Investigation on mechanical properties of artificially structured soils under different stress paths

Chong Zhang¹, Enlong Liu¹,²*, Yong Tang²

¹ Institute for Disaster Management and Reconstruction, Sichuan University, Chengdu, Sichuan 610065, China
² State Key Laboratory of Hydraulics and Mountain River Engineering, College of Water Resource and Hydropower, Sichuan University, Chengdu, Sichuan 610065, China

* Corresponding author’s e-mail: liuenlong@scu.edu.cn

Abstract. Natural soils are structured in deposit process. This is the biggest difference between the remolded soils and natural soils. As one of the stress-dependent materials, different kinds of stress-path have great influences on the mechanical properties of structured soils. Based on the triaxial tests on different kinds of stress path, the mechanical properties of structured soils and remolded soils are discussed in the paper. The main conclusions are as follows: under conventional triaxial compression tests, the sample of structured soils shows strain softening and volume dilation when the confining pressure is lower (25kPa); when the confining pressure becomes large (100 kPa and 200 kPa), the sample shows strain hardening and volume contraction; while, the remolded soils behave stress hardening and volume strain contraction under all kinds of confining pressures. Under triaxial extension tests, the sample of structured soils shows strain softening and volume dilation in the loading process; the remolded soils have strain hardening and volume contraction. Under constant mean stress loading path, the sample of structured soils shows plastic flow and volume strain contraction, while the remolded soils perform strain hardening and volume contraction.

1. Introduction

With the construction of super high-rise buildings and the excavation of super foundation pits, the stress path of the soil is no longer just a triaxial compression state, and the soil element will undergo different loading paths during construction or engineering operations. Therefore, it is necessary to carry out experimental research on the mechanical properties of structured soils under different stress paths, which could provide theoretical guidance and basis for the design and construction of buildings.

Natural soils are structured. Soil structure refers to the soil particle and pore properties and arrangement and the interaction between soil particles [1], or the shape, size, arrangement of soil particles, the state of the pores, and the state of contact and bonding between soil particles [2], or the sum of the geometric and mechanical characteristics of the soil [3]. However, for laboratory experiments, the properties of natural soils will be apparently affected by the sampling, transportation and preparation. In order to reduce the disturbance to the natural soils, different researchers have used different methods to artificially prepare structured soil samples [4-9].

Since Lambe proposed the concept of stress path, many researchers have carried out a lot of experiments on different stress paths of structured soils. Malandraki et al. [10] performed triaxial drained test under different stress paths for artificially weakly bonded structured soils. Based on a
series of experiments of red clay under different stress paths, Huang et al. [11] showed us that the proper parameters could be determined only by combing actual stress of the project. Chang et al. [12] carried out consolidated undrained triaxial tests on undisturbed clays in different areas of Hexi in Nanjing, and found that the stress-strain curves under different stress paths all exhibited similar strain-hardening, but the peak strength and the pore pressure fluctuated greatly. Liu and Shen [13] used artificially structured soils to carry out consolidation drained and consolidation undrained triaxial tests under different stress paths, and analyzed the strength properties and deformation mechanism of structured soils, pointing out that structured soils exhibited different stress-strain characteristics and pore-pressure characteristics under different kinds of stress path.

In this paper, the consolidated drained triaxial test of isotropic structured soils and remolded soils under three kinds of stress path of conventional triaxial compression, conventional triaxial extension and triaxial compression with constant mean stress was carried out, and the mechanical properties and deformation characteristics of structured soils and remolded soils under different stress paths were analyzed.

2. Test Description

2.1 Sample preparation method

In this paper, the existing sample preparation method [13, 14] is adopted to prepare isotropic structured soils (hereafter, structured soils) with the mixture of silty clay, kaolin clay, cement and salt particles. The mass ratios of the components are 65, 20, 5, 10%, respectively. The cement used is 32.5R, and the density of the salt particles is 2.165 g/cm³.

The materials of structured soils were crushed and dried, and mixed uniformly, and then placed in a mold with the same three parts to be compacted in four layers of a dry density of 1.49 g/cm³, and then the sample was saturated by vacuum saturation. After that, the sample was placed in a water flowing environment, and the flow rate was 6.65 cm³/s. After 7 days of curing, the sample could be taken out for testing. Large pores are generated when the salt particles flow along with the water, and the hydration of cement forms some materials bonding the soil particles together. The remolded soils were prepared by using the materials of the structured soils after testing. The dry density of remolded soils is controlled to 1.34 g/cm³, and the preparation process of remolded soils is consistent with structured soils.

