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The water storage capability and hydraulic conductivity of different expansive soils

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For the strong and medium expansive soils of the middle-route of South-to-North Water Transfer Project, pressure plate tests and double-ring infiltration tests were carried out. The water storage capability, its influence factors and the evolution of hydraulic conductivity was comparative studied on different expansive soils. The results show, the soil with stronger expansion potential, higher fine grain content and higher dry density has better water retention capability. Saturated permeability coefficient of strong expansive soil is low, and it decreases with the increase of dry density. Unsaturated hydraulic conductivity, which has power function relationship with matrix suction, decreases with the decrease of the moisture content.

Key words: Expansive soil, Water storage capability, Unsaturated soil, Hydraulic conductivity.

INTRODUCTION

Unsaturated expansive soil is a special soil, which contains a large number of hydrophilic clay minerals. The change in moisture content of expansive soil is the factor determining its deformation and reduction in strength, and it is also an important factor for geological disasters. So, expansive soil is particularly a major problem faced by engineering geologist in the construction of water conservancy projects.

Soil-water characteristic curve (SWCC) is an important method used in describing unsaturated soil water retention characteristics, many hydraulic parameters showing the relationship between matric suction and the water storage state of unsaturated soil can be obtained using SWCC [1-2]. Currently, there are a variety of models to describe the soil-water characteristic curve, such as Garden model [3], Brook and Corey model [4] with characterization of effective saturation, the Van Genuchten models [5] and Fredlund and Xing model [6] with characterization of volumetric water content. For the expansive soil water storage properties, studies were carried out from different angles, and achieved certain results [7-10]. At present, the research on the soil water storage are mainly concentrated on clayey soil, loess, silt and, weak and medium expansive soil, but very little for strong expansive soil.

In this paper, for the different expansive soil of the middle route of South-to-North Water Transfer Project, pressure plate tests and double-ring infiltration tests were carried out, and the same tests for medium expansive soil were taken for comparative study. According SWCC, the water storage capability and its influence factors, including physical properties, mineral composition and structure characteristics for different expansive soils were studied. Water volume change coefficient and variation characteristics of the hydraulic conductivity were discussed, and the regularity of the penetration characteristics was studied. It can provided the calculation parameters for disaster prevention and control.

EXPERIMENTAL

Materials

The soil samples were taken from the channel of the middle route of South-to-North Water Transfer Project. Strong and medium expansive soils were selected from TS95 channel bottom yellow-green clay and TS106 channel slope tan clay.

Table 1. Physical properties of expansive soil

Expansive soil	Moisture content (%)	Density (g/cm^3)	Liquid limit (%)	Plastic limit (%)	Free expansion ration (%)
Strong	27.77	1.94	89.03	29.30	109
Medium	25.85	1.94	59.54	27.12	69

Table 2. Mineral composition

Eexpansive soil	Mineral composition (%)				
	Montmorillonite	Illite	Kaolinite	Illite-montmorillonite	Kaolinite-montmorillonite
Strong	19.62	9.63	-	13.55	1.73
Medium	8.23	7.25	1.66	1.24	1.91

Table 1 shows the results of basic physical properties of each sample based on laboratory soil tests. Table 2 shows the results of the identification of the mineral composition of each sample by X-

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ray diffraction test using D8 Advance X-ray diffractometer.

Test methods

Soil-water characteristic curves of soil samples are obtained from the pressure plate test. The pressure plate apparatus are made in the United States Soil Moisture company (see Fig.1), and the clay plate intake is 15 bar. The test environment is a room temperature of 20 °C, and the test plan is shown in Table 3.

Each sample is saturated and weighed by vacuum saturation method at first, and then the sample is placed on clay board in a pressure cooker before installing and connecting the instrument and adjusting the sample chamber pressure. Sample should be weighed every 12 to 24 hours until the mass change less than 0.01 g within 24 h, which can be considered to achieve balance, then the next pressure level measurement can be continued. The test pressure series is 0.2, 0.5, 1, 2, 4, 7, 10, 13 bar. When the final pressure equilibrium, the samples should be placed in environment with 105 °C for drying to constant weight before weighing the mass of dry soil.

