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Correlation between Pile Displacement from Pile Load Tests and FE Modelling: Case Study of Piles in Cawthorne Channel Area in Nigeria

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Pile Load Test; FE; Displacement; Modelling, Validation

Abstract

Pile load static tests are used to confirm that a pile would not exceed a prescribed displacement at service or ultimate limit load. In this work, 600mm diameter steel piles were driven to 30m depths at the project site in the Niger Delta region of Nigeria. The relationship between pile displacements obtained from field pile load tests on these driven piles and those obtained from a finite element (FE) program, PileAXL, was studied. It was observed that for loads lower than the elastic limit of the soils at the pile toe, the FE program was able to accurately predict the displacements obtained from pile load tests. However, as the test loads on piles increased, the FE program was not able to accurately predict the displacements obtained from the pile load tests. This suggests that as significant plasticity sets in the end-bearing pile spring in the FE program, a more rigorous end bearing nonlinear spring would be required to model the load-displacement behavior of piles. This paper aims at presenting a technical reference to show that pile load test results can be easily validated using simplified FE models at low service loads using simplified nonlinear springs to model pile shaft interaction and end-bearing displacements.

1. Introduction

Pile load tests present field procedures to validate the design capacities of piles in projects. To this end, the static load test presents a reliable method for determining the capacities of single piles [1]. There are two main kinds of load tests on piles: vertical load tests and lateral load tests. The objectives of these load tests are to determine the capacity of installed piles either in the vertical (i.e., compression and uplift capacities) or in the lateral direction [2]. However, the most common pile load tests in Nigeria are the vertical load tests on piles, which are normally conducted in the simplified manner presented in ASTM- D1143 [3].

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A load-displacement graph from the static pile load test shows the relationship between the applied load and the induced displacement of the test pile. Thus, pile load tests are conducted with adequate instrumentation to measure applied loads and displacements [4]. The load-displacement curves from a pile load test usually have three regions: the elastic region, the plastic region, and the ultimate region [5].

The pile load tests validate the capacity of piles obtained from various geotechnical approach or soil mechanics procedures. However, as the process of determining pile capacity becomes more complex, models of soil-pile system using FEM software have been used to determine pile capacities. Numerical methods are used to determine the various bearing capacities of piles. Pile capacities such as shaft friction and end bearing can be accurately determined using numerical FE programs [6]. Results from geotechnical investigations (i.e., laboratory tests on soils supporting foundations) are traditionally used as input parameters for determining pile capacious – vertical, lateral and uplift capacities– using FE software such as PLAXIS and Abaqus [7]. Numerical analyses have efficiently been used to analyze the cyclic displacement of driven piles in residual soils [8].

Pile load tests play a significant role in understanding the behavior of piles under load. Research has shown that pile load tests could be used to monitor and understand how pile toe resistance and skin friction vary or change in different layers of soils along a pile length as test loads increase [9]. Also, the rate of change of pile toe resistance and shaft friction can be effectively monitored in a well-instrumented pile load test program as pile test loads increase [10]

To obtain the load-displacement behavior of a single pile, several static load tests can be used in the field. A typical test setup with reaction piles to supply reaction force is commonly used because of its ease of application and cost-effectiveness [11]. In this traditional procedure, loads are usually transferred to the soils around the test piles and the reaction piles in a manner that the loads in the reaction piles are in the opposite direction to the load applied in the test piles as shown in Figure 1. This suggests that in many instances the displacement in the test piles could be less than the individual piles displacements. Thus, the difference between the obtained vertical displacement and the tests piles would increase with a reduced midpoint to midpoint displacement between reaction piles and test piles. This implies that the reaction test piles could introduce significant uncertainties in the measured displacement of piles. Also, it has been established that installation effects impact on load-displacement curves from pile load tests [12].

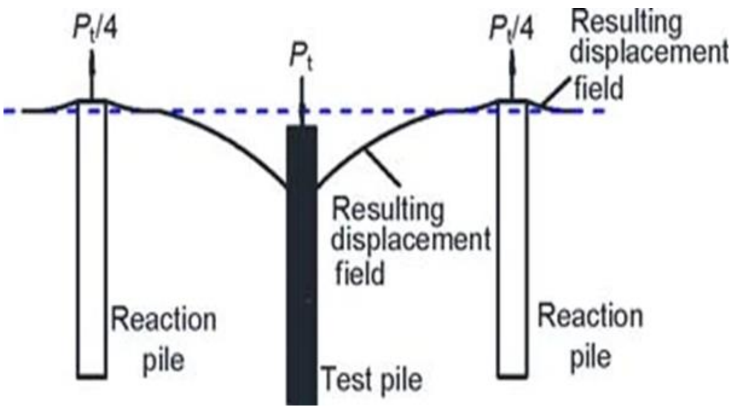

Figure 1: Displacement of test pile and reaction piles due to interactions between test and reaction piles (four reaction piles) [11].

To account for the influence of reaction piles on displacements of test piles, correction factors are introduced [11]. This paper investigates the relationship between displacements obtained for piles at various test loads and that obtained from an FE modelling using a case study of a piling project in the Niger Delta region of Nigeria. This paper closes a significant gap in the literature by attempting to increase the understanding of uncertainties that could result from pile load tests conducted in the field [13]. Thus, by using a case study project, this paper attempts to investigate and study some factors that contribute to uncertainties in the results of pile load tests. The results of a series of well-calibrated and accurately executed pile load tests were validated with FE predictions in this work. The relative difference in the results from FE models and experiments gives insight into the cause of uncertainties in pile load tests in this paper.

