Heliyon 5 (2019) e02380

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.heliyon.com

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

Rajitha Shehan Udukumburage *, Chaminda Gallage, Les Dawes

Science and Engineering Faculty, Queensland University of Technology, Brisbane, QLD, Australia

ARTICLE INFO

Keywords:
Natural hazards
Environmental science
Geochemistry
Structural engineering
Instrumented soil column
Vertical shrinkage
Oedometer test
Geo-environmental engineering
Expansive soils

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 Wösten, 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 Wösten, 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;

* Corresponding author.
E-mail address: rajithashehan.udukumburage@hdr.qut.edu.au (R.S. Udukumburage).

https://doi.org/10.1016/j.heliyon.2019.e02380
Received 10 January 2019; Received in revised form 21 May 2019; Accepted 23 August 2019

Punthutaecha et al., 2006; Puppala et al., 2014; Puppala et al., 2013). The significance of investigating the shrinkage behaviour using direct methods was emphasized by Puppala et al. (2014) for a better understanding of shrinkage strains during extreme dry seasons. However, extremely limited research has been carried out to investigate the oedometer based vertical shrinkage in conjunction with laboratory simulated ground conditions.

Established expansive soil displacement prediction methods utilize parameters obtained from the oedometer based approach. Aitchison 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 under different surcharges. The laboratory validation of the oedometer based test results were conducted by simulation of actual ground (Instrumented soil column) which required specialized technical expertise and considerable amount of funding. The soil column (1.0 m high and 0.4 m in diameter) was subjected to an induced drying cycle for 165 days to observe the subsoil moisture variations and vertical soil displacements at known levels. Desaturation was investigated from the saturated soil condition and specifically focussed on the normal and proportional shrinkage phase. Further, oedometer based parameters were used for comparison of different water content and suction based shrinkage estimation methods.

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 practical approach to ascertain one dimensional shrinkage characteristic for geotechnical decision making.

2. Materials

The expansive soil for the laboratory simulated ground and loaded swell tests series was extracted from Sherwood, South-east Queensland region. Table 1 summarises the laboratory tests conducted and results to determine the index properties of the soil according to Australian standards. This characterises the type of soil as CH (inorganic clays of high plasticity) on Casagrande's plasticity chart. Further, the results from the X-ray diffraction (XRD) analysis were used to verify the composition of montmorillonite (22%) and kaolinite (73%) minerals. According to the interpretation of the mineralogical analysis, the sample displays the attributes of smectite group minerals; classified as grey Vertosol according to the Australian classification system (Isbell, 2016).

Table 1
Soil classification tests results.

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 = 13.39 %	AS 1289.3.2.1 (2009)
X-ray diffraction (XRD)	Presence of Smectite minerals	
Specific Gravity	G_s = 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/cm^3, 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 (ρ_d) under different surcharges. The soil samples were prepared for known gravimetric moisture content (15%) and the field density of 1.2 g/cm^3 was achieved by static compaction of the test specimens. Subsequently, a representative sample was cut into a consolidation ring, followed 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

Table 2
Soil model and element test series.

Oedometer Based Shrinkage Tests (Element Tests)		
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

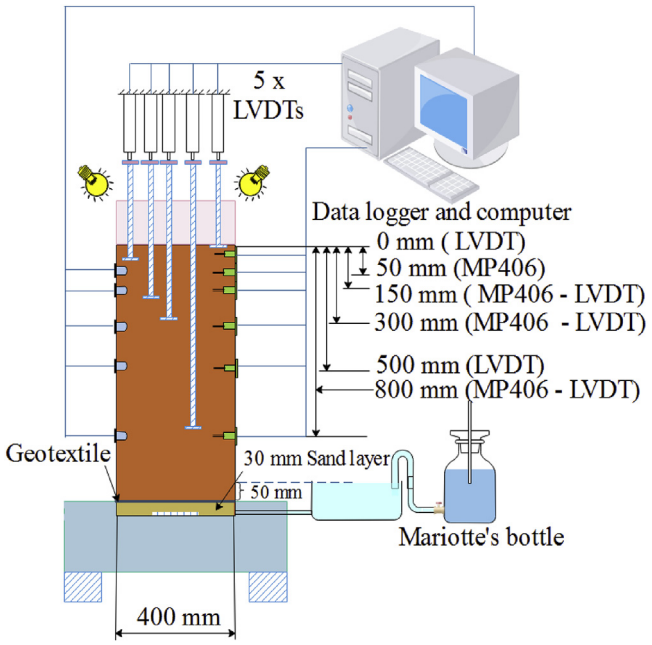


Fig. 1. Schematic diagram of the instrumented soil column during dry cycle.

