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Comparative Study on Prediction of Axial Bearing Capacity of Driven Piles in Granular Materials

Ehsan Momeni[a*], Harnedi Maizir[a], Nurly Gofar[a], Ramli Nazir[a]

[a]*Faculty of Civil Engineering, University Technologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia*

*Corresponding author: mehsan23@live.utm.my

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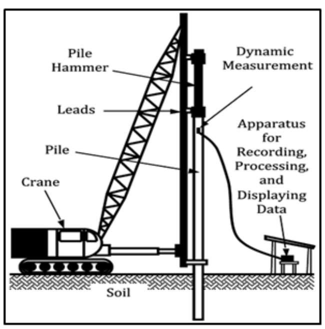
Graphical abstract



Abstract

Estimation of axial bearing capacity plays an essential role in pile design. A part from semi-empirical and numerical methods, axial bearing capacity of piles can be either predicted by means of a maintain load test or dynamic load test. The latter test is based on wave equation analysis and it is provided by Pile driving analyzer (PDA). Combination of wave equation analysis with dynamic monitoring of the pile can result in prediction of axial bearing capacity of the pile and its distribution. This paper compares the axial capacity of pile obtained from PDA records and maintain load test (static load test) with predicted axial capacities obtained using analytical, empirical and finite element analysis. From the results it is observed that axial bearing capacity derived from numerical modelling with the aid of the finite element code, Plaxis, is in a good agreement with estimated axial capacity through analytical-empirical methods, PDA, and maintain load test.

Keywords: Axial capacity; skin resistance; PLAXIS; PDA; driven pile

Abstrak

Perkiraan keupayaan cerucuk telah memainkan peranan penting dalam reka bentuk cerucuk. Sebahagian dari pada kaedah menggunakan formula semi-empirik dan numerik, keupayaan cerucuk boleh sama ada diramalkan oleh cara mengekalkan *maintained load test* (MLT) atau uji beban dinamik (DLT). Kedua uji ini adalah berdasarkan analisis persamaan gelombang dan ia disediakan oleh uji *Pile Dynamic Analyzer* (PDA). Gabungan analisis persamaan gelombang dengan pemantauan dinamik dari pada cerucuk boleh mengakibatkan dalam ramalan keupayaan cerucuk dan pengedaran. Kajian ini membandingkan keupayaan cerucuk yang diperolehi daripada rekod uji PDA dan uji beban statik dengan keupayaan ramalan cerucuk yang diperolehi daripada analitikal, empirikal formula serta analisis elemen hingga. Keputusan diperhatikan bahawa keupayaan cerucuk yang diperolehi daripada pemodelan numerik dengan bantuan *Plaxis software*, adalah memberikan hasil yang memuaskan dengan keupayaan cerucuk melalui analisis kaedah empirik, PDA dan uji beban statik

Kata kunci: Kapasiti cerucuk; keupayaan pengedaran; Plaxis; PDA; cerucuk konkrit

1.0 INTRODUCTION

Driven pile foundations are used to transfer the superstructure loads to the ground deep enough in order to prevent excess settlement. In this specific type of pile foundations, a large impact hammer is used to drive the structural element into the ground. Estimation of axial capacity plays an important role in foundation design. There are numerous methods for prediction of axial capacity in piles. However, most of these methods are analytical and the axial bearing capacity obtained from these analytical approaches mostly relies on empiricism and they are site specific [18]. Hence the analytical results must be validated by static load test [7]. Although static load test (SLT) is reliable but it has some disadvantages. Firstly the test is not economic and secondly it is time consuming. The aforementioned limitation was the reason of introducing other efficient approaches. A part from dynamic formulas which are site-specific and suffer from apparent deficiency *i.e* modelling the impact, High Strain Dynamic Pile Test (HSDPT) which is a combination between wave equation analysis [20] and Case method [10] is a proper technique to predict the bearing capacity of piles. Many studies [13, 14] have shown HSDT is in good agreement with SLT. On the other side, developing commercial softwares like PLAXIS have made it possible to use finite element method and numerical modelling for prediction on axial bearing capacity of driven piles.

Although many researchers have studied different aspects of axial bearing capacity of piles, however lack of comprehensive study on the axial bearing capacity of driven piles is observed.