2. Methodology

2.1. Pile Load Tests

A static axial pile load test was carried out on 5 test piles in a piling work project at Cawthorne Channel in the Niger Delta region of Nigeria. Cawthorne Channel is a navigation channel and is in Rivers State, Nigeria. It is located on Latitude 4.44902° or 4° 26' 57" north and Longitude 7.08384° or 7° 5' 2" east. Figure 2 shows some of the piles installed at the project site. The properties of the installed piles are presented in Table 1. The pile load test was executed as a vertical pile load test by using a hydraulic jack against a reaction frame to 150% of the Safe Working Load, i.e. (1.5 x SWL) on the test pile in the project area, in accordance with ASTM D-1143 procedures. The reaction load test is such that load is increased in stages -- in increments of 25%, until 150% of the SWL was reached. The settlement was recorded at each stage of loading and unloading. The safe working load (SWL) of the tested pile was given as 1200 kN. The test load was taken up to 180 tons. The pile load test components were properly mounted ensuring a symmetrical arrangement for axial transmission of load (in the manner presented in the version of the ASTM presented in this section). The load applied by the hydraulic jack was measured by a calibrated manometer gauge placed between the pump and the jack. The settlement was monitored with the aid of dial gauges fixed on a reference beam. Figure 3 presents the pile load set-up. During the pile load test, the following precautions were taken: (a) Vibration within proximity to the site was not allowed; (b) Two dial gauges were connected to the test pile so that the impact of the settlement/movement can be detected directly by taking average readings. See Figure 4 for the schematic layout used according to ASTM D1143 (note the simplified set-up presented in ASTM D1143-94 was followed in setting up the pile load test procedure in this investigation [3]); (c) The pressure was carefully monitored through the indicator of a load cell to control the adequacy of the applied pressure; (d) reaction beam was checked in order to ensure it was plump using a spirit level; (e) Relative heights of the top of reaction piles to referenced spot heights were taken and there were no uplifts recorded in the anchor piles; (f) Reaction beam was selected to ensure that it does not deflect during the test. Levelling instruments were used to check the deflections of the reaction beam and no deflections were observed. The hydraulic jack(s), hydraulic pump, and pressure gage were calibrated before the commencement of testing campaign.

Table 1: Property of Installed piles

Pile property	**Value**
Pile diameter	600mm
Total length of the pile	30m
Pile steel casing thickness	16mm
Pile Case	ASTM A252
Mode of installation of test piles	Driven pile with Direct Impact Hammer

