Investigation of piled foundations in swelling clays

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Abstract. This paper presents the results of element testing and centrifuge modelling to investigate the behaviour of piled foundations in swelling clays. The study revealed that the preparation procedure implemented, was able to retain key hydromechanical properties when compared with undisturbed specimens. Furthermore, the preparation method utilised to create an artificially 'fissured' fabric allowed for significant swell magnitudes to be achieved in the centrifuge within a reasonable timeframe. Centrifuge testing illustrated that, at lower magnitudes of swell, increases in lateral pressure against a pile shaft can increase shaft capacity. However, if swell is allowed to continue to large magnitudes, the effects of swell-induced softening tend to dominate, thus resulting in a reduction in shaft capacity. The effects of swell-induced softening are more prominent close to the clay surface where swell is allowed to occur more freely. However, at greater depths where swell is restricted, so too are the effects of swell-induced softening, resulting in local increases in shaft capacity at greater depths.

1 Introduction

In geotechnical engineering, the problem soil which has had some of the most severe economic implications has been that of swelling or expansive clays [1,2,3,4]. As a point of interest, even the lineage of this conference can be traced back to 1957 when the First Symposium on Expansive Clays took place in South Africa (the first of 11 similarly named symposia/conferences).

Typically characterised as being predominantly composed of active clay minerals, expansive clays exhibit large volumetric changes when subjected to fluctuations in water content. Additionally, if swell is restricted during a wetting process, increases in soil pressure can be harmful to overlying or adjacent structures. Measures taken to mitigate the effects of this problem soil can broadly be divided into three categories, namely, soil treatment or replacement, construction directly on the expansive profile, and isolation of the superstructure from the expansive profile.

The removal and replacement option is generally a feasible approach when the depth of expansive clay is shallow, and suitable inert material is readily available [5]. Alternatively, the soil can be 'treated' by pre-wetting such that swell occurs prior to construction. A drawback of this approach, however, is that the time required for full swell to occur may be significant. Arguably the most common approach to foundation design on expansive clays is to use a stiffened raft foundation [4,5,6]. Such an approach aims to limit differential movements across the foundation. Isolation of the superstructure from underlying soil is the most expensive of the three options mentioned. Such a foundation type typically involves the use of piles extending either to bedrock, or to non-expansive competent material where the piles can be socketed or anchored [5]. The piles are then used to support a suspended foundation which is entirely isolated from the soil surface. The gap provided between the underside of the foundation and the soil surface allows space for the clay to swell into without affecting the superstructure.

While this final design approach can double the cost of construction [7], it can result in almost no foundation movements. The foundation type is, however, not a fail-safe approach. Inadequate sizing of the void between foundation and soil can result in significant uplift forces beneath the superstructure. Examples of such case studies have been reported by Blight [8] and Meintjies [9]. This paper therefore reports a study combining element testing and centrifuge modelling, to investigate the behaviour of piled foundations founded in swelling clays.

2 Material description

The clay tested in this study is a highly expansive clay sampled from the Limpopo province of South Africa, approximately 350 km northeast of Pretoria. Following site investigations, the soil was described as a stiff, fissured and slickensided black clay containing scattered fine nodular calcrete [10].

The site was visited after wet and dry seasons to determine the range of water content and matric suction that is likely to be experienced within a given year. These investigations illustrated seasonal variations in

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gravimetric water content and matric suction of approximately 30–40% and 4–2.5 MPa respectively. Measurements of matric suction were conducted using the filter paper method in accordance with ASTM D5298–16 [11].

The particle size distribution curve, as well as basic classification information are presented in Figure 1 and Table 1 respectively, with the clay's mineralogical composition presented in Table 2.

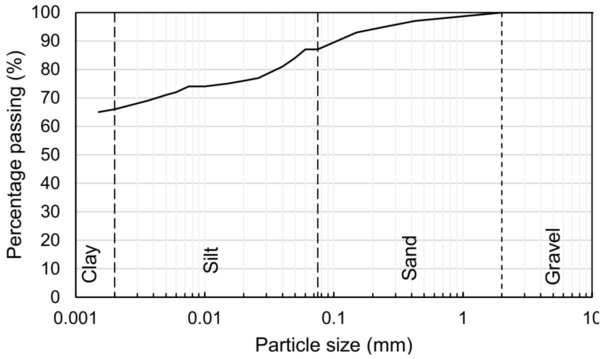


Fig. 1. Particle size distribution curve

Table 1. Basic material properties and soil classification.

