Characteristics of structure evolution of expansive soil and loess during loading and wetting

Caractéristiques de l'évolution structurale du sol expansif et du loess lors du chargement et du mouillage

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ABSTRACT: A CT-triaxial apparatus was used to study systematically the meso-structure evolution of expansive soil and loess. All soil samples were unsaturated. A group of CT-triaxial drained tests with net cell pressure and suction controlled and a group of wet-dry circles for expansive soil samples were conducted. A series of CT-triaxial inundation-collapse tests were conducted under certain suction and net mean stress as well as deviator stress for undisturbed Q_3 loess. A number of CT images and CT date of meso-structure evolution of the samples were obtained. Some regularity of holes and cracks developing in samples were discovered. The structure damage evolution equations for expansive soil and loess were proposed, respectively. A method to determine the yield stress in triaxial test was suggested.

RÉSUMÉ : Un appareil CT-triaxial a été utilisé pour étudier systématiquement l'évolution méso-structurale du sol expansif et du loess. Tous les échantillons de sol étaient insaturés. Un groupe d'essais CT-triaxial de drainage ont été faits sous le contrôle de la pression et de la succion de la salle blanche, ainsi qu'un groupe d'essais d'alternance humide-sèche pour les échantillons de sol expansif. Une série d'essais CT-triaxial de mouillage ont été effectués sur le loess Q3 intact sous une valeur définie de succion, de contrainte moyenne nette et de contrainte déviatorique.Un certain nombre d'images et de données CT de l'évolution méso-structurale des échantillons ont été prélevée. Quelques régularités du développement des trous et des fissures dans les échantillons ont été découvertes. Les équations d'évolution des dégâts structuraux du sol expansif et du loess ont été proposées respectivement. Une méthode de déterminer la limite d'élasticité en essai triaxial a été suggérée

KEYWORDS: CT-triaxial apparatus; suction; loading; wet-dry circle; collapse; structure evolution.

1 INTRODUCTION

Each type of soils, such as collapsible loess and expansive soil, has its own special structures. The mechanical properties of soils are related to their interior factors (i.e., mineralogical composition and structure) and the outer factors (i.e., loading and environmental changes). For example, the strength of collapsible loess and expansive soil are very high during the dry seasons. However, the strength will decrease drastically when they are inundation.

Since 2000, a series of researches have been conducted on the meso-structure analysis of loess and expansive soil using the CT-triaxial apparatus developed by the author. The meso-structure and evolution laws of expansive soil and loess under the loading and moisture changes were mainly investigated.

2 TEST EQUIPMENT

In recent years, great effort has been paid to study meso-structures and constitutive relations of special soils such as loess and expansive soil, et al, by the authors. A multifunctional triaxial apparatus of unsaturated soil combining with CT machine developed successfully (Chen, et al, 2001; Chen, et al, 2007), and over 30 of stress path tests on saturated soil, unsaturated soil and special soils can be conducted with the equipment (Figure 1). The CT machine made by GE is a spiral scanner type of Prospeed AL. Its spatial resolution is 0.38 mm and its density resolution is 0.3 % (3 Hu).

3 STRUCTURE EVOLUTION OF EXPANSIVE SOIL

Crack is one of important structural feature, which influences the mechanical properties of expansive soil. In order to discover the characteristics of the crack evolution of expansive soil, 9 groups of tests including 55 samples were conducted. These tests were CT-triaxial tests in loading and wet-dry circles. A total of 666 CT images and a number of CT data of the test samples were obtained (Lu, 2000; Wei, 2007; Yao, 2009; Chen, 2011; Yao, 2011; Wang, 2012). However, only a part of test results are presented in the paper because space is limited.

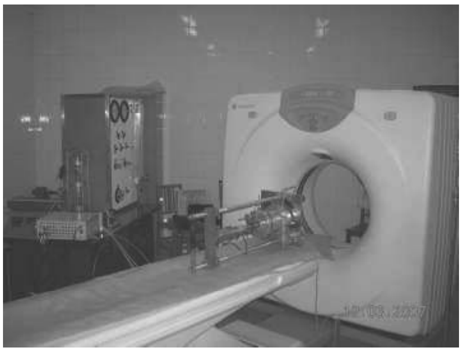

Figure1. CT-triaxial apparatus

3.1 *The characteristics of structure damage evolution of intact expansive soil during loading*

Fifteen CT-triaxial drained tests of intact expansive soils with net cell pressure and suction controlled were conducted. The size of samples was 39.1mm in diameter and 80mm in height. The initial conditions and index of samples are shown in table 1 (only the data of sample $2^{\#}$ are listed).