This study is aimed to give an insight into the prediction of axial bearing capacity of driven piles by means of different approaches. In other words in this paper the axial bearing capacity in granular material is estimated through static load test, and high strain dynamic load test. Consequently among piles used for high strain dynamic load test, the pile which its capacity is closer to the static load test result is selected as reference pile; then the axial capacity of reference pile is estimated through analytical, empirical and finite element methods.

2.0 AXIAL BEARING CAPACITY PREDICTION: ANALYTICAL METHOD

Analytical methods for prediction of the axial bearing capacity of pile were developed by, among others, Vesic [22], Meyerhof [15]. and Coyle and Castello [4]. Coyle and Castello analyzed 24 large-scale field load test of driven piles in sand, on the basis of the test result, they suggested that the axial capacity of pile in sand can be estimated by Equation 1.

$$q' N_q^* A_p + \Sigma \, p \, \Delta l \, (K \, \sigma_v' \tan \delta). \quad (1)$$

Where, q' is effective vertical stress at the pile tip, N_q^* is bearing capacity factor, K is the lateral earth pressure coefficient, σ_v' is average effective overburden pressure, δ is soil-pile friction angle, p is perimeter of the pile, Δl is incremental pile length, and A_p is cross sectional area of the pile.

2.1 Axial Bearing Capacity Prediction: Empirical Method

Accurate measurement of soil properties through laboratory tests is a prerequisite for estimation of axial bearing capacity of piles by using an analytical method. Determination of soil properties through laboratory test faces two problems: (1) the difficulties to obtain "undisturbed" sample and (2) the limitation related to the size of the sample. In-situ test such as Standard Penetration Test (SPT) provides data which represent a large mass of soil. Besides, the test is relatively simple and data are readily obtained during the site investigation. Empirical correlations have been developed between the results of insitu test and the bearing capacity of piles. Meyerhof [15] proposed correlations based on SPT (N) for which ultimate axial capacity (Equation 2) in homogeneous soil can be estimated through Equations 3 and 4.

$$Q_u = A_p \, q_p + plf_{ave}. \quad (2)$$

$$q_p \, (KN/m^2) = 40 \, N \, L/D \leq 400 \, N. \quad (3)$$

$$f_{ave} \, (kN/m^2) = 2 \, \tilde{N}. \quad (4)$$

In the above equations, Q_u is ultimate axial capacity, A_P is area of the pile, q_p is ultimate stress, D,L are diameter and length of the pile respectively, N is average SPT (N) value almost 10D above and $4D$ below tip of the pile. f_{ave} is average unit skin resistance, $\tilde{N}$ is average SPT (N) value, p is the perimeter of the pile.

2.2 Axial Bearing Capacity Prediction: Slt

Static load test (maintain load test) is an insitu test in which under a physically applied load, the pile head displacement is measured directly and it is considered as the bench-mark of pile performance. SLT is categorized into two different tests. Control strain tests and control stress tests. The latter is used much more than control strain test. The objective of SLT is to develop a load-displacement curve. The load is applied in increment and allows the foundation to move under each increment, the increments of loads usually are 25, 50, 75, 100, and 200 percent of the design load. Failure load can be estimated from load displacement curve [7].

An illustrative figure of the test is shown in Figure 1. Numerous methods may be used for failure load prediction in static load test. However, study by Michaelangelo [14] shows Davisson's method gives the most conservative value in compare to other methods. In the method of Davisson the failure load (ultimate load) equals to the load corresponding to the movement which exceeds the elastic compression of the pile by a value of 4mm plus a factor equal to the diameter of the pile divided by 120 [6].

2.3 Axial Bearing Capacity Prediction: High Strain Dynamic Load Test

A more recent development (HSDPT) which is provided by Pile Driving Analyzer (PDA) is relatively cost efficient, faster and easy to perform. The PDA test (Figure 2) is a quick test, hence; can be performed on more piles providing a bigger numbers of samples. Combination of this technique with dynamic monitoring of the pile during driving gives a significant effect on prediction of axial bearing capacity of pile and its distribution.

Dynamic testing of pile (PDA test) is based on the analysis of one dimensional waves generated when the piles was hit by a suitable hammer. Therefore, for the purpose of testing, the pile must be hit (re-strike if the pile has been driven) by a hammer capable to transfer sufficient impact energy to mobilize the pile capacity. Two types of instrument are required for the sake of dynamic testing of piles. One set of accelerometer and one set of strain transducer. They need to be installed at the upper part of the pile. To obtain a reliable ultimate capacity from dynamic testing, some guideline must be followed, such as hammer weight, impact factor, a few of them are mentioned, to mobilize the full soil strength. As mention by [13], the minimum suggested hammer weight 1% of the required ultimate pile capacity to be proved for shafts installed in soils, and for the piles with larger expected end bearing contributions, the recommended percentage increases to at least 2% of the ultimate pile capacity to be tested.

