Experimental research on compression and collapsible characteristics of saline soil

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Abstract. Fine-grained saline soil is widely distributed in the western region of China. Studying compression and dissolution characteristics of salty soil can provide technical support for local engineering design. In this paper, deformation characteristics of saline soil were studied by nuclear magnetic resonance experiment, compression and dissolution test. Results showed that the compression coefficient was negatively related to the pressure and dry density. When dry density was small, e-lgp curve in the back was a straight line. As dry density growing, e-lgp curve became more and more gentle, and feature of straight line disappeared gradually. As pressure increased, compression coefficient reduced. The maximum collapsible deformation was 25kpa pressure under ρd.=1.3,1.35g/cm³ condition. As dry density added, load corresponding to the maximum amount of collapse increased. With growing of confining pressure, pore size decreased gradually. After pressure consolidation of 50, 100, 200, 300 and 500kPa, 99.85% of the pore size is distributed between 0-0.1 μm.

1. Introduction

Saline soil is a kind of special soil containing a certain amount of salt, which is widely distributed in the west of China. The area of saline soil in Xinjiang is up to 4.583×10⁷ hm² and accounts for 9.5% of the local available land area[Wang 2016; Liu2019]. In recent years, some large construction projects have been built on saline soil area. Therefore, deformation of saline soil become an urgent and critical issue.

Disaster of saline soil is closely related to basic properties, and different types of salt affect the engineering properties[Sutherland 2017; Zhang2016]. As chloride content growing, crystal salt in the soil is easy to dissolve when encountering water, which makes the soil soft, and produces collapsible deformation[Messad2016; MuhannaIsmeik2017]. With the temperature and humidity change, saline soil containing sulfate will produce larger volume expansion,and cause salt expansion deformation. In addition, the saline soil with sulfate is soaked in water, the sulfate is also dissolved, resulting in compression deformation.

Compared with other soils, deformation of saline soil under external load are more complicated. This paper takes Xinjiang saline soil as the research object, deformation of saline soil were studied by nuclear magnetic resonance, X-ray diffraction test, compression and collapse test. Research results of this article could provide reference for engineering design of saline soil area.

2. Soil samples and test methods
The saline soil selected in this paper was sampled in the Alar city, Xinjiang (China), near the Taklimakan Desert. Saline soil sample was taken at depth of 0-20 cm, which is brown yellow, and the depth of groundwater level is 1.3 m. Particle size distribution and physical property indexes is shown in Table 1, from which the soil is classified as cohesive soil.

Types and contents of soluble salts in the sample were tested. HCO₃⁻ and CO₃²⁻ were neutralized by double indicator method, Cl⁻ by silver nitrate titration, SO₄²⁻ by EDTA titration, Ca²⁺ and Mg²⁺ by EDTA complexometry, K⁺ and Na⁺ by flame photometer. Base ion content were presented in Table 2.

Fig1 was an X-ray diffractogram for the saline soil. Quantitative analysis indicated that the following mineral phases are present: quartz (20.3%), albite (14.6%), calcite (11%), muscovite (29%), kaolinite (6.6%), chlorite (16.2%), Na₂SO₄ (2.2%).

### Table 1. Physical properties of saline soil

| Liquid limit | Plastic limit | Liquid index | Particle size (mm) | Effective particle size | Particle density | Coefficient of nonuniformity | Curvature coefficient |
|--------------|---------------|--------------|--------------------|------------------------|-----------------|----------------------------|---------------------|
| W_l          | W_p           | I_p          | >0.25              | 0.25-0.075             | 0.075-0.005     | <0.005                    |                     |
| %            | /             | /            |                    |                        |                 |                            |                     |
| 31.8         | 19.8          | 12           | 6                  | 66.5                   | 27.5            | 0.0013                    | 2.65                | 14.2               | 1.6                |

### Table 2. Test results of soil salt-based ions

| Sampling depth /m | Cl⁻ | CO₃²⁻ | SO₄²⁻ | Ca²⁺ | Mg²⁺ | K⁺ | Na⁺ | Total soluble salts | PH value |
|-------------------|-----|-------|-------|------|------|----|-----|---------------------|----------|
| 0-0.1             | 3.067 | 1.2   | 1.4   | 0.45 | 6.69 | 7.615 | 20.53 |                     | 8.26     |

**Fig.1.** X-ray diffraction pattern for the saline soil

### 2.1 Consolidation compression and collapsible test

After drying at 105 °C for 24 h, the saline soil was pulverized and dried. In order to remove the plant roots in the soil, Dry saline soil sample was through a stainless steel sieve of 0.5 mm (size 35) pore size. Under 17% moisture content condition, samples were made separately with dry density of 1.3, 1.35, 1.4, 1.45, 1.5, 1.55, 1.6, 1.65 g/cm³. To ensure the uniformity, the saline cohesive soil was wrapped with a plastic bag and kept for 12 h without evaporation. There are 16 samples which were divided into 2 groups. One group is used for compression test and the other group is used for collapsible test.

