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Centrifuge modelling of pile pull-out tests in expansive soil

Modélisation par centrifugation d'essais d'arrachement de pieux dans un sol expansif

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ABSTRACT: Designing foundations of wind turbines in expansive soils present a challenge. Piled foundations are often used to mitigate some of the problems associated with construction on expansive soils. Swelling clays frequently occur in an unsaturated state in many arid and semi-arid areas of the world. Upon wetting, soil surrounding the pile shaft simultaneously undergoes softening and expansion. While swelling of adjacent soil will increase confinement and thus pull-out resistance, the softening caused by an increase in saturation could lead to a reduction in pull-out resistance. The conflicting consequences of these two mechanisms have been previously documented by independent studies reporting the results of in-situ concrete plug pull-out tests. The interaction between the pile shaft and soil and the resulting shaft capacity in this context are not well understood. It is therefore not clear whether tests conducted in the wet or dry season will result in conservative or non-conservative indications of pile shaft capacity. This article presents the results of centrifuge tests undertaken to investigate shaft friction mobilised on concrete piles subjected to pull-out tests in expansive soils under in-situ and saturated moisture conditions. A comparison of results from tests performed prior to and after swelling showed that pull-out loads were substantially reduced during wetting and swelling, implying that softening dominated over increased swell pressures.

RÉSUMÉ: La conception de fondation d'eolienne dans un sol expansif est difficile. La fondation sur pieux est souvent utilisée pour atténuer les problèmes liées à la construction sur sols expansifs. Dans plusieurs régions arides et semi-arides, le gonflements des argiles est très fréquant dans les états non-saturés. En cas de saturation, le sol entourant l'arbre de pieu subit simultanément un ramollissement et une expansion. Bien que le gonflement du sol adjacent augmente le confinement et donc la résistance à l'arrachement, le ramollissement causé par une augmentation de la saturation peut entraîner une réduction de la résistance à l'arrachement. Les conséquences contradictoires de ces deux mécanismes ont déjà été documentées par des études indépendantes rapportant les résultats d'essais de retrait de bouchons de béton in situ. En revanche, l'interaction entre le pieu et le sol et la capacité de l'arbre résultante dans ce contexte ne sont pas bien comprises. Par conséquent, il n'est pas clair si les tests effectués pendant la saison humide ou sèche aboutiront à des indications conservatrices ou non conservatrices de la capacité de l'arbre de pieu. Cet article présente les résultats des essais de centrifugation entrepris pour étudier le frottement des arbres mobilisés sur des pieux en béton soumis à des essais d'arrachement dans des sols expansifs dans des conditions d'humidité in-situ et saturée. Une comparaison des résultats des tests effectués avant et après gonflement a montré que les charges d'arrachage étaient considérablement réduites lors du mouillage et du gonflement, ce qui impliquait que l'adoucissement dominait par rapport à la pression de gonflement.

Keywords: pull-out tests; expansive soils; unsaturated soils; centrifuge modelling; piled foundations.

1 INTRODUCTION

Africa is facing a challenge in terms of generating more power to meet existing and future demands. Currently, about one-half of Africa's total population is lacking access to electricity. However, the continent is well endowed with renewable energy resources; it is estimated that about 35% of the world resources for wind energy are located in the continent (Mukasa et al., 2013). There are many challenges which hinder the development of infrastructure for wind energy in Africa. Designing suitable foundations to sustain the loads typically applied by wind turbines represents a particular challenge. Site investigations have shown that many areas that have been identified as suitable for wind turbines are underlain with expansive soils. These soils are particularly sensitive to soil moisture changes; as the water content of the soil increases during the wet season, the soil swells causing surface heave. During the dry season, shrinkage occurs producing settlements. This seasonal swell/shrink cycle can cause significant damage to buildings directly founded on these soils (Driscoll & Crilly 2000, Nelson & Miller, 1992, Jones & Holtz, 1973).

The WindAfrica project is a joint collaborative project funded by the UK Engineering and Physical Sciences Research Council under the Global Challenges Research Fund (http://community.dur.ac.uk/wind.africa/). WindAfrica project aims to develop new design guidelines for foundations of wind turbines on expansive soils.

Piled foundations are often used to mitigate some of the problems associated with construction on expansive soils.

Upon wetting, soil surrounding the pile shaft simultaneously undergoes softening and expansion. While swelling of adjacent soil can be expected to increase lateral stress on the pile shaft (and thus pull-out resistance), the softening caused by an increase in saturation could possibly lead to a reduction in pull-out resistance.