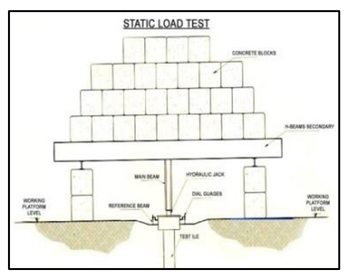


Figure 1 Static load test

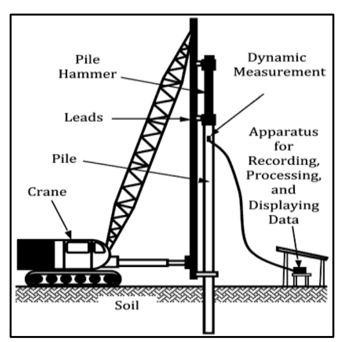


Figure 2 Schematic figure of PDA test

The accuracy degree of PDA data is subjected to uncertainties with respect to the energy transmitted to the pile during testing. The measurement were recorded by PDA test and analyzed with the well known "Case Method" using the Case Pile Wave Analysis Program (CAPWAP) software. Procedure for conducting the PDA test is presented in ASTM 4945-08 Standard Test Method for High Strain Dynamic Testing of Deep Foundation.

3.0 CASE STUDY

The Static load test data for this study was collected from one building project. It was a 8-stories building for which driven piles (prestressed concrete pile) were used as foundation. For the sake of comparative study, in a same site 7 restrike PDA test on driven piles were conducted. The piles diameter was 350 mm, and the piles were embedded about 10 to 12 m depth. Having the site investigation data including laboratory tests data, material properties are shown in Figure 3. The analytical and empirical analyses were performed by substituting the input data from Figure 3 into equations 1 through 4. The axial capacity obtained from analytical and empirical methods are tabulated in Table 1, however by picking up a value in between total axial bearing capacity can be considered to be 920.29 kN.

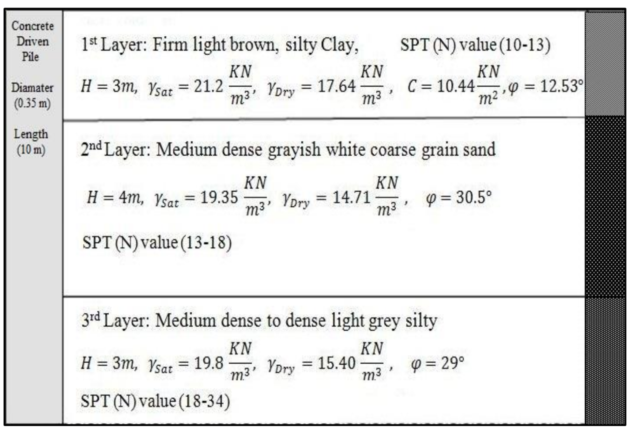


Figure 3 Soil profile according to site investigation

Table 1 Axial capacity of reference pile based on analytical and empirical methods styles

Methods	Axial Bearing Capacity of Driven Piles		
	Skin Resistance (kN)	***End-Bearing (kN)***	***Total Axial Capacity (kN)***
Analytical	140	418	558
Empirical	360	923	1282.59

It is worthy of mention that usually the results of empirical methods is higher than the results of analytical methods [5] more specifically in this case due to the fact that this study was not a comprehensive research, and the quality of the samples didn't represent the soil properties well enough *i.e* remolded samples. Taking into consideration that aforementioned analytical method relies on shear strength, and consequently on the laboratory tests and soil samples, it is expected to see the analytical results are less than empirical result which truly shows the soil resistance with depth.

The result of SLT as shown in Figure 4 indicates that the total axial capacity is 780 kN. It is worthy of mention that Static Load Test (SLT) was performed with a load equal to two times of the already estimated design load which was 450 kN.

The pile was not instrumented, hence; only the total axial bearing capacity is obtained. The axial capacity of pile estimated using Davisson`s method (Figure 4) is 780 KN.