Liquid limit, LL (%)	92
Plasticity index, PI (%)	55
Linear shrinkage (%)	25.5
Activity	0.8
Specific gravity, G_s	2.65
Unified soil classification	CH

Table 2. Mineralogical composition (after Moses, 2008)

Mineral	Composition (%)
Smectite	58
Palygorskite	19
Calcite	5
Plagioclase	5
Quartz	4
Enstatite	4
Kaolinite	3
Diopside	2

3 Sample preparation

A goal of the preparation procedure implemented was to mimic some degree of fissuring in the resulting samples, that could ultimately be incorporated in the centrifuge models. The purpose of this was to accelerate water ingress such that a significant amount of heave could be achieved in the centrifuge in a reasonable timeframe.

This fabric type was achieved by breaking down intact block samples with a cheese grater, at the clay's natural water content (gravimetric water content of approximately 31%). The clay gratings were then statically compacted to achieve the in-situ dry density as measured during the various site investigations (approximately 1350 kg/m^3).

4 Element testing

A series of tests were conducted to assess the extent to which the laboratory prepared specimens replicated key properties of undisturbed samples.

To test swell properties, one-dimensional swell and compression tests were conducted on both compacted and undisturbed samples. The sequence of this testing can be described as follows. The initial stage involved placing a sample in the oedometer at its in-situ water content, applying a predetermined vertical stress (referred to as the soaking stress), and then inundating the sample with distilled water. This test, otherwise known as the wetting after loading test [12] was repeated at a number of applied stresses to form a 'soaking under load' curve.

Once volumetric changes became negligible with time, conventional oedometer tests were conducted on each specimen. This allowed for compression and expansion indices to be measured. Furthermore, comparison of these tests with a consolidation test performed on a reconstituted specimen allowed for the effects of structure to be investigated. The results of this comparison between compacted and undisturbed specimens as reported by [13], revealed that the following properties remained, for all practical purposes, similar between compacted and undisturbed samples:

- The magnitude of swell at various overburden stresses.
- The magnitude of pressure required to completely prevent swell (i.e. swell pressure).
- Compression and expansion indices measured in one-dimensional compression tests.
- The effects of soil structure

By plotting the volume change achieved at the end of each wetting after loading test as a function of the applied vertical stress, the soaking under load curve illustrated in Figure 2 is achieved. From this figure, the similarities in swell magnitude and swell pressure between compacted and undisturbed specimens can be seen.

Upon completion of oedometer testing, soil water retention curves (SWRCs) were measured on each oedometer sample. The SWRC specimens were prepared by cutting out a disc from the main oedometer sample, measuring approximately 9.5 mm and 37 mm in height and diameter respectively. Suction and volumetric measurements were then taken at discrete points along a primary drying and wetting path (details of the procedure are provided by Gaspar [14]). Suction measurements were performed using a dewpoint hygrometer. The best fit Fredlund-Xing [15] curves are presented in Figure 3. From this figure it can be seen that the general shape of SWRCs measured on compacted and undisturbed specimens are similar. However, the undisturbed SWRC plots noticeably below the compacted SWRC. Such a result can quite simply be explained by the higher void ratios for the undisturbed samples. Another point of interest is the relatively low hysteresis between wetting and drying cycles, measured in both compacted and undisturbed samples.

