Research on the swelling behavior of unsaturated expansive soil in China Ankang area

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ABSTRACT

Based on a series of confined immersion tests on China Ankang reconstructed expansive soils conducted on the conventional laboratory oedometer, we have analyzed the characteristics of swelling potential and swelling pressure and described the relationship among swelling percent, water content and load in a spatial surface. First it was found a ridge-line divides the expansion and compression domains on the spatial surface. Second, the swelling pressure can be related to the initial dry density with a linear relationship in our experiments. Moreover a power function between the swelling pressure and the swelling percent was proposed. In addition the experiments also verified a unique relationship between the swelling pressure and the swelling percent, and proposed a reasonable expression for this relationship.

Keywords: expansive soils; swelling potential; swelling pressure; partial saturation.

1 INTRODUCTION

In the area around the Hanjiang River to the south of the China Qinling Mountains, there is a wide distribution of the expansive soil. This kind of expansive soil is characterized by high plasticity and ultra-consolidation and multi-fractures, affecting the stabilities of railway subgrade and buildings (Liao 1990; Rongjiu 1995). In the 1970s and even earlier, many authors attempted to understand soil microstructures in order to explain various experimental phenomena and engineering problems such as strength, sensitivity, compression and collapsibility.

In the past years, we have conducted a series of experiments to study the expansive behavior on clay from Ankang area in Shaanxi Province of China (Li *et al*. 2005; Li 2006; Li *et al*. 2006). In this paper, these experimental results are further re-examined. The Ankang soil has a specific gravity of 2.71 with a liquid limit of 51.0%, a plastic limit of 26.5 % and a plasticity index of 24.5%. The initial water content is 16.1%. The soil with particle size less than 0.02 mm accounts for 45% with an optimum water content of 23.8% and a maximum dry density of 1.57 g/cm^3. It can be classified into Class I expansive soil (Liao 1990). The soil sample was first sieved through 2-mm mesh and prepared to the target water content and measured with the final water content after standing for at least 48 hours. The soil specimens were prepared finally for oedometer tests by a compression method with a diameter of 80 mm and a height of 20 mm.

2 SWELLING POTENTIAL

The typical water-swelling curve is in "s-shape" (Sridharan and Gurtug 2004; Rao *et al*. 2006). Fig. 1 shows the swelling curve of Ankang expansive soil upon water immersion after stabilization of compression under different pressures tested by a conventional oedometer. Full saturation would be designed at the end of immersion. It is shown that at lower pressures less than 200 kPa, the swelling curve is in "s-shape", and the soil swells upon water immersion. Under the pressure of 200 kPa, however, the specimen undergoes a process of compression first, then expansion, and finally compression. Taking into account the swelling pressure is 190 kPa for these specimens having the same initial water content and the same dry density(Li *et al*. 2006), it is reasonable that the soil behavior upon water immersion is finally slightly compressed rather than expanded.

Unlike the experiment made by Alonso *et al* (1995), the shrinkage phenomenon was not observed in our water immersion, which may be due to a shorter immersion time and an insufficient saturation of the specimens. This was confirmed by measuring the saturation of the specimens after experiment. However, in another experiment in which the water content was controlled in stages after stabilization of compression under different pressures, a significant shrinkage was observed as shown in Fig. 2. It is shown at pressure less than 100 kPa, the specimens swell as the water content increases. However, at a pressure of 100 kPa and above, the specimen undergoes expansion and then compression as the water content continuously increases. We believed that the swelling or compression behavior of expansive soil is up to the combination of water content and the pressure.