Figure 2: Piles at project site

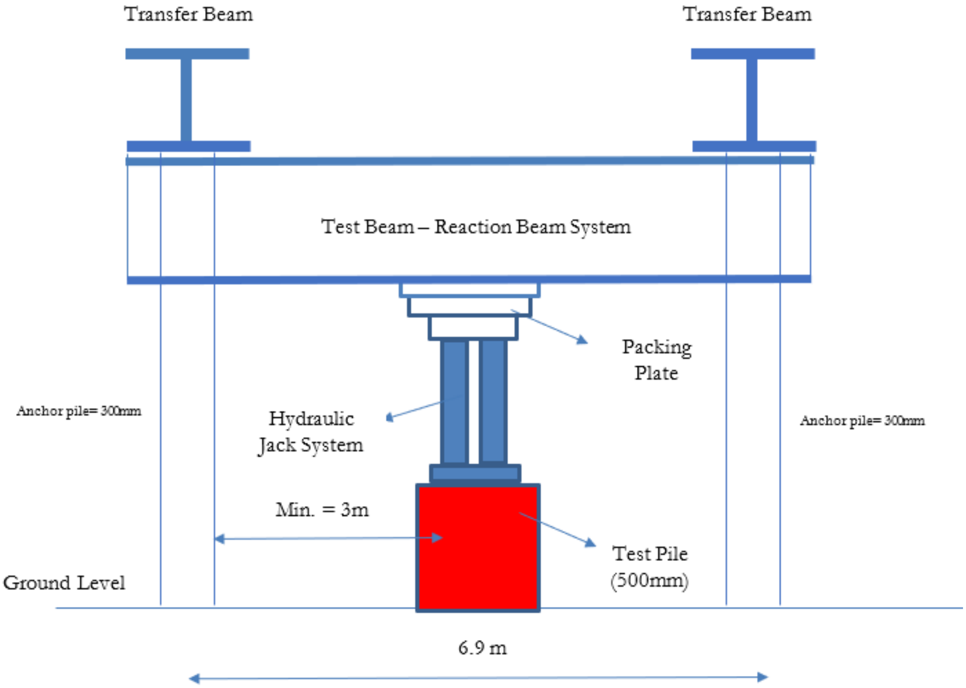

Figure 3: Schematic representation of pile load test set-up

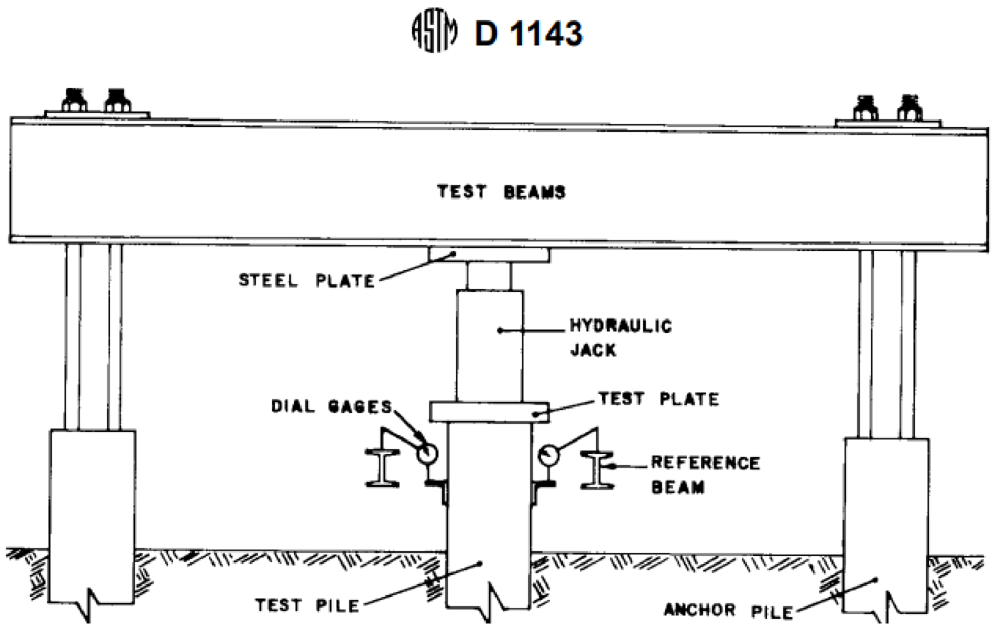

Figure 4: Reference procedure used in this experiment for setting up dial gages and reference beam according to ASTM D1143[3] .

2.2. Finite Element Modelling of Load Displacement of Curve

The pile capacity analysis was performed using PileAXL Geotechnical Software. This is commercial pile analysis software developed by Innovative Geotechnics Pty Ltd [14]. PileAXL analyzes the behavior of single piles under axial loading applied at the pile head. The driven pile is analyzed by the American Petroleum Institute Method (API RP2A). Ultimate end-bearing resistance within the layered soils is determined by Meyerhof 1976's approach considering the influence effects of upper and lower soil layers. Geotechnical analysis was conducted on the soil strata obtained from site boring using a percussion rig in order to characterize the soils layers at the site. Figure 5 shows the analytical idealization of the pile model used in PileAXL. Based on the geotechnical properties of soils around a modelled pile, PileAXL generates series of t-z springs along the pile shaft (models the shaft resistance i.e., pile-soil friction) and a Q-z spring at the toe of the pile (models the end-bearing interaction) using API 2010 recommendations. These springs depict the boundary conditions on the modelled pile. Figure 5 presents an idealized position of these springs concerning a modeled pile.

PileAXL discretizes the 30m pile length into several elements along its length. These pile elements are accompanied by corresponding soil element. The stiffness of each soil element, $k_{soil,\ shear}$ is obtained by using generated PILEAXL t-z curves to obtain unit skin friction as shown in:

$$k_{\text{soil,shear}} = \frac{T}{L_{segment}} \qquad (1)$$

Here, $T_{Segment}$ is the length of each pile segment, and T is the total of the unit skin friction, τ, of each pile segment. Th pile displacements in segments are obtained by solving the following differential equation form the free body diagram of each segment using finite element method:

$$-EA\frac{d^2u_z}{dz} + \tau.C = 0 \qquad (2)$$

In equation 2, E is the pile segment modulus of elasticity at corresponding depth z; C is the pile circumference; *A* is the cross-sectional and u_z is the displacement in pile element segment corresponding to a depth, z, under applied vertical load. In solving equation 2, the pile is assumed to isotropic and second effects are not considered in the pile shaft.