2.2 Test contents under different stress paths

Figure 1. The test apparatus of GCTS

The testing instrument used is a GCTS system shown in Figure 1. The stress paths adopted are presented in Figure 2. The three stress paths are: conventional triaxial compression test (OAC), conventional triaxial extension test (OAD), triaxial compression with constant mean stress test (OAB). Under different stress paths, the structured soils and the remolded soils were tested under different confining pressure conditions. In the legend below, "S" refers to structured soils, and "R" refers to remolded soils.
3. Test results and analysis

3.1 Triaxial compression test results and analysis

The structured soil and remolded soil samples were subjected to conventional triaxial compression tests at confining pressures of 25, 100, and 200 kPa. Here were strain-controlled tests with the shear strain rate of 0.06 mm/min. The consolidation time of the tests were 16 h, and the tests were stopped when the axial strain of the samples reached 15% during the shearing process.

![Curves of deviatoric stress and volumetric strain-axial strain (structured soils)](image)

**Figure 3.** Curves of deviatoric stress and volumetric strain-axial strain (structured soils)

![Curves of deviatoric stress and volumetric strain-axial strain (remolded soils)](image)

**Figure 4.** Curves of deviatoric stress and volumetric strain-axial strain (remolded soils)

3.1.1 Triaxial compression test results of structured soils

The deviatoric stress–axial strain curves and the volumetric strain–axial strain curves of structured soils under different confining pressures are presented in Figure 3. It is shown that structured soils exhibit strain softening under low confining pressure and strain hardening under higher confining pressure. The samples first contract and then dilate with increasing axial strain under a relatively low confining pressure state. Under high confining pressure, they behave volumetric contraction. Structured soils have shear bands under low confining pressure (25kPa), while bulging in the middle when confining pressure becomes large (100kPa and 200kPa).

3.1.2 Triaxial compression test results of remolded soils

The deviatoric stress–axial strain curves and the volumetric strain–axial strain curves of remolded soils under different confining pressures are shown in Figure 4. Compared with structured soils, remolded soils all behave strain hardening and volumetric contraction at confining pressure of 25, 100 and 200kPa. Remolded soils behave a failure pattern of bulging in the middle.

3.1.3 Analysis of triaxial compression test results

The tests results above could be analyzed by the binary medium theory [15, 16]. Structured soils can be regarded as a binary-medium material consisting of bonded elements (elastic brittle elements) and frictional elements (elastic plastic elements), while the remolded soils consist entirely of frictional elements (elastic plastic elements). After the consolidation test is completed, the bonded elements in
structured soils will be partially broken, but at the beginning of the test, the unbroken bonded elements will still mainly bear the external loads. As a elastic brittle material, the bonded element has a large elastic modulus, so the deviatoric stress of structured soils can be rapidly increased to a larger value within a small range of axial strain. The remolded soils are entirely composed of friction elements and the deviatoric stress tends to increase relatively gentle. So it is shown that the slopes of the curve in the structured soils stress-strain curve at the beginning stage are larger than those of remolded soils.

The external loads are mainly borne by bonded elements in structured soils at beginning. With the loads increasing, the bonded elements gradually reach its yield strength and lose its bearing capacity, and the broken bonded elements will transform to frictional elements at the same time, so the two components bear the loading collectively. The damage of the bonded elements will cause the deviatoric stress to decrease, and the increase of the frictional element will cause the deviatoric stress to increase. The larger the confining pressure, the larger the increase of the deviatoric stress caused by the frictional elements. Therefore, the structured soils exhibit strain softening under low confining pressure and strain hardening under high confining pressure. The remolded soils are composed entirely of frictional elements, the bearing capacity of the soil skeleton is borne by the friction elements. During the loading process, the friction between soil particles gradually increases, and the strength of the frictional elements gradually increases, so remolded soils behave strain hardening.

Structured soils behave volumetric contraction followed by dilatancy under low confining pressure. At the beginning of the test, there are some unbound soil particles fill the large pores inside the sample, the sample behaves volumetric contraction. With the loading, the bonded elements gradually transfer to frictional elements, and the sample reaches a relatively dense state. However, since the confining pressure is small and the soil particles are weakly bound, the soil particles could rotate and flip over, which cause the sample dilatancy. Under high confining pressure of 100kPa and 200kPa, soil particles can hardly rotate and flip over, the sample contracts at all times. Lacking of bonded elements, the soil porosity of remolded soils decreases gradually during the test, so remolded soils only exhibit volumetric contraction behavior.

![Figure 5. Schematic illustration of structure model of structured soils](image)

Schematic illustration of structure model of structured soils is shown in Figure 5. The hydration of cement forms some materials bonding the soil particles together. A certain amount of pores have been produced inside the cementitious materials because of the hydration of cement, and the cementitious materials and soil particles have formed the soil skeleton of the structured soils. Although the materials in the structured soil and the remolded soil sample are the same, the porosity of the remolded soil sample is larger than that of the structured soil sample due to the existence of internal pores in the cementitious materials. And during the loading, the destruction of the bonding between soil particles will dissipate part of the energy, while remolded soils are compacted all the time, without energy wasting. So the volumetric compaction of remolded soils is always larger than that of structured soils.

