Preparations for field testing for the performance validation of piled wind turbine foundations in expansive clays

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ABSTRACT: Field-testing of piles in an expansive clay is required for the validation of the design criteria for wind turbine foundations in such soil profiles. The test programme includes lateral load tests to investigate the horizontal stiffness of the soil and vertical plug pull-out tests to examine the axial capacity of pile-soil interface. These tests will be conducted in both dry and wet conditions to study the range of expected responses of the pile and evaluate how the changing soil moisture condition affects the pile behaviour. In addition, an instrumented pile socketed into bedrock will be used to determine the strain induced in the pile due to soil heave as the soil saturation levels increase. For the execution of these tests, a large open area with expansive clay of a sufficient depth is required; a stable stratum below the clay is desirable for the socketing of the long piles. An important component of the investigation is the characterisation of the expansive clay profile. A preliminary site investigation has been carried out on the field-testing site which will be supported by further laboratory testing. Details of the soil profile and site characterisation which will be used in the future analyses of the field-testing results are presented.

1 INTRODUCTION

Wind energy offers significant potential for the expansion of the capacity of renewable energy across the African content. However, the arid and semi-arid regions that cover large portions of the African continent result in unsaturated soils, including expansive clays. These conditions present a challenge for founding of wind turbines. Piled foundations are used in such soils to limit the differential settlement. However, the performance of the piles and the associated design procedures are not well understood in unsaturated, expansive soils that are subjected to seasonal moisture fluctuations.

The WindAfrica project has been initiated to explore this problem and to develop a set of design guidelines for piled wind turbine foundations in expansive clays. Large-scale field tests will be conducted in South Africa; the planned field-testing will investigate the performance of bored concrete piles in an expansive clay profile to establish the actual performance of the piles under representative loading and soil moisture conditions. The results acquired from the tests will be used to validate the assumptions made in the current design practice of such foundations.

This paper describes the proposed field-testing programme; in addition, an overview of the selection and characterisation of an appropriate site to conduct the field tests is presented.

2 TEST AIMS

The main considerations for the design of piles below a wind turbine foundation in expansive clay are:

- vertical load capacity of pile in compression;
- total uplift forces to be resisted (applied uplift forces at pile head plus heave forces on the pile shaft);
- ability of pile socket to resist total uplift forces;
- resistance of piles to lateral loading under static and dynamic loading; and
- the effect of changes in moisture content on the above.

The vertical load capacity of the pile in compression is unlikely to be a problem due to the presence of a stable stratum at depth. The field test programme for the WindAfrica project has been designed to address the remaining uncertainties; this is discussed further in the next section.

3 PROPOSED TESTS

The proposed field-testing includes three sets of tests:

i. Cyclic lateral load tests to measure lateral pile response and subgrade reaction;
ii. Vertical plug pull-out tests to measure shaft resistance with depth; and
iii. Full length, instrumented piles socketed into bedrock to determine axial strain due to moisture changes in the soil.

The tests will be conducted in two test areas. One will be kept 'dry', i.e. at natural moisture content (NMC), to evaluate the baseline behaviour. The second test series will be conducted in a flooded test area to accelerate the effects of heave. This would simulate the maximum heave and provide data for a comparison shaft resistance and subgrade reaction in the dry and saturated states.

These two test areas will need to be sufficiently far apart to ensure that flooding of the wet area does not impact the soil moisture profile in the 'dry' area. The required separation will depend on the soil permeability, extent of fissuring and the depth of the clay profile.

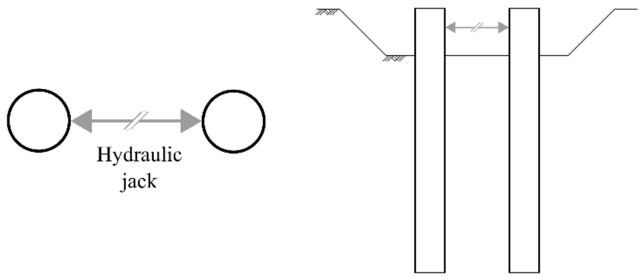
Each of the proposed tests is discussed in more detail in the sections that follow.

