



On the Swelling-Shrinkage Characteristics of Weakly Expansive Soil with Different Initial Water Contents

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Abstract. The swelling-shrinkage characteristics of expansive soils have great influence on the stability and settlement of electricity transmission towers, so that it is very important to estimate accurately the climate-dependent volume/stress change of the expansive soil foundations. In this paper, a kind of weakly expansive soil taken from a transmission tower foundation in Henan province were studied. One-dimensional swelling tests and constant volume tests were conducted to study the swelling ratio and swelling pressure of the expansive soils under different water contents which were chosen in accordance with the actual climate conditions. Results show that both swelling ratio and swelling pressure decrease linearly with the increase of initial water content, while the swelling rate increases with the decrease of water content; shrinkage ratio is linear to initial water content, while shrinkage anisotropy becomes more obvious with the increase of initial water content.

Keywords: Expansive soils · Volume change · Swelling pressure
Oedometer tests

1 Introduction

Due to the rapid urbanization progress of many areas in China, more and more transmission towers are under construction with the urgent demand of power transmission lines. Moreover, abundance of expansive soils in China [1] gives rise to the inevitability of the dependence of some towers on expansive soils. However, a transmission tower which is usually considered as a relatively tender structure is quite susceptible to the damage resulting from subsidence and stability due to the swelling-shrinkage characteristics of expansive soils. So it is very important for us to understand well how the foundation soils behave. Many researches show that the volume change behavior of an expansive soil is related to its initial state including initial water content, dry density, surcharge loads etc. [2]. During the operation period of a transmission tower, the dry density and surcharge loads of foundation soil remain constant. So initial water content, which is mainly effected by the climate and season, plays a dominant role in the settlement and heave of expansive soil foundation.

Many researchers have studied the problem of swelling and shrinkage of clays under different initial water contents. Some researchers concludes that the swelling-shrinkage

characteristics are linear to the initial water contents. Zou et al. [3] found that the swelling ratio of expansive soils decreases linearly with the increase of water contents under the same surcharge loads. Lu et al. [4] found that the swelling pressure of Nanjing weakly expansive soils was inversely linear to initial water contents. On the other side, Ding et al. [5] found swelling pressure was negatively but not linearly correlated with the initial water contents. Yang et al. [6] used an exponential function to describe the relationship between swelling pressure and initial water contents. According to Kong et al. [7], the plastic limit could be used as a critical point which divided the relationship curves of swelling pressure and shrinkage ratio with initial water contents into two parts. Although there are so many studies on the swelling or shrinkage characteristics of expansive soils, systematic research on deformation should be further conducted.

In this paper, both swelling and shrinkage characteristics of expensive soil under different water contents were observed for a transmission tower foundation. An accurate evaluation of settlement/heave and pressure change for expensive soil foundations was made according to test results, which could be good reference to the design and remedy of transmission tower foundations in the expensive soil area.

2 Material and Specimens

2.1 Experimental Material

The experimental material used in this study was a type of weakly expansive soil obtained from a transmission tower foundation in Nanyang, China. According to the geological investigation report, the soil is alluvial and diluvial cohesive soil formed in Quaternary pleistocene, colored in yellowish-brown, rigid-plastic, containing some Fe, Mn oxide nodules. The basic physical properties of the natural soil were determined with the test methods in accordance with SL237 (1999), and the results are listed in Table 1. The particle size distribution curve obtained by hydrometer analysis is shown in Fig. 1, which presents the clay size fraction was about 33.26%. The mineral composition was analyzed by X-ray diffraction technique (D/max-rB) and the result is shown in Table 2.

Table 1. Basic physical properties of the natural soil.

Density (g·cm ⁻³)	Dry density (g·cm ⁻³)	Void ratio	Specific gravity	Liquid limit (%)	Plastic limit (%)	Free swelling ratio (%)
2.07	1.69	0.621	2.74	37.70	18.20	59

Table 2. Mineral composition of the soil.