3.2 Triaxial extension test results

Triaxial extension tests were carried out on structured soils and remolded soils at confining pressure of 25, 50, and 100 kPa. The tests were stress-controlled, and the samples were consolidated for 16 h. The axial stress was kept constant after the consolidation tests were completed, and the confining pressure
was gradually increased with the growth rate of 20 kPa/h. The tests would be stopped when the axial strain reached -10% (compression was defined as positive).

3.2.1 Triaxial extension test results of structured soils
The deviatoric stress–axial strain curves and the volumetric strain–axial strain curves of structured soils under different confining pressures are presented in Figure 6. It is shown that the deviatoric stress tends to increase first and then decrease with the increase of axial strain under different confining pressures, and the peak value of deviatoric stress will appear earlier with the increase of confining pressure. The samples behave initially contract and then tend to dilate. The failure pattern of structured soils is mainly shear failure and accompanied by obvious necking phenomenon.

3.2.2 Triaxial extension test results of remolded soils
The deviatoric stress–axial strain curves and the volumetric strain–axial strain curves of remolded soils under different confining pressures are shown in Figure 7. Different from structured soils, under low confining pressure, the deviatoric stress of remolded soils tends to increase with the increase of axial strain, while at higher confining pressure, the deviatoric stress first increases and then decreases, but the degree of reduction was smaller than that of structured soils. The samples behave initially contract and then tend to be stable. The failure pattern is also different from structured soils, with only necking and no shear failure.

3.2.3 Analysis of triaxial extension test results
Compared with the triaxial compression tests, the increase of confining pressure in the triaxial extension tests increases the first principal stress and the second principal stress simultaneously. As the tests begin, the bonded elements of structured soils rapidly reach its yield strength and destroy, and the increase of the deviatoric stress caused by frictional elements is not enough to compensate for the deviatoric stress reduction caused by the damage of bonded elements, so structured soils behave strain softening. And with the increase of the confining pressure, elasticity modulus of bonded elements also increases and yield with less axial strain. Due to the simultaneous increase of the first and second

![Figure 6. Curves of deviatoric stress and volumetric strain-axial strain (structured soils)](image)

![Figure 7. Curves of deviatoric stress and volumetric strain-axial strain (remolded soils)](image)
principal stress, the porosity of the remolded soils gradually decreases and reaches a relatively stable state earlier, so remolded soils behave initially contract and then tend to be stable. The rotation and sliding between the soil particles of structured soils will cause a slight increase in volume at the confining pressure of 25 kPa, while the porosity of the sample has decreased to a relatively stable state under the confining pressure of 100 kPa, which shows that there is no obvious dilatancy.

3.3 Triaxial compression with constant mean stress test results
Triaxial compression with constant mean stress tests were carried out on structured soils and remolded soils at confining pressure of 50, 100, and 200 kPa. The tests were stress-controlled, and the samples would be consolidated for 16 h. After the consolidation, the axial stress was increased while the confining pressure was reduced, and the mean stress was kept constant. The tests were stopped when the axial strain reached 15%.

3.3.1 Triaxial compression with constant mean stress test results of structured soils
The deviatoric stress–axial strain curves and the volumetric strain–axial strain curves of structured soils under different confining pressures are presented in Figure 8. It is shown that the deviatoric stress rapidly increases to a higher level in the state where the axial strain is small, and then appears to be gradually stable or slowly increasing. They behave volumetric contraction all the time. Structured soils behave shear failure at 50, 100 kPa, accompanying the appearance of the shear bands. At a high confining pressure of 200 kPa, the samples are mainly bulging.

3.3.2 Triaxial compression with constant mean stress test results of remolded soils
The deviatoric stress–axial strain curves and the volumetric strain–axial strain curves of remolded soils under different confining pressures are shown in Figure 9. Compared with structured soils, remolded soils behave strain hardening and volumetric contraction at all kinds of confining pressure. The remolded soils exhibit a bulge failure at all times.
3.3.3 Analysis of triaxial compression with constant mean stress test results

According to Enlong Liu[9], the yield strength of structured soils is about 105.6 kPa. The confining pressure is reduced while increasing the axial stress in triaxial compression with constant mean stress tests. In order to ensure that the experimental condition is triaxial compression, the minimum confining pressure of the tests is 50 kPa.