3.1 *Cyclic lateral load tests*

One of the key considerations in the design of a piled foundation for a wind turbine is the assessment of how the cyclic loading changes the capacity and stiffness of the pile-soil structure. Horizontal pile load testing will be carried out to monitor the strains developed in the pile, and back analyse the changing stiffness of the surrounding soil. Vibrating wire strain gauges and fibre optic cables will be cast into the piles to monitor the strains. A series of cyclic lateral load tests to monitor changes in stiffness as a function of the applied load will be carried out with the first cycles applied to 25 % of the predicted ultimate load, followed by a series to 50 % of the ultimate load, with a final static loading of the pile until it fails.

The pile load testing will be carried out by using a hydraulic jack and jacking two test piles against each other as shown in Figure 1. Each pile is monitored individually; in this way, two results are obtained from each test.

An additional test configuration is planned as shown in Figure 2 to test the pile and soil response for a fixed-headed pile as would be expected in the base of a wind turbine with a pile cap connecting all the piles. This will allow the comparison of the behaviour of the free head and fixed head piles.



a) Plan view b) Section view

Figure 1. Layout of lateral pile load tests (not to scale)

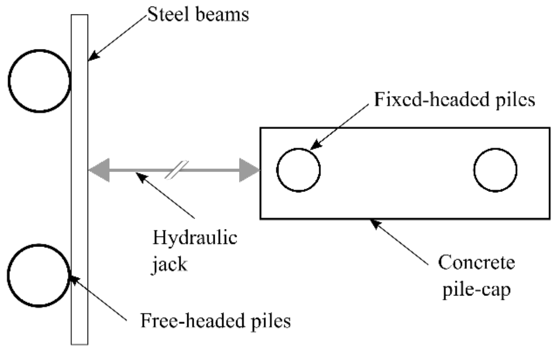


Figure 2. Layout of grouped lateral pile load tests (not to scale)

3.2 *Vertical plug pull-out tests*

The vertical plug pull-out tests are planned to ascertain the maximum transfer of load from the heaving soil to the pile shaft at different depths in the profile at both NMC ('dry') and under soaked ('wet') conditions. The intention of these tests is to determine whether the shaft resistance will increase due to the increased lateral stress or will reduce due to softening of the clay on wetting. The proposed test set-up is shown in Figure 3. Three plugs at different depths will be tested to get an indication of the variance in the shaft resistance with depth. These results will enable the determination of the maximum pull-out forced exerted on the pile.

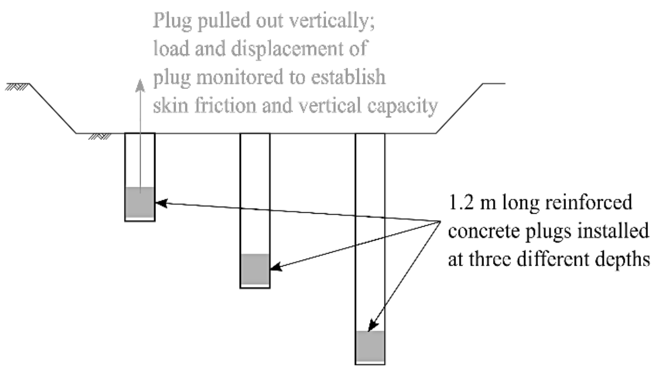


Figure 3. Schematic configuration of vertical plug-pull tests (not to scale)

3.3 *Full-length instrumented piles*

The final set of tests will be the long-term monitoring of the strains developed in piles socketed into bedrock as a result of the clay heave. This will give an indication of the depth to which heaving effects are significant and the additional uplift force that the clay applies to the pile. At some depth in the soil profile, the direction of the shear forces exerted by the soil on the shaft will change from those lifting the pile out of the ground to those resisting the uplift. This is the point of maximum tension in the pile. Its depth depends on the relative stiffness of the pile and the soil, the potential expansiveness of the soil and its moisture content at depth.

Two instrumented piles will be installed; a schematic example of one is shown in Figure 4. One pile will be subjected to accelerated heave by wetting the surrounding soil, and the second left to swell naturally and in response to seasonal moisture content changes. The strains in the pile will be measured using fibre optic cables and vibrating wire strain gauges cast in the pile.