On the other hand, results of PDA are tabulated in Table 2. The data were obtained through restriking seven concrete driven piles. As it can be seen from Table 2, the results of PDA varies may be due to the fact that pile driving hammer is not always able to mobilize the full soil resistance. Occasionally pile resistance determined from analysis of dynamic test data is smaller than the actual capacity of the pile. For instance if the pile penetration is very small and the toe reflection is weak, despite that the pile toe is in a dense soil, then there is a good chance that the end bearing resistance is not fully engaged and that the capacity value is an "unpredictable value" [9]. In fact one should consider that full mobilization of the piles capacity depends on whacks, providing that a whack will result in more mobilization of pile capacity. PDA data in this project are obtained by using simple drop hammer. Taking into consideration that in these kinds of hammers providing exactly same whacks in different situations is almost impossible, one may conclude that it is common to see different axial bearing capacity.

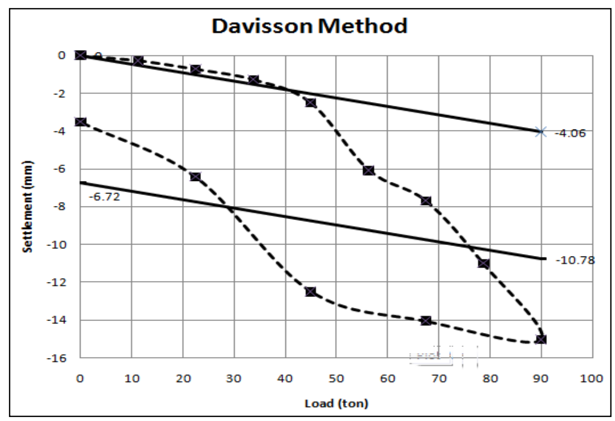


Figure 4 Load-displacement curve of static load test

Table 2 Pile capacity based on PDA

Pile No	Axial Bearing Capacity of Driven Piles			
	Length (m)	***Total Axial Capacity (kN)***	***Skin Resistance (kN)***	***End-Bearing (kN)***
Pile No.1	10.3	500	485	15
Pile No.2	8.8	452	438	14
Pile No.3	10	585	556	29
Pile No.4	10	603	576	27
Pile No.6	10.3	811	768	44
Pile No.7	10	770	733	36
Pile No.8	10	748	700	48

Comparison among SLT result and results of PDA show that among PDA data, the axial bearing capacity of Pile No.7 is the closest value to static load test. Hence this pile *i.e* Pile No.7 is considered as the reference pile for further analysis.

4.0 NUMERICAL ANALYSIS

The Finite Element Method (FEM) is a method of approximation the behavior of continua. In this numerical technique the system is discretecized into many meshes or element, then the equability and compatibility of each element, and whole system will be examined. In geotechnical engineering, PLAXIS is one of the most widely used finite element softwares. The version 2010 of this program is capable of modelling static plane strain or two dimensional axisymmetric problems using 6 or 15 nodes triangular soil element.

In order to model the reference pile *i.e* Pile No.7, into PLAXIS 2D, a working area of 17 m width and 17 m depth was used and the geometry was simulated by means of an axisymmetric model in which the pile was positioned along the axis of symmetry. With the aid of standard fixity boundary condition, the concrete driven piles with the total length of *10* meter was modelled (Figure 5). The pile had a diameter of *0.35 m*; hence it was defined as a column of *0.175 m* width. Both the soil and the pile were modelled with 15-noded elements.

The 15- noded triangle element provides a fourth order interpolation for displacements and the numerical integration involves twelve Gauss points. The layers were defined according to soil profile and the soil profile was estimated based on SPT (*N*) value (Figure 3). The ground water level was located 1 m below the soil surface. Hardening Soil (HS) model was used as the constitutive model for the soil. The main advantage of this constitutive law is its ability to consider the stress path and its effect on the soil stiffness and soil behavior. Since the soil was almost sandy soil, drained behavior of soil was considered. Linear elastic model was used for the concrete pile and it was considered as non porous material. Lebeau [12] conducted a mesh-convergence study. His study shows that in sandy soils the output curves have same shapes for calculations performed with coarse, medium and very fine mesh, hence in this study medium grain mesh was adopted however the generated mesh was enriched on top of the pile using refine line option.

Input parameters and material properties used in this study are tabulated in Table 3.

