Engineering Geology 193 (2015) 132–145

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Evaluation of strain and stress states of a compacted highly expansive soil using a thin-walled oedometer

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ARTICLE INFO

Article history:
Received 24 October 2014
Received in revised form 13 April 2015
Accepted 18 April 2015
Available online 21 April 2015

Keywords:
Volume change behavior
Expansive soils
Thin-walled oedometer
Swell-collapse equilibrium line
Lateral swelling behavior
Stress path

ABSTRACT

Investigation of the volume change behavior of expansive soils typically utilizes conventional oedometer which provide estimates of vertical strain and swelling pressure under fully lateral restrained conditions. In this study, testing was conducted on compacted highly expansive clay using a thin-walled oedometer to evaluate the state of stresses during inundation in both vertical and lateral directions in addition to the vertical strain. First, calibration, correction, and verification of the thin wall oedometer were described. Second, an experimental program was developed to evaluate the volume change behavior during inundation for a wide range of vertical stresses at inundation (σ_i) under two conditions: (i) constant vertical stress at inundation and (ii) constant volume. Results of tests under constant vertical stress at inundation indicate the dependency of strain state of expansive soil on the inundation vertical stress. Moreover, the vertical stress at inundation (σ_i) was observed to affect the vertical stress state after inundation for constant volume condition. Investigating the equilibrium vertical stress state after inundation under constant volume condition showed that there is one relation termed as "Swell-Collapse Equilibrium Line, SCEL" that represents the equilibrium condition after inundation for specimens subjected to different initial sample conditions prior to inundation. General trends of strain softening behavior for the evolution of lateral stresses with time were observed, particularly for the swelling zone. Stress path followed by tested samples was depicted. Interpretation of results in light of Barcelona Expansive Model (BExM) was also performed. An enlargement of yield envelop after loading to stresses greater than past stress history was observed.

1. Introduction

Estimation of swell or settlement behavior of expansive soils under one-dimensional loading using conventional oedometer testing is considered the most general technique used by geotechnical engineers as well as researchers. One of the drawbacks of the conventional oedometer is its inability to simulate the in-situ state of confinement. ASTM D4546 (2003) state that the unrepresentative simulation of lateral confinement in oedometer testing can lead to unrealistic estimation of swell or settlement of soils for the purpose of estimating in situ heave of foundations and compacted soils. Moreover, there are some reported cases that have mainly attributed damage to lateral swelling. This motivates designers as well as researchers to evaluate the stress and strain states of soils in both axial and lateral directions, in order to minimize the negative effects of unrealistic estimation for these parameters, either from the safety or economical point of views.

Several researchers have developed specially designed oedometers to evaluate lateral stresses in soil during swelling (Komornik and Zeitlen, 1965; Ofer, 1980, 1981; Edil and Alanazy, 1992; Habib et al., 1992; Windal and Shahrour, 2002; Marcial et al., 2006; Monroy et al., 2007, 2014; Brown and Sivakumar, 2008; Avsar et al., 2009). Monroy et al. (2014) divided the alternative oedometer designs into passive and active systems according to the dependency on a closed-loop feedback mechanism that corrects the induced lateral strain and ensure a true K_0 condition.

Possibility of measuring lateral stresses in oedometer enabled researchers to track the evolution of lateral stresses during inundation. Schreiner and Burland (1987) used a specially designed oedometer to trace the stress path during swelling under controlled suction. Studies revealed that trends for the variation of lateral swelling pressure with time, especially under low vertical stresses, showed an increase reaching a peak value followed by a decrease in value up to a residual stress (Joshi and Katti, 1984; Chen and Huang, 1987; Erol and Ergun, 1994; Windal and Shahrour, 2002; Brown and Sivakumar, 2008). Moreover, it was observed that increase in inundation stress caused the peak-residual behavior to be obliterated. Chen and Huang (1987) attributed this phenomenon to gradual change in the soil structure and clay particle orientation associated with the saturation process. Windal and Shahrour (2002) attributed this observation to stress relaxation phenomena in the soil. Brown and Sivakumar (2008) ascribed this behavior to change in the direction of major principle stress, once the lateral

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http://dx.doi.org/10.1016/j.enggeo.2015.04.012
0013-7952/

pressure becomes the major principle stress, reorientation of the expansion direction occurs to be in the direction of minimum energy condition.

Furthermore, several studies conducted on laterally confined samples showed an increase in lateral swelling pressure with increase in vertical stress at inundation (Joshi and Katti, 1984; Sudhindra and Moza, 1987; Edil and Alanazy, 1992). Edil and Alanazy (1992) attributed this increase to combined source of initiating lateral swelling pressure, swelling tendency and the lateral deformation tendency in response to the applied vertical pressure.

This paper presents an extensive experimental program to evaluate the state of stresses and strains for a compacted highly expansive soil under K_0 condition with simultaneous measurements of lateral stress during inundation.