Soils were filled into cylindrical specimens with the diameter of 79.8 mm and the height of 60 mm by use of a machine[8]. The soil sample is pushed by the demoulder, and the ring cutter of the cutting edge is placed on the soil sample. Then, surrounding soil of the ring was cut at the same time while the ring cutter is pressed down vertically. Until the soil sample extends out of the ring cutter, and
remaining soil is removed at both ends. Diameter and height of soil samples were 6.18cm, 2cm respectively. The soil sample photo is shown in Fig2.

![Saline soil sample](image1)

**Fig.2.** Saline soil sample

The consolidation compression and collapsibility test adopts GQZ type 16 joint high-pressure automatic consolidation instrument, and the experimental equipment is shown in Fig3. Pressure gradients of compression test were 12.5, 25, 50, 100, 200, 400, 800 and 1600kPa in sequence, a total of 8 level loads. Pressure gradients of collapsible test were 12.5, 25, 50, 100, 200, 300, 400, 600, 800kPa in sequence, a total of 9 graded loads. In order to minimize the evaporation of soil moisture during compression test, a slightly wet towel covered the oedometer.

![High pressure automatic consolidator experimental device](image2)

**Fig.3.** High pressure automatic consolidator experimental device

Compression and collapse test stability time is 0.01mm/hour, 0.005mm/hour respectively. In collapsible test, until pressure is increased to 25 kPa, soil samples are soaked in distilled water. In order to make the salt fully dissolved, distilled water is changed several times during the test.

2.2 Nuclear magnetic resonance (NMR) test

Nuclear magnetic resonance (NMR) relaxometry is becoming a promising method to evaluate the pore size distribution in soil science. The signals are generated from liquids when the sample is placed in a magnetic field and then excited with a brief pulse of radio frequency (RF) energy][Lai2016;Zhang2015]. The signal amplitude is an indication of total fluid present or related to characteristic pore abundance while the relaxation time (T2) is a measure of the rate at which the precession of hydrogen nuclei in the formation pore fluid gradually decay][Milia1998;Dunn2002;Ramia2010].

The soil sample is poured into the mould in five layers with average height of 20 mm, and layers are polished with a knife to make the layers rough. The moisture content of the sample is 23%, the dry
density \( \rho_d = 1.45 \text{g/cm}^3 \). Diameter of the specimen is 50 mm and height is 600 mm. Sample preparation process was shown in Fig4.

3 Results and discussions

3.1 Compression test results

Under one-dimensional condition, the relationship between the compression deformation and void ratio is eq. (1)

\[
e = e_0 - (1 + e_0) \frac{S}{H} \quad (1)
\]

According to initial void ratio \( e_0 \) of different dry densities, deformation amounts under various pressures, void ratio \( e \) under various loads is calculated, and the calculation results are shown in Fig5.

\[
C_c = \frac{\Delta e}{\Delta P} \quad (2)
\]
When dry density was small, characteristic of straight line was obvious at the back of e-lgp curve. With growing of dry density, however, the e-lgp curve became more and more gentle, and the feature of straight line at the back disappeared gradually. Reason was that compressibility of soil decreased with the growing of dry density, and change of void ratio (Δ e) is smaller with the growing pressure. Therefore, the characteristics of straight line at the back curve is less and less obvious. Ratio of variations in void ratio to the change of vertical load is the compression coefficient, and the equation is

\[ \alpha = \frac{e_1 - e_2}{P_2 - P_1} \]  

(3)

According to formula (3), compression coefficient of soil with different dry density under condition of lateral limit is obtained. The relationship between compression coefficient and pressure was shown in Fig6.

