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Performance-based design of pile foundations for wind turbines in African unsaturated expansive soils

Conception basée sur la performance des fondations sur pieux pour les éoliennes dans les sols expansifs non saturés africains

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ABSTRACT: The development of wind farms across Africa is an attractive solution to meet the increasing electricity demand of a growing and widely dispersed population, whilst ensuring that such electricity provision meets global standards in carbon emissions. However, since vast portions of the continent are underlain by expansive soils, foundation design for these structures is problematic. This paper presents an overview of a collaborative research project aimed to investigate the behaviour of piled foundations in swelling clays. Early results from laboratory testing, centrifuge modelling, numerical modelling and large-scale field testing are presented. The laboratory sample preparation method utilised has produced samples with characteristics which closely match that of undisturbed samples. This preparation method has allowed for a series of centrifuge tests to be conducted, investigating variations in pile shaft capacity before and after swell has occurred. Preliminary results show that a newly developed constitutive framework is able to capture some key features of expansive soils. Finally, the results of lateral cyclic loading tests under 'wet' and 'dry' conditions, on free end piles have illustrated key differences in the development of secant stiffness with increasing load cycles.

RÉSUMÉ : Le développement des parcs éoliens à travers l'Afrique représente une option prometteuse pour subvenir à des besoins en électricité constamment à la hausse d'une population croissante et largement dispersée, l'alignement aux normes internationales en matière d'émission de carbone va de pair avec l'expansion de cette source émergente d'énergie. Cependant, en raison de la large prédominance des sols expansifs sur le continent , la conception des fondations de ces structures peut constituer un véritable challenge. Cet article propose l'aperçu d'un projet de recherche collaboratif visant à étudier le comportement des fondations sur pilotis dans les argiles expansives. Les premiers résultats d'essais en laboratoire, de modélisation de centrifugeuses, de modélisation numérique et d'essais sur le terrain à grande échelle sont présentés. La méthode de préparation des échantillons de laboratoire utilisée a produit des échantillons dont les caractéristiques correspondent étroitement à celles d'échantillons non perturbés. Cette méthode de préparation a permis de mener une série d'essais par centrifugation, en étudiant les variations de la capacité de l'arbre de pieu avant et après la houle. Les résultats préliminaires montrent qu'un cadre constitutif nouvellement développé est capable de capturer certaines caractéristiques clés des sols expansifs. Enfin, les résultats des essais de chargement cyclique latéral dans des conditions «humides» et «sèches», sur des pieux à extrémités libres, ont illustré des différences clés dans le développement de la rigidité sécante avec des cycles de charge croissants.

KEYWORDS: expansive soils; unsaturated soils; piled foundations; wind turbines

1 INTRODUCTION

The past few decades have seen both substantial technological advancements as well as a considerable growth in population across the world. The combined effect of these two factors has led to a worldwide increase in electricity demand. Unfortunately, in developing countries access to electricity is limited. The African continent in particular is facing serious challenges in meeting both current and future electricity demands with only just over half the continent's population having access to electricity (Mukasa *et al.*, 2013).

Due to the global drive towards the development of renewable energy, the use of wind farms is one such approach that is being implemented to meet these growing demands. However, as considerable portions of the continent are underlain by unsaturated expansive clays, foundation design for wind turbines are potentially problematic. Wind turbine structures are inherently dynamic; loading from aerodynamic, rotational, and inertia sources all contribute to a system dominated by high overturning moments and vertical loads (Hamza and Abdelatif, 2020). Moreover, the seasonal volumetric changes to which these clays are prone result in significant swelling during the wetter seasons, followed by shrinking and desiccation cracking during the dry seasons. Recognising the stringent tolerances prescribed by wind turbine manufacturers on allowable foundation movements, foundation design on this problem soil is fraught with difficulty.

The WindAfrica research project (http://community.dur.ac.uk/wind.africa/), was therefore conceived to develop practical guidelines for the design of wind turbines in expansive soils. The project explores the use of piled foundations using i) laboratory testing, ii) centrifuge modelling, iii) numerical modelling and iv) large-scale testing. This paper presents a brief overview of work that has been conducted under the various work packages.

