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Physical Modelling in Geotechnics

Vertical cyclic loading of piled foundations in expansive clays

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ABSTRACT: In the design of onshore wind turbines constructed in swelling clays, the use of grouped-piled foundations is an attractive option. The large lateral forces to which the turbine is subjected, results in significant vertical cyclic loading of the piles. This study presents the results of a centrifuge test, conducted to analyse the response of scaled reinforced-concrete piles subjected to vertical cyclic loading. This study highlights the difficulties of performing cyclic testing on expansive clays in the centrifuge. Emphasis is placed on various facets of the model design which include the preparation of instrumented concrete piles cast "in situ", incorporating the use of a mix design and steel reinforcement, scaled for purpose. A description is then provided of the system used to perform load-controlled cyclic loading, through the use of a low-cost, open-source control system based on the use of a Raspberry Pi microcomputer. Results indicate that cyclic testing conducted in swelling clays is problematic since the magnitude of swell (and of swell-induced softening) is constantly changing throughout the duration of the test. Measurements from the instrumented concrete piles indicate that meaningful results can be obtained if strain gauges are attached to the reinforcement cage, rather than to the outside of the pile as is the more conventional approach. Finally, the low-cost, load and displacement control system developed at the University of Pretoria (termed Fly-by-Pi) is shown to provide almost perfect load control despite soil stiffness continuously changing due to cyclic loading and swell-induced softening.

Keywords: wind turbines, cyclic loading, expansive clays, Raspberry Pi, instrumented concrete piles, Fly-by-Pi

1 INTRODUCTION

Expansive, or swelling clays, are a problem soil that present difficulties for engineers across the world. Typically characterised as having a high plasticity, such clays tend to swell when wetted, and shrink and crack when dried. The differential movement this imposes on overlying or adjacent structures results in substantial economic implications (Jones & Holtz, 1973). The volumetric behaviour of such clays is particularly problematic for wind turbines, where stringent tolerances on differential foundation movements are typically prescribed. Furthermore, in the case of piled foundations, previous studies have shown that the aforementioned volumetric changes are accompanied by changes in shaft capacity (Blight, 1984; Gaspar et al., 2022c). For this reason, the WindAfrica research project (http://community.dur.ac.uk/wind.africa/), was conceived to develop practical guidelines for the design of onshore wind turbine (piled) foundations constructed in expansive soils.

The testing of expansive clays in any capacity is however, challenging. Such clays tend to occur in a highly fissured state in situ and as a result, this creates a natural bias towards the testing of stronger, less fissured samples (Thorne, 1984). If field testing is performed, the low hydraulic conductivity associated with such clays can make testing expensive and time consuming. Recognising the above factors, the attractiveness of centrifuge modelling becomes apparent. Centrifuge modelling offers a compromise between the carefully controlled boundary conditions possible in element testing, with the ability to test larger samples. Testing models at higher centrifugal accelerations also allows for processes involving the movement of water to occur at an accelerated rate.

The addition of reinforced-concrete piled foundations to such a model provides an additional layer of complexity. While centrifuge models investigating the behaviour of piled foundations often incorporate metal piles, research by Louw et al. (2020) illustrated that such models do not capture the non-linear behaviour of reinforced-concrete piles, which occurs at serviceability loads. This non-linearity is attributed to the tendency of reinforced concrete to crack under relatively small tensile loading.

Finally, to adequately replicate the cyclic loading to which a wind turbine will be subjected, it is necessary to utilise an appropriate load control system, which can be customised to address the intricacies of any particular model. Load control systems can however be prohibitively costly and require specialised software. However, recognising the increased availability of low-cost microcontrollers and microprocessor equipment, a customised solution can be readily engineered. In this study, a low-cost open source logger and control system was utilised. The system was designed at the University of Pretoria and makes use of a Raspberry Pi microcomputer (Broekman et al., 2020).

This study reports the findings of a centrifuge model, whereby scaled reinforced-concrete piles were subjected to vertical cyclic loading in both an unswelled and swelled state. The paper aims to briefly illustrate i) the general model layout and ability to induce swell in-flight, ii) the instrumentation and installation of scaled reinforced-concrete piles and iii) the low-cost, load-controlled system utilised.

