Hydromechanical characterisation of a highly expansive clay

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Abstract. The hydromechanical properties of a South African expansive clay are reported. In this study, swell potential and swell pressure were assessed by two oedometric approaches, namely, the loading after wetting test and the wetting after loading test. The data indicate that predictions of swell pressure from the two approaches remain similar, whereas greater predictions of heave are obtained for the loading after wetting approach. It is also observed that the magnitude of predicted heave from the loading after wetting test is dependent on the soaking stress considered, with greater swell being obtained for lower soaking stresses. Measurements of primary drying and wetting curves illustrate appreciable hysteresis in the intermediate suction range (≈17 MPa). The discrepancy of this finding with that of a previous study is attributed to differences in fabric. Additionally, when examining the volumetric response of a sample subjected to a drying and wetting path, negligible hysteresis is observed when void ratio is plotted as a function of gravimetric water content. Conversely, when the shrinkage/swell curves are plotted in terms of suction, irreversibly volumetric changes are apparent.

1 Introduction

Expansive clays are present across much of Africa, and the world [1]. Often referred to as swelling clays, expansive clays are highly affected by changes in water content, swelling when wetted and shrinking and cracking when dried [2]. Hence, extreme seasonal fluctuations in water content that occur in semi-arid, subtropical climates such as South Africa [3], can result in substantial volume changes. Such volumetric behaviour causes the soil to exert large forces on overlying structures. This presents problems in civil engineering design, often resulting in cracks in walls, damage to utilities, movement of foundations and lifting of structures [1]. In the USA, it is reported that annual damage to infrastructure by swelling clays costs more than twice that caused by hurricanes, earthquakes and tornadoes combined [4]. Similar accounts have reported annual costs of several billions for other countries [5].

To quantify the anticipated magnitude of surface heave and the pressure that is likely to be exerted on overlying or adjacent structures, oedometer testing is commonly utilised. The three types of oedometer tests available include:

- Loading after wetting test [6] – also referred to as the swell followed by consolidation test [7].
- Wetting after loading test [6] – sometimes referred to as soaking under load curve.
- Constant volume swell followed by rebound [8]

Recognising that the above tests represent different stress paths, it is worth considering the applicability of each to typical engineering scenarios. The wetting after loading test represents arguably the most typical stress path encountered in practice, whereby a structure is built on an expansive clay, and changes in water content occur sometime after construction. The loading after wetting test represents a case whereby the profile was pre-wetted prior to construction. The least common stress path is that followed by the constant volume test which represents a case whereby the profile would be wetted up under almost perfect restraint.

This study investigates the swell properties of a highly expansive clay using the first two approaches listed. The intrinsic clay properties are also established in accordance with the framework outlined by [9]. Finally, primary drying and wetting soil water retention curves (SWRCs) are presented.

2 Material description and experimental setup

2.1 Material description

The clay tested in this study was sampled from a Bentonite mine, near Vredefort in the Free State province of South Africa. While preliminary indicator tests showed that the most expansive layer occurred at a depth of approximately 3 m, samples were collected from the upper portions of the profile (≈1 m) since this is the region where the greatest fluctuations in water content occur. The particle size distribution curve and basic material properties are presented in Figure 1 and

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Table 1, with the clay's mineralogical composition provided in Table 2.

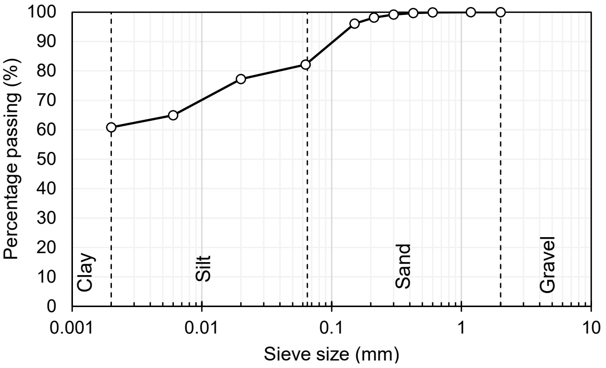

Fig. 1. Particle size distribution curve

Table 1. Basic material properties and soil classification.

Liquid limit, LL (%)	66.1
Plastic limit, PL (%)	18.
Plasticity index, PI (%)	47.3
Specific gravity, G_s	2.662
BS Classification	CH

Table 2. Mineralogical composition.