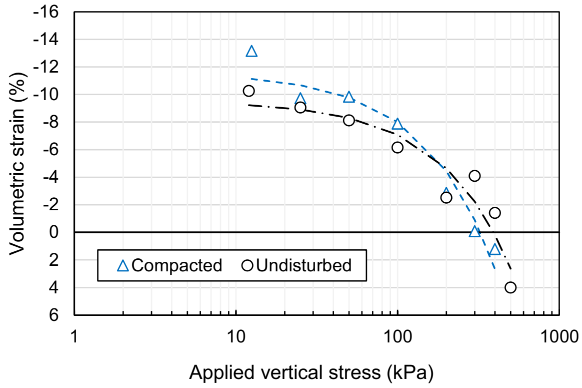
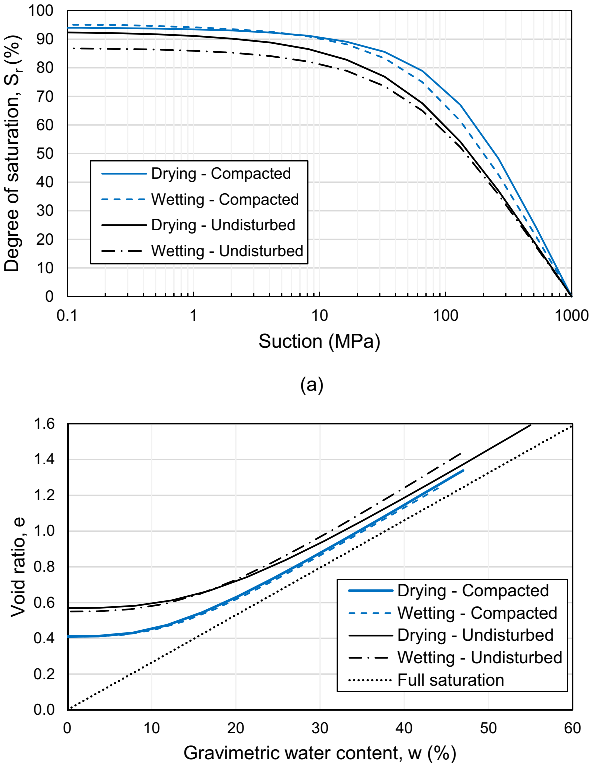


Fig. 2. Soaking under load curve



(a)

(b)

Fig. 3. Soil water retention and shrinkage curves

5 Centrifuge modelling

Using the 150 g-ton geotechnical centrifuge at the University of Pretoria [16], a series of centrifuge tests were conducted on the clay presented in the previous sections, at a centrifugal acceleration of 30 *g*. The first test conducted was aimed to monitor in-flight swell of an expansive clay profile under greenfield conditions (no external loads or embedded structures). Details of this study are provided by Gaspar et al. [17]

The model layout (presented in Figure 4) consisted of five 50 mm statically compacted clay slabs, separated by geotextiles used to allow for the rapid ingress of water. The five clay slabs were laterally restrained in position by two perforated steel plates, covered with the same geotextile used to separate the clay layers. The two spaces on either side of the model were used as water wells to facilitate water ingress. Once achieving a centrifugal acceleration of 30 *g*, the strongbox was flooded over a period of 30 minutes, until the water level was approximately 20 mm above the surface of the top clay slab. Swell of the clay profile was then monitored over a period of 4.5 days (model time).

Figure 5 illustrates the measured swell throughout the profile at various instances in time. Additionally, a swell profile determined using the Van der Merwe empirical swell prediction method [18] is superimposed onto the dataset. Being an empirical method commonly used in Southern Africa, this prediction was assumed to provide an adequate estimate of the average in-situ heave throughout the clay profile. From this figure it is seen that the measured swell at approximately 14 h correlates well with that predicted by the Van der Merwe [18] approach. It could therefore be stated that the model preparation procedure utilised allowed for a realistic magnitude of swell to be achieved within a reasonable timeframe.

A specific question of interest related to the performance of piled foundations, was the effect that the swell process would have on the shaft capacity of a pile. This issue is one which has produced conflicting results in the literature. Blight [8] conducted a series of full-scale pull-out tests on short length piles before and after wetting the clay profile for a period of 3-4 weeks. The results of this study indicated that after the clay had been allowed to swell, pull-out (shaft) capacity increased. This increase was attributed to an increase in lateral pressure around the pile shaft.

Conversely, a study by Elsharief [19] found a reduction in pile shaft capacity after swell had occurred. An explanation for this reduction is that, while swell can cause an increase in lateral pressure, swell-induced softening [20] produces a reduction in shear strength, thus reducing pile shaft capacity.

To investigate this matter further Gaspar et al. [21] conducted centrifuge models where pull-out tests were conducted on short length piles at various depths, as presented in Figure 6. The model piles were made from a rapid hardening grout with a 4 mm stainless steel rod at their centres. Installation of the piles was performed at 1 g by pouring the grout into augured holes measuring 20 mm in diameter. Figure 6 presents the results of two centrifuge tests where pull-out capacities were measured at the clay's in-situ water content, and after the swell predicted by the Van der Merwe approach had been achieved. From this figure, a notable reduction in shaft capacity is observed in upper portions of the profile. However, at greater depths where swell is (to some extent) restricted, so too are the effects of swell induced softening. For this reason, slight increases in shaft capacity were observed at the bottom of the profile.