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

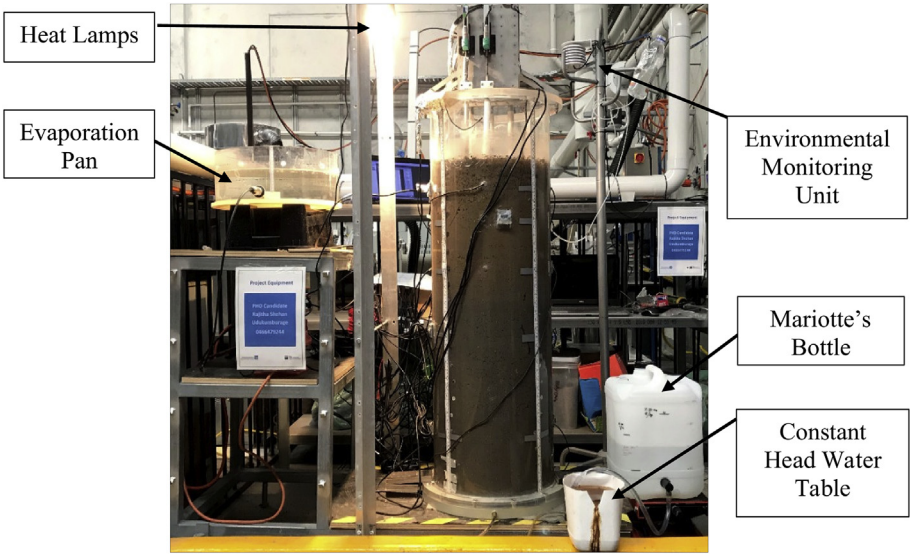


Fig. 2. Instrumented soil column for expansive soil shrinkage monitoring.

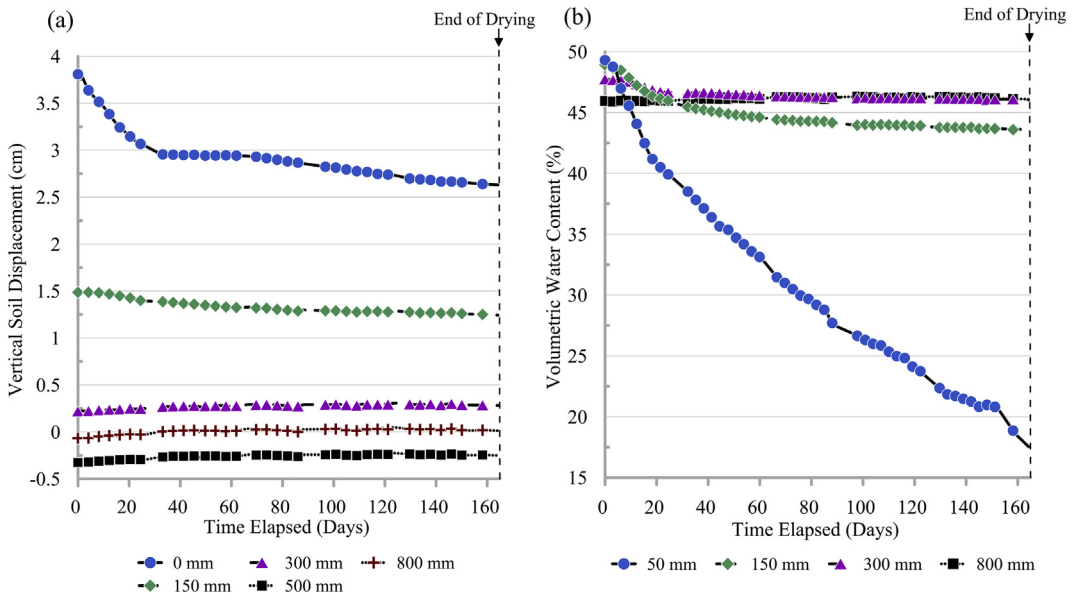
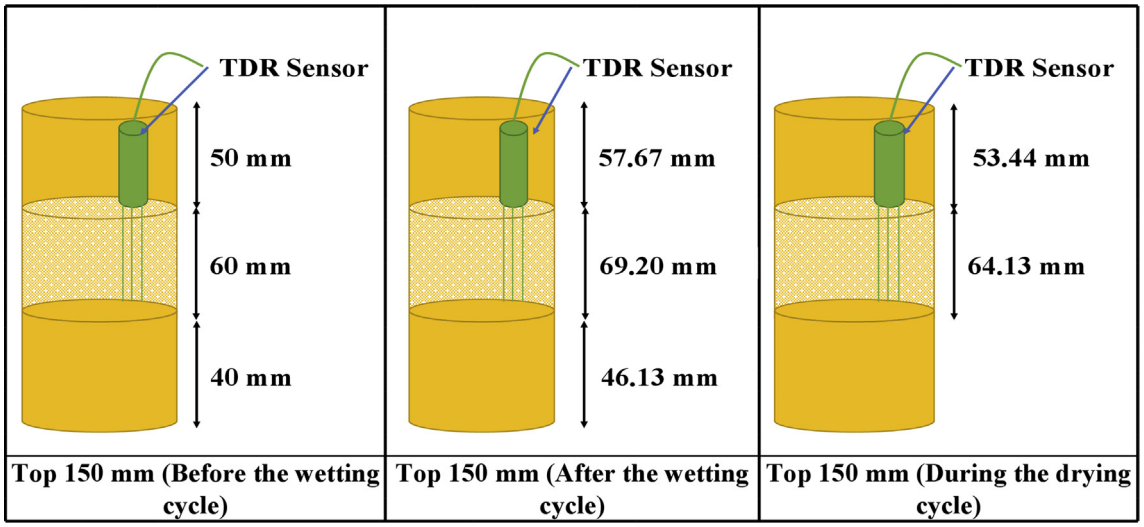