The scanning cross-sections which were marked 1 and 2 located at 1/3H and 2/3H from the top of specimen. Each sample was scanned 6 times and the scanning pictures were marked as a, b, c, d, e and f successively. 1a, 1b, 1c, 1d, 1e and 1f were corresponding to the cross-section of 1/3H (Fig. 2).

The CT images of sample $2^{\#}$ clearly illustrate that the structures of the samples change obviously from initial deformation to failure and several cracks gradually developed. The test results of the samples indicate similar crack evolution rules. 1) The initial damage of structure of intact expansive soil is great and heterogeneous in space. 2) Shear makes an obvious

Table 1 Initial conditions and test parameters of sample 2#

Initial conditions		Test parameters		
		Scanning sequence	Deviator stress / kPa	Deviator strain / %
		a	0	0.00
Dry density ρ_d /(g/cm^3)	1.68	b	153	0.95
Water content w / %	22.1	c	302	3.30
Void ratio e	0.63	d	283	5.38
Matric suction s / kPa	100	e	238	8.19
Net cell pressure p / kPa	50	f	211	11.24

development of structure damage (which is from fissure development to several crack connection). 3) Both suction and cell pressure affect damage evolution. The higher the cell pressure or suction is, the lower the damage degree of sample will be. 4) The formation of fracture plane of undisturbed soil has several characteristics as follows: a) Inevitability: preexisting fissures, or weakness planes or large cavity, which are the weak areas of samples, easily extend to fracture plane (dash line ① in figure 2). b) Randomness: there are no signs before fracture plane forming, however, fissure occurs with shear and develops to fracture plane (dash line ② in figure 2). c) Correlation: new fracture plane grows due to other fracture planes (dash lines ③ and □ in figure 2)

Taking the mean value of CT data of undisturbed samples as the base value, a damage variable D_1 can be defined as the relative difference of base value and the mean value of CT data in the process of tests. Damage evolution equation can be obtained through analysis on test date:

$$D_1 = D_0 + \exp\left(\frac{p_0}{p}\varepsilon_s^{s/p_{atm}}\right) - 1 \qquad (1)$$

where D_0 is the initial value of damage variable, ε_s is deviator strain, s is suction, p_{atm} is atmospheric pressure, p and p_0 are spherical stress and pre-consolidation pressure, respectively.

Equation (1) can reflect the influence of deviator stress, pre-consolidation pressure, suction and initial damage degree on expansive soil in the process of shear. It is convenient to use equation (1) in constitutive relationship because of its simple style and a few of parameters involved.

3.2 *Characteristics of structure damage evolution of remolded expansive soil in the process of wet-dry circles*

Twelve wet-dry cycle tests of remolded expansive soils were carried out. Each sample went through 5 wet-dry circles. The sizes and the scanning cross-sections of the samples were as same as in section 3.1. However, the scanning pictures were marked as a0~a5 and b0~b5, successively, were corresponding to the cross section of 0.3H and 0.7H from the top of the simples, respectively. The picture marked as a0 and b0 associated with the initial state of the specimen. A total of 66 CT images were obtained. Let H and SD denote the mean value and the standard deviation of CT data of a scanning section, respectively, the results of the tests show that H decrease and SD augment as the times of wet-dry circles increase. The images show that the cracks initiate and extend continuously. At last, the crannies becomes connectivity each other as shown in figure 3.

Taking the CT data corresponding to the initial state of specimen as the base value, a damage variable D_2 can be defined as the relative difference of base value and the value of CT data in the process of wet-dry circles tests.

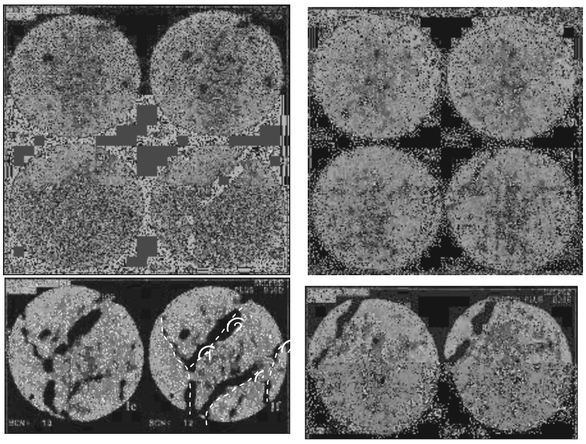

Figure 2. Scanning images during triaxial shear test of sample 2# of intact expansive soil.