2 CLAY CHARACTERISATION

The clay tested in this study, is a highly expansive black clay, sampled from the Limpopo province of South Africa. Basic classification data and the particle size distribution curve for this material has been provided in Table 1 and Figure 1 respectively More detailed characterisations of this material have been provided by Gaspar et al. (2022a).

Table 1. Soil classification data.

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

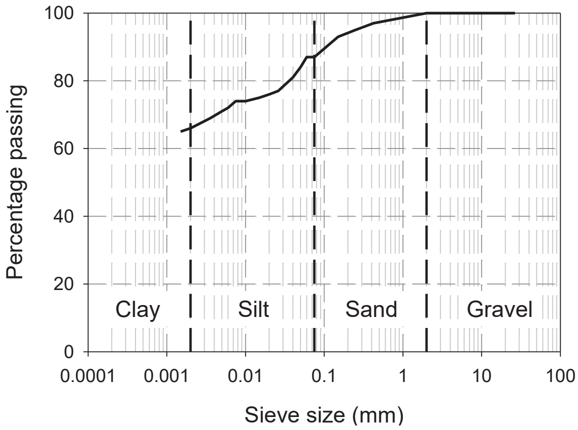


Fig. 1. Particle size distribution.

3 CENTRIFUGE MODEL

A simplified representation of the model presented in this study is illustrated in Figure 2. Any dimensions provided are specified in model scale. The centrifuge model consisted of 8 statically compacted clay slabs (50 mm thick) separated by layers of needle-punched non-woven geotextile. The clay slabs were restrained in position by two perforated plates, covered by the same geotextile. The layout included two reinforced-concrete piles, which were tested at the clay's in-situ water content, and after achieving a targeted magnitude of swell. The two tests are referred to as the unswelled and swelled test respectively. For the unswelled test, the model was placed inside the centrifuge and accelerated to 30-g. Upon achieving the targeted acceleration, the unswelled pile was cyclically loaded at an amplitude and frequency of 250 N and 0.03 Hz respectively, for approximately 494 cycles. Thereafter, the amplitude and frequency were changed to 600 N and 0.025 Hz respectively, for approximately 1450 cycles. The swelled test was performed after achieving a targeted magnitude of swell. To induce swell in-flight, the strongbox was flooded with water, until the water level was 20 mm above the surface of the top slab. Water was then allowed to flow into the clay profile, with swell being monitored using surface linear variable differential transformers (LVDTs). Once the targeted magnitude of swell was achieved, vertical cyclic loading was applied to the second pile at an amplitude and frequency of 300 N and 0.07 Hz respectively, for approximately 1750 cycles. More detailed explanations of sample preparation and model layout are presented by Gaspar et al (2022b).

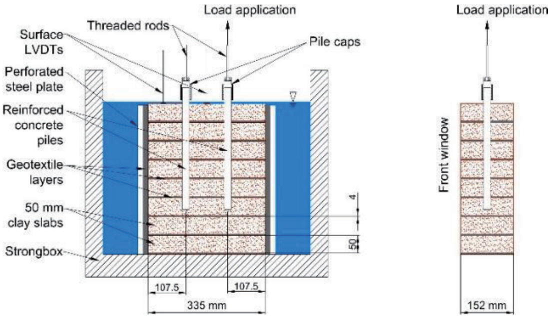
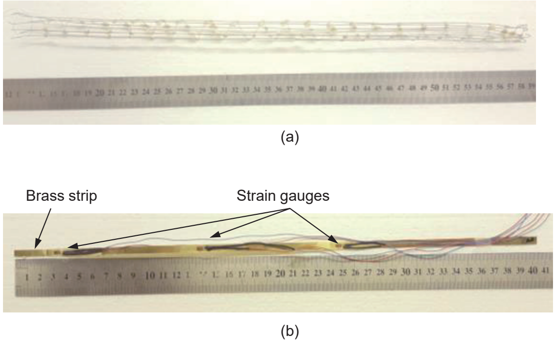


Fig. 2. Model layout.