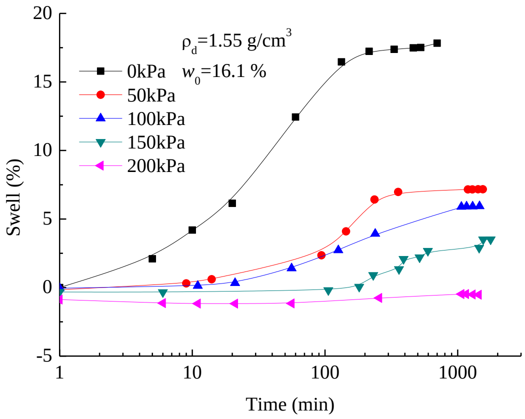


Fig. 1. Swelling curve of expansive specimens under various loads versus time in water immersion [After Li (2006)]

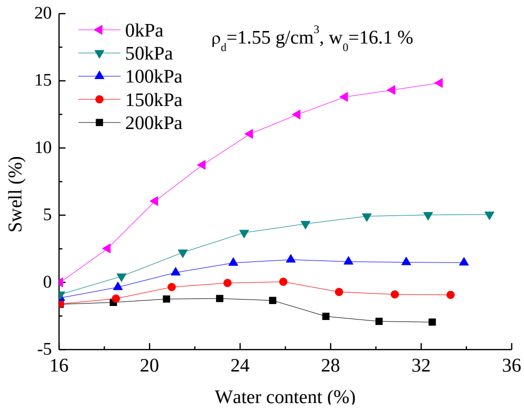


Fig. 2. Swelling curve of specimens under various loads versus water contents in staged water immersion [After Li (2006)]

In our water immersion experiment, the final water content was measured to calculate the degree of saturation by taking a water density of 1.0 g/cm^3. It was found that the final degrees of saturation of all the specimens were less than 1.0, indicating that the specimen didn't attain full saturation. For the specimens in the staged water immersion, the degrees of saturation of the specimens were all larger than 1.0 except for the specimen undergoing free expansion without pressure, specifically, 1.13 for 50 kPa pressure, 1.18 for 100 kPa pressure, 1.17 for 150 kPa pressure and 1.09 for 200 kPa pressure. This phenomenon that the degree of saturation exceeding 1.0 can be explained by the fact that the crystal expansion occurs, and the adsorbed or attach water is crystallized and should be regarded as solid rather than liquid. Thus the adsorbed or attach water has a density greater than the density of liquid water. This phenomenon was also observed in by Villar and Lloret (2008).

3 MODELLING OF EXPANSION BEHAVIOR

If we plot the experimental results of the staged water immersion in a three-dimensional space of swelling percent, the water content and overlaying pressure, we will obtain a spatial surface as shown in Fig. 3. An important feature of this spatial surface is the presence of a ridge line that represents the maximum expansion of the soil at a certain pressure, as the dividing line between expansion and compression. The projection of this ridge line on the plane of vertical pressure and matric suction is the LC yield trajectory in the Alonso's Barcelona Basic Model (BBM), i.e. the soil expansion-contraction boundary (Alonso *et al*., 1990).

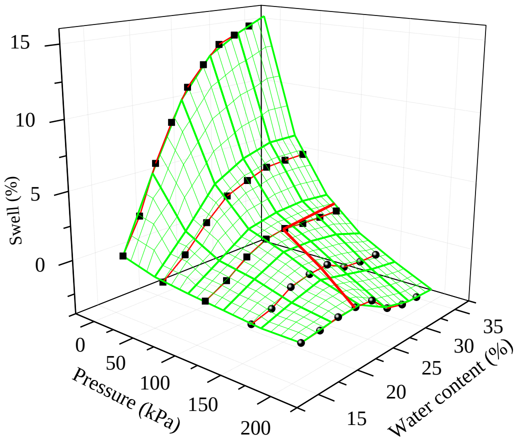
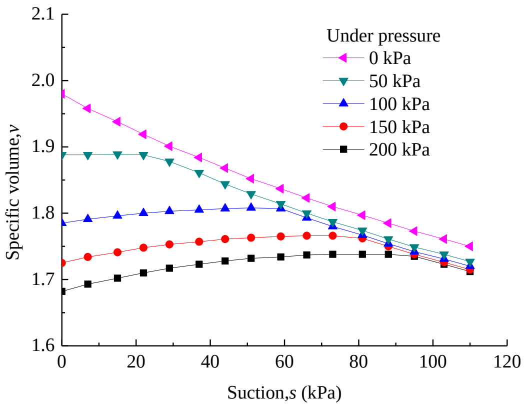