While insightful, the results presented in Figure 6 investigate the consequences of the swell process, rather than either of the mechanisms at play (i.e. variations in lateral pressure or swell induced softening). For this reason, an additional centrifuge test was conducted using an aluminium pile, instrumented to measure variations in lateral pressure against the pile shaft [21]. These results are provided in Figure 7. Additionally, in-flight cone penetration testing conducted at the clay's

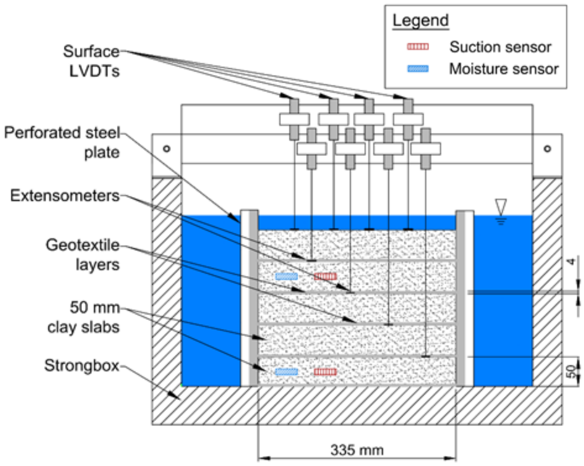


Fig. 4. Model layout

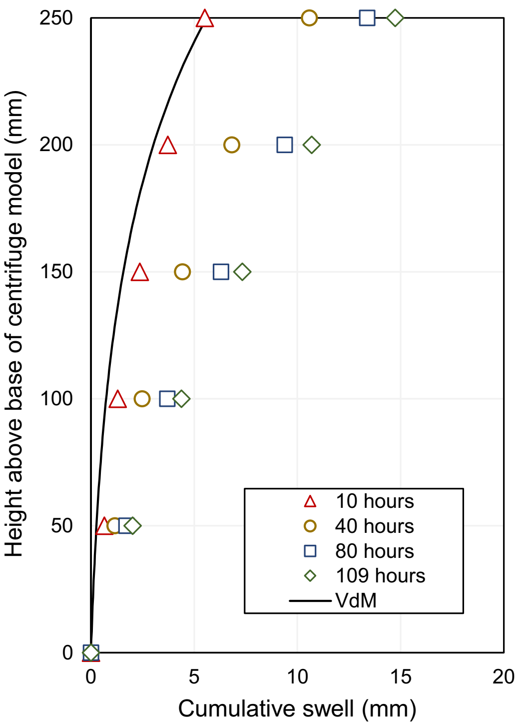


Fig. 5. Measured and predicted heave along profile depth (after Gaspar et al. (2020))

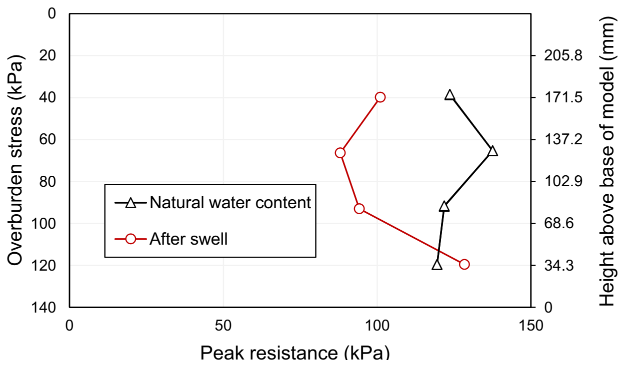


Fig. 6. Comparison of pull-out capacity of short length piles

in-situ water content, and after achieving Van der Merwe swell are also presented in Figure 8.

From Figure 7 it is seen that the lateral pressure against the pile does in fact increase at lower magnitudes of swell. However, if swell is allowed to continue to relatively large values, lateral stresses can reduce to values less than what was experienced at the clay's in-situ water content. For reference, the pull-out capacities presented in Figure 6 were conducted at approximately 2.2% average surface swell (where significant reductions in lateral stress are shown in Figure 7). This is also when the "swelled state" penetration test presented in Figure 8 was conducted.

