Oedometer based estimation of vertical shrinkage of expansive soil in a large instrumented soil column

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ABSTRACT

The moisture variations in expansive soils cause shrink-swell behaviour, resulting in distress to the structures founded in/on problematic soils. The oedometer based tests can be used to determine swell behaviour of soil; however, limited research has been conducted for vertical shrinkage estimations. In this study, a series of conventional oedometer tests were conducted to investigate the vertical shrinkage of grey Vertosol due to soil moisture variations under different surcharges. A statistically strong relationship ($R^2 = 0.99$) was observed for shrinkage per unit change in volumetric water content under shallow overburden pressures (surcharges). The validation of the shrinkage was conducted by simulating field conditions under induced drying cycle. Derived shrinkage prediction equation and Aitchison's method showed underestimations of 10.1% and 44.0% of the actual shrinkage respectively. Briaud's and Dhowian's models overestimated the value by 59.0% and 44.5% respectively. This study emphasizes the applicability of the conventional oedometer based shrinkage test for a reasonable estimation of vertical shrinkage for a given expansive soil. Thereby, proposing a simple and practical approach to obtain shrinkage characteristics for geotechnical engineering applications.

1. Introduction

Expansive soils tend to exhibit shrink-swell behaviour during climate variations (Bouma and Wöstten, 1984; Bronswijk, 1988; Chan et al., 2015; Gallage et al., 2009; Gallage et al., 2017; Puppala et al., 2014; Talsma, 1977; Tang et al., 2011a, 2011b; Zemenu et al., 2009). The moisture evaporation from such soils cause shrinkage in vertical as well as in horizontal directions. More importantly, the vertical shrinkage behaviour exerts an additional distress to the structures founded in/on problematic soils (Chan et al., 2016; Karunarathne et al., 2014; Kodikara et al., 2013; Puppala et al., 2011; Zhan et al., 2006). In extreme drying periods subsequent to heavy rainy seasons, expansive soils are prone to shrink by significant volume which eventually paves the way for a considerable vertical strain (Bouma and Wöstten, 1984; Bronswijk, 1988; Favre et al., 1997; Talsma, 1977; Udukumburage et al., 2018). Therefore, the shrinkage characteristics of expansive soils are critical in determining the expected surface movement for geotechnical engineering applications (Albrecht and Benson, 2001; Gallage et al., 2012; Groenevelt and Grant, 2004; Novak, 1999; Puppala et al., 2014; Tang et al., 2011b; Vogel et al., 2005; Zemenu et al., 2009).

During dry spells after long rainy seasons, the saturated expansive soils tend to lose moisture and as a result; behaves in the ‘normal’ shrinkage phase until they reach the air-entry or cracking point. Further desaturation due to desiccation causes ‘proportional’ shrinkage (Groenevelt and Grant, 2004) and final phase; ‘residual’ shrinkage can be observed under extreme drying conditions in arid and semi-arid regions across the world. However, most expansive soils in field conditions behave in proportional shrinkage region due to cyclical climatic effect (Allaire et al., 2009; Cornelis et al., 2006; Julina and Thyagaraj, 2018; Udukumburage et al., 2019). The shrinkage characteristics of such soils have been investigated during the past two decades using simple-to-complicated approaches under both field and laboratory conditions (Albrecht and Benson, 2001; Allaire et al., 2009; Ata-Ur-Rehman and Dunford, 1993; Cornelis et al., 2006; Konrad and Ayad, 1997; Peng et al., 2006; Por et al., 2015; Por et al., 2017; Tang et al., 2011a; Tang et al., 2011b; Zemenu et al., 2009).