Mineral	Composition (%)
Quartz	36.8
Plagioclase	7.2
K-feldspar	5.5
Mica	9.4
Smectite	40.0
Kaolinite	1.1
Pyrite	<0.5

2.2 Experimental setup

For all tests presented in this study, natural clay was first air dried for a period of at least one week. The air-dried clay was then broken up with a pestle and mortar and passed through a 2 mm sieve prior to being wet up to initial testing conditions. To establish the clay's intrinsic properties in accordance with the framework outlined by [9], a one-dimensional consolidation test was conducted on a specimen reconstituted at a water content of 1.1LL. After adding the desired amount of water to air-dried clay, the mixture was left to equilibrate for a period of 48 hours prior to testing.

To assess the soil's swell properties, oedometer samples were prepared to match the in-situ water content and dry density as measured from auger cuttings at the site (w=21.5% and 1450 kg/m^3 respectively). To achieve the desired water content, air-dried material was slowly wetted up inside a humidity chamber. Once reaching the desired water content, the wetted material was placed inside sealed bags and allowed to equilibrate prior to sample preparation. Following equilibration, oedometer samples measuring 75 mm and 20 mm in diameter and height respectively, were statically compacted to the targeted bulk density.

To measure soil water retention curves (SWRCs), saturated samples measuring 15 mm and 10 mm in diameter and height respectively were prepared. Due to experimental difficulties, the prepared sample achieved a dry density of 1550 kg/m^3 (slightly above the in-situ dry density). Once prepared, suction readings were taken using a dewpoint hygrometer at various degrees of saturation to establish a primary drying curve. Drying was initially performed under ambient laboratory conditions. However, as the soil approached its residual water content further drying was not possible. For this reason, rather than placing the sample in the oven which is known to affect certain properties of tropical soils [3], it was placed in a desiccator chamber with a low relative humidity as suggested by [10]. Using this approach, the sample was dried out to a gravimetric water content of approximately 4%. At this point, the sample was deemed to have achieved its residual water content and a primary wetting curve was then measured. To increase the sample's water content, it was placed in a desiccator chamber, partially filled with distilled water to achieve a high relative humidity environment. The sample was then left in the chamber to absorb moisture for various periods of time, with suction measurements being taken at different water contents to establish a primary wetting curve. It should be noted that while the measurement capacity of the dewpoint hygrometer used is 300 MPa, drying was continued beyond this point such that the residual water content could be reached, and a full shrinkage curve measured.

3 Results

3.1 Measurement of intrinsic clay properties

Burland [9] outlined a framework whereby the 'intrinsic' properties of a clay could be determined. According to this framework, intrinsic properties are those determined from a sample which has been reconstituted at a water content of between LL and 1.5LL. The sample is then consolidated, preferably under one-dimensional conditions [9].

The term 'intrinsic' is used to refer to properties which are inherent to the soil and independent of its natural state. The framework outlined by [9] is defined in terms of intrinsic void ratios, e^*_{100} and e^*_{1000}, the void ratios at vertical effective stresses of 100 and 1000 kPa respectively, and the intrinsic compression index, $C^*_c = e^*_{100} - e^*_{1000}$.

In this study, difficulties in the measurement of the initial sample volume made accurate measurement of the intrinsic void ratios problematic. However, since the intrinsic compression index is determined using the difference between these properties, this parameter was unaffected and calculated to be 0.494. Using the void ratio at the soil's liquid limit (e_L=1.759), the intrinsic compression index of the clay under investigation could be compared to that of previous studies as illustrated in Figure 2. The calculated value of C^*_c fits within the general range suggested by [9]. However, the data point corresponding to the clay in this study fits the theory proposed by [2] that reconstituted tropical soils may possess slightly higher values of C_c^* when compared to Burland's initial relationship.

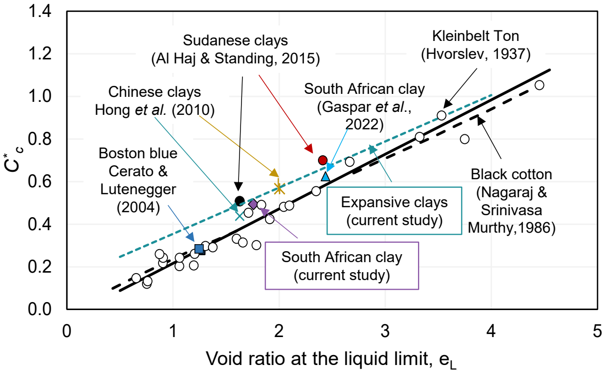

Fig. 2. Relationship between $\boldsymbol{e_L}$ and $\boldsymbol{C_c^*}$

A possible explanation for this deviation is that tropical soils tend to exhibit large volumetric changes when reconstituted and hence, exhibit greater compressibility upon loading.

