Evaluation of Lateral Stress States for a Compacted Highly Expansive Soil

Évaluation des états de stress latéral pour un sol compacté et hautement expansif

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ABSTRACT: There are reported cases where the lateral soil swelling is the main cause of structural damage. Therefore, evaluation of lateral stress states due to swelling is essential to minimize the negative effects of unrealistic estimation for lateral stresses, either from the safety or economical point of views. In this study, an extensive experimental program was developed to evaluate the state of lateral stresses using thin-walled oedometer. The experimental program included a wide range of axial wetting stress (σ_{aw}) under two conditions: (i) constant axial stress (CS_Ko) and (ii) constant volume (CV_Ko). Lateral stress emerged during all testing phases (i.e., dry loading, wetting, wet loading and unloading) were presented. General trends of strain softening behavior for the evolution of lateral stresses with time were observed, particularly for the swelling zone. Variation of the lateral stress state after wetting with the axial wetting stress showed that the axial wetting stress (σ_{aw}) and boundary condition significantly affect the development of lateral stresses.

RÉSUMÉ : Il ya des cas signalés où le gonflement latéral des sols est la cause principale des dommages structurels. Par conséquent, l'évaluation des états de contraintes latérales dues au gonflement est essentielle pour minimiser les effets négatifs d'une estimation irréaliste des contraintes latérales, soit du point de vue de la sécurité, soit du point de vue économique. Dans cette étude, un vaste programme expérimental a été développé pour évaluer l'état des contraintes latérales à l'aide de l'oedomètre à parois minces. Le programme expérimental comprenait une large gamme de contraintes de mouillage axial (σ_{aw}) sous deux conditions: (i) une contrainte axiale constante (CS_Ko) et (ii) un volume constant (CV_Ko). La contrainte latérale a émergé pendant toutes les phases d'essai (c'est-à-dire, chargement à sec, mouillage, chargement par voie humide et déchargement). On a observé des tendances générales du comportement de ramollissement des déformations pour l'évolution des contraintes latérales avec le temps, en particulier pour la zone de gonflement. La variation de l 'état de contrainte latérale après mouillage avec la contrainte de mouillage axial a montré que la contrainte de mouillage axiale (σ_{aw}) et l' état limite affectent de manière significative le développement des contraintes latérales.

KEYWORDS: *Lateral stress state, Expansive soil, Thin-walled oedometer, At rest stress ratio.*

1 INTRODUCTION

Characterization of the volume change behavior of expansive soils is usually carried out using one-dimensional oedometer test. In spite of its simplicity, this test cannot fully portray changes in lateral stresses during swelling. Several researchers have developed specially designed oedometers to evaluate the evolution of lateral stresses during swelling under laterally confined conditions (Ofer 1981, Edil and Alanazy 1992, Windal and Shahrour 2002, Brown and Sivakumar 2008, Monroy et al. 2014). From these studies, it was observed that lateral stress increases due to wetting. Furthermore, the lateral stress increases with applied vertical stress (Sudhindra and Moza 1987, Edil and Alanazy 1992).

Moreover, these studies revealed different trends for the variation of lateral stress during wetting with time depending on applied axial stress (Chen and Huang 1987, Erol and Ergun 1994, Windal and Shahrour 2002, Brown and Sivakumar 2008).

This paper presents the results of an extensive experimental program to evaluate lateral stresses developed in compacted highly expansive soil under two different axial boundary conditions; namely, constant axial stress and constant volume test.

2 MATERIAL USED

The expansive soil used in this study was obtained from of Al-Qatif town located in the eastern province of Saudi Arabia along the shoreline of the Arabian Gulf (approximate latitude 26º 56' N and longitude 50º 01' E). Al-Qatif clay is calcareous clay that is highly expansive in nature (Abduljauwad and Al-Sulaimani 1993, Azam et al. 1998). Soil samples were obtained from a test pit at a depth of about 2.0 – 3.0 meters below ground surface and were transferred to laboratory for full geotechnical characterization. A summary of soil characterization data are provided in Table 1.