2 LABORATORY TESTING

Element testing was conducted on a highly expansive black clay, sampled from the Limpopo province of South Africa. The testing was aimed at evaluating the swell and soil water retention properties of undisturbed samples, as well as recompacted laboratory prepared specimens.

The testing of the swell properties incorporated a series of one-dimensional swell and compression tests, the sequence of which can be described as follows. The first stage of testing 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 (ASTM, 2014) was repeated at a number of applied stresses.

Once volumetric changes had achieved steady-state, 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 bonding to be investigated.

In developing the sample preparation procedure for the recompacted specimens, an effort was made to retain some degree of fissuring as is typical of expansive clays in situ. The results of this investigation illustrated that the following properties remained, for all practical purposes, similar between the compacted and undisturbed specimens (Gaspar, 2020; Gaspar *et al.,* 2021):

i) The magnitude of swell at various overburden stresses
ii) The magnitude of pressure required to completely prevent swell (i.e. swell pressure)
iii) Compression and expansion indices measured in one-dimensional compression tests
iv) The effects of bonding (measured by means of one-dimensional compression tests)

If the volume change at the end of the wetting after loading tests are plotted as a function of the applied vertical stress, a *soaking under load* curve can be obtained. Figure 1 illustrates these curves for both the undisturbed and compacted samples. From this figure, the similarities in swell magnitude and swell pressure between the compacted and undisturbed specimens can be seen.

Considering that the sample preparation method retained key characteristics of the undisturbed clay, it was implemented in subsequent centrifuge tests. Gaspar (2020) also presented the results of soil water retention curves (SWRCs) measured on compacted, undisturbed and reconstituted specimens. Comparisons of SWRCs measured on reconstituted samples from this site were also conducted by Alhaj *et al.* (2019) who compared these results with SWRCs measured on a Sudanese expansive clay.

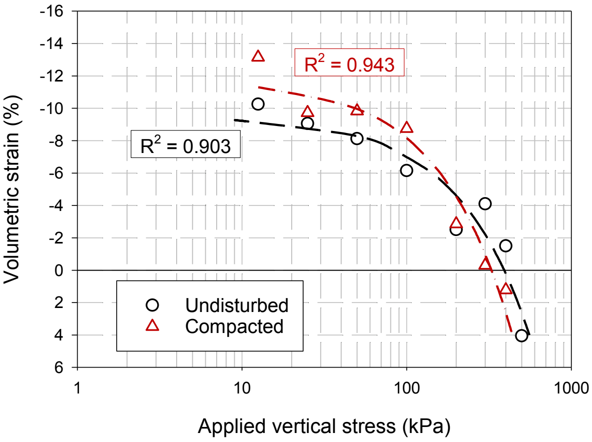

Figure 1. Comparison of swell characteristics between compacted and undisturbed specimens

3 CENTRIFUGE MODELLING

Centrifuge modelling using the same material characterised in the laboratory testing was used to conduct controlled studies of the greenfield swell in the expansive material, as well as the pull out (shaft) capacity of piles installed in this soil. These tests were conducted in the 150 g-ton geotechnical centrifuge at the University of Pretoria (Jacobsz *et al.,* 2014) at a target acceleration of 30 *g*.

As for the compacted element tests, the expansive clay for the centrifuge models was prepared using a method to create a degree of fissuring and macro structure to more adequately represent a field situation; details of the procedure are described by Gaspar *et al.* (2019). The first test conducted aimed to monitor the swell of a clay profile under greenfield conditions (i.e. no external loads or embedded structures) in the geotechnical centrifuge. The model layout (illustrated in Figure 2) consisted of five 50 mm thick statically compacted clay slabs, separated by layers of geotextile to facilitate the rapid ingress of water in-flight; this total model depth corresponds to an expansive clay profile with a depth of 7.5 m. Once the model had achieved the targeted centrifugal acceleration, the centrifuge strongbox was flooded from the base and water was allowed to infiltrate the clay profile. The flooding process was completed in approximately 30 minutes, and after that the clay was left to swell for a total of 2.5 days.