The conflicting consequences of these two mechanisms have been previously documented by independent studies reporting the results of in-situ concrete plug pull-out tests (Blight, 1984, El-sharief et al. 2007).

The interaction between the pile shaft and soil and the resulting shaft capacity in this context are not well understood. It is therefore not clear whether tests conducted in the wet or dry season will result in a conservative estimate of pile shaft capacity.

This paper presents the results of centrifuge tests undertaken to investigate pile shaft capacity mobilised during pull-out tests of concrete piles. The piles considered were installed in a highly expansive clay profile under a relatively dry natural moisture content. Pull-out tests were then conducted both at the soil's in-situ moisture content and after inducing swell by inundating the clay profile. The objective of this study was to address discrepancies in the literature regarding the effect of heave on the pull-out capacity of bored piles. The centrifuge tests were carried out using the geotechnical centrifuge at the University of Pretoria (Jacobsz et al., 2014).

2 CENTRIFUGE MODEL

Pile pull-out tests were conducted in the centrifuge at a centripetal acceleration of 30 g. Piles were installed with the expansive clay profile in a relatively dry (in-situ) state and tests were conducted at the soil's initial moisture content and after the profile was saturated to induce swell. For the purposes of these experiments it was necessary to develop an expansive soil that would swell in a time frame short enough to be practical for centrifuge testing. The development of this material and the relevant properties are described by Gaspar et al. (2019). Selected properties are repeated in this paper where necessary.

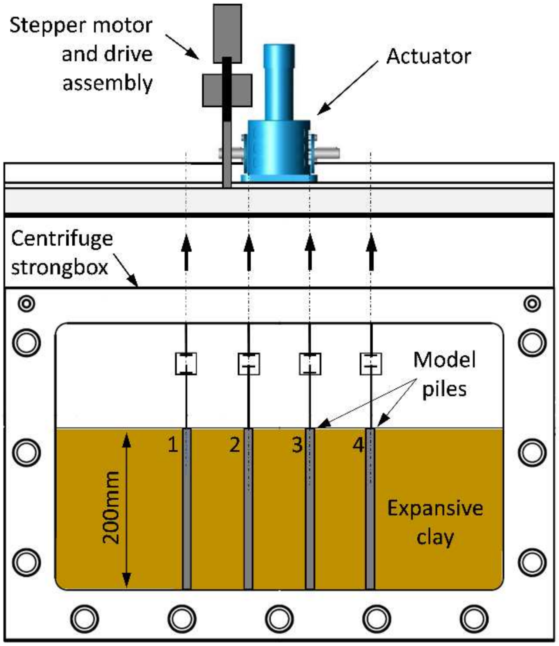

Figure 1. Model setup and instrumentation

The centrifuge model is shown in Figure 1. Four clay slabs measuring approximately 50 mm x 152 mm x 335 mm were prepared as described by Gaspar et al. (2019) and stacked in the centrifuge strongbox. The clay slabs were separated by continuous filament nonwoven needle-punched geotextile layers in between the slabs to aid drainage. Side drains were provided consisting of stiffened perforated steel plate covered by the same geotextile. The stiffened side drains and back plate confining the model were equipped with extendable jacks to ensure that the expansive clay was firmly confined prior to testing.

Four 20 mm diameter rapid setting cement bored piles were installed in the clay. Threaded rods were cast into each pile and each rod was connected to a separate load cell and linear variable differential transformer (LVDT) allowing for local load and displacement measurements to be made for each pile. The threaded rods were connected to a loading frame which pivoted about the rear edge of the strongbox. To pull the piles out of the soil profile, the frame was lifted at the front edge of the strongbox at a constant rate using a displacement controlled actuator.

2.1 Clay slabs

The clay used in the centrifuge test was obtained from a highly expansive natural clay deposit from Steelpoort, South Africa. To accelerate the swell of the clay in the centrifuge test, the permeability was increased by breaking down intact blocks of clay from site by grating and then compressing the grated clay into approximately 50 mm thick slabs by means of static compaction. The bulk density of the slabs after preparation was measured to be approximately 1840 kg/m³. The properties of the clay material are as follows with more detail reported by Gaspar et al. (2019).