Fig. 1. Pressure plate test device

Table 3. Test plan of pressure plate test

Soil type	Dry density (g/cm^3)	Number of tests
Strong expansive soil	1.51	1
	1.53	1
Medium expansive soil	1.49	1
	1.53	1

Double-ring infiltration test is commonly used to determine the stable water infiltration rate of the soil. The test devices are primarily stylus, the inner and outer ring with 30cm in height, 26.2 cm and 47 cm in diameter (see Fig.2).

According to the situation, graduated cylinder is used to replace the flow bottle to put water to the two rings. During the test, it must to maintain the inner and outer ring water level. When the water surface drops after the needle tip during infiltration, a certain amount of water (100 to 200 mL) should be put into the inner ring before recording the time until infiltration speed is stable.

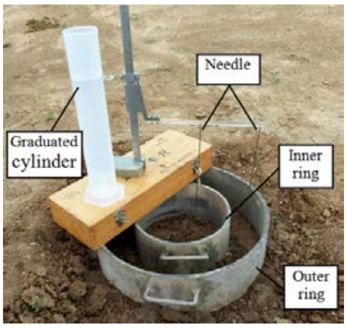

Fig. 2. Double-ring infiltration test device

Field test site is located in Nanyang segment of the main canal. Mainly Quaternary reddish brown - brick red, brown clay and silty clay, containing Calcareous and Ferromanganese concretions in the formation of leaching by groundwater. The reddish brown - brick red clay contains many vertical fissures, filled with the gray clay with strong expansion, such a clay overall is strong - medium expansive soil. However, the brown clay and silty clay contain extensive internal irregular meshed fracture, the soils always are weak - medium expansive soils. Engineering geological conditions of typical test points are shown in Table 4.

Table 4. Engineering geological conditions of typical test points

Location	Depth (m)	Density (g/cm^3)	Moisture content (%)	Free expansion ration (%)	Swelling potential *
TS102	10	1.96	19.82	63	W
TS102	6	1.96	16.09	70	M-
TS102	6	1.91	17.94	73	M
TS105	4	2.04	20.95	71	M
TS105	15	2.08	16.72	86	M+
TS105	15	2.05	18.54	90	S
TS105	5	2.03	19.37	77	M
TS105	3	2.05	18	85	M+
TS95	9	2.03	21	93	S

* W/M-/M/M+/S are respectively weak / weak-medium / medium / medium-strong / strong.

RESULTS AND DISCUSSION

SWCC characteristics and its influencing factors

Fig. 3 shows the soil water characteristic curve of expansive soils. SWCC of strong expansive soil is located above that of the medium expansive soil, with matric suction increasing, the saturation of strong expansion soil changes slower.

Analyzing from the physical properties of soil, the sample with stronger swelling potential and higher plasticity index contents more fine particles and it has larger specific surface area and bound water content, and the slower rate of dehydration.

Analyzing from the mineral composition of soil, Table 2 shows that clay mineral (montmorillonite, illite, etc.) content of the strong expansive soil is greater than 30%, and no amount of water molecules can be absorbed between montmorillonite unit cells, therefore, strong expansive soil has better water retention capacity and slower dehydration rate.

For the samples with the same swelling potential, SWCC of the one with greater dry density is located in the top. With the increasing of matric suction, saturation of expansive soil with greater dry density changes slower and also the rate of dehydration. This is because soil samples with greater dry density has higher density and smaller internal pore structure, the drainage channel of which is limited when matric suction increases.

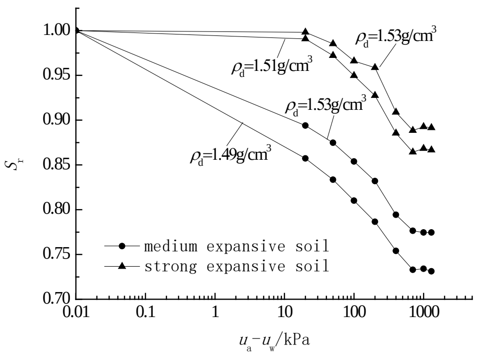

Fig. 3. SWCC of expansive soil with different dry densities

SWCC mathematical model

The result of soil moisture content in different matric suction obtained by the pressure plate test is a series of discrete data points. SWCC model can be used to fit the points into a continuous function, which can be taken to calculate the parameters of the non-saturated water movement.