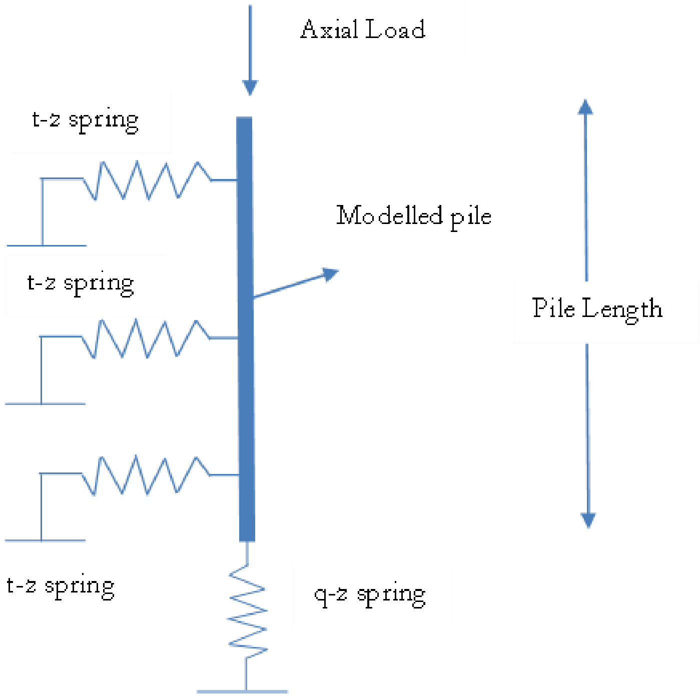

Figure 5: Theoretic idealization of pile model in the FE analysis

3. Results and Discussion

To carry out the FE modelling to obtain the corresponding displacements of piles under test loads, laboratory tests were carried out to determine the geotechnical properties of the soils from the project site. The FE modelling forms the basis for validating field test data. Table 2 presents the geotechnical properties of the soil used to model the soil strata in the FE program. Table 3 shows a summary of the tests results from the pile load tests at the project site, i.e., applied load and corresponding settlement obtained in tested piles. The displacements were obtained with test loads ranging from 120ton to 180ton. Five (5) pile load tests were conducted and each of the pile load test took an average of 2 working days to conduct. Figure 6 presented the typical pile load tests graphs obtained from this investigation. It demonstrates the loading and unloading curves obtained during the pile load tests. Figure 6 presents the results for the pile load test in Pile No. 1 shown in Table 1.

Figure 6 presents a typical pile log of the project site. This log was presented in a simplified form in Table 2. The properties were obtained from an average of 3 bores of 40m depth in the project site. It is important to note that after the application of SWL during the pile load test, it was observed that that there was no significant permanent deformation after unloading. This suggests that the soil at the pile toe is still in the elastic domain even after the removal of the loads with the magnitude of the SWL.

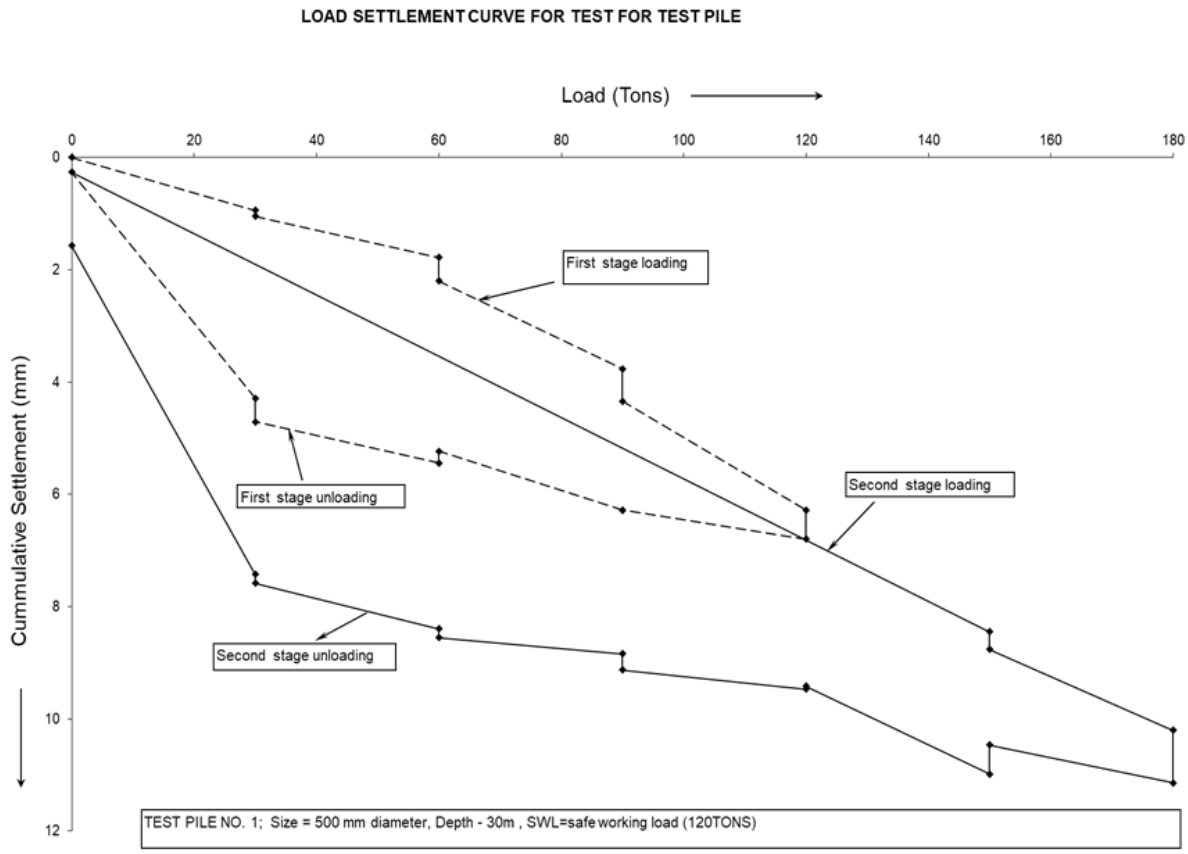

Figure 6: Typical load displacement curve (Pile No.1)