When the minimum confining pressure is 50 kPa in the triaxial compression with constant mean stress tests, the incremental stress of the frictional elements is greater than the deviatoric stress reduction caused by the failure of bonded elements for the structured soils. So there is no strain softening in this stress path. Since the confining pressure is gradually reduced during the test, the increase of deviatoric stress caused by frictional elements is not as good as that of the conventional triaxial compression test, resulting in the structured soils always being in a plastic flow state. Also, due to the continuous reduction of the confining pressure during the test, the degree of restraint between the soil particles is smaller than that of the conventional triaxial compression test, so that the obvious shear bands appear when the structured soil sample is destroyed under the condition of low confining pressure.

4. Conclusions

(1) Under the conditions of conventional triaxial compression test, the structured soils exhibit strain softening and dilatancy under low confining pressures and is accompanied by shear band. Under high confining pressures, the samples exhibit strain hardening and volumetric contraction. Under high confining pressure, the strength of remolded soil exceeds that of structured soils.

(2) Under the triaxial extension test conditions, the structured soil samples basically exhibit strain softening and volumetric contraction followed by dilatancy. There is no obvious hardening or softening phenomenon in the remolded soils. The final value of the deviatoric stress is slightly changed under different confining pressure conditions. The samples firstly contract and there is no obvious change in the later stage. The failure pattern of structured soils is mainly shear failure, accompanied by necking. The failure pattern of remolded soils is necking.

(3) Under the conditions of triaxial compression with constant mean stress test, structured soils behave plastic flow, while the remolded soils becomes more and more hardened with the increase of confining pressure. Both of them exhibit volumetric contraction. However, the failure of structured soils under low confining pressure is accompanied by the appearance of shear bands, which are the same as the remolded soils under the high confining pressure.

References

[1] Mingjing Jiang, Zhujiang Shen, Suying Xing. Review of structural clay research[J]. Advances in Science and Technology of Water Resources, 1999, 19 (1):26-30.

[2] Enlong Liu, Zhujiang Shen, wen Fan. Advance in researches on structured clay[]. Rock and Soil Mechanics, 2005, 26:1-8.

[3] Jilin Qi, Zhenzhong Zhang. Consideration of the constitutive relation of structural soil[J]. Chinese Civil Engineering Journal, 2000, 33 (4):35-41.

[4] Saxena S, K, Lastrico M. Static properties of lightly cemented sand. J Geotech Engng Div, ASCE. 1978, 104(GT12):1449-1464

[5] Clough G W, Sitar N, Bnchus R C, Shaffi N. Cemented sands under static loading. J Geotech Engng Div, ASCE. 1981, 107 (GT6):799-817.

[6] Maccarinic, M. Laboratory studies of weakly bounded artificial soil:[dissertation]. University of London. 1987.

[7] Sudhakar M , R, Asuris Konanur P R. Collapse behavior of an artificially cemented clayey soil. Geotechnical Testing Journal, GTJODJ, 1995, 18 (3):334-341.

[8] Mingjing Jiang, Zhiqiang Shen. A method of artificial preparation of structured collapsible loess samples. In:Accepted by the 2nd international conference on unsaturated soils, Beijing 1998, 5.
[9] Enlong Liu, Zhujiang Shen. Experimental study on mechanical properties of artificially structured soils [J]. Rock and Soil Mechanics, 2007, 28 (4): 679-683.

[10] Malandraki V., Toll D.G.. Triaxial tests on weakly bonded soil with changes in stress path [J]. Journal of geotechnical and geoenvironmental engineering, 2001, 127 (3): 282-291.

[11] Zhihong Huang, Lijun Zhu, Yiling Liao, Qing Zhao. Mechanical properties of red clay under different stress paths [J]. Chinese Journal of Rock Mechanics and Engineering, 2004, 32 (15): 2599-2603.

[12] Yinsheng Chang, Xudong Wang, Jinmin Zai, Jianlong Xu. Experimental of clay under different stress paths [J]. Journal of Nanjing Tech University, 2005, 27 (5): 6-11.

[13] Enlong Liu, Zhujiang Shen. Mechanical behavior of structured soils under different stress paths [J]. Chinese Journal of Rock Mechanics and Engineering, 2006, 25 (10): 2058-2064.

[14] Kaitai Luo, Qing Nie, Enlong Liu. Investigation on artificially structured soils with initial stress-induced anisotropy [J]. Rock and Soil Mechanics, 2013, 34(10): 2815-2820.

[15] Zhujiang Shen, Enlong Liu, Tielin Chen. Generalized stress-strain relationship of binary medium model for geological materials [J]. Chinese Journal of Rock Mechanics and Engineering, 2005, 27 (5): 489-494.

[16] Enlong Liu, Hai-Sui Yu, Cheng Zhou, et al. A binary-medium constitutive model for artificially structured soils based on the disturbed state concept (dsc) and homogenization theory [J]. International Journal of Geomechanics, 2017. 04016154: 1-15.