Fig. 3. (a) Subsoil displacement and (b) vwc variations during the dry cycle.



Top 150 mm layer;	
Ratio	4:06:05
Heave	23 mm

For the 60 mm layer;	
Heave	9.20 mm

Top (69.2 + 57.7) mm layer;	
H (ini)	126.87 mm
Total Shrinkage	9.3 mm
Ratio	69.2 : 57.7
Shrinkage (TDR)	5.07 mm

For the 69.2 mm layer;	
h (i)	69.2 mm
h (f)	64.13 mm
Δε	7.33%
Δθ	32%
Δε/Δθ	0.23

Fig. 4. Subsoil vertical shrinkage analysis in the instrumented soil column.

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.

$$\frac{\Delta\varepsilon_{oed}}{\Delta\theta} = f\ (s) \tag{1}$$

$$\frac{\Delta\varepsilon_{oed}}{\Delta\theta} = -0.0117*S - 0.1287 \tag{2}$$

$$\Delta\varepsilon_{oed} = (-0.0117*S - 0.1287)*\Delta\theta \tag{3}$$

Where; ε_{oed} = Vertical strain(%)

θ_i = Initial volumetric water content (%)
θ_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 $\Delta\varepsilon_{oed}/\Delta\theta$, 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 $\Delta\varepsilon_{oed}/\Delta\theta$ 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.