Fig. 3. Spatial surface of soil in water staged immersion

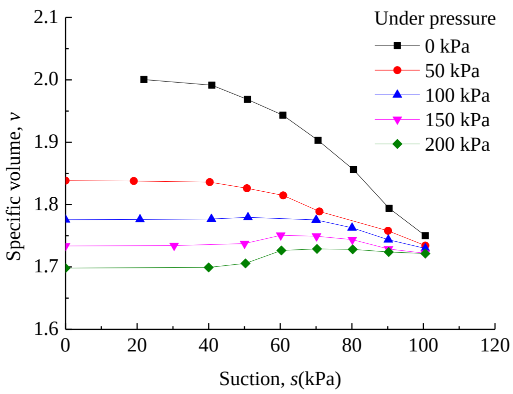
Based on the theory in Alonso's BBM model, the ridge line in Fig. 3 is bounded between elastic and plastic deformation domains. We examined the existence of LC faces in the BBM model based on the other authors' experimental data in literatures(Li *et al*. 2014), and concluded that there are two initial yield trajectories of LC in the plane due to the hydraulic hysteresis properties of unsaturated soils, and two subsequent yielding faces since yielding is the beginning of plastic deformation. These two different LC initial yield trajectories mean that the elastic domains are different for different water variation paths. In Fig. 3 only a water-absorbing spatial surface is plotted. The other surface should be the water-dehydrated surface located below this surface, and these two surfaces have the similar shapes.

In order to further verify the applicability of the BBM model to Ankang expansive soil, we tried to basically model the experimental results. Since we did not measured suction in these odometer tests, we took the suction measurement result on Ankang expansive soil with a dry density of 1.55 g/cm^3 identical to these specimens in oedometer tests (Li *et al*. 2008). We could just roughly obtain a soil-water characteristic curve (SWCC) by use of the VG model by replacing the volumetric water content with the mass water content

(Van Genuchten 1980). There are several other parameters in BBM that can not be accurately determined in this paper. By continuously making trial calculation, we roughly determined the model parameters as follows: atmospheric pressure value p_{at} = 100 kPa, $\lambda(0)$ = 0.16, κ = 0.01, r = 0.43, β = 12 kPa^{-1}, reference stress p^c = 2 kPa, κ_s = 0.32, and p_0^* = 30 kPa. The above assignation may not be optimum but just for demonstration of the applicability of BBM to Ankang expansive soil. For the sake of simplicity, it is assumed that the suction does not change during compression before water immersion.



(a)Modelling results



(b)Experimental results

Fig. 4. Comparison of simulation and experimental data

As shown in Fig. 4, there are some deviations between the modeling results Fig. 4(a) and the experimental results Fig. 4(b), especially in the case of the pressure of 50 kPa. Since we take a low saturated yielding strength of 30 kPa (less than the minimum stress shown in Fig. 2), the modelling results shows a slight collapsibility in the case of a pressure of 50 kPa. However, if we take a higher saturated yielding strength such as 90 kPa, the case with a pressure of 50 kPa will be fully covered into the elastic domain on the LC plane. We also found that if the elastic stiffness parameter was related to the average net stress, the calculation results can be better, but this relationship will destroy the path independence of the BBM in the elastic domain. Experiments also showed that, the elastic stiffness parameter is not constant during the suction reduction and could be related to the pre-consolidation pressure (Thom *et al.* 2007). Moreover, the modelling results do not reflect the gentle flat part at the curve end upon the specimens attaining full saturation, meaning the BBM model cannot simulate the secondary consolidation (Gens and Alonso 1992).