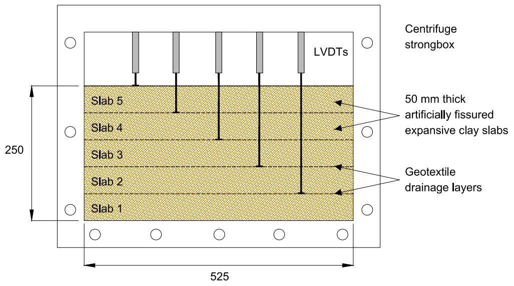

Figure 2. Centrifuge model layout

Figure 3 illustrates the measured swell throughout this profile at various instances in time. Also presented in Figure 3 is an empirical prediction conducted using the Van der Merwe (1964) approach for a clay of *very high potential expansiveness*. Being an empirical method commonly used in Southern Africa, this prediction was assumed to provide an adequate estimate of the anticipated in situ heave throughout the clay profile. The results presented in this figure illustrate that at approximately 4 hours, the swell profile predicted by Van der Merwe (1964) had been reached.

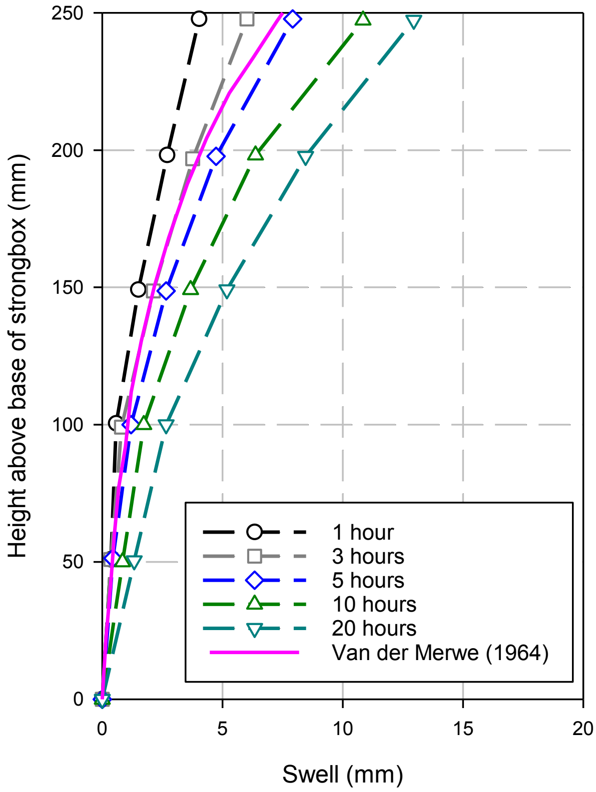

Figure 3. Measured and predicted heave along profile depth (after Gaspar et al. (2019))

The result presented in Figure 3 illustrates that the model setup presented by Gaspar *et al.* (2019) allowed for a realistic magnitude of swell to be achieved in a reasonable time frame. As a result, similar model layouts were used to investigate pile shaft capacity at different moisture conditions and levels of swell.

The seasonal variation in shaft capacity for piles in swelling clays is an issue for which alternated contradictory theories have been postulated. Blight (1984) conducted a series of full-scale pull-out tests on short length piles before and after wetting the profile for a period of 3–4 weeks. His results indicated that an increase in pile pull-out (shaft) capacity was observed after wetting. This result, however, is in direct contradiction with the findings of Elsharief (2007) who reported a reduction in shaft capacity after allowing swell to occur. An explanation for this contradiction is that, while swell can produce an increase in lateral stresses against a pile shaft, swell induced softening of the clay (Gens & Alonso, 1992) results in a reduction of shear strength which can reduce shaft capacity.