By considering the data point from this study, together with those proposed by [9] and [11] a linear relationship between C_c^* and e_L can be established, which follows a gradient similar to the original dataset, but with an upwards vertical shift. This trendline is defined by Equation 1.

$$C_c^* = 0.217e_L + 0.1379 \qquad (1)$$

Equation 1 fits the data corresponding expansive tropical clays with an R^2=0.980 which supports a shifted trendline for expansive clays, as suggested by Al Haj & Standing [2].

3.2 Measurement of swell properties

The results of loading after wetting and wetting after loading tests are presented in Figure 3 and Figure 4 respectively. In Figure 3, loading after wetting tests are presented for a range of soaking stresses. From these results, it can be seen that, so long as the soaking stress was less than the swell pressure (pressure required to produce zero volume change upon inundation), similar predictions for swell pressure are obtained (between 100 and 117 kPa). An estimate of swell potential can also be obtained at stresses less than the swell pressure, by reading off the volumetric strain at a given applied vertical stress from a loading after wetting curve. Using this approach, it can be seen that the prediction of swell potential is affected by the magnitude of the soaking stress, with smaller soaking stresses indicating greater magnitudes of heave. This finding is consistent with that of [12].

When interpreting the loading after wetting data presented in Figure 4, the test conducted at 1.1 kPa was omitted when fitting a best fit relationship through the data points. The reason for this omission is due to the fact that such a low stress is unrepresentative of typical foundation stresses encountered in engineering practice.

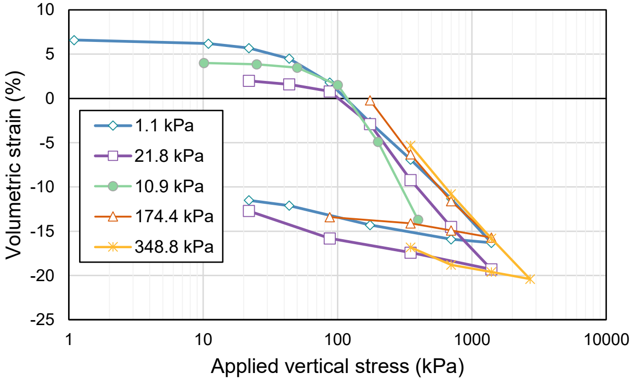

Fig. 3. Loading after wetting curves

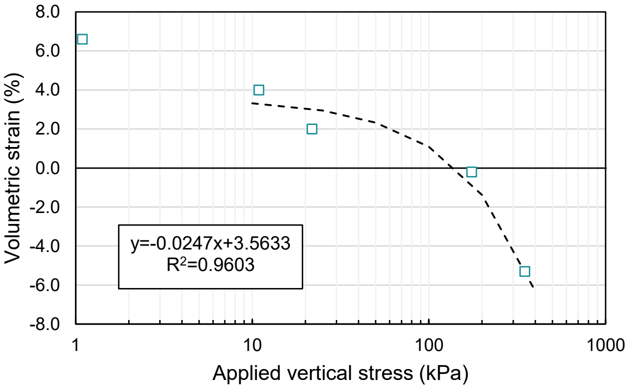

Fig. 4. Wetting after loading curve

The resulting best-fit curve through the remaining data points produces a linear relationship for the wetting after loading curve for the stress range considered. Using this relationship, a swell pressure of 144 kPa is obtained. Prediction of a larger swell pressure from the wetting after loading curve is consistent with the findings of Gaspar et al. [11] but contrary to that of Sridharan *et al.*[13]. Nevertheless, as highlighted by Gaspar *et al.* [11], predictions from the two approaches remain close from a practical engineering perspective.

What is perhaps peculiar from the data presented in Figure 3, is that the various tests do not conform to a unique normal consolidation line as would be expected within the traditional critical state framework. A potential explanation for this finding could be related to soil fabric. As pointed out by [14], compacted clays have a distinct bimodal pore size distribution which is altered during the swell process. If it is recognised that yield of soil structure (where structure is the combination of fabric and bonding) is a function of strain or strain energy [15], then it can be appreciated that samples allowed to swell to different magnitudes will have a fabric that is altered by different amounts when compared to their initial state. In such a scenario it is theoretically plausible that normal consolidation lines different from that determined on a reconstituted specimen could be followed. Further research is however required to explore this hypothesis.

3.3 Soil water retention and shrinkage curves

Figure 5 illustrates the primary drying and wetting curves for the material tested. Also included in the figure are the Van Genuchten [16] best fit curves, which were used to quantify the magnitude of hysteresis observed across the range of suction considered. In the figure, hysteresis is plotted on a secondary vertical axis as the difference in saturation between the drying and wetting curves.