Van Genuchten model has the following expression [5]:

$$\theta(h)=\begin{cases}\theta_{\mathrm{r}}+\dfrac{\theta_{\mathrm{s}}-\theta_{\mathrm{r}}}{[1+|\alpha h_{\mathrm{u}}|^{n}]^{m}} & (h<0)\\ \theta_{\mathrm{s}} & (h>0)\end{cases} \qquad (1)$$

Where θ_s and θ_r are saturated and residual moisture content (%), h_u is pressure head (mm), m and n are the empirical parameters, m=1-1/n.

Williams proposed model expression [11] is:

$$\ln s = a_1 + b_1 \ln\theta \qquad (2)$$

Fredlund based on soil pore size distribution and statistical analysis theory, drawn Fredlund and Xing model [6], which is applicable to the whole suction range of various soils:

$$\begin{cases}\theta=\dfrac{C(s)\theta_s}{\{\ln[e+(s/a)^n]\}^m}\\ C(s)=\dfrac{1-\ln(1+s/s_r)}{\ln[1+(10^6/s_r)]}\end{cases} \qquad (3)$$

Based on the soil mass distribution and the fractal characteristics of pores, the researchers obtained the SWCC fractal model establishing on the fractal relationship between pore volume and pore size and Young-Laplace equation [12]:

$$\frac{\theta-\theta_r}{\theta_s-\theta_r}=(\varphi/\varphi_b)^{D_v-3} \qquad (4)$$

Through research and division of vapor form for the unsaturated soil, researchers found that the points of intake values and residual water content in Fredlund curve are approximately linear relationship [13], based on this, SWCC of the logarithmic equation form was proposed:

$$\frac{\theta-\theta_r}{\theta_s-\theta_r}=F(\varphi)=\frac{\lg\varphi_r-\lg\varphi}{\lg\varphi_r-\lg\varphi_b} \qquad (5)$$

SWCC model fitting

In this paper, using Van Genuchten model, soil-water characteristic curves of expansive soils are fitted by the method of least squares, and fitting results and parameters are shown in Fig. 4 and Table 5. The saturated moisture content θ_s and the residual moisture content θ_r are measured by tests.

α is a scale parameter related to the average pore radius, it is about the reciprocal of air intake values. With the expansion potential enhancing, intake value increases, α is significantly reduced. Air intake value can be influenced by soil physical properties and mineral content, which has linear relationships with the plasticity index and the free expansion ration (see Fig. 5).

Table 5. The fitting parameters of SWCC model

Soil type	Fitting parameters				
	θ_s(%)	θ_r(%)	a(mm^{-1})	n	m
Strong expansive soil	44.25	16.31	0.000213	1.0785	0.0728
Medium expansive soil	44.27	11.93	0.012852	1.0637	0.0599

The water volume change coefficient

In the dehumidifying process, the water volume change coefficient m_2^w reflects the dehydration rate changes. m_2^w is the rate of change of the volumetric moisture content with the matric suction changing, which can be used the following formula to determine [6].

$$m_2^{w}=-d\theta / d(u_a-u_w) \qquad (6)$$

Pressure head h_u can be calculated by the equation 3.

$$h_u=(u_a-u_w) / (\rho_w g) \qquad (7)$$

Where u_a and u_w are pore air pressure (kPa) and pore water pressure (kPa), ρ_w is the density of water (kg/m^3). Substituting equation 7 into equation 6

$$m_2^w = -d\theta / (\rho_w g \, dh_u) \quad (8)$$

m_2^w can be determined by SWCC model through substituting the Van Genuchten model equation 1 into equation 8

$$m_2^w = mna(\theta_s - \theta_r)|ah_u|^{n-1} / [\rho_w g (1+|ah_u|^n)^{m+1}] \quad (9)$$

Water volume variation coefficients of different expansive soils can be calculated by equation 9, its relationship with the moisture content is shown in Fig. 6.