Shrinkage behaviour of expansive soils has been investigated using both direct and indirect methods in literature. Indirect methods involve the basic soil properties which can be empirically correlate with shrinkage behaviour of reactive soils. Direct methods are very time consuming, exorbitant and need specialized knowledge which involves direct measurement of shrinkage potential (Abeykoon et al., 2017;
Established expansive soil displacement prediction methods utilize parameters obtained from the oedometer based approach. Atchison and Peter (1973) proposed a suction based method to predict soil heave and shrinkage using an Instability index, that can be determined from the oedometer based approach. Water content based shrinkage predictions were further investigated by Lytton (1997), Briaud et al. (2003), Dhowian (1990) and Al-Shamrani and Dhowian (2003). However, little to none research has been published in the stream of conventional oedometer based shrinkage compared to the investigations carried out in swell-based approaches.

Bridging this gap, a series of element tests and instrumented soil column test were conducted to investigate the mechanical responses of expansive grey Vertosol under drying cycle. A series of conventional oedometer based shrink tests were conducted to experimentally determine the variation of the vertical shrinkage due to the moisture changes oedometer based shrinkage compared to the investigations carried out in swell-based approaches.

| Classification Test | Results | Standard |
|---------------------|---------|----------|
| Grain size distribution | % finer than 75μm > 77% | AS 1289.3. 6.3 (2003) |
| | Fraction of clay - 50.1 % | AS 1289.3.5.1 (2006) |
| Atterberg Limits | LL = 67.0 % | AS 1289.3.4.1 (2008) |
| | PI = 37.2 % | AS 1289.3.1.1 (2009) |
| Linear Shrinkage | LS = 15.39 % | AS 1289.3.2.1 (2009) |
| X-ray diffraction (XRD) | Presence of Smeectite minerals | |
| Specific Gravity | Gs = 2.67 | AS 1289.3. 6.1 (2009) |

Note: LL = Liquid limit; PI = Plastic index; LS = Linear shrinkage.

3. Methods

Methodology adopted in this study comprises of a laboratory simulated expansive soil model test and a series of oedometer based shrinkage tests. A laboratory simulated large expansive soil model (column) was used to monitor the actual subsoil displacement of saturated expansive grey Vertosol under drying conditions. Simultaneously, a series of oedometer based shrinkage tests were conducted to investigate the applicability of these element tests in prediction of the actual ground displacements of expansive grey Vertosols. Table 2 presents the experimental programme of the model and element tests.

3.1. Laboratory simulated instrumented soil column

A large instrumented soil column of 0.4 m in diameter and 1.0 m in height was built by compacting 50 mm lifts of ground expansive soil material. The initial gravimetric water content and the dry density of the compacted soil was selected according to the observed field conditions; 15% and 1.2 g/cm³, respectively. The soil column was initially subjected to a constant head wetting to reach full saturation.

The instrumented soil column was then subjected to an induced heating cycle by employing two 150W heat lamps and the corresponding sensor responses were monitored and recorded for 165 days period until the surface movements were stabilized. Fig. 1 shows the schematic diagram of the instrumented soil column and the sensor embedded depths. The subsoil moisture variations were captured using MP406 moisture sensors and the corresponding subsoil displacements were investigated using settlement plates attached to LVDTs (Linear Vertical Displacement Transducers). MP406 moisture sensor responses and the corresponding sub-soil movements were analysed to correlate the soil displacements under controlled drying conditions. The sub-soil movements were captured by the displacement of the adjacent settlement plates. Idealising the soil displacements under drying conditions, the sub-soil were layered according to the placement of the settlement plates and thereby correlates with the expansive soil shrinkage. The laboratory simulated ground for shrinkage analysis is shown in Fig. 2.

3.2. Oedometer based shrinkage tests

In this study, a series of oedometer based shrinkage tests were conducted for samples which maintain the same initial gravimetric water content (ω) and dry density (ρd) under different surcharges. The soil samples were prepared for known gravimetric moisture content (15%) and the field density of 1.2 g/cm³ was achieved by static compaction of the test specimens. Subsequently, a representative sample was cut into a consolidation ring, folowed by the placement of filter papers and porous disks, at the top and the bottom of the sample. The samples were subjected to different surcharges to account for the vertical stress variation within the soil column under fully saturated condition. The selected surcharges for the loaded swell test series were 1 kPa, 5 kPa, 10 kPa and

