Swell and shrink tests in modified oedometer apparatuses

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ABSTRACT: The paper deals with the constraints on geotechnical structures due to swelling and shrinking of cohesive soils. Two new oedometer apparatuses have been developed to investigate the volume change behaviour of partially saturated fine-grained soil. With the oedometer apparatus A it is possible to measure the swelling pressure both in the radial and the axial direction. The radial pressure is obtained via strain gauges mounted on the outer surface of the oedometer ring. Suction is measured by a tensiometer in the mid-height of the soil sample. The oedometer apparatus B is similar to apparatus A. However, the radial pressure can be independently controlled, thus corresponding to triaxial loading conditions. The oedometer ring is fitted inside with a membrane. Systematic investigations on the swelling behaviour of kaolin clay are carried out with these devices covering a wide range of values for moisture content, initial void ratio and temperature by measuring the variation of swelling pressure in dependence of vertical strain. Tests under constant volume conditions yield the initial value of swelling pressure. Increase of vertical strain due to swelling leads to a reduction of swelling pressure. The test carried out show that the attainable initial swelling pressure is significantly lower for higher values of the void ratio. The same tendency is observed for fixed values of initial void ratio and increasing values of initial degree of saturation. Shrink tests are performed with oedometer B by investigating the shrinking potential in dependency on the initial swelling pressure at various levels of void ratio and degree of saturation.

1 INTRODUCTION

The investigation presented herein has been carried out within the frame of a project funded by the German Science Foundation entitled “Mechanics of unsaturated soils”. The aim of the investigation is the measurement of the volume and pressure changes of swelling cohesive soils in dependence of the moisture content and the temperature. The soil material behaviour with respect to swelling and shrinking is essential to the design of geotechnical structures, e.g. earth retaining walls. Various research papers deal with swell-test apparatuses for swelling clay and rock, Komine & Ogata (1999), Steiger (1993), Pregl et al. (1980). They all deal with triaxial equipment. One convenient way to investigate the swelling behaviour of clay or swelling rock is however the oedometer test. Investigations on swelling and shrinking at any state of stress or deformation have been carried out in two special oedometer devices. With these apparatuses it is possible to measure both the axial and the radial pressure. Furthermore, in the oedometer B it is also possible to fully control pressures and deformations in the axial and the radial direction.

In the following, the constitutive relation proposed for modelling the volume change behaviour is formulated, the developed oedometer apparatuses are described and representative test results are presented.

2 CONSTITUTIVE RELATIONS

Constitutive equations for the description of the volume change behaviour of fine-grained soils due to moisture changes have been suggested by several authors, e.g. Gens & Alonso (1992), Grob (1972). The latter reference is widely used in practice and assumes a logarithmic variation of swelling strain with swelling stress under oedometric conditions.

Based on tests results from the literature Dobrowolsky (2003) proposed in an initial study a parabolic variation of the swelling strain vs. stress relationship. However, subsequent tests showed that this distribution is not appropriate for fine-grained soils and particular testing method followed, e.g. watering under loading and loading after watering yield different curves, Justo et al. (1984). A modification is proposed here for the stress-strain
curve as depicted in Figure 1 in a semi logarithmic scale. This curve corresponds to oedometer tests with deviatoric initial stress conditions. In that graph the swell pressure vs. strain relationship of Grob (1972) would be a straight line and is in contrast to the observed SW paths in soft soils.

Figure 1. Oedometric volume change behaviour due to swelling and shrinking.

The nonlinear path SW in Figure 1 describes the correlation between the swelling strain $\varepsilon_{SW}^z$ and the vertical stress $\sigma_z$. The intersection of the curve with the $\sigma_z$ – axis is denoted by $\sigma_{max}$ and indicates the maximum swelling pressure that can be exerted by the soil sample in dependence of the degree of saturation and the void ratio.

In the oedometer test the sample is first loaded under a vertical stress $\sigma_z,0$ to eliminate imperfections due to sample seating. It is assumed that the soil behaviour is independent of the magnitude of this stress. Under triaxial loading conditions this assumption is replaced by the assumption that the swelling curve is independent of the first invariant of the initial stress tensor $I_{\sigma,0}$.

With respect to shrinkage due to dewatering, it can be stated that this effect will occur at any point on the path SW, and subsequent water absorption will be described by the path SN, as plotted in Figure 1. The shrinkage deformation $\Delta \varepsilon_{SN}^z$ takes place only after the swelling pressure has been eliminated due to the dewatering. It is thereby assumed that the swell coefficient, defined as the slope of the $\varepsilon_{SN}^z$ - $\ln \sigma_z$ curve, is infinite-valued, i.e. the path SN is horizontal. The amount of shrinking deformation may be larger than the swelling deformation accumulated up to this level.