Table 1. Material properties

Property	Natural clay
Liquid limit (%)	92
Plasticity index	55
Linear shrinkage (%)	25.5
Activity	0.8
In situ density (kg/m^3)	1840
In situ moisture content (%)	35.03
Unified Soil Classification	CH

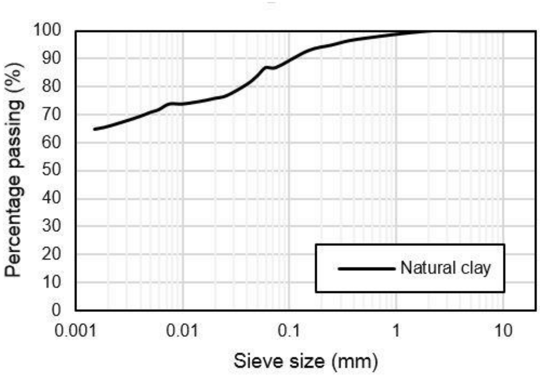

Figure 2. Particle size distribution curve

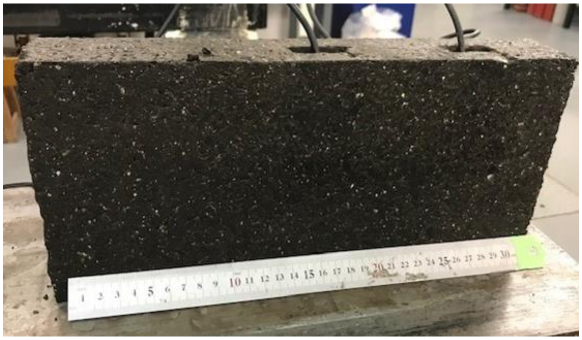

Figure 3. Pressed clay slab

2.2 Piles

Model bored piles were installed into the stacked clay slabs by drilling 20 mm diameter holes into the clay and filling the holes with fast setting hydraulic cement compound normally used for anchoring purposes. A 4 mm diameter threaded rod was pushed down into the wet mix and allowed to set overnight.

Figure 4. Augered pile hole (diameter 20 mm)

To confirm their actual dimensions, the model piles were removed from the clay after the test, cleaned and measured. The piles had a relatively uniform surface finish, with mean diameters ranging between 19.68 mm and 19.87 mm. The pile lengths ranged from 182 mm to 190 mm. The actual dimensions were used for the calculated of mobilised shaft friction stresses during pull-out.

The piles did not pull out cleanly from the clay, indicating that shear occurred through the clay rather than along the concrete-clay interface. The interface frictional properties can therefore be expected to be that of a clay-clay interface.

Figure 5. Model piles (cleaned)

2.3 Test procedure

During the test, the model was accelerated to 30 g, settlements were allowed to stabilise and the pull-out of the first two piles (Piles 2 and 4) commenced. After the peak and residual pull-out forces were observed (Pile 2 was displaced by 6.5 mm and Pile 4 by 7.1 mm), the actuator on the loading frame was stopped. The box was then flooded by introducing water from the base of the strongbox and the clay was allowed to swell for 10 hours. After swelling, the last two piles (Piles 1 and 3) were pulled out.

3 RESULTS

The results from the centrifuge test are presented in this section focusing on changes in moisture content, the resulting swell, heave of the piles during swell and a presentation of pull-out forces before and after swell.

3.1 *Moisture content*

As listed in Table 1, the bulk density of the clay at the start of the test was 1840 kg/m^3. The initial moisture content was 20.6 %, resulting in an initial degree of saturation of 40.2 %.

Two moisture probes were installed into the top slab and two in the slab second from the bottom which allowed changes in moisture content during the test to be monitored.

3.2 *Swell of clay*

The swell of the clay following the raising of the water level in the model was recorded by an LVDT resting on the soil surface. The amount of heave over time is presented in Figure 6. It can be seen that the total surface heave of the 200 mm deep clay layer amounted to 4.5 mm or an average heave percentage of 2.25 % of the profile depth. Van der Merwe (1964) studied heave profiles in South African expansive clays and presented a method to predict the heave profile with depth for clays of different degrees of expansiveness. Based on the plasticity index and clay fraction of a soil, Van der Merwe (1964) described various classes of expansiveness, starting with non-expansive soils up to very highly expansive soils and recommended unit free-swell percentages for each category. For a very highly expansive profile he recommended a unit free-swell of 8.33 %, 4.17 % for a highly expansive profile and 2.08 % for a medium expansive profile.

The amount of heave occurring with depth needs to be factored down from the free-swell values depending on the overburden stress. Gaspar et al. (2019) showed that the heave profile achieved using the expansive clay slabs in the centrifuge described in Section 2.1 closely matched the heave profile predicted using the Van der Merwe (1964) approach. Figure 7 presents the surface heave recorded after 10 hours of swell in the centrifuge at 30 g and also presents Van der Merwe (1964) heave profiles for the centrifuge model for highly and very highly expansive clays. It can be seen that the achieved heave plotted between the two profiles, indicating that the centrifuge test modelled a heave profile which would typically be predicted for a highly expansive soil.