| Series | Shrinkage Test | Surcharge (kPa) | Shrinkage Readings Time (Days) |
|--------|----------------|----------------|--------------------------------|
| Series 01 | 1 | 0, 5, 9, 13, 16, 20, 25, 30 |
| Series 02 | 5 | 0, 1, 6, 15, 19, 21, 30 |
| Series 03 | 10 | 0, 5, 9, 13, 16, 20, 25, 30 |
| Series 04 | 15 | 0, 5, 9, 13, 16, 20, 25, 30 |

| Instrumented Soil Column Test (Model Test) |
|--------------------------------------------|
| Test Phase | Duration (Days) | Purpose |
| Wet Cycle | 160 | For saturation of soil |
| Dry Cycle | 165 | Study vertical shrinkage |
15 kPa. The water was introduced from the top of the compacted soil sample until the sample was inundated. Subsequently, the samples were allowed to swell for 72 h to reach the maximum swell strain under the test conditions. The saturated samples were carefully removed and the excess water was drained prior to the drying cycle. Subsequently, the samples were subjected to the same surcharges and air-dried for 30 days period. Most shrinkage tests were conducted for less than 5 days (Briaud et al., 2003); however, in this study authors tested the samples for extended period. The bulk mass of the samples were weighed every 4 days and the corresponding vertical shrinkages were measured. After, the top porous disk was removed, the sample mass with the ring was weighed and a representative portion of the sample was oven-dried to ascertain the final moisture content.

4. Results & discussion

4.1. Soil column based vertical shrinkage analysis

The soil column based shrinkage for the expansive soil was analysed for the vertical direction. The vertical shrinkage is primarily analysed for the one dimensional deformations of the subsoil layers. Expansive soils tend to shrink when they desaturate and the observations from Fig. 3 confirm this. The moisture evaporation from the instrumented soil column caused 11.80 mm vertical shrinkage at the surface as depicted in Fig. 3a. The corresponding moisture loss from the saturated soil is shown in Fig. 3b for the monitoring period of 165 days. From the LVDT sensor responses, it is conspicuous that there has not been considerable shrinkage at 300 mm, 500 mm and 800 mm levels and hence, the critical shrinkage effect takes place in between 0 mm and 150 mm LVDT levels.

It should be clearly noted that these LVDT levels are given with respect to the initial reference points; i.e. prior to saturation (soil displacement = 0 mm).

The shrinkage analysis for the top 150 mm (before wetting cycle) was conducted as depicted in Fig. 4. During the initial saturation of the instrumented soil column, observed swell for the top layer (150 mm) was 23 mm. Due to homogeneity of the soil layer and comparatively less surcharge, it is a fair assumption to distribute the total heave equally among the total initial depth of 150 mm, resulting in a 173 mm layer for the initiation of induced-drying cycle. The MP406 moisture sensor embedded at 50 mm level provides the average moisture content of the soil surrounded by the needle length (60 mm). Therefore, to be more realistic in water content calculations, the top 150 mm (before the wetting cycle) has been sub-divided into 3 separate layers such that the needle length covers an individual layer.

The shrinkage ascertained for the sub-layer number 2 can be specifically evaluated with respect to the moisture responses from MP406 embedded at 50 mm level. The calculated shrinkage for the sub layer 2 was 5.07 mm which amounts to a delta strain ($\Delta \varepsilon$) of 7.33%, resulting in $\Delta \varepsilon/\Delta \theta$ value of 0.23. This derivation is clearly shown in Fig. 4.

4.2. Oedometer based vertical shrinkage analysis

The vertical (one dimensional) shrinkage of the expansive soil was investigated from the saturated condition. Generally, most of the shrinkage studies conducted in literature does not exceed more than 5 days of drying period (Briaud et al., 2003). Further, field measured...
The volumetric water content of the grey Vertosol soil varied in between 18% to 22%; hence a representative average value of 20% was selected to complete the test. This study considered both time (30 days) and volumetric water content (20%) as test completion criterions. Each test was completed when either of the criterion is satisfied. The desaturation of the soil due to the desiccation depicted a linear variation throughout the monitoring period of 30 days. Fig. 5 shows the variation of vertical shrinkage with decreasing volumetric water contents at different surcharge conditions. The effect of the surcharge was identified to be a prominent factor during the period.