The deformation behaviour due to swelling is generally described here by the following relationship in terms of the first stress and strain invariants:

$$I_{\sigma}^{SW} = I_{\sigma,0}^{SW}(e_0, S_{z,0}, S_{\varepsilon,0}, T) \cdot f_1(I_{\sigma}), I_{\sigma,0} \leq I_{\sigma} \leq I_{\sigma,\max}$$  \hspace{1cm} (1a)

$$I_{\sigma}^{SW} = 0, \quad I_{\sigma} > I_{\sigma,\max}$$  \hspace{1cm} (1b)

where $I_{\sigma,\max}^{SW}$ is the maximum swelling pressure under constant volume conditions, $I_{\sigma}^{SW}$ is the swelling strain, $I_{\sigma}$ is the actual stress, $e_0$ is the initial void ratio, $S_{z,0}$ is the degree of saturation at the begin of the swelling stage, and $S_{\varepsilon,0}$ the respective value at the stress level $I_{\sigma,\max}^{SW}$. $T$ is the temperature.

Analogously, the deformation due to shrinking can be written as:

$$I_{\sigma}^{SN} = f_2(I_{\sigma}, e_0, S_{z,0}, S_{\varepsilon,0}, T)$$  \hspace{1cm} (2)

Special oedometer tests have been conducted to determine these constitutive parameters. They are described next.

3 TEST MATERIAL

The material chosen for the tests is a kaolinite (fine-grained clay IBECO-Uniton) which is described in detail by Dobrowolsky & Becker (2002). The clay mineral fractions according to manufacturer specifications as well as the relevant soil properties are listed in Table 1.

Table 1. Clay fractions and soil properties.

<table>
<thead>
<tr>
<th>Clay minerals</th>
<th>Kaolinite &gt; 40%</th>
<th>Illite &lt; 20%</th>
<th>Smectite &lt; 5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid limit</td>
<td>$w_L = 54.0%$</td>
<td>$w_P = 21.3%$</td>
<td>$w_A = 73.5%$</td>
</tr>
<tr>
<td>Plastic limit</td>
<td>$w_P = 21.3%$</td>
<td>$w_A = 73.5%$</td>
<td>$w_A = 73.5%$</td>
</tr>
<tr>
<td>Water absorption value after 4 h</td>
<td>$w_A = 73.5%$</td>
<td>$w_A = 73.5%$</td>
<td>$w_A = 73.5%$</td>
</tr>
</tbody>
</table>

The soil – water characteristic curve (SWCC) of the kaolinite is needed for determining the correlation between the swell pressures and the suction. The test results on the dry side (low values of degree of saturation) are determined by means of the vacuum drying method. The test results on the wet side (high values of degree of saturation) are determined by stepwise saturation in an oedometer apparatus at a constant volume by means of a T5 tensiometer. The inherent hysteresis of the SWCC is neglected here since in the relevant saturation range this effect is of minor importance. Typical results are summarized in Figure 2 together with an approximation of the pF vs. $S_{\varepsilon}$ curve, where

$$pF = \log_{(1cm)} \left( \frac{\psi}{1cm} \right)$$  \hspace{1cm} (3)

and $\psi$ denoting the soil water suction in cm water column.

The suction $\psi$ for the watering branch of the SWCC (increasing degree of saturation) is approximated by means of the following equation in dependence of the void ratio $e$ and the volumetric water content $0$ [cm$^3$/cm$^3$]:

$$\psi = 1000 \cdot \left[ \frac{0.09 \cdot \ln(e - 0.46) + 0.54}{\theta} \right]^{4.4} - 1$$  \hspace{1cm} (4)
This equation is valid for $0 \leq \theta \leq 0.465$ and for $0.68 \leq e \leq 0.89$.

4 TEST EQUIPMENT

Two new oedometric apparatuses have been developed to determine the parameters in the constitutive equations 1 and 2. The equipment allows the measurement of the maximum swell pressure $T^{SW}_{\text{max}}$. Furthermore, both the axial and the radial swell pressure components can be determined to detect possible anisotropy in the soil behaviour. Two different devices have been used as described next.

4.1 Oedometer A with axial and radial pressure measurement

The oedometer ring with an inner diameter of 100 mm and a height of 75 mm is designed for specimens with a thickness of up to 50 mm. It is provided with eight strain gauges on the outer surface with which the radial deformations of the ring are measured, cf. Figure 3. The radial strain of the ring is less than 0.008 % and the ring can therefore be assumed rigid.