Table 3 Material properties and input parameters

Material	Symbol	1st layer Silty Clay	2nd layer Sand	3rd layer Sand	Pile	Unit
Material Model	-	HS	HS	HS	Linear Elastic	-
Unit weight	γ	20.19	18	18.17	24	kN/m^3
Saturated unit weight	γ_{sat}	21.2	19.5	19.63	24	kN/m^3
Stiffness	E	4000	14392	21552	2.6E7	kN/m^2
	$E^{ref}_{(oed)}$	6031	15990	25860	-	
	$E^{ref}_{(50)}$	12060	15990	25860	-	
	$E^{ref}_{(ur)}$	36190	47970	77580	-	
Poisson`s ratio	ν_{ur}, ν	0.2	0.2	0.2	0.15	-
Power (Stress level)	M	1	0.5	0.5	-	-
Earth pressure coefficient	K_o	0.79	0.49	0.51	-	-
Friction angle	Φ	12	30.5	29	-	º
Cohesion	C	10.44	0.06	0.08	-	kN/m^2

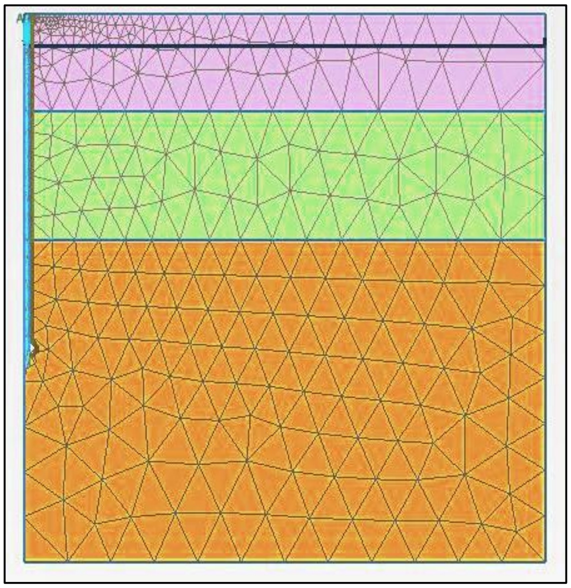


Figure 5 Global geometry of the reference pile

Along the length of the pile an interface had been modeled. In order to prevent stress oscillation in this stiff corner area, the interface was extended to 0.5 m below the pile`s tip inside the soil body. The strength reduction factor ($R_{inter}$) was considered to be equals to 1 as recommended by PLAXIS experts. Coefficient of earth pressure, $K_o$, was approximated by considering Jacky`s estimate of $K_o = 1\text{-}sin\Phi$ [11]. Unloading reloading poisson`s ratio was considered 0.2 according to Plaxis manual, and Soil stiffness parameters were approximated by means of different correlations which were based on site investigation data [16, 19, 1, 2]

In the calculation stage, three different phases were used. In initial phase, water level was defined and the initial effective stresses were generated by K_o procedure, hydrostatic pore water pressure was also generated in the whole geometry according to water level. Second phase dealt with assigning pile material into the relevant clusters. In the last phase the plastic analysis was selected as type of analysis, and the load was applied by means of distributed load approach.

In load distribution approach, usually a load which is guessed to be more than failure load should be applied. Hence ultimate load obtained from empirical approach *i.e* 1283 kN was considered as initial load for finite element analysis in PLAXIS. Using stage construction option, analysis was performed. Deformed mesh is shown in Figure 6. However, load displacement curve (Figure 7) plotted for the node point located at the top right side of the pile shows that soil body is collapsed under this load. The maximum load obtained from Figure 7 which is 919 KN was considered for subsequent analysis. The result of final analysis confirms that the pile can carry 919 kN and the soil will resist as shown schematically in Figure 8. Hence the total capacity of the pile was obtained to be 919 KN.

Comparison among axial capacities obtained through different methods is shown in Figure 9. It is worthy of mention that in Figure 9 axial bearing capacity obtained from analytical, empirical, and PLAXIS are ultimate axial bearing capacities meanwhile in a case of static load test and PDA they are not ultimate. It is mentioned earlier that in SLT the pile did not load up to failure, hence it is usual to see estimated axial capacity using static load test is a lower than axial capacities through empirical and finite element methods.