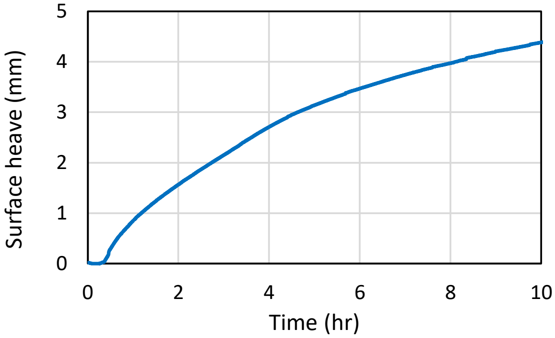

Figure 6. Surface heave observed in model

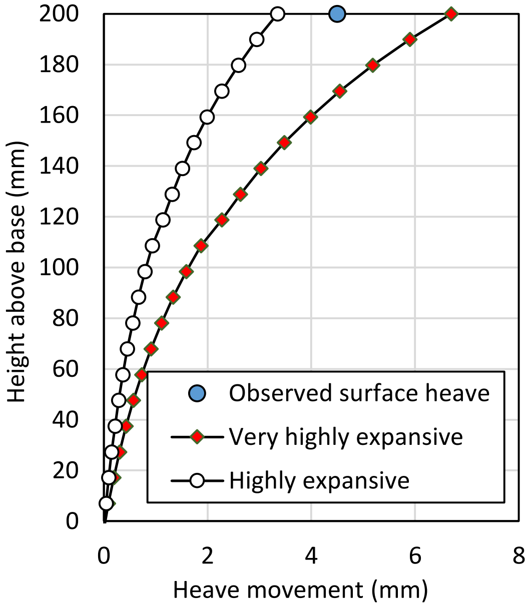

Figure 7. Observed surface heave compared against heave profiles by Van der Merwe (1964)

3.3 *Pile heave*

The swell which occurred following raising of the water level in the strongbox resulted in some uplift of the piles since the piles were not anchored to the base of the strongbox. The pile heave is presented in Figure 8 with the surface heave shown in Figure 6.

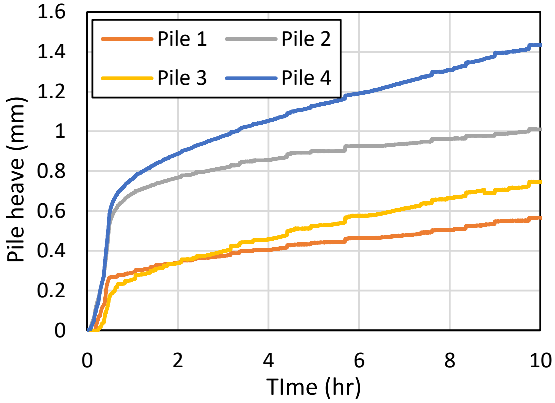

Figure 8. Pile heave observed in model

It is evident that the surface heave was substantially greater than the pile heave as the pile shafts extended to the bottom of the clay layers which experienced significantly less swell. The piles would therefore have been subjected to an increase in tensile load due to swelling. This illustrates a need for the use of instrumented model piles to allow for the development of tensile load due to swell to be studied.

The tensile load generated due to swelling will be affected by the stiffness of the soil and change in stiffness upon wetting in addition to the amount of swell induced. The latter is a function of depth below ground surface.

Due to the fact that Piles 2 and 4 were pulled out prior to swell being induced, the measured uplift of these piles due to the induced heave was approximately double that of the piles which were only pulled out after swelling had taken place. This result highlights how the shaft friction along Piles 2 and 4 had been reduced to a residual value following the pull-out test. In contrast, the interface friction between Piles 1 and 3 and the sides of the augered boreholes provided substantially higher resistance to swell induced uplift.

Examining the pile heave vs. time record reveals two distinct phases in the swell record, i.e. rapid initial swelling, followed by a more gradual swell process. It is believed that the first phase is related to water infiltrating the fissures in the clay slabs, resulting in suction dissipation between the clay gratings inducing rapid primary swell. The second phase is related to a slower diffusion process (see Caicedo et al. 2006) as water infiltrated the clay aggregations, resulting in a secondary swell mechanism.