A T5 – tensiometer placed in the middle of the specimen is used for the measurement of the soil – water suction. This tensiometer is designed for a measurement range of up to $pF = 3$ with an accuracy of 1 cm water column. For the soil material used, depending on its density, the suction can be accurately measured starting at a degree of saturation of approximately 87%. A photograph of the equipment during operation is given in Figure 4.

4.2 Oedometer B with both, adjustable axial and radial pressure and deformation control

The structure of Oedometer B is identical to Oedometer A except for the oedometer ring, cf. Figure 5. A rubber membrane is mounted on the inner side of the oedometer allowing the control and measurement of radial pressure and deformation. The space between membrane and ring is filled with a fluid. Thus, the Oedometer B works similar to a triaxial apparatus. In shrink tests the volume of the fluid behind the membrane can be adjusted to avoid gaps between the ring and the specimen.
5 TEST PROCEDURE

The aim of the investigation is the determination of the parameters in equations 1 and 2 and the assessment of their importance in the modelling of the soil behaviour. Three different types of test series have been carried out in the oedometers A and B and also in a standard oedometer.

The dry kaolinite material is first mixed in a mixer at specified water content. Based on measurements it is assumed that swelling is completed after 48 hours. Subsequent the sample is loaded by a prescribed vertical pressure $\sigma_v$ until the desired void ratio $e_0$ is reached. The pressure $\sigma_v$ must be smaller than the maximum vertical swelling pressure expected in the subsequent oedometer test. In preliminary tests the reproducibility of the preparation method and the homogeneity of the specimens in terms of water content and void ratio have been checked. The swell/shrink oedometer test start after the sample has reached a stable condition under the pressure $\sigma_v$.

The tests of series 1 are used for the determination of the maximum swell pressure $\sigma_{sw,max}$ at a constant volume, as given in equation 1. These tests have been carried out in a standard oedometer and will later be repeated in the modified equipment. In these tests the following variation of the parameters was selected: initial degree of saturation: 0.63 to 0.88; final degree of saturation: 0.78 to 1.0; initial void ratio: 0.68 to 0.88. The temperature was 20 °C. Additional tests are foreseen at 5°C and 35°C.

The cylindrical samples had diameter $d = 100$ mm and height $h_0=20$ mm. They are saturated from an initial degree of saturation $S_{r,0}$ to a specified saturation $S_{r,\infty}$ with fixed top plate, i.e. $\varepsilon_z = 0$. The swelling pressures corresponding to $S_{r,0}$ are already dissipated at the beginning of the test.

Test series 2 are currently conducted in oedometers A and B for selected values of the initial and the final degree of saturation, and of the initial void ratio. Herein results are reported only for $e_0 = 0.78$. The correlation between axial swell strain $\varepsilon_z^{SW}$ and vertical stress $\sigma_v$ (path SW in Figure 1) is measured in oedometer A. A specified deformation in the z-direction is permitted for the determination of $\varepsilon_z^{SW}$ as a function of $\sigma_v$ in oedometer A after reaching the maximum swell stress $\sigma_{sw,max}$. According to von Wolffersdorff et al. (2004) this type of test yields the best results when compared with in-situ measurements. The correlation between $t_z^{SW}$ and $t_{\sigma}^{SW}$ is determined in oedometer B.

Test series 3 consists of shrinking tests on oedometer A along the path SN in Figure 1. Since this type of device enables only the shrinkage under constant volume down to the $\sigma_{z,0}$ (horizontal branch of the SN path), additional tests will be conducted in oedometer B to cover the path corresponding to volume reduction at constant stress (vertical branch of the SN path). In the latter, the membrane technique developed prevents the formation of a gap between specimen and ring.

The applied sample preparation technique has been optimized, as described by Dobrowolsky (2003), where also its influence on the results is investigated.

6 TEST RESULTS AND INTERPRETATION

6.1 Test series 1

Figure 6 exemplary presents the results of swell pressure tests with constant volume and void ratio $e_0 = 0.68$ and initial stress condition $\sigma_{z,0} = 8$ kPa. Isotropy is assumed yielding $t_{\sigma_{sw,max}}^{SW} = 3 \cdot \sigma_{sw,max}$. This assumption is checked on the basis of the test results in series 2 on oedometers A and B, cf. Figure 8.