Table 1 Summary of characterization for tested soil

Physical Properties	Value
Specific gravity, G_S	2.74
Liquid limit, w_l (%)	140
Plastic Index, I_p (%)	80
% Fine (passing # 200) (%)	98
Unified soil classification system	CH

3. SPECIMEN PREPARATION

Bulk clay samples were air dried, pulverized, and sieved using sieve no. 40 (mesh opening size 0.420 mm) to remove oversized particles and to obtain clay powder. The soil was hand mixed with distilled water at target water content. Mixing was conducted for about 30 minutes to ensure uniform distribution of water in the mixture. Tested specimens were statically compacted to final dimensions at maximum dry density (γ_d =12 kN/m3) and optimum moisture content (w_{op} = 32%) evaluated using standard compaction effort according to ASTM D698 standard (2000). Specimen dimensions for oedometer testing were 20 mm high and 50 mm in diameter.

4. EQUIPMENT USED

The lateral stress evolved during swelling was measured using specially design thin walled oedometer test shown in Figure 1. This cell comprises of a copper ring with a reduced wall thickness of 1.5 mm that is instrumented with four strain gauges adhered every 90º on the outer surface of the ring's circumference. The instrumented thin-walled ring provides an indirect method for the measurement of lateral stresses during expansive soil testing. Lateral strains measured are transformed to lateral stresses via appropriate calibration factor. Detailed description of the calibration and correction to be applied to raw data is provided in Abbas et al. (2015).

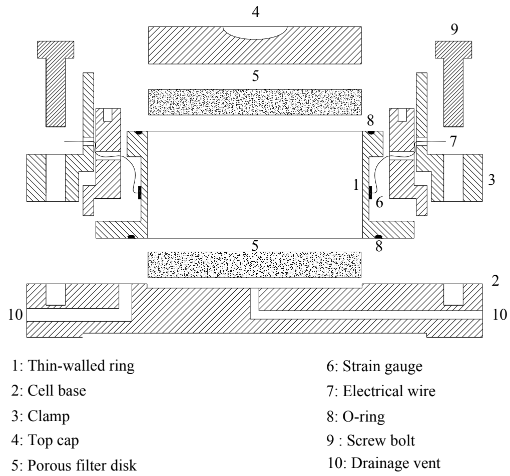

Figure 1. Schematic diagram showing the components of the thin-walled oedometer cell.

5. EXPERIMENTAL PROGRAM

The testing program comprised of two series according to the boundary condition applied at the wetting stage. The first series is referred to as wetting under constant axial stress (CS_Ko series), the volume change due to wetting under different axial wetting stresses (σ_{aw}) varying from 50 kPa to 900 kPa is permitted in the axial direction only. The second series is referred to as wetting under constant volume (CV_Ko series), the volume change due to wetting under different axial wetting stresses (σ_{aw}) varying from 50 kPa to 1000 kPa is restraint in both axial and lateral directions. For both series, lateral stress developed during all testing phases (i.e., dry loading, wetting, wet loading and unloading) were examined.

For convenience of reference, each test was labeled to represent the type of oedometer used, testing method and axial wetting stress. For instance, "CS_230_Ko" refers to a one-dimensional test performed using swell under constant axial stress of 230 kPa.

6. RESULTS AND ANALYSIS

The results of current study concerning the lateral stress development for different testing phases are presented in this section. Moreover, this section provides a detailed analysis of the wetting stage results for both examined boundary conditions.

6. 1 *Lateral Stress – Log Axial Stress Relations*

To examine the development of lateral stress during testing, plots for the variation of lateral stress with logarithm of axial stress applied during different test stages (i.e., dry loading, wetting, wet loading and unloading) for specimens wetted under examined boundary condition (i.e., CS_Ko and CV_Ko) are presented in Figures 2-(a, b) and 3-(a, b), respectively. From these figures, the variation of lateral stresses with axial stress showed similar trends except during the wetting stage.

During dry loading stage, Figures 2 and 3 show that the lateral stresses decreased with increase in axial stress. However, if the axial stress applied during dry loading exceeds 500 kPa, as shown in Figs. 2-(b) and 3, a significant increase in lateral stress is observed with sharp bend in the curve. It shall be pointed out that the axial stress state of this yield point is almost equals the axial yield stress at as-compacted condition, $\sigma_o(s_o)$ = 520 kPa.