Table 2: Summary of geotechnical properties of soil at project site

Soil Strata	Description	Geotechnical Parameter
0 – 15m	Soft clay	Undrained shear strength, Su = 8kPa; bulk unit weight, γ = 13 kN/m^3
15 – 20m	Soft clay	Undrained shear strength, Su = 7kPa; bulk unit weight, γ = 13 kN/m^3
20 - 30	Sand	Phi =30 degrees, bulk unit weight, γ = 21kN/m^3
23 – 25m	sand	Phi =30 degrees, bulk unit weight, γ = 21kN/m^3
25 – 30m	Sand	Phi =30 degrees

Figure 8 presents the FE model for the pile and the corresponding soil layers at the project site. Each of the soil layers was modelled in the FE program, PileAXL using the philosophy described in the preceding sections. To carry out the FE numerical iteration using nonlinear spring, FE uses the API 2010 clay model and API 2010 sand model for the clay and sand, layers respectively. By using the geotechnical properties of the soil at the toe, PileAXL generates a non-linear t-z spring used to model the interaction between the shaft of the pile and surrounding soil while a non-linear q-z spring is used to model the displacement load curve for the toe of the pile. Details of this philosophy can be found in [15]. Note that in PileAXL t-z springs (models the shaft resistance i.e., pile-soil friction) and q-z spring (models the end-bearing interaction).

BOREHOLE LOG						
LOCATION:CAWTHORNE CHANNEL, RIVERS STATE		DATE: 15/01/2023				
BOREHOLE NO: 1		BORING METHOD: MANUAL PERCUSSION				
SCALE: To fit			SPT			
DESCRIPTION OF STRATA	LEGEND	DEPTH	0.150m	0.300m	0.450m	REMARKS
Brownish Soft Clay		0				D
Brownish Soft Clay		1.50m				D
Brownish Soft Clay		3.00m				D
Brownish Soft Clay		4.50m				D
Brownish Stiff Silty Clay		6.00m				D
Brownish Soft Clay		7.50m				D
Brownish Soft Clay		8.25m				D
Brownish Soft Clay		9.00m				D
Dark Soft Clay		10.50m				D
Brownish Soft Clay		12.00m				D
Brownish Soft Clay		13.50m				D
Brownish Soft Clay		15.00m				D
Dark Soft Clay		16.50m				D
Dark Soft Clay		18.00m				D
Dark Soft Clay		19.50m				D
Brownish Coarse Sand		21.00m	7	17	19	SPT
Brownish Coarse Sand		22.50m				D
Brownish Coarse Sand		24.00m	8	11	23	SPT
Brownish Coarse Sand		25.50m				D
Brownish Coarse Sand		40m	11	14	24	SPT
Disturbed Sample - D						
Water level @ 0m -						