To investigate this matter further, Smit *et al.* (2019) conducted a centrifuge test to assess the change in pull-out (shaft) capacity for piles pulled out of the clay at a) in-situ moisture conditions, and b) after the surface swell predicted by Van der Merwe (1964) had been achieved. The model layout, illustrated in Figure 4, consisted of four bored piles cast from rapid hardening grout in an expansive clay prepared following the same process as for the greenfield test. The piles were 20 mm in diameter and approximately 185 mm in length (corresponding to 0.6 m and approximately 5.6 m in diameter and length respectively at prototype scale). The centrifuge model was placed in the geotechnical centrifuge and brought up to the desired centrifugal acceleration of 30 g. At this stage, two piles were pulled out of the clay profile. The strongbox was then flooded with water as for the greenfield test. After achieving the targeted magnitude of swell as measured by two LVDTs on the soil surface, the remaining two piles were pulled out of the clay. The results of this test are presented in Figure 5.

From Figure 5 it can be seen that the peak pull-out capacity of full-length piles reduced by approximately 40% after swell had occurred. While this result supports the findings of Elsharief *et al.* (2007), further testing by Gaspar (2020) has illustrated that the variation in shaft capacity is dependent on the magnitude of swell which has occurred. This suggests that, at lower levels of swell, an increase in pile shaft capacity (such as that observed by Blight (1984)) may occur.

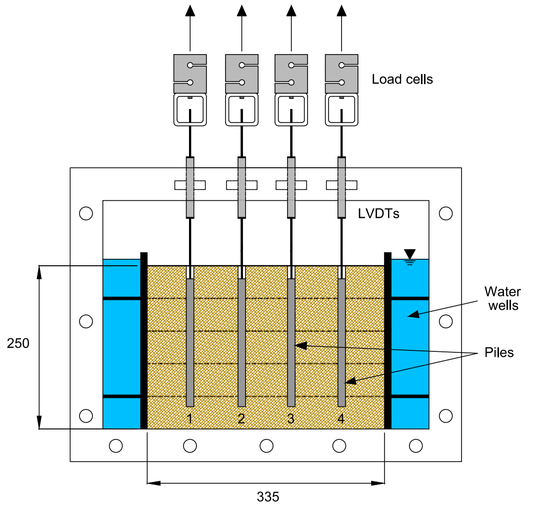

Figure 4. Centrifuge model layout (pile pull-out test)

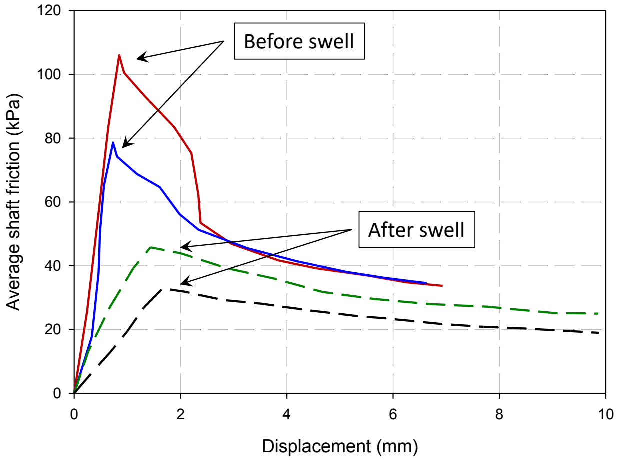

Figure 5. Average shaft friction versus pile head displacement for tests conducted at in situ moisture conditions and after swell had occurred (after Smit *et al*. (2019))

4 NUMERICAL MODELLNG OF EXPANSIVE SOILS

A constitutive model for expansive unsaturated soil was developed. The constitutive model used can be considered as an extension to the Barcelona Basic Model (BBM) (Alonso *et al.*, 1990). However, in contrast to the BBM which uses net-stress and suction, this model is based on a Bishop stress approach whereby the material parameter χ proposed by Bishop (1959) has been replaced by degree of saturation. Furthermore, the model used in this study incorporates an additional constitutive parameter (ξ) which accounts for the volumetric changes induced as a result of a change in suction. The use of a Bishop stress approach has allowed for relatively straight forward implementation of the model into the commercial software package, ABAQUS using a FORTRAN user subroutines. Another key difference is that the new model is formulated in term of finite strain (Coombs & Crouch 2011) rather than using the small-strain formulation.