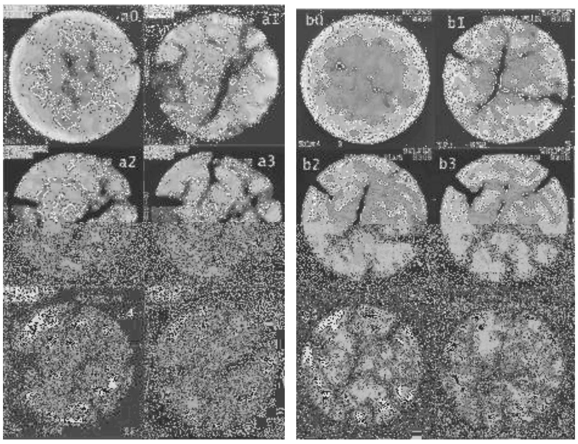

Figure 3. Scanning images through 5 times of wet-dry circles of sample 5# of remolded expansive soil

The damage values related to various volumetric strains in wet-dry circle tests are show in figure 4. Through curve-fitting, the damage evolution equation upon the wet-dry circle test is:

$$D_2 = \exp(A\varepsilon_v) \qquad (2)$$

Where A is a soil parameter, and ε_v is volumetric strain. It is obviously that the damage evolution equation is in good agreement with the experiments.

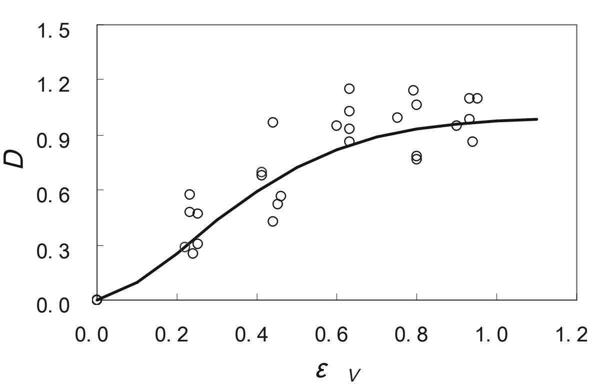

Figure 4. The damage values vs. volumetric strains of samples in the process of wet-dry circles test

Tab.2 Initial physical parameters and stress states of samples before soaking

No.of sample	Initial dry density g / cm^3	Initial water content /%	Void ratio	Net cell pressure (σ_3-u_a) / kPa	Matric suction s / kPa	Deviator stress q / kPa	Water pressure during soak / kPa
1	1.31	11.0	1.08	100	150	0	4
2	1.31	11.0	1.08	200	150	0	12
3	1.32	11.0	1.04	100	150	200	14
4	1.32	11.0	1.05	100	250	0	12
5	1.31	11.0	1.06	100	150	100	14
6	1.30	11.0	1.08	100	150	250	14

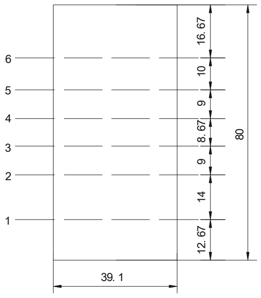

Figure 5. Scanning position (length unit: mm)

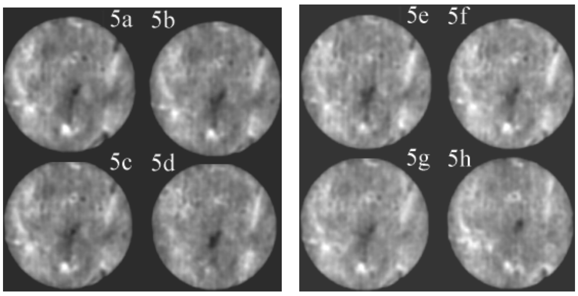

Figure 6 Scanning images of 5th section of sample 3$^\#$ of Q$_3$ loess during loading

Tab.3 CT data and stress state of sample 3# during loading

Stress state	Scan sequence	5th Section H	SD
Initial state	a	821.1	49.4
End of consolidation	b	854.6	44.7
q = 25 kPa	c	856.5	44.7
q = 50 kPa	d	852.7	41.4
q = 75 kPa	e	854.1	42.6
q = 100 kPa	f	854.0	41.7
q = 150 kPa	g	887.0	45.9
q = 200 kPa	h	927.2	43.4

4 STRUCTURE EVOLUTION OF LOESS Q$_3$

Collapsibility is the most important feature of loess. However, collapsibility depends on the meso-structure of loess. In order to discover the characteristics of the meso-structure evolution of loess, 10 groups of CT-triaxial tests including 49 samples of Q$_3$ loess were conducted. A total of 847 CT images and a number of CT data were obtained (Zhu, 2007; Fang, 2008; Li, 2010).