Figure 7: Typical pile log from the project

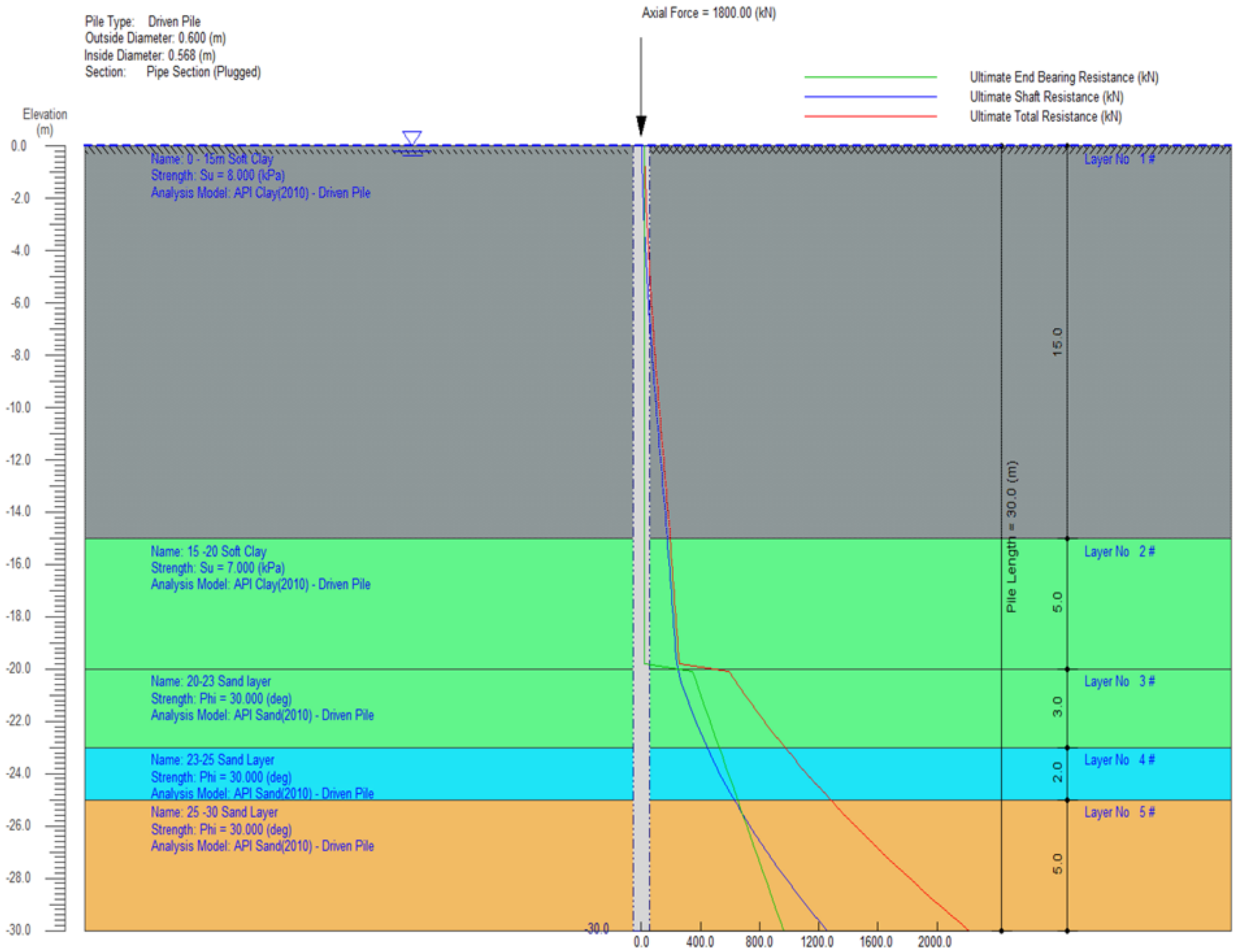

Figure 8: Pile Load in FE program

Figures 9 and 10 present the displacements obtained from the FE program at 1200kN and 1800kN axial compressive loads on the modelled pile respectively. From Figures 9 and 10, it is observed that beyond 1500kN (150ton) compressive load, the displacement of the pile becomes highly nonlinear. This implies at the service load of 1200kN, the response of the pile is still relatively linear. The predicted displacement at 1800kN clearly does not correlate well with the displacements from pile load tests. This is because of the complex nature of the plastic phase of the pile load test displacement curve. This obviously would require a more complex FE model. It is important to note that considering layered soils, the ultimate end-bearing resistance is determined by Meyerhof (1976)'s approach and the shear capacity is predicted using the nonlinear t-z springs along the pile shaft. The pile displacement is predicted with the q-w spring at the toe.