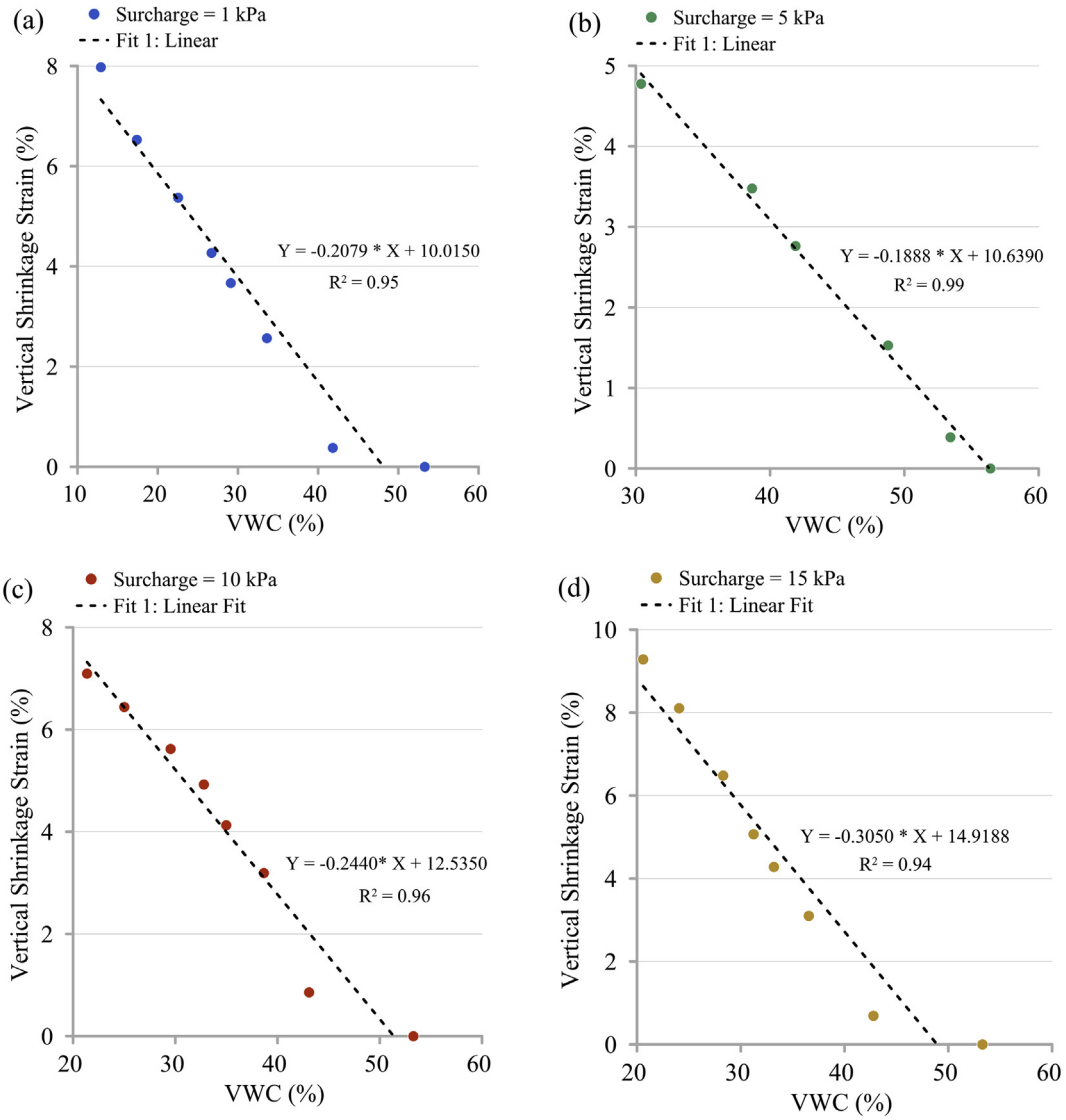


Fig. 5. Oedometer based vertical shrinkage analysis: (a) 1kPa (b) 5kPa (c) 10 kPa (d) 15kPa.

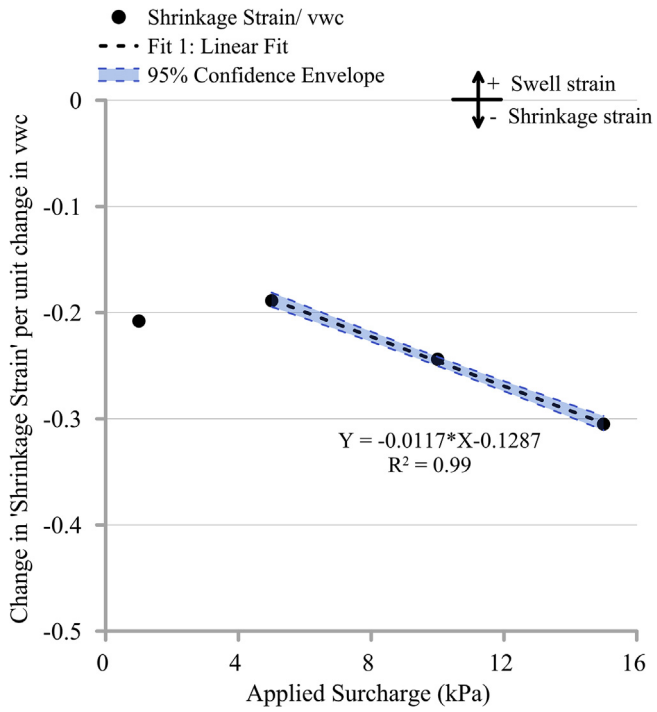


Fig. 6. Variation of shrinkage strain per unit change in vwc under applied surcharge.

Δh_{shrink} = Thickness of the layer × ($\Delta\varepsilon_{oed}/\Delta\theta$) × Change in volumetric water content

= 173 × 0.151 × 0.32

= 8.36 mm

This one dimensional 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, $\Delta\varepsilon_{oed}/\Delta\theta$ determined from oedometer test may underestimate the actual factor which resulted in a slight underestimation in shrinkage. However, the investigation of the boundary effect need to be addressed with effect of lateral shrinkage and the sample size; which is out of scope for this study.

4.3. Vertical shrinkage prediction methods

4.3.1. Briaud's method

Briaud et al. (2003) have suggested that the vertical shrinkage of expansive soils can be estimated using equation (Eq. (4)).

$$\Delta h_{sh} = \frac{z_i.f.\Delta w}{E_w} \quad (4)$$

Briaud's estimation model consists of four main parameters; namely, thickness of the shrinking soil layer (z_i), axial shrinkage strain for unit volumetric strain (f), reduction of the gravimetric water content of the soil layer (Δw) and shrink-swell modulus (E_w). From Fig. 3, initial thickness (before drying) of the soil layer of interest (z_i) is 173 mm (57.67 mm + 69.2 mm + 46.13 mm). Generally, f is considered as 0.33 for one-dimensional (vertical) shrinkage (Briaud et al., 2003); hence the same approach was used in this study. The reduction in the gravimetric water content was determined based on the relationship between the volumetric water content and dry density of soil. Total change in volumetric water content at the layer of interest was captured as 32% according to the MP406 (50 mm) sensor responses (Fig. 4). Considering insignificant change in average soil dry density across the entire layer (1.2 g/cm^3) during desiccation, it was deemed that gravimetric water content of the soil as 26.7% (i.e. change in volumetric water content/dry density). From the studies conducted by Briaud et al. (2003), average final shrink-swell moduli values ranged around 0.71–0.73 for clay materials, which agrees with author assumed shrink-swell modulus of 0.72. Calculated shrinkage (Δh_{sh}) based on Briaud's model amounts to 21.17 mm. 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.