Mineral	Quartz	Albite	Microcline	Kaolinite	Illite	Illite-smectite	Mixed-layer ratio
Percentage (%)	50	10	6	1.36	0.68	31.96	10

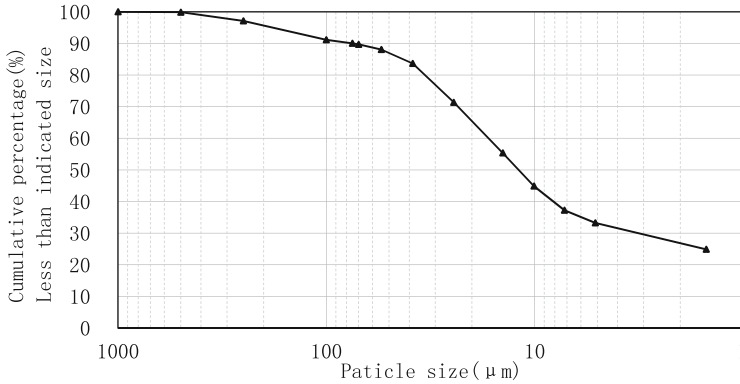


Fig. 1. Particle size distribution curve

2.2 Specimen Preparation

The specimens were prepared for the tests to obtain the vertical swelling ratio, swelling pressure and free shrinkage of the expansive soil. All the specimens were compacted into the same density of 1.7 g/cm^3 with different water contents ranging from 14% to 23%, which were chosen in accordance with the actual climate conditions [8]. At first, the naturally dried soil was grinded into powder and then passed through a 0.05 mm sieve. In order to control the initial water content of each specimen, the amount of water added was calculated according to the corresponding target water content and naturally dried water content (7.3%). The soil powder was sufficiently mixed with water, and then was sealed and stored in a plastic bag for 24 h to ensure a homogeneous water distribution. Finally the desired amount of wet soil was compacted into a specimen ring (61.8 mm in diameter and 20 mm in height) in three layers with a 2.5 kg hammer falling from a height of 30 cm.

3 Testing Methods

3.1 One-Dimensional Swelling Test

The specimens with different initial water contents were placed in oedometers under a seating load of 1 kPa. Then they were completely immersed in water and allowed to swell freely. The readings of vertical swelling deformation were recorded regularly until the deformation within 6 h did not exceed 0.01 mm. The swelling ratio is defined as the ratio of the maximum heave in specimen upon wetting to the specimen's initial height. The whole swelling process took about 3 days.

To simulate the swelling characteristics of the expansive soil under light load, the swelling ratio under a surcharge of 50 kPa was tested. The process was centrally similar to that of the free swelling test, except two differences: (a) the specimens were compressed under a 50 kPa pressure before being saturated, (b) after reaching the maximum swelling deformation, the specimens were unloaded to the seating load of 1 kPa. In this

situation, the specimens would continue to swell since the load decreased. The final swelling deformation were recorded and compared with the free swelling ratio.

3.2 Constant Volume Oedometer Test

In this test, the specimens were sustained at the initial void ratio by continuously adding balance loads on the consolidation frame. The largest vertical deformations of specimens were controlled to be less than 0.01 mm. The balance loads were applied by gradually adding sands into a bucket hanged on the loading arm until no deformation was observed. Then the swelling pressure was calculated as the load required to retain zero swell divided by the specimen area.

3.3 Shrinkage Tests

The shrinkage tests of specimens with different initial water contents were performed in the free shrinkage apparatus, where the soil specimens were placed on porous plates. Then specimens were slowly dried in air at a constant temperature of 20 °C. The weight of each specimen was measured to calculate gravity water content changes during the desiccation process; while vertical and horizontal shrinkage deformation were measured by dial gauge and slide caliper respectively. The experiment was stopped when the dimensions of specimens remained constant, which took 3–4 days. Geometry factor (γ_s) [9] was analyzed to evaluate anisotropy of soils shrinkage deformation. It is a factor related to the volume shrinkage and height shrinkage:

$$\gamma_s = \frac{\ln(V_s/V_0)}{\ln(Z_s/Z_0)} \quad (1)$$

Where, V_s is the final volume of the specimen after being dried, V_0 is the initial volume of specimen; Z_s is the final height of specimen after being dried, Z_0 is the initial height of specimen; $\gamma_s = 3$: isotropic shrinkage; $1 < \gamma_s < 3$: subsidence dominates cracking; and $\gamma_s > 3$: cracking dominates subsidence.

4 Results and Discussion

4.1 Swelling Ratio

Figure 2 shows the free swelling ratio versus time of compacted specimens. Figure 3 shows swelling ratio versus time under 50 kPa, here the negative value indicates that specimens are compressed under the load before swelling. The swelling ratio is calculated by the instant specimen height divided by the initial height (20 mm). The corresponding swelling ratio versus initial water contents is shown in Fig. 4.