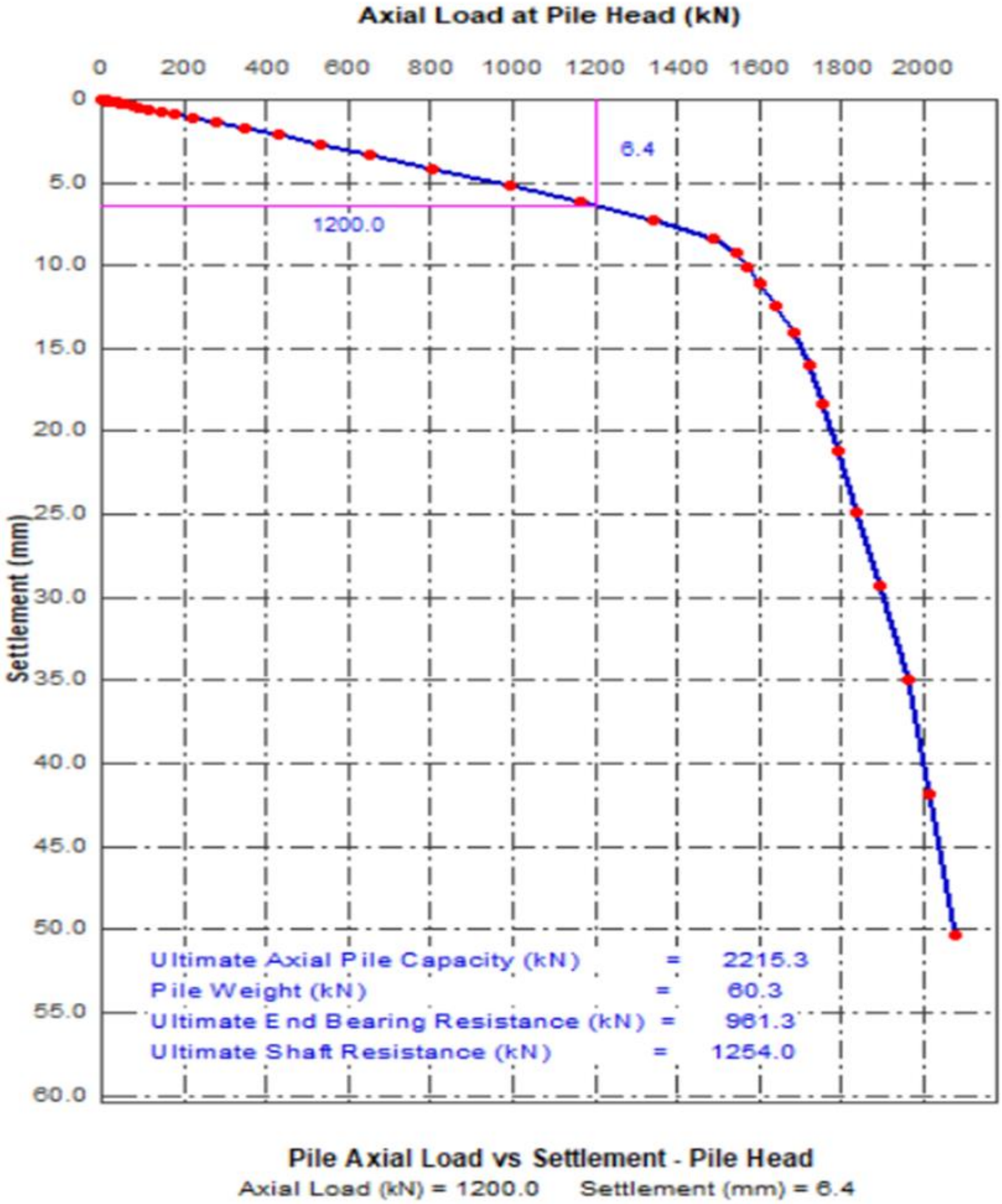

Figure 9: Predicted settlement at 1200kN load

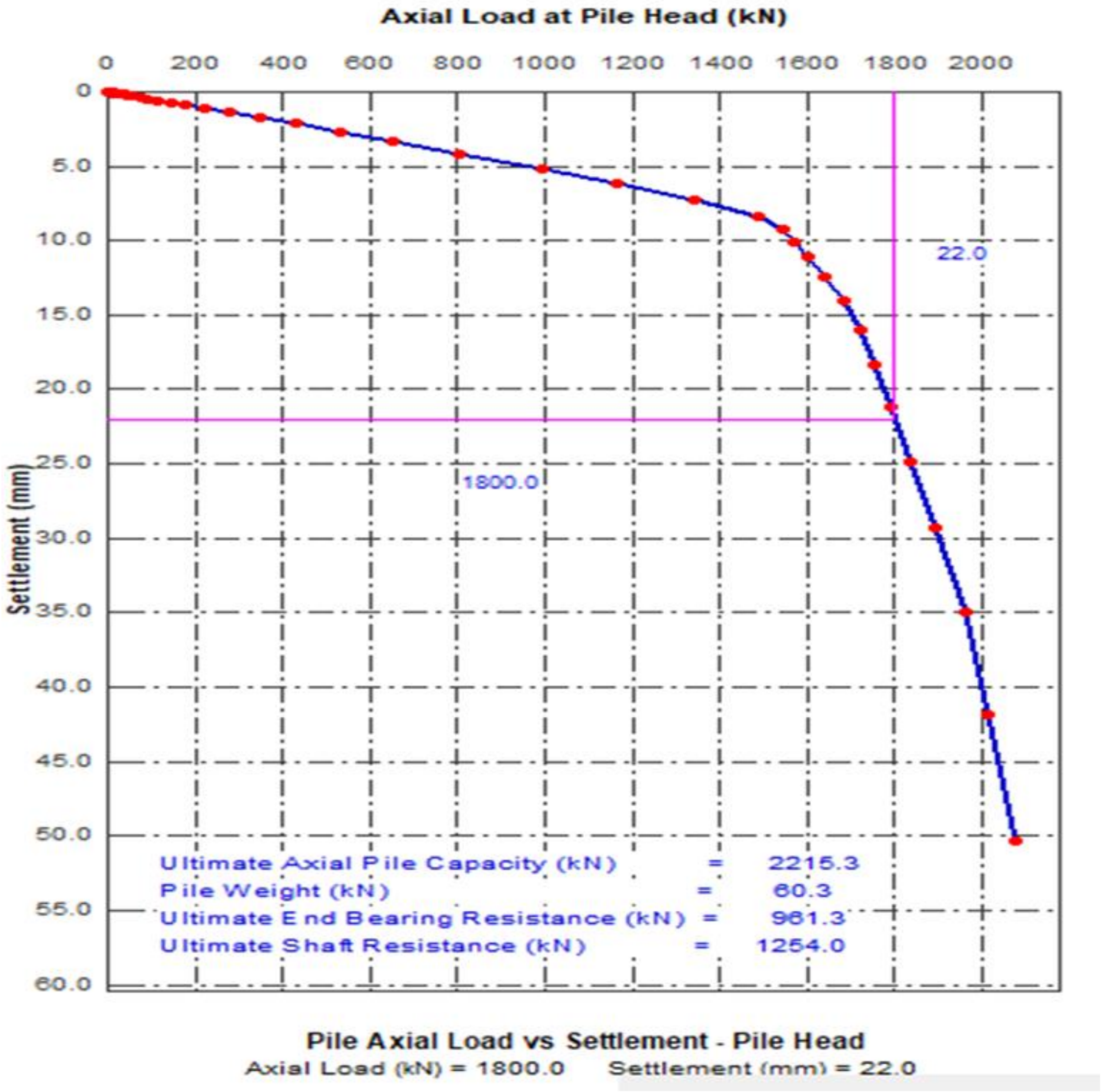

Figure 10: Predicted settlement at 1800kN load

The Q-W curve presents the toe-resistance with displacement is presented using equivalent Q-z springs developed by the FE program in Figure 4. The nonlinearity of the toe deflections beyond load values of 800kN is evident from Q-W curve presented in Figure 9. This reinforces the point that the plastic region of the pile load test displacement curve (see Figure 6) could result in significant uncertainties when pile load test results are numerically and analytically modelled or conducted. Note that the load-displacement curves from a pile load test usually have three regions: the elastic region, the plastic region, and the ultimate region.