$\Delta h_{sh\ (corrected)} = 14.80$ 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 method 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_{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).

$$\text{Instability Index} = \frac{\partial\varepsilon}{\partial\ \log(\varphi)} \quad (5)$$

$$\frac{\partial\varepsilon}{\partial\ \log(\varphi)} = 1.17$$

Where; $\partial\varepsilon$ = Change in vertical strain

$\partial\ \log(\varphi)$ = Soil suction change (in log scale)

$$\Delta H = \frac{1}{100}\left[\frac{\partial\varepsilon}{\partial\ \log(\varphi)}\right].H.\ \Delta\log(\varphi) \quad (6)$$

$\Delta H = 0.01*1.17*173*(\log 1800/8)$

$\Delta H = 4.76$ mm

The vertical shrinkage obtained using the oedometer based test results (Eq. (5)) in conjunction with the Aitchison's heave estimation

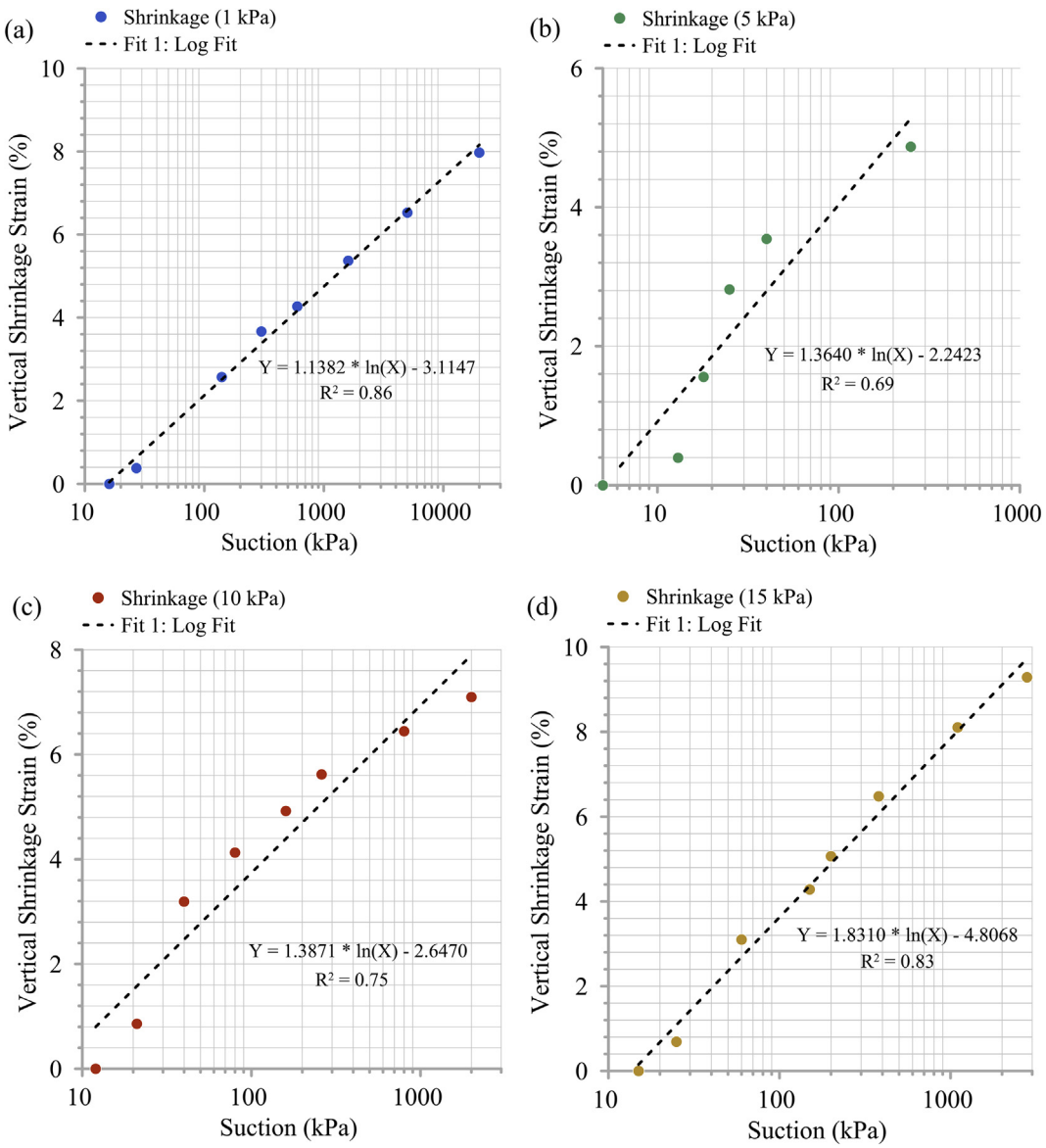


Fig. 7. Oedometer based shrinkage index analysis: (a) 1kPa (b) 5kPa (c) 10 kPa (d) 15kPa.