The observed variation of the vertical strain during the desiccation depicted an inversely proportional relationship between the sample
volumetric water content. Therefore vertical shrinkage strain increases with decreasing volumetric water content of the soil samples. This phenomenon is reflected by the negative gradient values of Fig. 5. The desaturation process was extremely time consuming and the rate of actual evaporation tends to decrease with time. However, due to the observed linearity of the oedometer based shrinkage during air drying process, the test series was concluded when one of the criterions are met (either 30 days or 20% vwc).

Fig. 6 shows the ‘change in shrinkage strain of soil per unit change in vwc’ at different surcharge conditions. Experimental results depicted an increment in vertical shrinkage strain for a unit volumetric water content change for surcharges from 5 kPa to 15 kPa. Considering this trend, vertical shrinkage per unit change in volumetric water content was outside of the 95% confidence envelope; hence, was not included in the linear fit in Fig. 6.

Derivation of the equations (Eq. (1), (2), (3)) is based on the relationship obtained in Fig. 6.

\[
\frac{\Delta \varepsilon_{oed}}{\Delta \theta} = f(s)
\]  
(Eq. (1))

\[
\frac{\Delta \varepsilon_{oed}}{\Delta \theta} = -0.0117s - 0.1287
\]  
(Eq. (2))

Where:
- \(\varepsilon_{oed}\) = Vertical strain (%)
- \(\theta_i\) = Initial volumetric water content (%)
- \(\theta_f\) = Final volumetric water content (%)
- \(\Delta \theta\) = \((\theta_i - \theta_f)\); Change in Volumetric water content (%)
- \(S\) = Applied Stress (kPa)

For the same conditions discussed in soil column based shrinkage analysis section, the obtained relationship provides a \(\frac{\Delta \varepsilon_{oed}}{\Delta \theta}\) value of 0.151 and the calculated vertical shrinkage amounts to 8.36 mm. To calculate this ratio, a representative surcharge value for the layer is needed; hence, the initial total stress acting at the mid-point of the layer (173/2 = 86.5 mm) was selected. This surcharge is the summation of the effect of ponding water pressure (0.49 kPa) and overburden soil pressure (1.44 kPa) at the mid-point. Substituting the surcharge of 1.93 kPa in Eq. (2), provided \(\frac{\Delta \varepsilon_{oed}}{\Delta \theta}\) of 0.151. As the mid-point located in second sub-layer, the reduction in volumetric water content is determined as 32% from Fig. 4. The total shrinkage based on this method amounts to 8.36 mm. This calculation is illustrated below.

![Fig. 5. Oedometer based vertical shrinkage analysis: (a) 1kPa (b) 5kPa (c) 10 kPa (d) 15kPa.](image-url)
The vertical shrinkage obtained directly from the oedometer based method is an underestimation of 10.1% from the actual observations of the soil column. This variation may be due to the boundary effect which hinders the vertical shrinkage of small samples, yet can be applicable with an appropriate correction factor. Soil-wall interaction is considered as the 'boundary effect' and this phenomenon is influential on vertical soil displacements as discussed by Tang et al. (2009). Smaller soil samples induce greater boundary effect on the soil displacements; hence, the same dimensional (vertical) shrinkage (Briaud et al., 2003); hence the same volumetric water contents using the SWCC of the grey Vertosol. These soil suction values were determined by converting the soil suction with vertical shrinkage during soil desiccation. Fig. 7 shows the relationship between soil suction and the vertical shrinkage strain of the soil. These soil suction values were determined by converting the soil suction with vertical shrinkage during soil desiccation. According to Lytton (1994) a correction factor of 0.7 should be incorporated for the final shrinkage calculations when cracks are present. The main reason for the correction factor is that a considerable vertical shrinkage is transformed into lateral shrinkage during desiccation.

\[ \text{Corrected vertical shrinkage} = \frac{\Delta h_{\text{b (corrected)}}}{14.80 \text{ mm}} \]

The corrected vertical shrinkage for the soil layer overestimated the soil column based observations (9.30 mm) by 59%. Therefore, Briaud's expansive soil heave estimation can be considered as a conservative estimation method for expansive grey Vertosol soils.