The decrease in lateral stresses during dry loading is attributed to the technique used during specimen preparation. Specifically, specimens prepared using static compaction were subjected to a given axial stress followed by an unloading imposing a specific stress history on these specimens. The specimens were observed to undergo lateral stress relaxation (decrease) during dry loading stage); especially under axial stress less than the maximum axial stress applied during static compaction. However, as the dry loading exceeds the past maximum compaction stress, the specimens experience significant increase in axial compression accompanied by notable increase in lateral stress as shown in Figs. 2-(b) and 3. Wetting process resulted in an increase in lateral stresses for specimens that experienced either swell or collapse for both examined boundary conditions.

The wet loading phase is distinguished by an increase in lateral stress up to a maximum applied axial stress of 1800 kPa. Finally, the lateral stress decreased with unloading for all tests.

6. 2 Lateral Stress Evolution during Wetting Stage

The development of lateral stress with time due to wetting under both CS_Ko and CV_Ko conditions is illustrated in Figures 4 and 5. From Figures 4 and 5, a characteristic "strain softening" behavior characterized by a definite peak value followed by reduction to a residual value is observed for all wetted specimens except for specimens subjected to collapse during wetting under constant axial stress (i.e., $\sigma_{aw} > \sigma_o(so)$). The strain softening behavior becomes obliterated during wetting under constant high axial wetting stress. Similar observations to the strain softening behavior were reported by (Windal and Shahrour 2002, Brown and Sivakumar 2008).

The dependence of the equilibrium lateral stress state after wetting on the axial wetting stress (σ_{aw}) is depicted in Figures. 6 and 7 for examined boundary conditions during wetting (i.e., CS_Ko and CV_Ko, respectively). For CS_Ko condition (Figure 6), a bi-linear relationship is observed between the lateral stress after wetting and the logarithm of the axial wetting stress. This bi-linear relationship indicates a significant increase in lateral stresses as the specimen wetted at axial wetting stress greater than 500 kPa (i.e., yield point under as-compacted condition). Moreover, the lateral stress state after wetting consists of two components pre-wetting lateral stress (σ_{Lw}) and change in lateral stress due to wetting ($\Delta\sigma_L$). Inspecting the variation of pre-wetting lateral stresses (σ_{Lw}) with axial wetting stresses (σ_{aw}), depicted in Figure 6, indicates that there is a significant increase in lateral stress experienced by specimen dry loaded beyond 500 kPa.

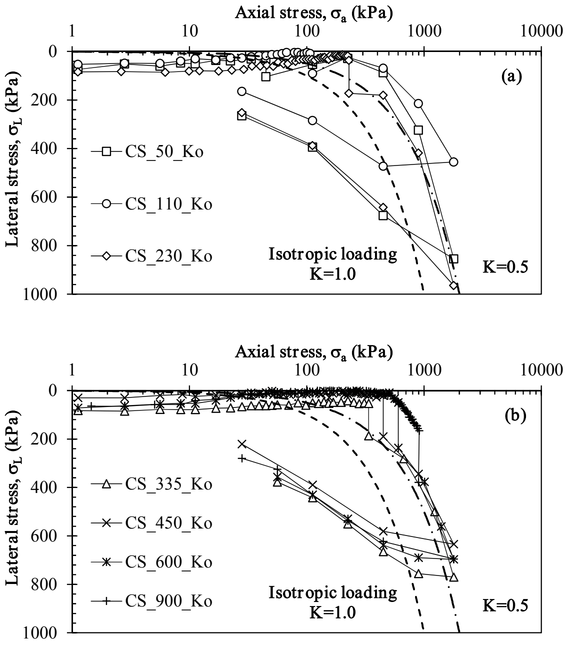

Figure 2. Relationship between lateral stress and axial stress for specimens inundated under constant axial stress condition

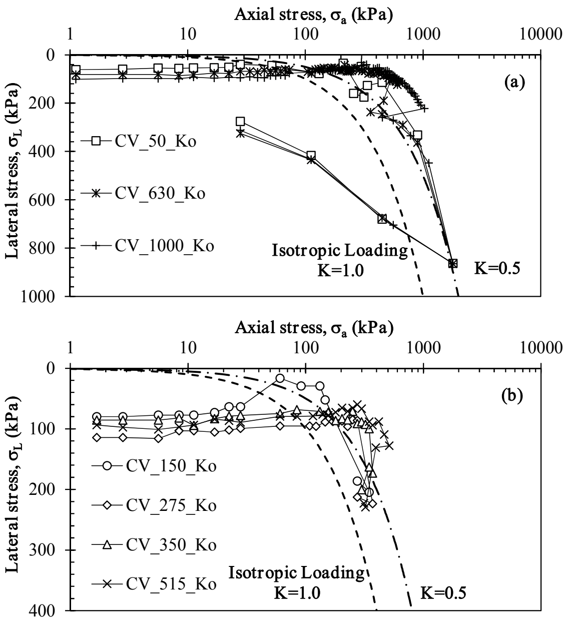

Figure 3. Relationship between lateral stress and axial stress for constant volume testing