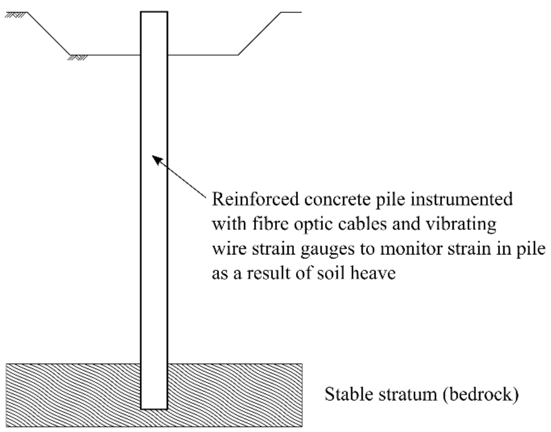


Figure 4. Layout of grouped lateral pile load tests (not to scale)

3.4 *Long term soil and weather monitoring*

In addition to the long-term monitoring of the instrumented pile, the rainfall, ambient temperature and relative humidity will be monitored, as well as the soil temperature, moisture content and suction. This will allow the observed changes in the soil heave to be related to the ambient and soil temperature and moisture changes. The extent of the change in the moisture content and suction in the soil will also give an indication of the expected heave that is likely from the soil profile under consideration.

4 SITE SELECTION

4.1 *Alternatives*

Once the field-testing programme had been determined, a suitable site with expansive/heaving ground for the pile installation had to be identified. Expansive clays are a well-known problem soil in South Africa with a widespread distribution (Williams et al. 1985).

Three alternative sites were considered, all with documented history with potential heave causing severe damage to structures or requiring mitigation in the design of infrastructure.

The first site was the Colinda Primary School in Vryburg, approximately 420 km south-west of Pretoria. Damage to the school and further investigations were reported by Meintjes (1991) and Meintjes & Pellissier (1994). A site visit to the area showed extensive cracking in the buildings in this area giving further indication of the large extent of the expansive soil profile. An open area to the south of the school was available for testing. However, due to the limited area of the site, additional health and safety requirements to keep scholars away from the testing area, and potential impact of inducing heave on adjacent buildings, this site was not considered suitable.

The second site that was considered was the Lethabo Power Station, located approximately 140 km south of Pretoria. This has a proven history of swelling clays known from the construction of the power plant (Blight and Lethabo Ad Hoc Foundation Committee 1984). A site visit was conducted to establish the suitability of the site for the proposed tests; this showed that, although a significant expansive clay deposit does exist in this area, it is mostly covered by approximately 10 m of less expansive soil. This would thus require a large number of earthworks to install the piles in the clay, and was therefore not considered suitable.

The third area considered was the Steelpoort area (300 km north east of Pretoria) where heave of structures has been experienced (Jacobsz & Day 2008). Further analysis of the expansive soils from this area has been conducted by Stott & Theron (2018).

A visit was conducted to a potential site at the AttaClay mine which extracts attapulgite and bentonite clays by shallow surface mining. These minerals are processed and sold for use in applications such as binders, cat litter and dam sealing. A photograph of the clay quarry wall is shown in Figure 5; the excavator teeth mark on the sidewall give an indication of the stiffness of the clay profile. Evidence of cracking in buildings on site, an example of which is shown in Figure 6, indicates the expansive nature of the soil and thus the suitability for our project. Boreholes that had been drilled by the mine to 9 m depth indicated a clay profile to at least this depth.

This site was selected as the best alternative to proceed with the field testing due to the large open area, presence of expansive clay from the surface, absence of infrastructure likely to be impacted by the testing, and sufficient presumed depth for the intended piles to be installed.

Figure 5. Attapulgite and bentonite quarry wall at the AttaClay mine.

Figure 6. Cracked buildings on site showing evidence of expansive clays

4.2 *Final selection*

A map of the site location is shown in Figure 7 with the corresponding lithology from the Council for Geoscience (2019) geological map shown in Figure 8. A close-up of the proposed field-testing area is shown in Figure 9.

These figures show that the site is located in an alluvial plain between two formations of the Rustenburg Layered Suite of the Bushveld Complex: the mountains of the Dsjate Subsuite to the west and outcrops of the Dwars River Subsuite to the east.

As described by Williams et al. (1985), the expansive clay identified on site is likely to be a combination of residual soils formed from the weathering of the Rustenburg Layers Suite and active material transported from the weathering of the adjacent basic igneous rocks.

5 SITE CHARACTERISATION

After confirmation of the potential of the site for the intended field test programme, further characterisation was conducted. This comprised the excavation, profiling and sampling of test pits followed by rotary core drilling. The details of these investigations are described below.

5.1 *Test pit investigation*

Two tests pits were excavated at the end of the dry season to describe the soil profile in the proposed testing area north of the existing quarry (see Figure 9).