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.

$$\Delta H = C_{w,dry}.H.(w_i - w_f) \quad (7)$$

$$C_{w,dry} = \frac{\alpha.G_s}{1 + e_0} \quad (8)$$

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 = gravimetric water content × specific gravity). Volume compressibility factor (α) 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 ($C_{w,dry}$) using Eq. (8) amounts to 0.416. The shrinkage (ΔH) 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.

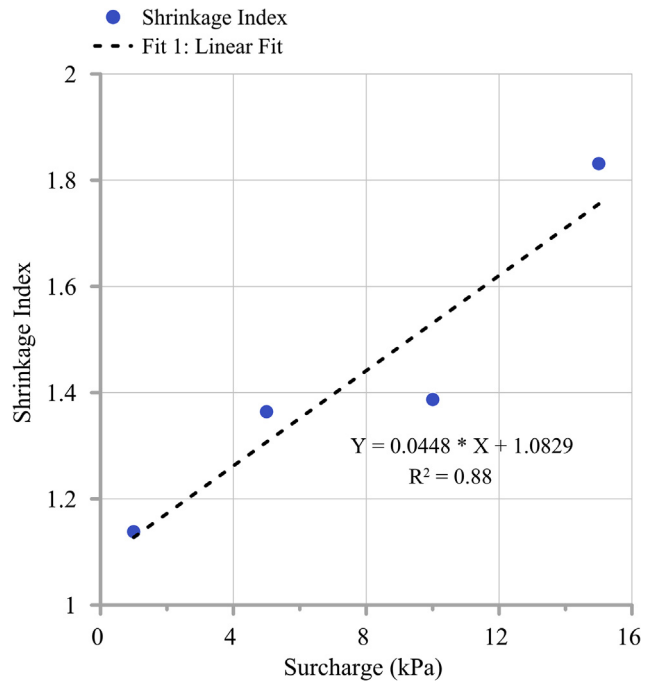


Fig. 8. Effect of surcharge on shrinkage Index.

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 underestimates 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% overestimated) 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.

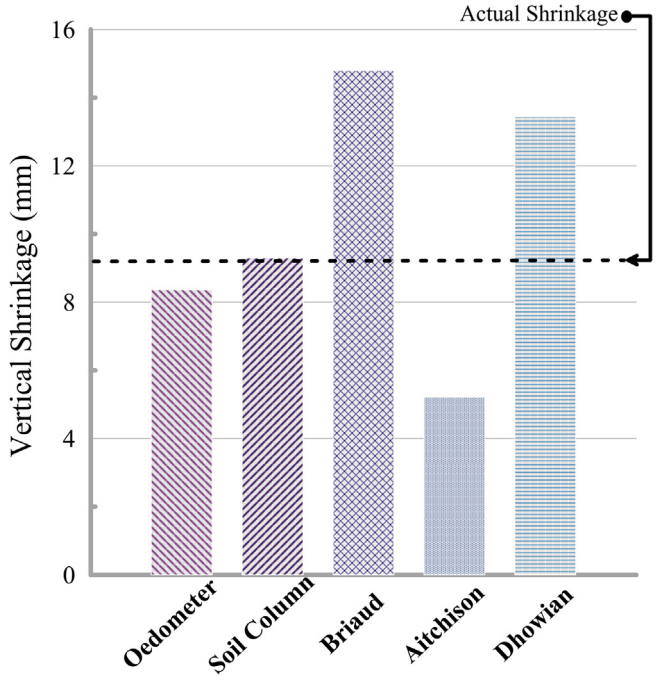


Fig. 9. Comparison of the shrinkage results.

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.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

Acknowledgements

Authors gratefully acknowledge the technical staff at Queensland University of Technology (QUT) for providing the on-campus & off-campus (Banyo Pilot Plant) laboratory facilities to conduct the test series. Further, gratitude should be extended to Steve Hackworth from THE SOILTESTERS for providing the in-kind support for the project. The first author acknowledges the scholarship for doctoral degree received from QUT, Australia.

References

Abeykoon, A.M., Udukumburage, R.S., Gallage, C., 2017. Comparison of direct and indirect measured soil-water characteristic curves for a silty sand. Int. J. GEOMATE 13 (39), 9–16.

Aitchison, G.D., Peter, P., 1973. Quantitative description of the stress deformation behaviour of expansive soils. In: 3rd International Conference on Expansive Soils, Haifa, Israel.

Al-Shamrani, M.A., Dhowian, A.W., 2003. Experimental study of lateral restraint effects on the potential heave of expansive soils. Eng. Geol. 69 (1), 63–81.

