerals. This indicates that section 3 has a position which is just on the shear failure surface. Due to the shear slipping failure, the structure of the dredge fill is completely damaged, resulting in the rearrangement of mineral particles. As sections 2 and 4 are closer to the shear failure surface, partial shear cracking is apparent, but the whole structure has not been damaged irrevocably. Sections 1 and 5 show macropore developments and flocculated structures as a whole, mainly due to the dilatation during shear testing.

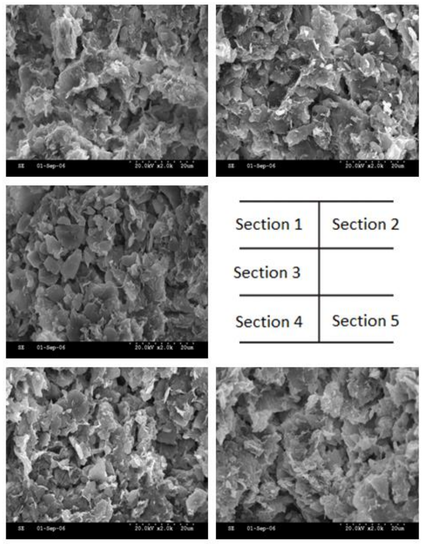
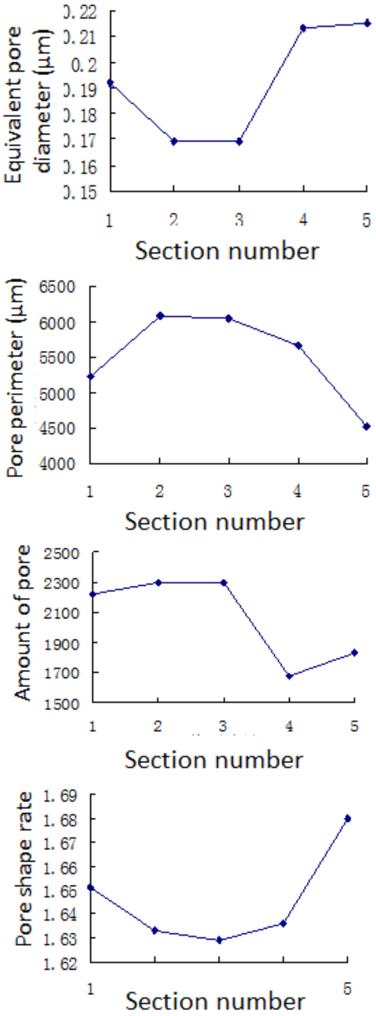


Figure 10 The SEM picture of soil sample at different distances to shear failure surface

3.4.2 Microstructure parameter variation at different distances from the shear failure surface and interpretation

To investigate the range of influence of the shear failure in soil, five sections are taken parallel to the shear failure surface and their microstructure parameters is obtained. This allows one to analyze the microstructure properties of the soil mass at different distances from the shear failure surface.

Figure 11 shows the microstructure parameter curves on the shear failure surface and its pores on both sides. As can be seen from the figure, the equivalent diameter, morphology ratio, and roundness of the third soil sample are the smallest compared to the other samples. Meanwhile, its pore number and perimeter are the largest. These changes may be explained by the fact that the third sample is much closer to the shear failure surface. The reason for this is that aggregates of the dredge fill are crushed when the shear stress exceeds the shear structure strength of the dredge fill. However, shear dilatation is not distinct when the shear failure of the soil sample occurs under a confining pressure of 300 kPa and the microscopic sample lies in the middle of the shear sample. Therefore, compared to both sides of the shear failure surface, the average pore diameter, pore morphology ratio, and pore roundness at the shear failure surface are smaller, while its pore number and perimeter are larger. These results are mainly due to the increase in pore number and irregularity of the morphology driven by the slipping and crushing of aggregates [13].



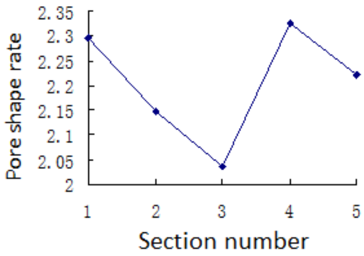


FIGURE 11 The micro-structure parameter curve of soil sample at different distances to shear failure surface

4 Conclusions

1) This is specifically illustrated by the existence of a yield stress in the compression process. When the stress is smaller than the yield stress, the compression test curve shows a strain softening type of behaviour and when the stress is larger than the yield stress, it presents a strain hardening type. Meanwhile, the shear strength envelop has a broken line form.

2) Based on a quantitative analysis of the microstructure of the dredge fill during consolidation, the turn stage of the stress-strain curve of the dredge fill coincides with the mutation phase of the microstructure parameter variation curves. This is explained by the fact that the variation in the mechanical properties of the soil is basically caused by the changes in microstructure.

3) The quantitative microstructure analysis of the effect of shear testing on the dredge fill show that the microstructure parameters mutate when the axial strain is 10–15% (instead of varying linearly with an increase in axial strain). This demonstrates that the structural properties of the dredge fill change during shear failure in a macroscopic way.

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