In Figs. 2 and 3, the curves of swelling ratio can be divided into three stages: fast swelling stage (0–3 h), slow swelling stage (3–6 h) and steady stage (more than 6 h). In the fast swelling stage, water infiltrates into specimens and reacts with clay particles

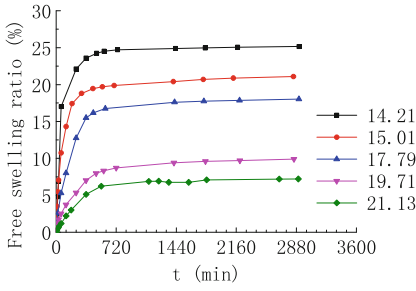


Fig. 2. Free swelling ratio versus time

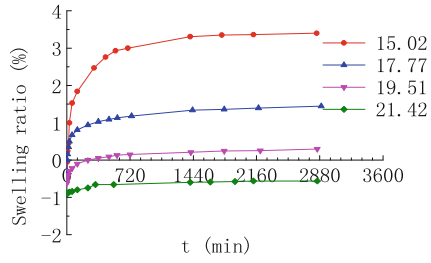


Fig. 3. Swelling ratio versus time under 50 kPa

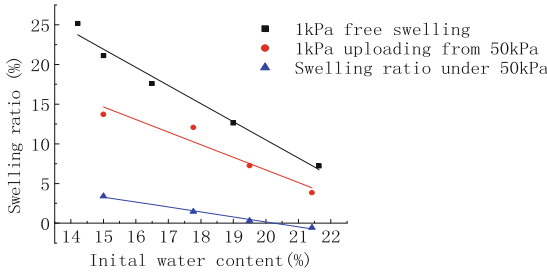


Fig. 4. Swelling ratio versus initial water contents

which increases the thickness of moisture film around soil particle. Specimens swell at a high speed, and the swelling ratio can account for 80% of the total swelling ratio. In slow swelling stage, the swelling speed slows down and the specimens only absorb little water. The swelling is deduced by the reorganization of soils' internal structure. The steady stage lasts for a relatively long time until reaching a steady state, but the swelling during this stage is small.

These three figures also illustrate that with the decrease of initial water contents, specimens swell faster and end at a higher swelling ratio. Because a lower water content leads to a higher suction, and the existence of higher suction helps soils specimens to absorb water faster when they are immersed in water. In addition, aggregates show greater swelling potential under higher initial suction during the reaction between water and illite-smectite mixed layer [10].

The middle line in Fig. 4 represent swelling ratio under 1 kPa unloading from 50 kPa which indicates that loads limit specimens from swelling, while unloading could allow specimens to continue swelling. However the final swelling ratio is less than the free swelling ratio because internal structure reorganization makes soil particles arranged more closely. This can also be understood as that the former loads 50 kPa has done negative work during the process of expansion, which consumes the swelling potential of specimens.

4.2 Swelling Pressure

Swelling pressure refers to the pressure that needed to keep the volume of expansive soils at a constant value during water infiltration. Figure 5 shows the evolution curves of swelling pressure corresponding to different initial water contents. The trend of the curves is similar to that of swelling ratio, which can be also divided into three stages. However, by comparing Fig. 5 with Figs. 2 and 3, it can be found that swelling pressure takes less time than swelling ratio to reach the steady state, probably lies in the difference of physical mechanism behind between swelling pressure and swelling ratio. Swelling ratio serves as a cumulative quantity. The swelling ratio reaches its peak level (namely steady state) after the specimen arriving at its full hydration, while the swelling pressure does not. This can be better understood by investigating the hydration process of the specimen. As shown in Fig. 6, during an early period of hydration, the specimen was partially hydrated due to the low permeability of expansive soils, where the lower part was fully hydrated but the upper part remained almost dry. As a result, the stiffness of the upper part will be much larger than that of the hydrated lower part, so that the upper part and the steel components above can be collectively treated as an effective rigid piston that transfers the axial load induced from the hydrated lower part to the consolidation frame, just as the swelling test were conducted solely on the lower part that acts as a separated specimen. In this way, the obtained swelling pressure during that period will be quite close to the maximum swelling pressure of the whole specimen and can be fairly approximated as the peak (steady) swelling pressure of it.

Figure 7 illustrates that swelling pressure, as with swelling ratio, also decreases linearly with the increase of initial water contents. This can be explained by the swelling mechanism of expansive soils. The swelling behavior of expansive soils is due to the forming of moisture film around the clay particles. For a certain soil, the maximum thickness of moisture film is fixed. However adding some water during specimen preparation can partially thicken the moisture film around clay particles, resulting in the decrease of swelling ability. So specimens compacted with a higher initial water contents would have less swelling potential.