With respect to change in lateral stress due to wetting ($\Delta\sigma_L$) component, Figure 8 shows a bi-linear trend with σ_{aw}. The break in the linear trend appears at σ_{aw} around 330 kPa, where specimen start to experience final collapse after wetting. This break in linear trend implies an additional component for the source of increase in lateral stress, which can be attributed to the axial collapse initiated in specimen. The axial collapse initiated after wetting at constant axial stress under fully lateral restraint condition resulted in rearrangement of the particle aggregates in less volume. Consequently an additional increase in lateral stress is observed.

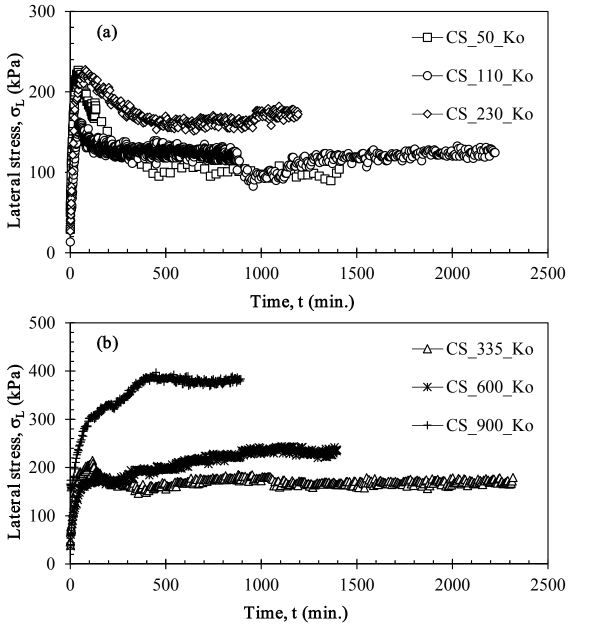

Figure 4. Lateral stress evolution for specimens experienced (a) swell and (b) collapse under CS_Ko condition.

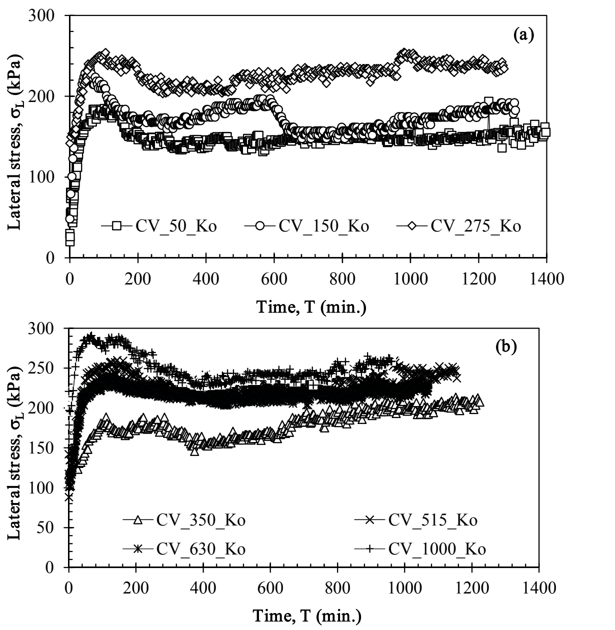

Figure 5. Lateral stress evolution during wetting at axial wetting stress (a) lower than 300 kPa (b) higher than 300 kPa under constant volume condition

For CV_Ko condition, a linear relationship is observed between the lateral stress after wetting and the logarithm of the axial wetting stress (Figure 7). Examination of the components of lateral stress after wetting (i.e., σ_{Lw} and $\Delta\sigma_L$) revealed that the lateral stress component due to dry loading showed a significant increase for loading higher than σ_o(so) similar to CS_Ko testing. On the other hand, the change in lateral stress due to wetting reduces with the increase in axial wetting stress beyond 300 kPa, as shown in Figure 9, where tested specimen experienced tendency to collapse under constant volume condition. This reduction of $\Delta\sigma_L$ after wetting at collapse zone (Figure 9) is due to the tendency of specimens to collapse laterally as well as axially with maintaining the sample's volume constant. This is in contrast to the condition of constant axial stress where the axial collapse is translated to a reduction in specimen's height resulting in developing an additional lateral stress on the bounds.