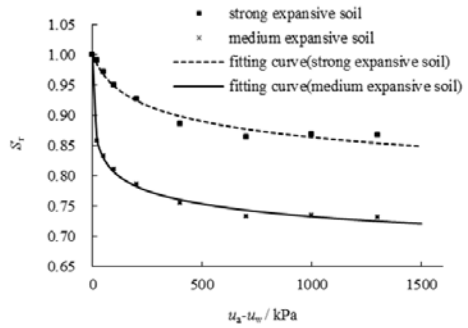

Fig. 4. Curve of SWCC model of expansive soil

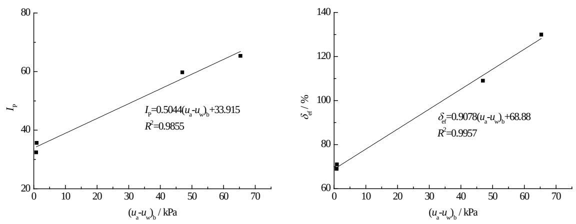

Fig. 5. Correlation between intake values and physical indicators

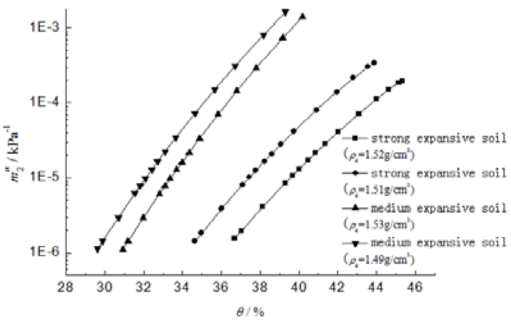

Fig. 6. Curve between m_2^w and water content

m_2^w of unsaturated expansive soil decreases with the decreasing of moisture content during the dewatering process. Strong expansive soil has gentle curve of m_2^w, which changes slowly with moisture content. The m_2^w of samples with greater dry density has smaller range of variation in the wet removal process.

Obtained by calculating, the water volume change coefficient of expansive soil has power function relationship with matrix suction.

Permeability coefficient calculation method

Unsaturated hydraulic conductivity is one of the key parameters during non-saturated soil water movement quantitative analysis. Under isothermal conditions, specific water capacity C_w reflects the quantitative relationship between matric potential and volumetric water content. C_w is the product of the water volume variation coefficient and water weight

$$C_w = m_2^w \rho_w g \quad (10)$$

Soil water diffusivity $D(\theta)$ is a necessary parameters to study water movement in soil, it is controlled by the physical and chemical properties of soil and other factors.

$$D(\theta) = k(\theta) \frac{-\partial (u_a - u_w)}{\partial \theta} \quad (11)$$

Based on the test results of a large number of studies, it is found that $D(\theta)=ae^{b\theta}$ can better describe the relationship between moisture content and $D(\theta)$ [14]. For expansive soil, $D(\theta)$ can be determined by equation 12 obtained by fitting the test results

$$D(\theta) = 7.67 \times 10^{-9} e^{14.493\theta} \quad (12)$$

Unsaturated hydraulic conductivity of expansive soil is the product of specific water capacity and soil water diffusivity

$$k_w = C_w D(\theta) = m_2^w \rho_w g D(\theta) \quad (13)$$

Saturated hydraulic conductivity characteristics

Fig. 7 shows the stable infiltration rates of different expansive soils testing by the double-ring infiltration test.

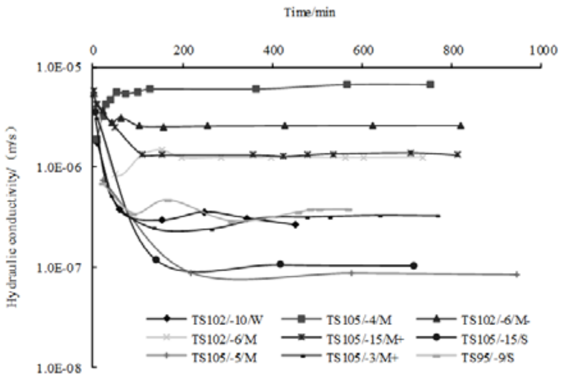

Fig. 7. Penetration time curve (‘TS102/-10/W’ represents ‘Location/ Depth/ Swelling potential’)

Infiltration of different types expansive soil is similar, it experiences constant penetration - deceleration penetration - steady penetration. Permeability is related to the swelling and fissured of expansive soils. Hydraulic conductivity decreases with the increase of the swelling potential. Fissures accelerate the water infiltration at the beginning.

Generally, Fig. 8 shows the infiltration rate of expansive soil tested by double-ring infiltration test. It requires a long time to achieve the steady infiltration for stronger swelling potential soil, which has smaller saturated permeability coefficient. k_s of medium expansive soil is the 10^{-7} m/s order of magnitude, and it is 10^{-8} m/s order of magnitude for strong expansive soil.