The results show that swell pressure significantly decreases with an increase in the value of the degree of initial saturation. The same tendency is observed when the final degree of saturation $S_{r,\infty}$ decreases. The results can be approximated by means of an
exponential function. Combining results for void ratios e₀=0.78 and e₀=0.88 we obtain:

\[
P_{\sigma_{\text{max}}}^{SW} = 3.29 \cdot p_a \cdot e^{-3.65 S_{r,\infty} - 4.7 e_0} \cdot (S_{r,\infty} - S_{r,0})^{(0.95 S_{r,\infty} - 0.54)}
\]

where \( p_a \) is the atmospheric pressure.

The above equation is valid for \( 0.68 \leq e_0 \leq 0.88; \) \( 0.6 \leq S_{r,0} \leq 1.0 \) and \( 0.78 \leq S_{r,\infty} \leq 1.0 \). Figure 7 depicts the surface curve for \( S_{r,\infty} = 1.0 \). That graph shows that the swell pressure significantly decreases with increasing void ratio.

\[\text{Figure 7. Maximum swell pressure in dependence of the initial saturation and the void ratio, } S_{r,0} = 1.0, T = 20^\circ \text{C, } \sigma_{z0} = 8 \text{ kPa}\]

6.2 Test series 2

The swell stress values in radial and axial direction during the saturation stage are depicted in Figure 8 for a typical test in oedometer A. At the beginning of the saturation process only an axial pressure of approx. 8 kPa is developed. However, at the end of saturation the ratio between the axial and radial pressure is almost 1 indicating isotropic soil behaviour.

This variation of stress ratio reflects the water absorption process from the bottom to the top of the sample. It can be explained by the fact that the strain gauges which measure the radial deformation of the ring are mounted in the centre of the outer face and the ring non-uniformly deforms during the infiltration process.

This behaviour is observed in all tests in oedometer A. In addition, as demonstrated in Figure 8, the modified oedometer B, enables controlled isotropic conditions also during the saturation stage.

\[\text{Figure 8. Axial swell pressure in relation to the radial swell pressure, } e_0 = 0.78, T = 20^\circ \text{C, } S_{r,0} = 0.88, S_{r,\infty} = 1.0.\]

A representative swelling test in oedometer A is displayed in Figure 9 in a linear scale. The sample with the initial void ratio of \( e_0 = 0.78 \) is saturated at a constant volume from \( S_{r,0} = 0.7 \) to fully saturation. The maximum swell pressure, estimated by equation 5 to \( \sigma_{z,\text{max}}^{SW} = P_{\sigma_{\text{max}}}^{SW} / 3 = 65.88 \text{ kPa}, \) has been approximately reached after complete saturation.

\[\text{Figure 9. Swell pressure in dependence of the volume change, } e_0 = 0.78, S_{r,0} = 0.7, S_{r,\infty} = 1.0, \sigma_{z0} = 8 \text{ kPa}, T = 20^\circ \text{C.}\]

A significant increase of the swell strain \( e_2^{SW} \) is occurring with a decrease in the stress \( \sigma_2 \). Results of four tests are plotted in normalized form in Figure 10. It can be seen that the increase of swell strain is stronger for lower values of the initial degree of saturation. Combined with the findings in the other tests this means that the swelling potential of the sample increases with decreasing initial degree of saturation.
The experimental results displayed in Figure 10 curves can be approximated by the following equation:

$$
\varepsilon_{SW} = \frac{a}{\sigma_{SW}^{\max}} \cdot \log \left( \frac{\sigma_z}{\sigma_{SW}^{\max}} \right)
$$

(6)

The constants $a$ and $b$ will be determined after completion of the testing program.

6.3 Test series 3

The tests of the series 3 are an extension of series 2: several dewatering – watering – cycles have been added at selected stress levels on the path SW, as shown in Figure 1.

The results in Figure 11 show that the strain increment $\Delta\varepsilon_{SN}^Z$ (as defined in Figure 1) due to dewatering and subsequent watering is negligible. This holds until the swell pressure completely disappears. Only beyond this point the strain $\Delta\varepsilon_{SN}$ becomes significant. This effect will be investigated in more detail in oedometer B.

7 CONCLUSIONS

Tests have been conducted on modified oedometer apparatuses. They showed that the swell pressure behaviour of the kaolinite clay is isotropic. The equipment allows the saturation from an initial to a final degree of saturation at a constant volume. In oedometer A both the axial and radial swell pressure can be determined. In addition oedometer B allows the control of stresses and deformations, both in axial and radial direction. Shrink tests with subsequent watering showed that the cyclic swell-shrinkage behaviour of the material tested is approximately elastic. Finally, it has been demonstrated that the proposed constitutive relations are capable in describing the essential features of the soil behaviour.

8 REFERENCES