### 4.3.2. Aitchison’s method

Aitchison and Peter (1973) introduced a suction based method to determine swell/shrink behaviour of expansive soils. In this method, shrinkage behaviour of expansive soils can be determined using a soil specific (suction based) shrinkage index; also known as Instability Index. The oedometer based results can be employed in conjunction with soil water characteristic curve (SWCC) of the grey Vertosol to correlate soil suction with vertical shrinkage during soil desiccation. Fig. 7 shows the relationship between soil suction and the vertical shrinkage strain of the soil. These soil suction values were determined by converting the soil volumetric water contents using the SWCC of the grey Vertosol.

The instability index \( I_{\text{ps}} \) of the soil was determined using Eq. (5) based on a series of air-drying tests conducted on the test material and observed as a function of surcharge applied on the soil (Fig. 7). The investigation was extended for different surcharge conditions to obtain a valid relationship between the instability index and surcharge as shown in Fig. 8. The representative shrinkage index for the mid-point (86.5 mm) of the top layer (173 mm) was determined based on the overburden pressure at 86.5 mm. Shrinkage index corresponds to 1.93 kPa pressure was ascertained as 1.17. Soil suction variation of the soil column was monitored at 50 mm depth using MPS6 suction sensor. Initial \( t = 0 \) days and final \( t = 165 \) days suction responses of the sensor during the drying period were 8 kPa and 1800 kPa respectively. Hence change in suction at the top surface of the layer can be considered as 8–1800 kPa, as the actual top surface (0 mm) suction cannot be realistically measured due to drastic variations with the atmosphere. This is a valid assumption supported by Masia et al. (2004).

\[ I_{\text{ps}} = \frac{\partial \epsilon}{\partial \log(\varphi)} \]

Where \( \delta \epsilon = \text{Change in vertical strain} \)

\[ \frac{\partial \log(\varphi)}{\partial \log(\varphi)} = \text{Soil suction change (in log scale)} \]

\[ \Delta H = \frac{1}{100} \left( \frac{\partial \epsilon}{\partial \log(\varphi)} \right) H. \Delta \log(\varphi) \]

\[ \Delta H \approx 0.01 \times 1.17 \times 173 \times (\log 1800/8) \]

\[ \Delta H = 4.76 \text{ mm} \]

The vertical shrinkage obtained using the oedometer based test results (Eq. (5)) in conjunction with the Aitchison’s heave estimation
method (Eq. (6)), provided a subsidence of 4.76 mm which is an underestimation for the actual observations in the soil column. However, this suction based estimation provided clear disparity with actual shrinkage observed. Main reason for this underestimation could be the underestimation of the ’change in surface suction’. According to Briaud et al. (2003), expansive clays are generally subjected to 3000 kPa of high suction values at surface levels due to desiccation (dry climates) and this fact was verified by Tripathy et al. (2016). Assuming the surface (0 mm) suction as 3000 kPa, authors ascertained a shrinkage value of 5.21 mm, which is an underestimation of 44.0% of the actual shrinkage observed from the soil column.