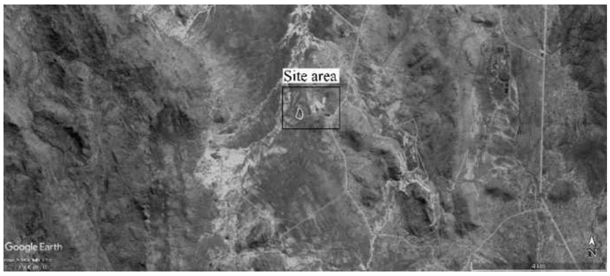


Figure 7. Google Earth image of field-testing site location

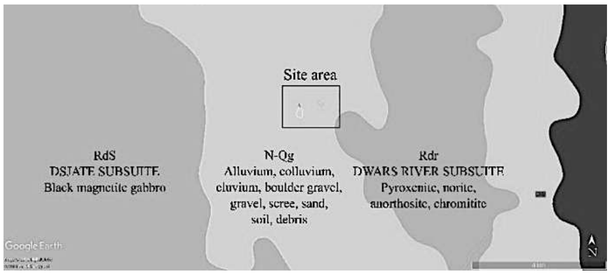


Figure 8. Overlay of geological zones (Council for Geoscience 2019) over site location

Figure 9. Existing clay quarry and mine area showing proposed field-testing area

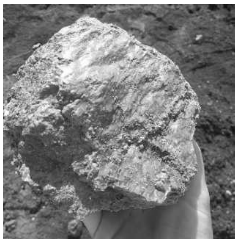
The first test pit (TP1) was excavated from the floor of the existing mining pit which was approximately 5 m below natural ground level to get information about the possible depth and nature of the clay deposits. It was initially dug to a depth of 5 m (the reach of the excavator), and then a bench was cut, and an additional 2 m was dug (final depth 7 m). The profile showed a black, stiff silty clay to a depth of 2.60 m, underlain by an olive brown sandy clay to a depth of 5 m. The bottom 2 m of the test pit was in an inert sand layer, presumed to be alluvial.

The second test pit (TP2) was excavated from NGL to the maximum reach of the excavator. The profile showed a black, stiff silty clay to the base of the excavation at 5.20 m.

Significant fissuring and slickensiding was noted in all the clay material encountered in both test pits. Figure 10 shows photographs of blocks of clay removed from the spoils of the excavations; the smooth, shiny surfaces (slickensides) in the clay are evidence of movement along these planes due to cycles of wetting and drying confirming the expansiveness of the material.

Together, these pits showed expansive material to a depth of approximately 10m, which was sufficient for the purposes of this research. No water table was encountered in the excavations.

a) Black clay from surface to approximately 7.5 m below NGL



b) Olive brown clay from approximately 8.5 to 10 m below NGL

Figure 10. Example of slickensided blocks of clay removed from the spoils of the test pit excavation

5.1.1 *Block sampling*

Block samples were retrieved from the test pits to be used for further laboratory tests to investigate the strength and stiffness of the material. Due to the fissured nature of the material, these block samples could not be taken in the conventional manner where the material around the desired block is removed using a geological pick. A chainsaw was used to cut into the stiff clay, and the aim was to place a 200 x 200 x 200 mm metal box into the created cuts and remove the now structurally protected block sample. The process of cutting and removing the block samples is shown in Figures 11 and 12 for the samples of the olive brown and black clay taken from TP1 and TP2 respectively.

In TP1, the test pit was widened to create a bench about 1 m off the intermediate base of the pit. The chainsaw was used to cut into the soil from the top, loose material was removed, and the metal box was placed over the sample. Expanding foam was used to fill the gaps and secure the sample in place; the base of the sample was broken off to remove the block from the test pit. Whilst this method worked relatively well, the stress relief from the removal of the overburden material above the blocks caused the fissures to open, and several attempts were required to get a reasonably full sample box.

In an attempt to obtain better block samples in the second test pit, the chainsaw was used to cut directly into the pit sidewall as shown in the image sequence in Figure 12. This proved more successful, and once the metal box was in place, wedges of soil surrounding the sample could be removed allowing the sample to finally be removed.