Viewing these results in conjunction with the work reported by Blight [8] and Elsharief [19], explanations for the discrepancies can be provided. While Blight [8] allowed the profile to be wetted for 3-4 weeks, Elsharief [19] allowed a wetting period of 2 months. Considering the results presented in Figures 7 and 8, it is likely that the tests conducted by Blight took place early in the swell process where there was still an increase in lateral pressure. However, the longer wetting period allowed by Elsharief place these tests in the later stages of swelling, where swell-induced softening becomes the dominant mechanism. From this result it can be stated that, for an accurate prediction of shaft capacity for piles founded in expansive clays, information is required on the likely magnitude of swell that will be achieved during the structure's lifetime.

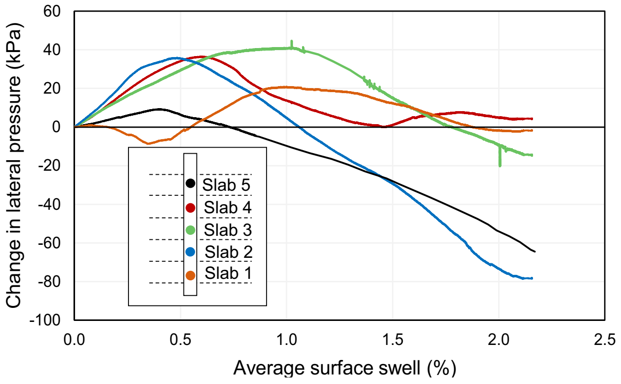


Fig. 7. Changes in lateral pressure against pile shaft

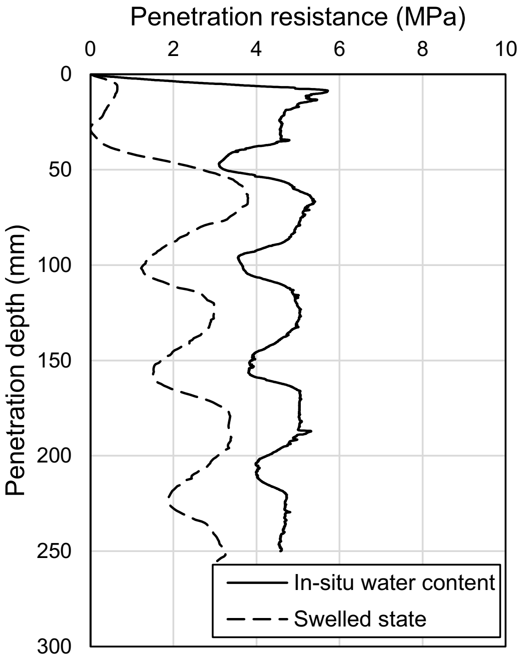


Fig. 8. In-flight cone penetration testing

6 Conclusions

This paper reports the results of a study combining element testing and centrifuge modelling to investigate the behaviour of piled foundations in swelling clays. Element testing was conducted to assess the hydromechanical properties of artificially ‘fissured’, statically compacted specimens, compared to that of undisturbed specimens. The investigation revealed that swell properties, and the effects of soil structure were similar for both compacted and undisturbed samples. Soil water retention curves (SWRCs) on compacted and undisturbed specimens were found to have similar shapes and exhibited negligible hysteresis between primary wetting and drying.

A preliminary centrifuge model illustrated that the sample preparation procedure implemented, allowed for a significant amount of swell to be achieved in-flight, within a reasonable timeframe. The measured swell profile was also found to match well with that determined from an empirical prediction method.

To assess the effect of the swell process on the shaft capacity of piles in swelling clays, a series of centrifuge models were conducted. Firstly, pull-out tests conducted on short length piles revealed reductions in shaft capacity after swell, close to the clay surface. A result attributed to the effects of swell-induced softening. Conversely, at greater depths were swell is largely restricted, so too are the effects of swell-induced softening, resulting in slight increases in shaft capacity after swell. Finally, an instrumented pile test showed that while increases in lateral pressure against a pile shaft are in-fact observed at lower magnitudes of swell, at large swell magnitudes, the effects of swell in-induced softening tend to dominate, thus resulting in a reduction in shaft capacity.

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