3.4 *Load displacement response upon pile pull-out*

During the centrifuge tests Piles 2 and 4 were pulled out after the test acceleration of 30 g had been reached prior to inducing swell. Piles 1 and 3 were pulled out after the clay had been allowed to swell for 10 hrs. The average mobilised shaft friction on the pile shafts during pull-out are plotted versus pile displacement in Figure 9. It can be see that the shaft capacities of the piles pulled out prior to swell was approximately double the capacities of the piles pulled out after swelling. In addition, the slopes of the friction-displacement curves before swell are also substantially steeper than the slopes of the pull-out curves after swell, indicating a much stiffer response.

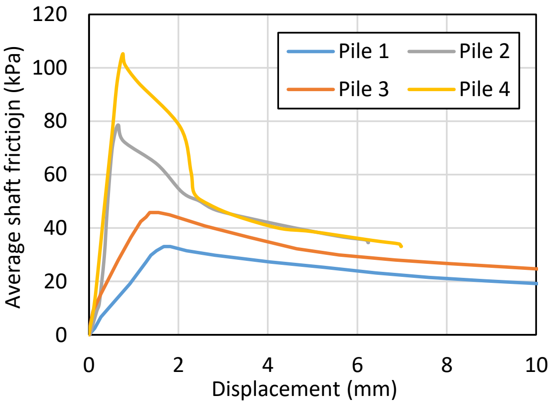

Figure 9. Pile shaft friction

The substantial reduction in pull-out resistance after inducing swell resulted from a decrease in effective stress in the adjacent soil after flooding of the clay, as well as softening of the clay upon wetting. The results show that for this experiment, softening of the clay was the dominant mechanism governing pull-out resistance after swell, with the increase in lateral pressure against the pile shaft having a lesser effect. For this reason, the measured pull-out capacity was substantially reduced upon swelling.

4 DISCUSSION

Using the methodology described in this study and by Gaspar et al. (2019), a reworked expansive clay profile was allowed to swell in the centrifuge to magnitudes which would typically be representative of full scale. This process took place in a short time frame thus allowing soil-structure inter-action problems involving expansive clays to be investigated by means of centrifuge modelling.

Swell was induced by flooding the model with water by raising the water level from the base of the strongbox. This process represents an extreme case compared to what would be expected in practice where moisture ingress is usually associated with rainfall infiltrating from the ground surface and/or preventing evapotranspiration at the soil surface. However, it is believed that the two scenarios, i.e. pre and post flooding, represent the extremes of what can be expected in practice.

The swelling resulted in uplift movement of the piles. Piles which were pulled out before swelling underwent approximately twice the amount of uplift compared to the piles which were not previously disturbed.

Allowing the clay to swell resulted in the pull-out capacity of the piles being approximately halved. This was the result of a reduction in effective stress due to flooding, undrained loading of the piled foundations and softening of the clay. The results showed that an increase in shaft capacity resulting from increased lateral pressure due to the induced swell swelling causing increased normal stress against the pile shaft did not occur.

The results apply to a soil that was relatively dry prior to inducing swell. For these conditions the clay profile underwent a large change in moisture content and substantial softening so that softening, rather than increased lateral pressure governed the pile shaft capacity. Smaller increases in moisture content may result in reduced softening and possibly still substantial swell. In such a situation the mechanism governing on shaft capacity may be different and should be investigated. The effect of the initial moisture content of the soil prior to swelling also requires investigation.

Due to the confinement provided by overburden pressure, swell is increasingly restricted with depth below the ground surface. Due to increasing confinement with depth, changes in shaft capacity upon moisture ingress may vary with depth. It is recommended that a series of plug pull-out tests be carried out to allow shaft capacity of short sections of pile shaft at a range of depths and possibly a range of moisture content changes to be studied. Also, the use of instrumented model piles equipped to measure axial load and lateral stress will allow changes in pile shaft capacity upon moisture ingress in expansive soils to be studied in greater detail.

5 CONCLUSIONS

The following conclusions are presented:

Using a previously established methodology (Gaspar et al., 2019), a reworked expansive clay capable of achieving significant swell in a short time frame was used to investigate the pull-out resistance of piles before and after inducing swell.

Swelling resulted in pile heave. Piles which were subjected to pull-out testing prior to swelling, experienced twice the amount of heave in comparison of the undisturbed piles. This is due to the disturbance of the pile shaft/soil interface.

Inducing soil swell resulted in a substantial reduction in pile shaft capacity as the effect of softening within the clay overshadowed the swell induced increase in lateral pressure against the pile shaft.

6 ACKNOWLEDGEMENTS

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