Albrecht, B.A., Benson, C.H., 2001. Effect of desiccation on compacted natural clays. J. Geotech. Geoenviron. Eng. 127 (1), 67–75.

Allaire, S.E., Roulier, S., Cessna, A.J., 2009. Quantifying preferential flow in soils: a review of different techniques. J. Hydrol. 378 (1-2), 179–204.

AS 1289.3. 6.3, 2003. Methods of Testing Soils for Engineering Purposes—Soil Classification Tests—Determination of the Particle Size Distribution of a Soil-Standard Method of fine Analysis Using Hydrometer. SAI Global.

AS 1289.3.5.1, 2006. Methods of Testing Soils for Engineering Purposes—Soil Classification Tests—Determination of the Soil Particle Density of a Soil-Standard Method.

AS 1289.3.4.1, 2008. (R2016) – Methods of Testing Soils for Engineering Purposes—Soil Classification Tests—Determination of the Linear Shrinkage of a Soil-Standard Method.

AS 1289.3.1.1, 2009. (R2017)-Methods of Testing Soils for Engineering Purposes—Soil Classification Tests—Determination of the Liquid Limit of a Soil-Four point Casagrande Method.

AS 1289.3.2.1, 2009. Methods of Testing Soils for Engineering Purposes—Soil Classification Tests—Determination of the Plastic Limit of a Soil-Standard Method. SAI Global.

AS 1289.3. 6.1, 2009. Methods of Testing Soils for Engineering Purposes—Soil Classification Tests—Determination of the Particle Size Distribution of a Soil-Standard Method of Analysis by Sieving. SAI Global.

Ata-Ur-Rehman, T., Dunford, D.S., 1993. Soil volumetric shrinkage measurements: a simple method. Soil Sci. 155 (5), 325–330.

Bouma, J., Wösten, J., 1984. Characterizing ponded infiltration in a dry cracked clay soil. J. Hydrol. 69 (1-4), 297–304.

Briaud, J.-L., Zhang, X., Moon, S., 2003. Shrink test–water content method for shrink and swell predictions. J. Geotech. Geoenviron. Eng. 129 (7), 590–600.

Bronswijk, J.J.B., 1988. Modeling of water balance, cracking and subsidence of clay soils. J. Hydrol. 97 (3-4), 199–212.

Chan, D., Gallage, C.P., Rajeev, P., 2015. Field performance of in-service cast iron water reticulation pipe buried in reactive clay. Can. Geotech. J. 52 (11), 1861–1873.

Cornelis, W., Corluy, J., Medina, H., Diaz, J., Hartmann, R., Van Meirvenne, M., Ruiz, M., 2006. Measuring and modelling the soil shrinkage characteristic curve. Geoderma 137 (1-2), 179–191.

Chan, D., Rajeev, P., Kodikara, J.K., Gallage, C., 2016. Field performance of in-service cast iron gas reticulation pipe buried in reactive clay. J. Pipe. Sys. Eng. Pract. 7 (2), 1–15.

Dhowian, A.W., 1990. Heave prediction techniques and design consideration on expansive soils. J. King Saud Univ.

Favre, F., Boivin, P., Wopereis, M., 1997. Water movement and soil swelling in a dry, cracked Vertisol. Geoderma 78 (1-2), 113–123.

Fityus, S.G., Smith, D.W., 1998. A simple model for the prediction of free surface movements in swelling clay profiles. In: Proceedings of the 2nd International Conference on Unsaturated Soils, pp. 473–478. Beijing, China.

Gallage, C., Chan, D., Gould, S., 2009. Behaviour of an In-Service Cast Iron Water Reticulation Pipe Buried in Expansive Soil.

Gallage, C., Kodikara, J.K., Chan, D., 2012. Response of a plastic pipe buried in expansive clay. In: Proceedings of the Institution of Civil Engineers: Geotechnical Engineering, 165, pp. 45–57, 1.

Gallage, C.P., Tehrani, N., Williams, D., 2017. Instrumented large soil-column to investigate climate-induced ground deformation in expansive soil. In: Proceedings of the 19th International Conference on Soil Mechanics and Geotechnical Engineering, pp. 1147–1150.

Groenevelt, P., Grant, C., 2004. Analysis of soil shrinkage data. Soil Tillage Res. 79 (1), 71–77.

Isbell, R., 2016. The Australian Soil Classification. CSIRO publishing.

Julina, M., Thyagaraj, T., 2018. Determination of volumetric shrinkage of an expansive soil using digital camera images. Int. J. Geotech. Eng. 1–9.

Karunarathne, A.M.A.N., Sivanerupan, S., Gad, E.F., Disfani, M.M., Rajeev, P., Wilson, J.L., Li, J., 2014. Field and laboratory investigation of an expansive soil site in Melbourne. [Article]. Aust. Geomech J. 49 (2), 85–94.