As shown in Fig6, compression coefficient was negatively related to load. Under same load condition, the smaller dry density, the larger compression coefficient was. Taken the compression coefficient of dry density 1.35g/cm³ as an example, compression coefficients of 0~50, 50~100, 100~200, 200~400, 400~800, 800~1600KPa are 3.32, 1.86, 0.73, 0.315, 0.1475 and 0.075 respectively. Pressure ranging from 0 to 400KPa, compression coefficient reduced rapidly, and this phenomenon was clear with the smaller the dry density. When load was more than 400kPa, reduction rate of compression coefficient slowed down. In 800~1600kPa load range, compression coefficient values with different dry density conditions were nearly equal, and compression coefficient value is between 0.07 ~ 0.1.
The essence of soil compression was pore compaction in the soil. In Fig7, there was a clear trend of decreasing. With growing of dry density, void in the soil decreased, and amount of soil compression decreased. Fig7 displayed compression deformation and fitting curve under pressure of 400kPa. Compression deformation of $\rho_d=1.65, 1.3g/cm^3$ was 1.364, 3.945mm respectively, $\rho_d=1.3$ deformation was 2.9 times of $\rho_d=1.65g/cm^3$. Relationship between compression and dry density is in good polynomial function, which can be expressed as follows:

$$S = a + b_1 \rho_d + b_2 \rho_d^2 + b_3 \rho_d^3$$

In the formula, $a$, $b_1$, $b_2$, and $b_3$ were model parameters, with values of 8.93, 31.98, -47.36 and 15.27 respectively.

3.2 Collapsible test results

After salinized soil was immersed in water, soluble salt ions was dissolved, and resulting in collapse deformation. Partial or complete dissolution of soluble salt lead to structural damage, strength reduction and rearrangement of soil particles. Amount of collapsibility was not only related to content of soluble salt, but also to permeability coefficient and compactness of soil. Fig 8 showed relationship between collapsible deformation and pressure under dry density of 1.3-1.35g/cm$^3$ condition, and Fig9 displayed collapsible deformation of dry density from 1.4 to 1.65g/cm$^3$. 

![Fig. 8. dry density 1.3−1.35g/cm$^3$ settlement](image-url)
Collapsibility of saline soil is closely related to dry density and pressure. Collapsible deformation reduced with growing of dry density, and maximum collapsible amounts corresponded to the pressure which diminished with dry density reduced. Fig8 illustrated that sample reached maximum amount of dissolution under 25kPa pressure. Pressure ranging from 25 to 200kpa, collapsible deformation decreased rapidly. As pressure was more than 400kPa, collapsible deformation has little change.

![Fig. 9. Dry density 1.4-1.65g/cm³ collapsible deformation](image)

Fig8,9 illustrated that collapsible amounts increased first and then decreased with the growing of pressure, and this phenomenon was more obvious under the smaller dry density. As dry density growing, pressure corresponding to maximum dissolution amount gradually increased. Maximum collapsible deformation of dry density 1.4, 1.45, 1.5, 1.55, 1.6 and 1.65 corresponding to pressure is 100, 100, 200, 300, 400 and 400 KPa respectively. When the load was greater than 400KPa, change of collapsible deformation was small, and collapsible amounts was basically stable.

### 3.3 Nuclear magnetic resonance test results

Nuclear magnetic resonance technology can quantitatively describe the distribution and content of soil micro pores. Pore size distribution of saline soil samples was between 0–1.6 μm before consolidation, and pore size contents of 0-0.1, 0.1-0.16, 0.16-0.25, 0.25-0.4, 0.4-0.63, 0.63-1 and 1-1.6 μm were 87.6, 5.52, 3.16, 0.8, 1.38, 1.41 and 0.04 percent, respectively. The pore size distribution before consolidation was shown in Fig10.
With growing of consolidation time and confining pressure, macro pores were gradually compressed. After 50, 100, 200, 300, 500kPa confining pressure of consolidation, content of pore diameter greater than 0.1 μm was 0.01%, 99.99% pore diameter distribution was between 0~0.1 μm.

4 Conclusions
In this paper, Alar city township saline soil from Xinjiang was taken as research object. Through nuclear magnetic resonance test, compression test and collapsibility test, the deformation properties of saline soil was studied, and main findings from this study are summarized as follows:

(a) Feature of straight line at the back of e-lgp curve was obvious under small dry density condition. With growing of dry density, characteristics of line at the back of e-lgp curve gradually disappeared. Reason was that under the same pressure change of void ratio(Δ e) was small with higher dry density. 

(b) Compressibility of saline soil decreased with dry density added. Compression coefficient reduced with increasingly of pressure, and this phenomenon was more obvious under smaller dry density. When load was greater than 800 KPa, the compression coefficient was close to 0.

(c) Results of collapsibility test showed that there was a negative correlation between dry density and the collapsible deformation. Maximum collapsible amounts was related to pressure. When dry density was 1.3~1.35g/cm3, maximum collapsible amounts was under 25KPa pressure. With added of dry density, pressure of maximum collapsible amounts was growing.

(d) Essence of soil sample compression was pore compaction. After 50, 100, 200, 300 and 500KPa confining pressure consolidation, 99.99% pore size distribution was between 0-0.1 μm.

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