4 REINFORCED-CONCRETE PILES

The procedure used in this study to manufacture scaled reinforced-concrete piles is based on that described by Louw et al. (2020). The steel reinforcing utilised, consisted of 6 x 0.60 mm stainless steel wires for the main reinforcing bars. The main reinforcing was confined by a 0.21 mm stainless steel wire with a pitch and diameter of approximately 10 mm and 17 mm respectively. Strain gauges were then attached to two brass strips, (approximately 4 mm in width and 0.5 mm deep) which was ultimately attached to the longitudinal reinforcing of the piles. The reinforcing cage and instrumented brass strips are shown in Figure 3.



(a)

(b)

Fig. 3. a) Reinforcing cage and b) instrumented brass strip.

Installation of the piles into the clay profile was performed at 1-g. The two reinforcing cages were positioned within two pre-drilled 20 mm diameter holes. The relevant quantity of concrete was then slowly placed into the holes and agitated with a needle to ensure proper compaction. The scaled mix design used, was that specific by Louw et al (2020). Concrete cubes and cylinders were placed inside the centrifuge strongbox which was sealed for a period of 28 days after installation of the piles. The cubes and cylinders were therefore allowed to cure in the same temperature and relative humidity conditions as the piles themselves and as such, the measured properties were deemed to be representative of the two piles. The average compressive strength, indirect tensile strength and Young's modulus of the concrete are summarised in Table 2.

Table 2. Concrete properties.

Compressive strength (MPa)	35.9
Indirect tensile strength (MPa)	3.1
Young's modulus (GPa)	20.5

5 RESULTS

Figures 5 and 6 illustrate pile head displacement and the surface displacement of the clay, for the unswelled and swelled tests respectively. From these figures it is seen that for the unswelled and swelled tests, the clay surface was shrinking and swelling respectively, for the entire test duration. This is reflected in both the displacement measurements conducted on the clay surface, as well as on the pile heads. The rate of volume change measured at the surface can however be seen to occur at a faster rate than the movement of the piles. This finding is indicative of some interaction between the pile shaft and the adjacent clay.

If it is recognised that soil stiffness is strain dependent, this finding poses difficulties in the interpretation of data for long-term centrifuge models investigating soil-structure interaction, whereby the soil in question is susceptible to volume changes. Nevertheless, the results can be useful to illustrate the successful application of cyclic loading, as well as of displacement and strain measurements within piles.

Figures 7 and 8 illustrate the first 30 minutes of pile head and surface displacement for the two tests. The enlarged view presented in these figures makes it possible to observe the near-perfect sine waves measured as a result of cyclic load application to the pile heads. The data shown in these two figures illustrate that both surface LVDTs responded to the load applications (the edge surface LVDT being 9.25 pile diameters from the unswelled pile). This illustrates that, for the embedded pile length considered, load applications caused displacements in the clay (albeit at a fraction of a millimetre) throughout the centrifuge model.

To illustrate the successful measurement of strain within the piles, Figure 9 presents measurements at two depths (50 and 100 mm beneath the clay surface) in the unswelled pile. Also included on a secondary axis, is the applied load. From this figure it can be seen that the sine waves of load application and of measured strain align well. Furthermore, the strain measured at both depths is within the range that would be expected for a 20 mm diameter reinforced-concrete pile, subjected to the loads illustrated. This result indicates that the approach used to measure strains within the pile was successful. Furthermore, the amplitude of strain measured at the top of the pile is greater than that measured in the centre (≈30 and 15 $\mu\epsilon$ respectively). This is intuitively correct as the lower portions of the pile would be confined to a greater extent, thereby reducing the induced strain. It is also seen that the strain in the top and centre of the pile was in tension and compression respectively. Bearing in mind the shrinkage that occurred in the upper portions of the clay, it is likely that a portion of the pile would have been in compression prior to load application. Conversely, closer to the soil surface, mobilised shaft friction would not be great enough to induce compression in the pile.