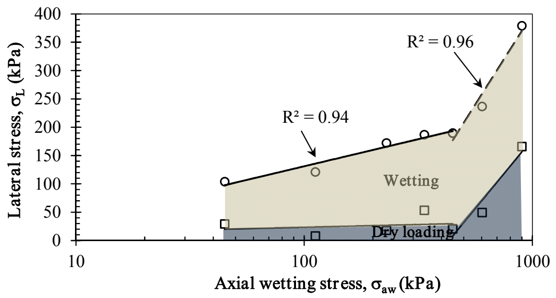

Figure 6. Relative contribution for components of lateral stress after wetting under CS_Ko condition

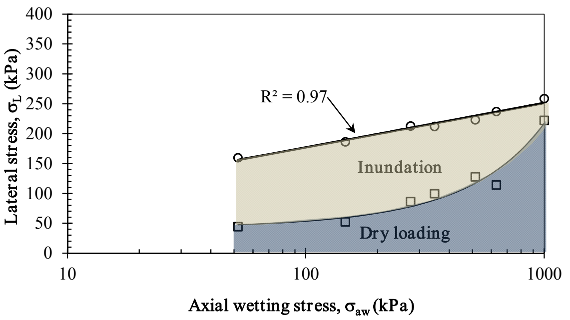

Figure 7. Relative contribution for components of lateral stress after wetting under CV_Ko condition

7. CONCLUSION

The lateral stress state during different testing phases was presented with concentrating on the lateral stress behavior during wetting under examined boundary condition. the development of lateral stress with time during wetting revealed a strain softening behavior with this behavior less visible under high wetting stress.

The axial wetting stress (σ_{aw}) was observed to have significant effect on the development of lateral stresses after wetting. Examining the components of lateral stress after wetting (pre-wetting lateral stress, σ_{Lw} and change in lateral stress due to wetting, $\Delta\sigma_L$) indicates a significant increase in σ_{Lw} for σ_{aw} exceeding the past maximum compaction stress (or in other word, the yield stress at as-compacted suction). In addition, the variation of change in lateral stress due to wetting, $\Delta\sigma_L$ with σ_{aw} exhibited that swell, in general, results in an increase of the lateral stress for both examined boundary conditions. On the other hand, collapse under CS_Ko condition initiates an additional component for the source of increase in lateral stress, while it results in reduction in lateral stress for CV_Ko condition.

8. ACKNOWLEDGEMENTS

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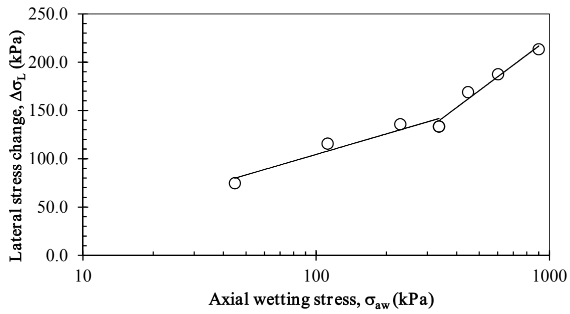

Fig. 8 Relationship between change in lateral stress due to wetting and axial wetting stress under CS_Ko condition

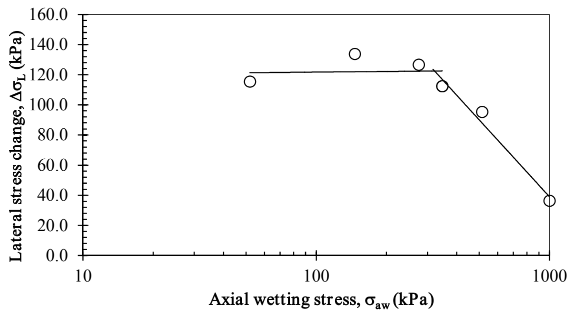

Figure 9. Relationship between change in lateral stress due to wetting and axial wetting stress under CV_Ko condition

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