4.1 The structure evolution of Q$_3$ loess during loading and collapsing

Six tests of intact Q$_3$ loess were conducted. The size of samples was 39.1mm in diameter and 80mm in height. The initial conditions and test parameters of the samples are shown in table 2. Each sample was scanned 6 sections (Figure 5), and each section was scanned from 6 to 8 times. The scanning pictures were marked as a, b, c, d, e, f, g and h corresponding to a section in successive scanning (Zhu, 2008a). A total of 273 CT images were obtained.

Figure 6 shows the Scanning images of 5th section of sample 3$^\#$ of Q$_3$ loess during loading. The scanning pictures were marked as a, b, c, d, e, f, g and h corresponding to the initial state, the end of consolidation, and deviator stress (q) equal to 25 , 50 , 75 , 100 , 150 and 200 kPa of the 5th section (Table 3). H and SD in table 3 are the mean value and the standard deviation of CT data of the 5th section.

It is clear from Figure 6 and Table 3 that consolidation has significant effect on the meso-structure of sample, and there is no evident change in the meso-structure of sample 3$^\#$ before deviator stress less than 150 kPa. In addition, the defect region (black part in Figure 6) not vanishes completely at the end of loading.

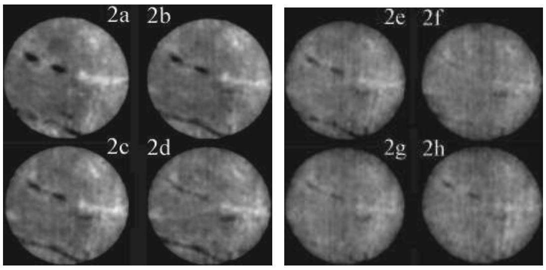

Figure 7 Scanning images during triaxial collapse of 2nd section of sample 4# of intact Q3 loess

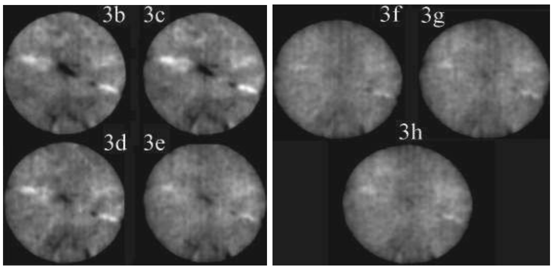

Fig.8 Scanning images during triaxial collapse of 3rd section of sample 4# of intact Q3 loess

The CT-triaxial collapse tests of Q_3 loess have been done under various mass of inundation. The scan images of CT-triaxial inundation tests for sample $4^{\#}$ are show in figures 7 and 8. The following understanding can be summarized from CT images:

1) For certain stress state, the original structure of the loess is damaged during collapse and a new stable homogeneous structure is formed simultaneously. In the CT images, the fissures and the cavity in the undisturbed loess samples shrink gradually, even disappear at last.

2) Either spherical stress or shear stress can lead to collapse including volume strain and shear strain. The 1#, 2# and 4# samples (Table 2) are in hydrostatic state of stress, and their collapsible volume strains are 4.3 %, 1.27 % and 4.79 %, respectively. It can be seen that the structure of 4# sample occurs a substantial change from an non-homogeneous (even with cracks) to a quite homogeneous state. For example, from Fig.7-2b to Fig.7-2c, the mean value of the CT data increases from 829.06 to 983.26 with an increment of 154.2. However, from Fig.7-2f to Fig.7-2g and from Fig.8-3f to Fig.8-3g, the mean values of the CT data change only in the fractional part.

The above two opinions proposed by the first author of the paper in 1986 firstly (Chen, 1986a, 1986b) are proved by the CT images, which give the visual evidence to the structure changes of the loess in the process of collapse. These two characteristics of collapse also show that collapse is different from shear failure, in other words, shear deformation during collapse process of loess is generally limited and taking the M-C criteria as initial collapse condition is unreasonable, which was pointed out by the first author of the paper in 1986 (Chen, 1986b).

4.2 Determining yield stress of intact loess with the help of CT scanning data

Figure 9 shows the relations of CT number vs. stress of two scanning sections of $3^{\#}$ simple Q_3 loess during shear (Table 2). It can be seen that there is a characteristic point at each curve. The CT numbers of pre- and post- the point change significantly, which means that the point is yield point. Thus, a method to determine yield point is proposed with the help of CT scanning data.