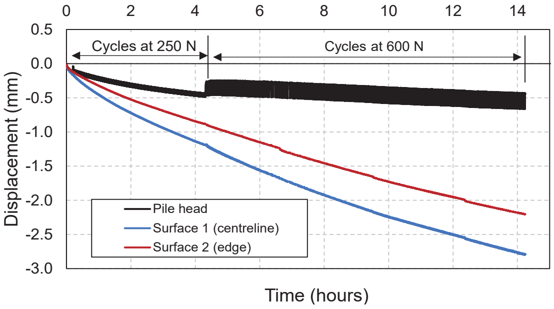


Fig. 5. Pile head and surface displacement (unswelled test)

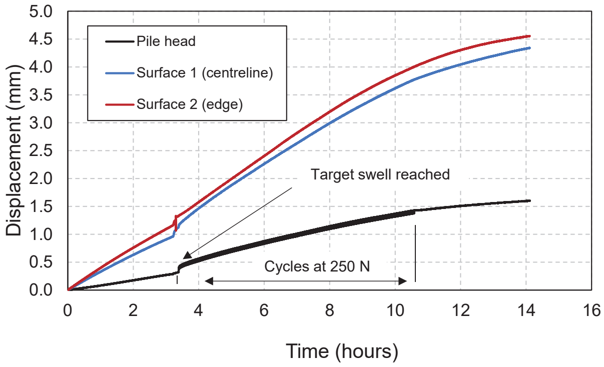


Fig. 6. Pile head and surface displacement (swelled test)

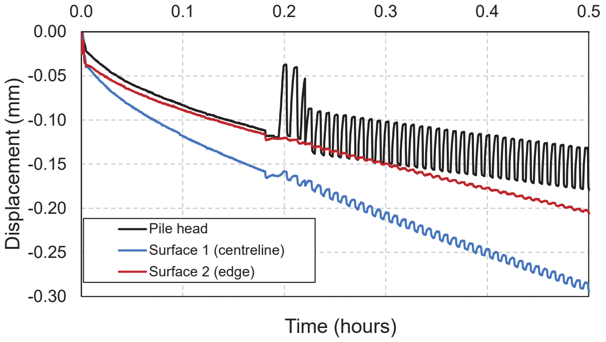


Fig. 7. Pile head surface displacement – 30 min (unswelled test)

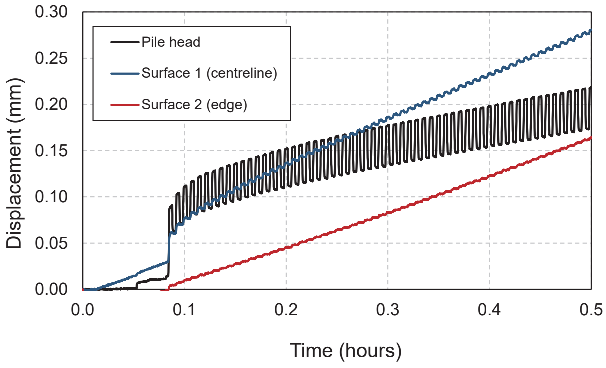


Fig. 8. Pile head and surface displacement – 30 min (swelled test)

6 CONCLUSIONS

This paper presents the results of a centrifuge model, whereby cyclic vertical loading was applied to reinforced-concrete piles cast in an expansive clay profile. The results illustrate that the use of concrete piles cast in-situ allowed for interaction between pile shaft and adjacent clay. Furthermore, it is shown that the approaches utilised to measure pile head and surface displacements, as well as strain within the piles was successful. Issues arising from this model are related to the difficulty in restricting volumetric change in the clay during a long-term test. While environmental chambers have been used in centrifuge modelling, the ability to induce swell in-flight within a reasonable time frame, and then to test at a single magnitude of swell might pose difficulties in this approach. While the instrumentation used in this model has been showed to work as intended, further work is required to guide long-term, soil-structure interaction testing at a single magnitude of swell.

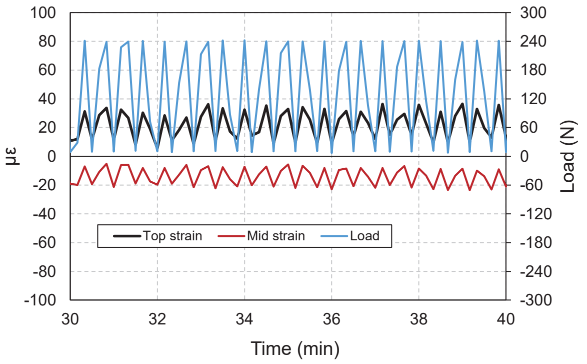


Fig. 9. Strain measurements and load application (unswelled test)

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