Figure 6 illustrates typical stress paths in a log-log plot of specific volume,v, as a function of mean effective stress, $\overline{p}^*$, to highlight some key aspects of the constitutive model. From Points 1 to 2, an unsaturated sample is loaded along it's normal consolidation line (NCL), the slope of which is denoted by λ_s. Points 2 to 3 show an unloading path at constant suction at a slope of κ (equivalent to the elastic stiffness of a saturated sample). The sample is then reduced to a state of zero suction between Points 3 and 4. Along this path, volume change occurs at a slope of $\kappa + \xi$. Finally, when the sample is loaded at a fully saturated state, volume change is dictated by the soil's elastic stiffness κ, up until the saturated NCL is reached at Point 5. Further loading from this state will be controlled by the elasto-plastic saturated stiffness parameter, λ_0.

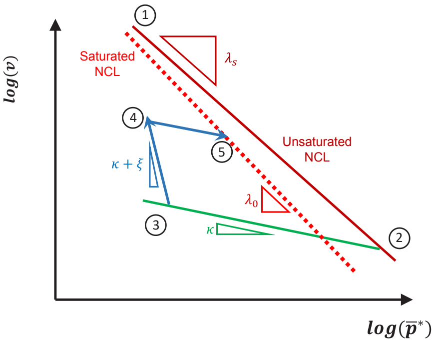

Figure 6. Illustration of some key aspects of the constitutive model used

As an initial calibration of the model, the results for the compacted samples presented in Figure 1 were simulated. Tests conducted on the compacted, rather than the undisturbed samples were simulated, since more control over the initial conditions of these samples was possible. Figure 7 illustrates that proposed model is able to predict the volume change of the odometer samples during swelling.

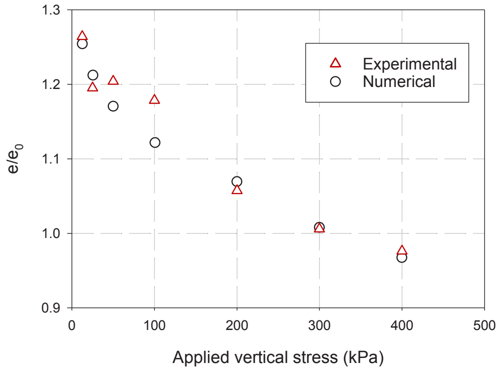

Figure 7. Comparison of numerical simulations with experimental data for oedometer swell tests

5 FIELD TESTING

Due to complications with access to the originally identified field testing site from which the material was sourced for the field and laboratory testing (see da Silva et al. 2019), an alternative site was identified for the large-scale pile loading tests and long term in situ monitoring. This site was adjacent to an existing bentonite clay quarry near Vredefort in the Free State province of South Africa. This area has historically been known to have problems with expansive clays (Williams et al., 1985). This site was selected due to the presence of a thick deposit (approximately 6 m) of highly expansive clay. Furthermore, the site had no nearby infrastructure which could be affected by the installation and testing (da Silva Burke et al. 2021). The locations of the original site used for sourcing of clay material for the laboratory and centrifuge modelling and the field test site for the large-scale in situ testing is shown in Figure 8.

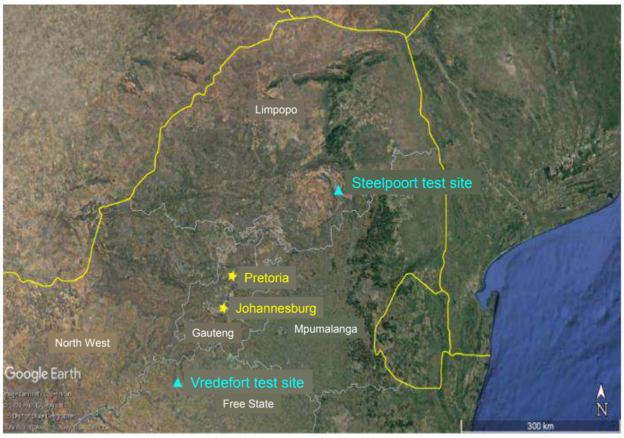

Figure 8. Location of field site for soil samples used for laboratory and centrifuge tests (Steelpoort test site) and for large-scale field monitoring (Vredefort test site) (Google Earth Pro, 2021)

The field testing conducted for this project aimed to investigate three different aspects of piled foundations in swelling clays:

i) cyclic lateral load tests on fixed and free end piles to investigate lateral stiffness and the degradation of stiffness with increasing cycles;
ii) vertical plug pull-out tests to measure shaft resistance with depth; and
iii) full length, instrumented piles socketed into bedrock to measure induced strains during a swell process.