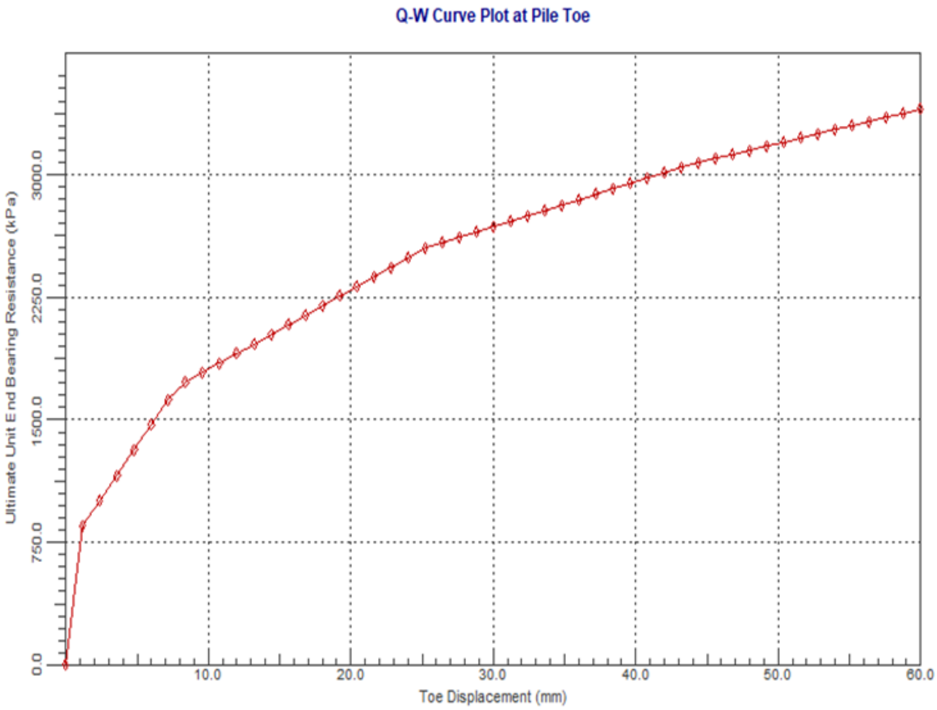

Figure 11: Q-W curve for pile

Table 3 presents the summary of the displacements obtained from the pile load tests and the FE modelling. It can be seen that at 1200kN (120ton), the FE model predicts the displacement obtained from pile load tests- i.e., the two results correlate well. However, at a very high compressive force of 1800kN- this corresponds to the highly plastic behavior of the pile toe – the FE program over-predicts the displacement of the pile. This over-prediction can be regarded as a conservative prediction in this case. The maximum settlements observed in the FE and pile load tests are less than 10% of the pile diameter. This is in line with the Eurocode 7 guideline with allows for maximum settlement of piles at ULS failure to equal to 10% of the pile diameter [16], [17].

Table 3: Summary of test results

Pile Ref No.	Safe working load (SWL) (120 ton)	1.5 x SWL (180 ton)	Settlement at SWL (mm)	FE predicted settlement at SWL (mm)	Settlement at 1.5 x SWL (mm)	FE predicted Settlement at SWL (mm)
No. 1	120	180	6.2mm	6.4mm	10.2mm	22.0mm
No.2	120	180	6.1mm	6.4mm	10.5mm	22.0mm
No.3	120	180	6.5mm	6.4mm	10.8mm	22.0mm
No.4	120	180	6.2mm	6.4mm	10.6mm	22.0mm
No.5	120	180	6.6mm	6.4m	10.8mm	22.0mm

4. Conclusions

The following conclusion can be drawn from this investigation:

a) It has been established from literature that there could be a couple of uncertainties in pile load tests. Thus, there is need for a quick assessment tool to validate pile load tests results and outputs. This work establishes that a simple FE tool could conservatively estimate the expected deflection from a pile load test at low test loads. Simple FE program can be used to predict displacement of the test piles at low test loads as shown in the results in this investigation. This is because at relatively low loads, the displacement of the soil at the toe of the pile is within its elastic range and simple load displacement curves are able to predict the displacement behaviour under these loads before plasticity sets in.

b) As test loads increase, the displacement of piles becomes highly non-linear. This can be seen in this investigation. Under this condition, FE modeling requires advanced or user-defined nonlinear springs to model soil load-displacement behavior in order to be able to adequately capture the displacements obtained from field pile load tests. The implication of this is that the uncertainty associated with pile load tests as reported by several literature is exacerbated at high tests loads, where significant nonlinearity sets in the load-deflection response of soils surrounding test piles.

c) In this investigation, the uncertainty associated with a pile load test is seen in the fact the simple FE springs (i.e., springs used to model load-displacement behaviour of soils around piles) were able to predict the displacement from pile load tests at low test loads but were not able to do so accurately at high test loads – i.e., the plastic phase of response. Thus, this work presents a significant understanding of the cause of the uncertainty in pile load test results and gives some basic insights on how to address it when validating the results of a static pile load tests with other methods, especially FE methods.

d) The results and procedure presented in this work can serve as a quick assessment tool for design engineers when the reliability of a pile load test is desired or when there is a need to validate pile load test results. The procedure presented in this investigation comes in very handy in pile load test where required test loads do not trigger significant plasticity in soils surrounding test piles.

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