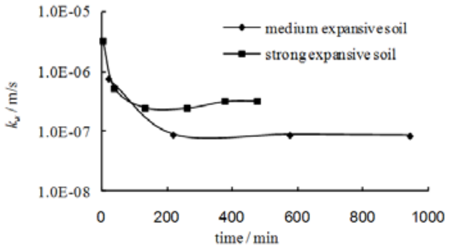

Fig. 8. Permeability coefficient change with time

Combined with the SWCC fitting formula and the water volume variation coefficient, Table 6 shows the saturated permeability coefficient of expansive soil with different dry density when saturation S_r = 1, which is calculated by the equation 13.

Table 6. Saturated permeability coefficient

Expansive soil	Dry density (g/cm^3)	saturated permeability coefficient (m/s)
Strong	1.51	1.125×10^{-8}
	1.53	7.072×10^{-9}
Medium	1.49	9.290×10^{-7}
	1.53	3.185×10^{-7}

The calculation result is consistent with the in-situ test results. Saturated permeability coefficient of expansive soil is generally 10^{-7}-10^{-9} m/s. The saturated permeability coefficient is smaller when the swelling potential is stronger. Influence of dry density is more significant, soil with greater dry density has smaller saturated permeability coefficient, and it often exhibits differences on the order of magnitude.

Unsaturated hydraulic conductivity characteristics

Fig. 9 shows the curve between unsaturated hydraulic conductivity and degree of saturation for typical expansive soil. It can be seen that the expansive soil saturated hydraulic conductivity decreases with the decrease of soil moisture content.

Fig. 10 shows the fitting curve of strong and medium expansive soils unsaturated hydraulic conductivity and matric suction, which shows a good fit power function. The empirical relationship and correlation coefficients are shown in Table 8. Unsaturated hydraulic conductivity decreases and its rate of change slow down with the increase of the matric suction. Known matric suction, unsaturated hydraulic conductivity of typical expansive soil of South-to-North Water Transfer Project can be calculated, which provides the basic parameters for the simulation of seepage for moisture in the soil.

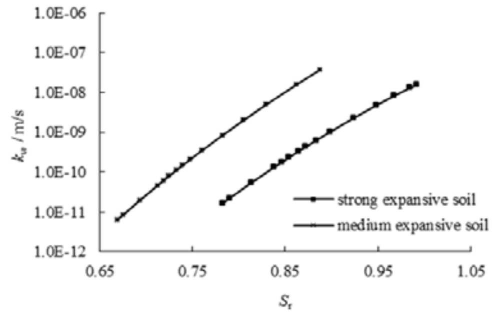

Fig. 9. Curve between unsaturated hydraulic conductivity and degree of saturation

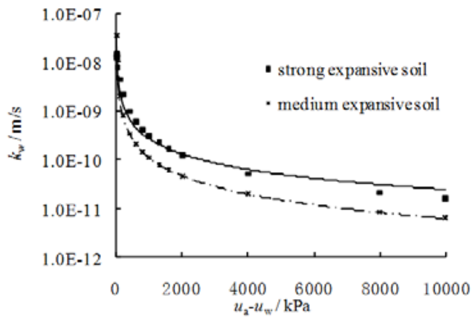

Fig. 10. Curve between unsaturated permeability coefficient and matric suction

CONCLUSION

Water storage capability of expansive soil is influenced by the physical properties, mineral composition and structure characteristics. The sample with stronger swelling contents more fine particles, it has slower dehydration rate, higher intake value and smaller storage coefficient. Soil samples with greater dry density have smaller internal pore structure, which exhibits stronger water storage capacity.

Water volume variation coefficients m_2^w of the unsaturated expansive soil decreases with the decreasing of moisture content. m_2^w of Strong expansive soil changes slowly with moisture content. The m_2^w of samples with greater dry density has smaller range of variation in the wet removal process.

Saturated permeability coefficient of expansive soil is generally 10^{-7}-10^{-9}m/s. The saturated permeability coefficient is smaller when the swelling potential is stronger and dry density is greater. Unsaturated hydraulic conductivity, which has power function relationship with matrix suction, decreases with the decrease of the moisture content, and the rate of hydraulic conductivity change decreases with the increase of matrix suction.

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