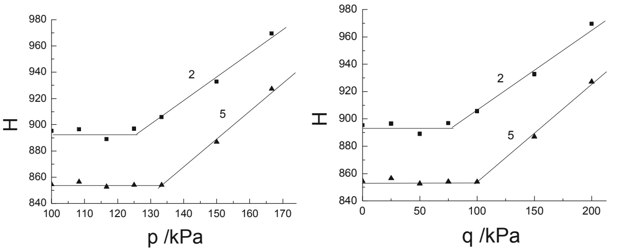

Fig.9 CT number vs. stress of two scanning sections of 3# simple Q_3 loess during shear

5 CONCLUSIONS

(1) The macro-scale behaviors of the soil samples are closely related with their mesostructural evolutions.

(2) Fissures sprout and grow during loading or during wet-dry circles for undisturbed expansive soil for remolded expansive soil.

(3) The original structure of the loess is damaged and a new homogeneous structure is formed during wetting and for certain stress state. The holes and fissures of intact loess may become gradually small even disappear during loading or inundation depending on stress state of soil.

(4) Based on CT data, the definitions of the structure damage variable of the loess and expansive soil are given. The structural damage evolution equations of two kinds of soils are obtained in various test conditions.

CT technology give the visual evidence to the structure changes of soils, and makes a solid test foundation to establish the damage evolution equation and structure constitutive model of soils.

6 ACKNOWLEDGEMENT

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7 REFERENCES

Chen Z.H. & Liu Z.D. 1986a. Mechanism on collapse deformation of loess. *Chinese Journal of Geotechnical Engineering* 1986(2): 1-12.

Chen Z.H. & Liu Z.D. 1986b. Some problems on collapsibility of loess. *Chinese Journal of Civil Engineering* 1986(3): 62-69.

Chen Z.H. 1994. New development in research of unsaturated soils. *Sino-Canadian Symposium on Unsaturated / Expansive soils*, June 1994: 145-152.

Chen Z.H. 1999. Deformation, strength, yield and moisture change of a remolded unsaturated loess. *Chinese Journal of Geotechnical Engineering* 21(1): 82-90.

Chen Z.H. , Lu Z.H. & Pu Y.B. 2001. The matching of computerized tomography with triaxial test apparatus for unsaturated soils. *Chinese Journal of Geotechnical Engineering* 23(4): 387-392.

Chen Z.H., Sun S.G., Fang X.W., Zhu Y.Q. & Xie Y. 2007. Development and application of multifunction triaxial apparatus. *Journal of Logistical Engineering University* 23(4): 1-5.

Chen Z. H, Yao Z. H. & Miao Q. Q. 2011. Influence of structure damage to the yielding of expansive soils[c]. Proc. AP-UNSAT, 14-16 November 2011, Thailand, Vol.Ⅱ : 679-684.

Li J.G., Chen Z.H., Huang X.F. , etal. 2010. CT-triaxial shear tests on the meso-structure evolution and strength of unsaturated loess Q_3 during unloading confining pressure. *Chinese Journal of Rock and Soil Mechanics*, 31(4): 1084-1091.

Lu Z.H. 2001. Elasto-plasticity-damage constitutive model of unsaturated expansive soil and applications on multi-field coupling numerical analysis for Soil Slope. Chongqing: Ph. D. dissertation, Logistical Engineering University.

Wang S.J., Chen Z. H. & Li X. The verification of damage variable of expansive soil based on CT numbers. Chinese Journal of Rock and Soil Mechanics, 2012, Underreview.

Wei X.W. 2007. Research on wet-swelling deformation and characteristics of structure evolution of expansive soil. Chongqing: Master Degree Dissertation, Logistical Engineering University.

Yao Z.H. 2009. Evolution characteristics of meso-structure of expansive soils in triaxial soaking test. Chongqing: Master Degree Dissertation, Logistical Engineering University.

Yao Z. H , Zang J. H & Chen Z. H. 2011. Study on meso-structure changes of remolded expansive soils during wetting-drying cycles and triaxial soaking test[c]. Proc. AP-UNSAT 2011, 14-16 November, Thailand, Vol.Ⅱ : 685-692

Zhu Y.Q. & Chen Z.H. 2008b. New methods for research of collapsibility of loess. *Chinese Journal of Geotechnical Engineering* 30(4): 524-528

Zhu Y.Q. 2008a. Research on constitutive model of unsaturated undisturbed collapse loess based on evolution of meso-structure. Chongqing: Ph. D. dissertation, Logistical Engineering University.