4.3.3. Dhowian’s method

After modifying Dhowian’s original equation to water content based approach, a simple heave estimation equation can be derived. Equation (Eq. (7)) was used to determine the shrinkage by considering a moisture index for the drying phase. The volume compressibility factor was calculated in order to determine the total vertical shrinkage as follows.

\[ \Delta H = C_{w,\text{dry}} \cdot H \cdot (w_i - w_f) \]  

\[ C_{w,\text{dry}} = \frac{\alpha \cdot G_s}{1 + e_0} \]  

Dhowian’s method is a function of four basic parameters. Thickness of the soil layer (H) is 173 mm as discussed previously. Initial \( w_i \) and final \( w_f \) gravimetric water content is corrected as 41.2% and 14.5% (ratio of final volumetric water content and soil dry density) respectively. Initial void ratio \( e_0 \) was determined as 1.12, using the fundamental phase relationship \( e = \text{gravimetric water content} \times \text{specific gravity} \). Volume compressibility factor \( \alpha \) for clay materials is selected as 0.33 in line with studies conducted by Dhowian (1990), Fityus and Smith (1998), and Briaud et al. (2003). Therefore the calculation of moisture index for drying \( C_{w,\text{dry}} \) using Eq. (8) amounts to 0.416. The shrinkage \( \Delta H \) calculated using Eq. (7) amounts to 19.21 mm. According to Lytton (1994), a correction factor of 0.7 for the surface cracks can be incorporated for desiccated soil displacement calculations. Therefore, the corrected shrinkage estimate is 13.44 mm which overestimates the actual shrinkage by 44.5%. Therefore, Dhowian’s model can be considered as conservative estimation method for expansive grey Vertosol soils.

Fig. 7. Oedometer based shrinkage index analysis: (a) 1kPa (b) 5kPa (c) 10 kPa (d) 15kPa.
4.3.4. Method comparison

Comparison of the actual and estimated shrinkage from the selected models are presented in Fig. 9. The oedometer based shrinkage predictions from Briaud’s and Dhowian’s methods conservatively overestimated the observed shrinkage from the model test whereas Aitchison’s method underestimated the actual shrinkage. The percent overestimation of the shrinkage from Briaud’s and Dhowian’s are 59.0% and 44.5% respectively. Aitchison’s method underestimated the actual shrinkage by 44.0%. Overall moisture based prediction methods overestimated and suction based methods underestimated the actual shrinkage observations from soil column. The main difference of the estimations from water content and suction based methods may be due to the different indices these models utilize. Both water content based methods consider the volumetric water content change at the midpoint of the layer, whereas the suction based method considers the design suction change at the soil surface. This could be the second reason for the difference of results between the estimation models. Average of Briaud’s, Aitchison’s and Dhowian’s models provided a better match (20% over-estimated) to the actual shrinkage rather than individually considered. Direct estimation from the oedometer based vertical shrinkage analysis resulted in an underestimation of 10.1%, depicting the best estimation out of all the selected methods.

5. Conclusion

In this study, a series of conventional oedometer based shrink tests were conducted to experimentally determine the variation of the vertical shrinkage due to the moisture changes under different surcharges. The observed variation of the vertical strain during the desiccation depicted an inversely proportional relationship between the sample volumetric water content. A relationship between the surcharge and shrink strain/water content was obtained to facilitate a reasonable shrinkage prediction. The validation of the shrinkage was supported by simulating actual ground conditions to investigate the expansive soil behaviour under induced drying cycle.

The shrinkage based on volumetric water content depicted a disparity (underestimation of 10.1%) between the soil column and oedometer based analysis. The oedometer based results were used to further investigate the existing heave/shrink prediction models. Oedometer based shrinkage method proved to be the best shrinkage estimation method compared to all the selected analytical estimation models. Out of the selected prediction methods, water content based models overestimated the actual shrinkage in soil column whereas the suction based model underestimated the shrinkage. The major limitation of the oedometer based shrinkage method is the time consuming nature; however this is compensated by greater accuracy of prediction and simplicity of the method. Future studies on the shrinkage of different types of expansive soils will enhance the practicality of using this method. Overall, this study supports the applicability of the conventional oedometer based shrinkage test for the estimation of vertical shrinkage for a given expansive soil; thereby, encouraging a practical approach to ascertain shrinkage characteristic for routine geotechnical decision making.

Declarations

Author contribution statement

C. Gallage, L. Dawes: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

R. S. Udukumburage: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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The authors declare no conflict of interest.

Additional information

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