2. Material used

The expansive soil used in this study was obtained from Al-Qatif town. Al-Qatif town is located in the eastern province of Saudi Arabia along the shoreline of the Arabian Gulf (approximate latitude 26° 56′ N and longitude 50° 01′ E). Al-Qatif clay is calcareous clay that is highly expansive in nature (Abduljauwad and AI-Sulaimani, 1993; Azam et al., 1998; Al-Shayea, 2001; Azam, 2003). Soil samples were obtained from a test pit at a depth of about 2.0–3.0 m below ground surface and were transferred to laboratory for full geotechnical characterization. A summary of soil characterization data are provided in Table 1. The mineralogical characterization of Al-Qatif clay was performed using the X-ray diffraction technique identified the presence of montmorillonite which is a typical swelling mineral, see Fig. 1.

3. Equipment

The experimental device used in this study was a thin-walled oedometer which is similar in principle to that developed by Ofer (1980). The advantage of this device is its ability to monitor changes in lateral stresses developed by samples during the test. The main component of the thin-walled oedometer is a brass ring of diameter 50.0 mm and wall thickness of 1.5 mm. The ring was instrumented with four electrical resistance strain gauges attached to the outer surface of the ring at an angular spacing of 90°. Each strain gauge was oriented such that the change in strain in the circumferential direction (ε_c) of the ring can be measured. The thin-walled oedometer cell was fitted with a linear variable differential transformer (LVDT) with an accuracy of 0.001 mm for axial strain measurement. All strain gauges and LVDT were connected to a portable data logger (TDS-303) for the continuous recording of strains during the test. Fig. 2 provides a detailed diagram showing the different components of the thin walled oedometer. Through circumferential strain measurements, the lateral stresses generated during the test can be calculated via an appropriate calibration factor; therefore, the instrumented thin-walled ring provides an indirect method for the measurement of lateral stresses which, together with the vertical stress applied, enables the evaluation of the stress path followed by the sample during the test.

Table 1
Summary of soil characterization data for Al–Qatif tested clay.

Physical properties	Value
Specific gravity, G_S	2.74
Liquid limit, w_l (%)	140
Plastic limit, w_p (%)	60
Shrinkage limit, w_s (%)	20
Plasticity index, *PI* (%)	80
Unified soil classification system	CH[a]
Standard compaction characteristics [b]	
Optimum moisture content (%)	35%
Maximum dry unit weight (kN/m^3)	11.8

[a] CH refers to clay with high plasticity.
[b] According to ASTM D 698 (2000).

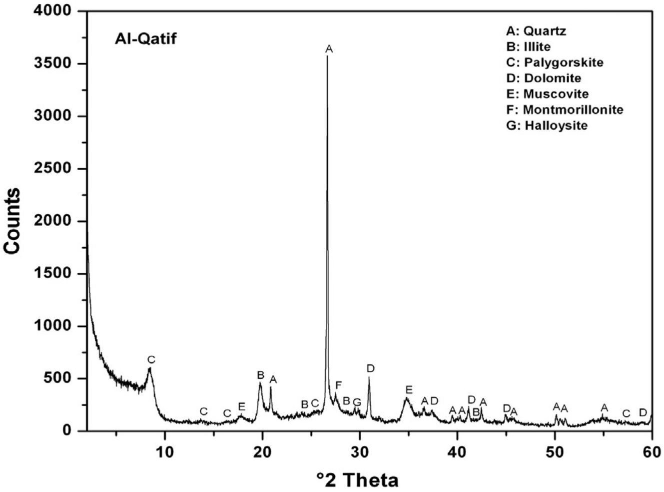

Fig. 1. X-ray diffraction analysis for Al-Qatif expansive soil.

The performance of the thin walled oedometer was verified by conducting a series of comparable tests using a conventional oedometer (with no lateral strain measurements). The ring used for the conventional oedometer was made of stainless steel with dimensions of 50.0 mm in diameter and 20.0 mm high with wall thickness 2.5 mm. For both conventional and thin-walled oedometers, vertical stresses were applied on tested samples via a benchtop consolidation loading frame with a lever arm ratio of 11:1.

4. Thin-walled oedometer calibration

As stated above, the circumferential strains recorded using strain gauges are transformed to lateral stresses via a calibration factor. This section describes the calibration procedure performed to assess the lateral stresses from circumferential strains of the thin walled oedometer. In addition, the effect of temperature variation on the strain readings and lateral stress determinations was assessed and appropriate correction factors were proposed.

4.1. Circumferential strain versus lateral stress calibration

The calibration procedure performed involved assembling the components of the thin-walled oedometer while encasing the thin-walled ring between a top plate with an inlet port and a thick plastic sheet from the bottom as shown in Fig. 2. This encasement will form a sealed chamber for the application of pressurized air through the inlet port. Air pressure was applied in increments and the circumferential strains corresponding to each air pressure increment were recorded. Variation of circumferential strains with air pressures for each of the installed strain gauge is presented in Fig. 3. Based on Fig. 3, a linear relationship was observed between circumferential strains and air pressure applied (i.e., lateral stress). The slope of this line is considered as a calibration constant for each strain gauge. From Fig. 3, it is apparent that the calibration factor is nearly equal for three strain gauges except for strain gauge # 1. Examination of this strain gauge indicated that strain gauge #1 was installed on the lower third of the ring in contrary to the rest of the strain gauges which were installed at the ring mid height. This highlights the significance of strain gauge location on the strain gauge measurements and consequently test results. Furthermore, several cycles of air pressure loading and unloading were performed to ensure the reliability and the repeatability of calibration results. Consistent calibration factors were obtained during each loading and unloading cycle.