4 SWELLING PRESSSURE

As another important indicator of expansive soil, the swelling pressure is usually determined by three methods. Sridharan *et al*. (1986) concluded that the swelling pressure by the consolidation test took the upper limit, the swelling pressure by the equilibrium void ratio method under different consolidation loads took the lower limit, and the swelling pressure by constant volume method took an intermediate value.

Experiments shows that the swelling pressure of the Ankang expansive soil with the same dry density measured by these three methods are close to each other (Li *et al*. 2005), and conform to the relationship proposed by Sridharan *et al*. (1986). Fredlund and Rahardjo (1993) believed that an exponential relationship existed between the swelling pressure and the initial dry density. In this our research covering an initial dry density range of 1.4 g/cm^3 to 1.6 g/cm^3, it is more reasonable to use a linear relationship to relate the swelling pressure and initial dry density.

5 RELATION OF SWELLING PRESSURE AND SWLLING PERCENT

The swelling pressure and swelling percent are often related to dry density or initial water content, or a combine of both (Xu 1997; Li 2006; Xie *et al.* 2007). Zhang *et al.* (2005) believed that the energy (or compaction effort) absorbed in the preparation of the specimen determined its mechanical characteristics. We believe that for a compacted soil without hydraulic hysteresis, a unique relationship can be established between the absorbed energy and a combination of dry density and water content. Since the swelling pressure and swelling percent can also be regarded as the indicators of the amount of energy absorbed, there should be a unique relationship between them. Several specimens with an initial water content of 16.1% were made with various dry densities of 1.40 g/cm^3, 1.45 g/cm^3, 1.50 g/cm^3, 1.55 g/cm^3 and 1.60 g/cm^3, and were then tested as shown in Fig. 5. The relationship can be expressed by a power function:

$$P = 0.0095\delta^{3.4726}\ (\text{kPa}) \tag{1}$$

where δ is the swelling percent (%), P is the swelling pressure (kPa), and coefficient of determination R^2 = 0.9588. A unique relationship confirms the conclusion by Zhang *et al.* (2005).

Sridharan and Gurtug (2004) suggested a straight line across the origin for the swelling pressure less than 1000 kPa. Since Eq. (1) is a power function, it will come across the origin naturally, i.e. the swelling pressure is taking zero value when the swelling percent is zero.

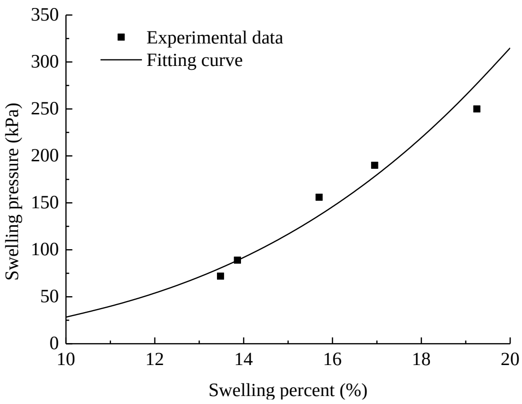


Fig. 5. Relationship between swelling pressure and swelling percent

6 CONCLUSION

Through re-analysis of our oedometer experiments on China Ankang expansive soil, the following conclusions are drawn:

1) The expansion of unsaturated expansive soil is determined by its macro- and microstructures, but affected by the external load. The swelling curve has an “s-shape” upon water immersion under low pressure. Under large pressure, the soil will be compressed upon water. This phenomenon denotes a ridge line in a three-dimensional space of swelling percent, the water content and overlaying pressure, corresponding to the LC yielding trajectory in the BBM model. Such a finding was obtained with the experimental data, so the expansive properties of Ankang soil can be simulated with BBM.

2) A unique relationship can be obtained between swelling pressure and swelling percent since they are indicators of the energy (or compaction effort) absorbed by the specimen, and a power function is suitable for Ankang expansive soil. The swelling pressure can be related to the initial dry density with a linear expression with experimental range.

3) The swelling pressure can be related to the initial dry density with a linear relationship in our experiments.

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