Two separate test areas were established, a 'dry' area where natural moisture content conditions were maintained for the duration of testing and a 'wet' area that was kept flooded for a period of six months after the pile installation prior to the testing. The two test areas were set up sufficiently far apart so as to avoid infiltration of water from the 'wet' area into the 'dry' area.

The site was also instrumented so that suction and water content changes in the expansive clay profile could be monitored for the duration of testing. An accompanying paper by Murison *et al.* (2022) describes the measured volumetric changes throughout the clay profile which occurred during the flooding process of the 'wet' area. The effect of this swell on the generation of uplift tensile forces in a pile socketed below the expansive layer is addressed by da Silva Burke *et al.* (2021). The results showed that significant uplift forces, enough to cause cracking of the concrete piles, can be generated. Additionally, shrinkage of the expansive clay in the 'dry' site was shown to generate downdrag forces in excess of the generated uplift forces in the 'wet' site.

In this paper, the intention is however to provide an overview of some preliminary results relating to the lateral cyclic loading of the free end piles, and the vertical plug pull-out tests. For the cyclic loading tests, the piles tested were 600 mm in diameter and embedded 6 m into the expansive clay profile. Lateral loads were applied to the pile head 500 mm above the natural ground level using a load actuator. The free piles were installed in pairs, and jacked against one another using the actuator, such that each pile acted as a reaction pile for the other. Linear variable differential transformers (LVDTs) were used to measure pile head displacement at the level of the applied load; the displacement of each pile was independently measured against a reference beam. A graphical illustration of this layout is presented in Figure 9.

For each load-unload cycle, an indication of the stiffness of the pile-soil system was given by the lateral cycle secant stiffness. This parameter is defined as the slope of the line joining the peak (maximum) and trough (minimum) of a single load-unload versus displacement cycle. Cycle secant stiffness was expressed in kN/mm, and has also been illustrated in Figure 9.

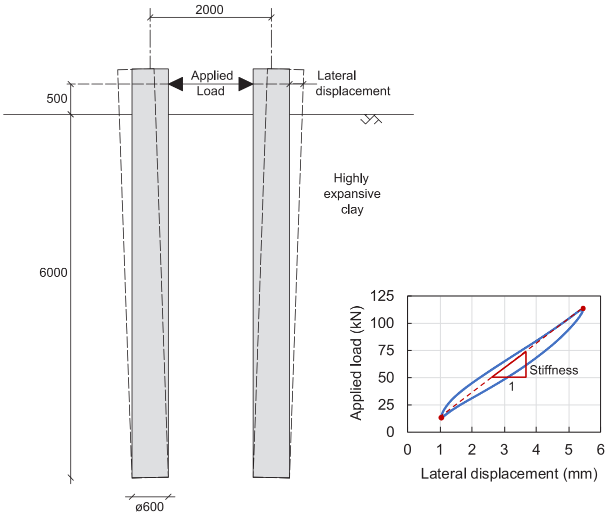

Figure 9. Free pile test layout and definition of cycle secant stiffness

The tests discussed in this paper involved the free ended piles which were subjected to 500 load cycles. The magnitude of applied lateral loads ranged from 10 – 110 kN. As load cycles were applied to the free piles in the wet site, the lateral stiffness decreased, indicating a softening response of the foundation system. By the 500th cycle, the lateral cycle secant stiffness had decreased by approximately 8%.

Conversely, the equivalent free piles in the dry site exhibited a stiffening response with an increase in number of load cycles. The lateral cycle secant stiffness increased by approximately 14% over 500 cycles. Figure 10 shows the percentage change in secant stiffness versus cycle number for free piles in the wet and dry sites.