From the data presented it can be seen that the curves illustrate significant hysteresis, which peaks at intermediate suctions of approximately 17 MPa. This is contrary to the findings of [10] who observed negligible hysteresis between primary drying and wetting curves measured on compacted and undisturbed expansive clay specimens. A possible reason for the discrepancy is related to differences in fabric. Whereas this study measured SWRCs on specimens compacted in a saturated state, [10] measured SWRCs on samples which had undergone inundation, loading, and unloading in an oedometer. Appreciating that undisturbed specimens have both a mechanical and hydraulic stress history, it is worth questioning to what extent compacted samples (for which both mechanical and hydraulic stress history have been eliminated to a certain degree) represent the hydraulic behaviour of in-situ material.

Figures 6 and 7 present shrink/swell curves in terms of gravimetric water content (w) and degree of saturation (S_r) respectively. From Figure 6 it can be seen that the drying curve begins to deviate from full saturation at approximately w=19%, reaching the shrinkage limit at around w=8%. It is worth noting that while the plot of void ratio (e) versus w does not appear to indicate significant hysteresis, when void ratio is plotted in terms of S_r, hysteresis can be clearly observed. Recognising this hysteretic response, it can be stated that the effects of irreversible volume change (together with fabric realignment) was a contributing factor to the hysteresis observed in Figure 5.

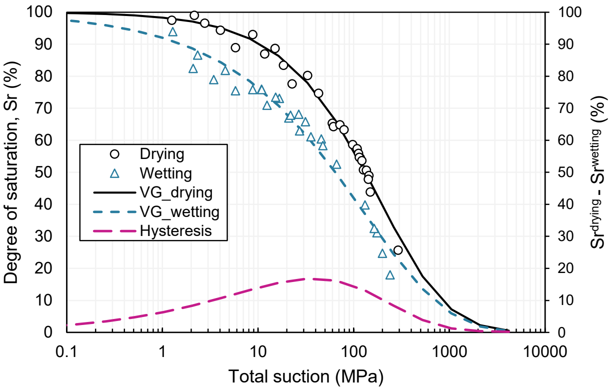

Fig. 5. Soil water retention curves

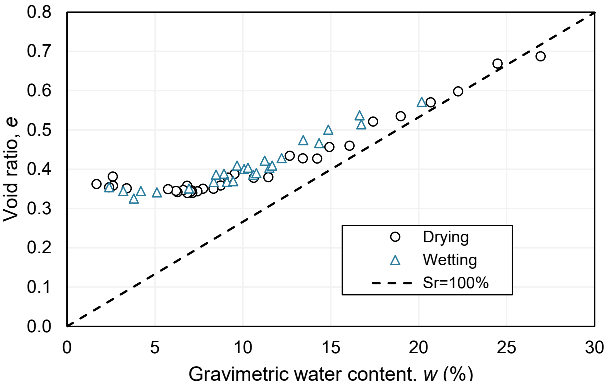

Fig. 6. *e*-*w* shrinkage/swelling curves

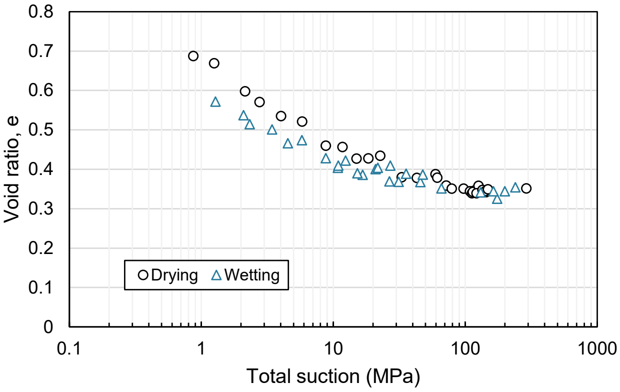

Fig. 7. *e*-suction shrinkage/swelling curves

4 Conclusions

This study investigates the hydromechanical behaviour of an expansive clay, sampled from the Free State province of South Africa. The swell magnitude and swell pressure were assessed using two approaches, namely, the loading after wetting test, and the wetting after loading approach. While the wetting after loading approach predicted a slightly higher magnitude of swell pressure, the difference was deemed to be negligible from a practical engineering perspective.

Estimates of heave from the loading after wetting approach are shown to overpredict swell at low stresses when compared to predictions from the wetting after loading tests. The magnitude of overprediction is found to decrease with an increase in soaking stress.

Measurements of primary drying and wetting curves illustrate appreciable hysteretic behaviour in the intermediate suction range (≈17 MPa). Differences between this finding in comparison to a previous study are attributed to the effects of fabric induced during the sample preparation process.

Finally, whereas the shrinkage/swell curve plotted as a function of gravimetric water content illustrated negligible hysteresis, when viewed in terms of total suction, irreversible volumetric changes induced during drying are highlighted.

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