The metal boxes were covered with a wooden board on each side and secured with threaded rods to protect the sample during storage and transport. Any gaps around the sample were filled with expanding foam injected through holes in the boards.

a) Cutting into the bench with a chainsaw

b) Removal of material surrounding the cut-out block

c) Placing the metal box around the undisturbed sample

d) Filling the remaining gaps with expanding foam to protect the sample

Figure 11. Removal of a block sample from the olive brown clay in TP1

a) Metal box being fitted over cuts made into the sidewall

b) Removed sample showing more complete sample retrieval

Figure 12. Removal of a block sample of the black clay from the test pit side wall in TP2

5.1.2 *Soil classification*

A sample of each of the black clay (surface deposits) and the olive brown clay (deeper clay deposits) were sent for grading and indicator tests. The black clay was classified as a high plasticity clay (CH), and the olive brown clay as a high plasticity silt (MH). The moisture contents of the clays were 34.2% and 36.5% respectively; the degree of saturation of the black clay was measured as 86.2 % from the average of eight samples. This high degree of saturation has important implications: this was sampled at the end of the dry season, and it is thus likely that many aspects of saturated soil mechanics can be applied in the analysis of the clay behaviour.

Figure 13 presents the activity chart as per Van der Merwe (1964) indicating potential expansiveness, based on the plasticity index (PI) of the whole sample and clay fraction. Both samples fall well within the very high expansive region, primarily due to the high PIs. The black clay has a significantly higher clay fraction than the olive brown clay, although the PIs are similar. This confirms the suitability of the material on site for the proposed field-testing.

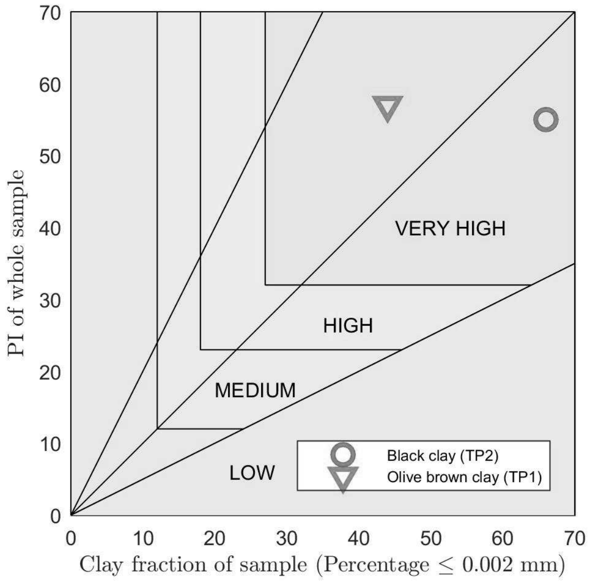


Figure 13. Expansive potential of the clays on site plotted according to the activity chart of Van der Merwe (1964)

5.2 *Rotary core drilling*

Further investigation was conducted to determine the full depth of the expansive material and the properties of the underlying rock. Two N-sized rotary core boreholes were drilled in the proposed wet and dry test areas. Undisturbed Shelby tube samples were taken from the boreholes for advanced laboratory testing.

Rock was encountered at approximately 12 m in both boreholes. The core logs showed a reasonably consistent profile across the site, similar to that logged in the test pit investigation with a dark black brown sandy clay from the surface to a depth of 5-6 m, underlain by a light grey brown clayey silt until the transition to bedrock. Slickensided or partially slickensided material was recorded throughout the soil profile.

A thin transition was observed from the residual soil into the bedrock. The bedrock was described as hard to very hard rock, either norite or anorthosite; a photograph of a portion of the core is shown in Figure 14.

This investigation confirmed the suitability of the site for the installation of the short piles for the lateral load testing and the pile plugs. The hard rock encountered will allow the installation of the instrumented piles with a good socket to ensure that the base does not move, and the strains in the pile due to soil heave can be determined.

6 CONCLUSIONS

Field-testing of piles in an expansive clay is required for the validation of design criteria for wind turbine foundations in similar soil profiles.

Figure 14. Portion of the residual norite core from 13.33 -14.02 m (BH1)

The proposed tests will determine the lateral stiffness of the piles under cyclic loading, uplift forces on the pile shaft and the impact of changes in moisture content.

The selected site is well suited to the proposed test programme with 12m of highly expansive clay overlying competent rock into which the piles can be socketed. There is sufficient space on site for the proposed wet and dry test areas and no adjacent infrastructure to be affected by the accelerated heave tests. Although the clays in the test pits were observed to be slightly moist and fissured, the degree of saturation was relatively high even at the end of the dry season.

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