The vertical plug pull-out tests included short length piles, with diameters and lengths of 0.6 m and 1.2 m respectively, installed at base depths of 2.5 m, 4.5 m and 6.5 m in the expansive clay profile in both the wet and dry test areas. After the wet test area had been kept flooded for a period of six months, the surface was left to dry out to allow access to the installed plugs. The plugs in both test areas were then tested for their pull out capacity; this was conducted using a hydraulic jack with a load cell to measure the pull out load. An LVDT was used to measure the displacement of the plug.

The results of the tests from the plugs installed at a base depth of 4.5 m are shown in Figure 11. This result shows that the shaft capacity is reduced after swell is allowed to occur in the soil, and supports the result shown from the full length pile tests conducted in the centrifuge shown in Figure 5. Despite the different clay materials used in the centrifuge and field testing, the overall result appears to be consistent in that a large magnitude of swell can reduce shaft capacity.

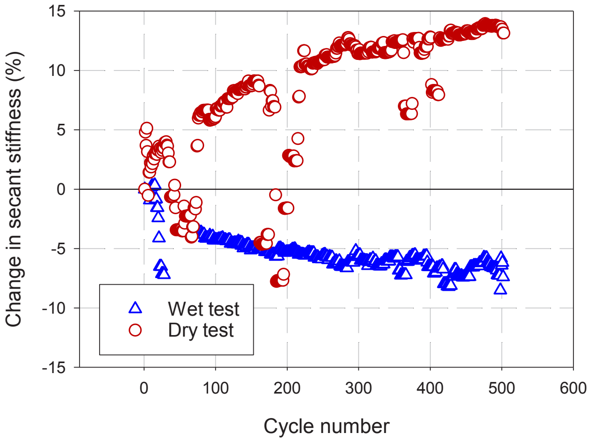

Figure 10. Change in lateral cycle secant stiffness over 500 load cycles of 10–110 kN for free piles in the wet and dry sites

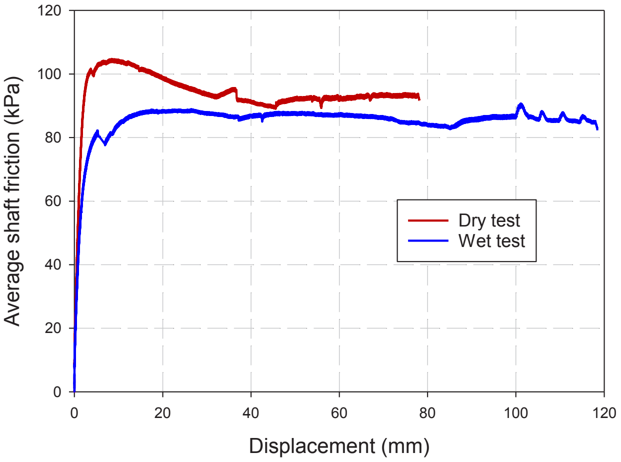

Figure 11. Average shaft friction versus pile head displacement for tests conducted at in situ moisture conditions and after swell had occurred

6 CONCLUSIONS

The results presented in this paper are intended to provide a brief overview on some early developments in the various work packages of the Wind Africa project. From the element testing conducted, it was found that the sample preparation procedure implemented, was able to retain key aspects of the mechanical properties of the expansive clay. This allowed for a series of centrifuge tests to be successfully conducted, which investigated the shaft capacity of piled foundations, before and after swell had occurred. These results illustrate that after allowing swell to occur, the shaft capacity reduced by approximately 40%.

The results of some preliminary numerical simulations have illustrated that the constitutive model developed, is able to replicate the results of a series of oedometer swell tests.

Finally, large-scale, lateral cyclic loading of free ended piles have highlighted the dependency of secant stiffness on soil saturation. After the application of 500 load cycles, it was revealed that while testing under ‘wet’ conditions resulted in an 8% reduction in stiffness, an equivalent test conducted under ‘dry’ conditions experienced a 14% increase in secant stiffness.

Large scale vertical plug pull-out tests have illustrated that after a large magnitude swell has occurred, pile shaft capacity is reduced. This supports the findings of similar centrifuge pull-out tests conducted on another expansive soil.

7 ACKNOWLEDGEMENTS

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