Kodikara, J., Rajeev, P., Chan, D., Gallage, C., 2013. Soil moisture monitoring at the field scale using neutron probe. Can. Geotech. J. 51 (3), 332–345.

Konrad, J.-M., Ayad, R., 1997. Desiccation of a sensitive clay: field experimental observations. Can. Geotech. J. 34 (6), 929–942.

Masia, M.J., Totoev, Y.Z., Kleeman, P.W., 2004. Modeling expansive soil movements beneath structures. J. Geotech. Geoenviron. Eng. 130 (6), 572–579.

Lytton, R.L., 1994. Prediction of movement in expansive soils. In: Proceedings of Settlement 94 Conference. Geotechnical Special Publication No. 40. ASCE, Reston, pp. 1827–1845.

Lytton, R.L., 1997. Engineering structures in expansive soils. In: proceedings of N. Sat 97. Freitas Bastos Editora, pp. 333–354.

Novak, V., 1999. Soil-crack characteristics—estimation methods applied to heavy soils in the NOPEX area. Agric. For. Meteorol. 98, 501–507.

Peng, X., Horn, R., Peth, S., Smucker, A., 2006. Quantification of soil shrinkage in 2D by digital image processing of soil surface. Soil Tillage Res. 91 (1-2), 173–180.

Por, S., Likitlersuang, S., Nishimura, S., 2015. Investigation of shrinkage and swelling behaviour of expansive/non-expansive clay mixtures. Geotech. Eng. J. SEAGS AGSSEA 46 (1), 117–127.

Por, S., Nishimura, S., Likitlersuang, S., 2017. Deformation characteristics and stress responses of cement-treated expansive clay under confined one-dimensional swelling. Appl. Clay Sci. 146, 316–324.

Punthutaecha, K., Puppala, A.J., Vanapalli, S.K., Inyang, H., 2006. Volume change behaviors of expansive soils stabilized with recycled ashes and fibers. J. Mater. Civ. Eng. 18 (2), 295–306.

Puppala, A.J., Manosuthikij, T., Chittoori, B.C.S., 2013. Swell and shrinkage characterizations of unsaturated expansive clays from Texas. Eng. Geol. 164, 187–194.

Puppala, A.J., Manosuthikij, T., Chittoori, B.C., 2014. Swell and shrinkage strain prediction models for expansive clays. Eng. Geol. 168, 1–8.

Puppala, A.J., Manosuthkij, T., Nazarian, S., Hoyos, L.R., Chittoori, B., 2011. In situ matric suction and moisture content measurements in expansive clay during seasonal fluctuations. Geotech. Test J. 35 (1), 74–82.

Talsma, T., 1977. A note on the shrinkage behaviour of a clay paste under various loads. Soil Res. 15 (3), 275–277.

Tang, A.M., Ta, A.N., Cui, Y.J., Thiriat, J., 2009. Development of a large-scale infiltration tank for determination of the hydraulic properties of expansive clays. Geotech. Test J. 32 (5).

Tang, C.-S., Cui, Y.-J., Shi, B., Tang, A.-M., Liu, C., 2011a. Desiccation and cracking behaviour of clay layer from slurry state under wetting–drying cycles. Geoderma 166 (1), 111–118.

Tang, C.-S., Shi, B., Liu, C., Suo, W.-B., Gao, L., 2011b. Experimental characterization of shrinkage and desiccation cracking in thin clay layer. Appl. Clay Sci. 52 (1-2), 69–77.

Tripathy, S., Sahar, A., Cleall, P., Baille, W., Schanz, T., 2016. Soil suction measurement of unsaturated soils with a sensor using fixed-matrix porous ceramic discs. Indian Geotech. J. 46 (3), 252–260.

Udukumburage, R.,S., Gallage, C., Dawes, L., 2018. Loaded swell tests to estimate the heave of the expansive soil in instrumented soil column. In: 8th International Conference on Geotechnique, Construction Materials and Environment. The Geomate International Society, Kuala Lampur, Malaysia, pp. 390–395.

Udukumburage, R.,S., Gallage, C., Dawes, L., 2019. Investigation of the effect of initial water content and surcharge on volume change behaviour of compacted grey Vertosol. In: 13th Australia Newzealand Conference on Geomechanics. Australian Geomechanics Society, Sydney, Australia, pp. 1029–1034.

Vogel, H.-J., Hoffmann, H., Roth, K., 2005. Studies of crack dynamics in clay soil: I. Experimental methods, results, and morphological quantification. Geoderma 125 (3-4), 203–211.

Zemenu, G., Martine, A., Roger, C., 2009. Analysis of the behaviour of a natural expansive soil under cyclic drying and wetting. Bull. Eng. Geol. Environ.

Zhan, T.L., Ng, C.W., Fredlund, D.G., 2006. Instrumentation of an unsaturated expansive soil slope. Geotech. Test J. 30 (2), 113–123.