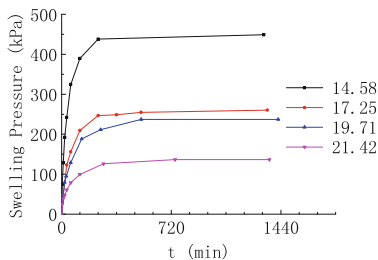


Fig. 5. Swelling pressure versus time

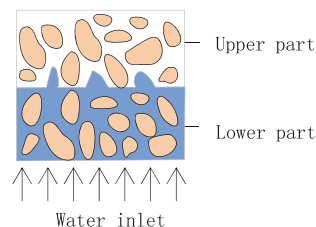


Fig. 6. Hydration process of specimen

4.3 Shrinkage Characteristics

Figure 8 illustrates that the shrinkage process due to drying can be divided into two stages. Firstly, shrinkage ratio is proportional to the variation of water contents. In this stage, the matric suction in soil specimen increases with the evaporation of pore water.

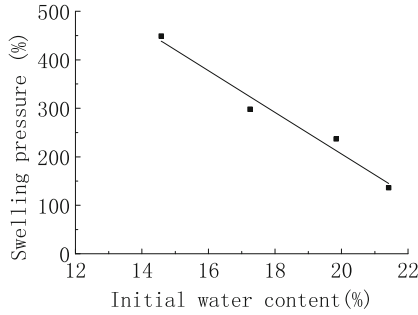


Fig. 7. Swelling pressure versus water content

Under the action of matric, the particles of soil get closer to each other gradually, which contribute to the volume shrinkage of specimens. The slopes of these curves under different water contents are nearly the same. That is to say, initial water contents have little influence on shrinkage index. The second stage is a drying process with slight volume change at the water contents less than the shrinkage limit (about 9%). In this process, although matric suction continues to increase, its action area is decreased and soils fabric has become stable. The force deduced by the matric suction has little effect on the position of soils particles. So the specimens do not show any shrinkage further. It is also worth mentioning that specimens did not crack during the whole drying process since they were dried in a relatively slow speed and the final water content was not low enough to induce cracking.

Figure 9 shows that the final horizontal shrinkage ratio increase linearly with water contents. The obtained relationship is consistent with the past observations presented by Ref. [11]. The geometry factors calculated with formula (1) are shown in Table 3. The factors of the specimens with different water contents are all greater than 3.0, which indicates that the volume change are mainly caused by horizontal shrinkage. Furthermore the anisotropy becomes greater with the increase of water contents.

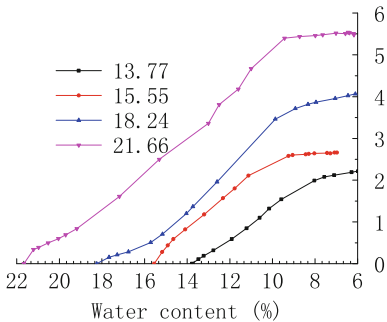


Fig. 8. Shrinkage ratio versus water content

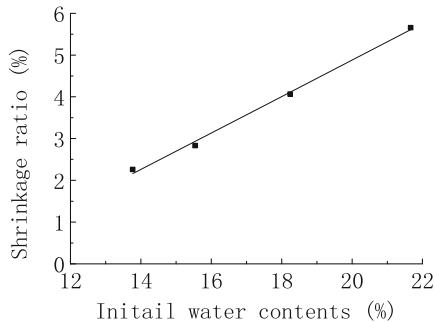


Fig. 9. Shrinkage ratio versus initial water content

Table 3. Relationships between geometry factor and initial water contents.

Water content (%)	13.77	15.55	18.67	21.66
Geometry factor	3.44	3.47	3.70	3.75

5 Conclusions

From these laboratory tests, the effect of initial water content on the swelling-shrinkage characteristics of compacted expansive soils is investigated. Following conclusions can be drawn as follows:

- (1) Swelling properties including swelling ratio and swelling pressure act inversely with the initial water content. Specimens under lower water contents absorb more water and show stronger swelling potential during stabilization process.
- (2) The swelling pressure or swelling ratio versus time can be divided into three stages: fast swell stage, slow swell stage and steady stage (more than 6 h).
- (3) Vertical shrinkage ratio increases linearly with the initial water content. However the water contents have little influence on the shrinkage index.
- (4) Geometry factors of the specimens with different water contents are all greater than 3.0, which indicates horizontal shrinkage contributes to the volume shrinkage slightly more predominantly than vertical shrinkage. The geometry factor becomes greater with the increase of initial water content, which indicates that the shrinkage anisotropy becomes more evident.

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