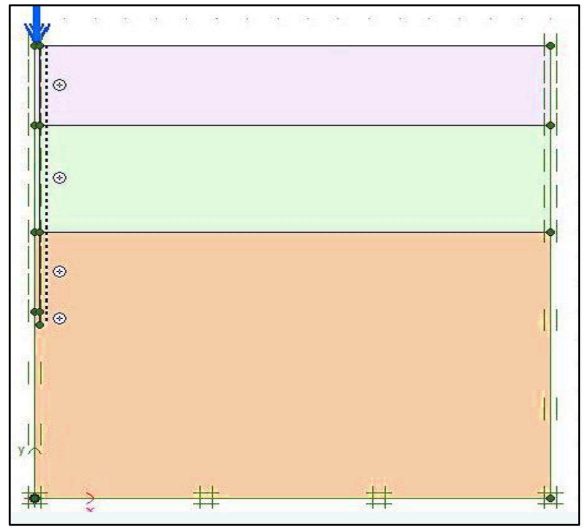


Figure 6 Deformed mesh of the reference pile

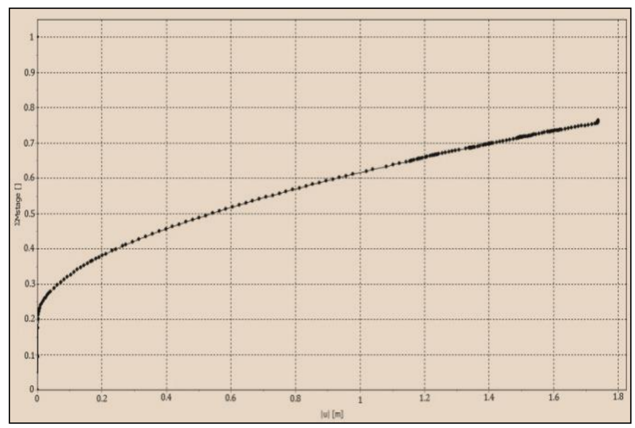


Figure 7 Load-displacement behavior of reference pile under empirical load (Soil body collapsing)

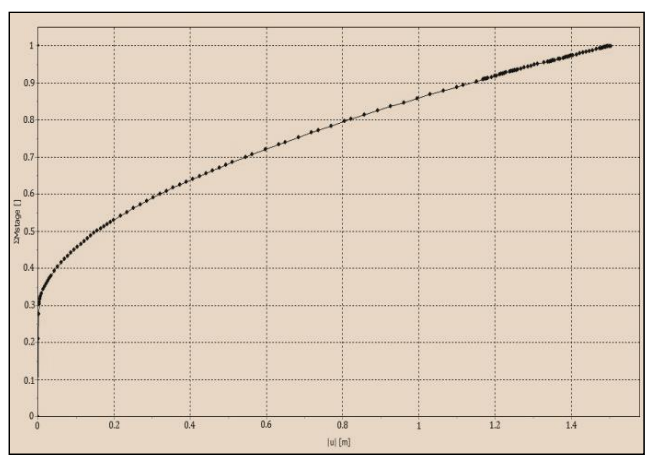


Figure 8 Load-displacement curve for ultimate load obtained from last analysis

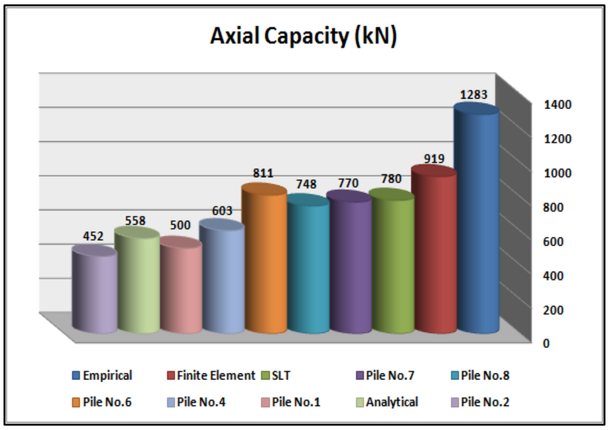


Figure 9 Estimated axial capacity (kN) using different methods

5.0 CONCLUSION

Based on the results obtained from the analyses, the following conclusions can be drawn.

(1) The result of finite element analysis shows that the ultimate axial capacity is in good agreement with the axial capacities obtained using empirical method, PDA, and SLT.
(2) The PDA results show that axial bearing capacity of piles obtained by means of pile driving analyzer are quite variable hence they must be validated with other reliable methods such as static load test.
(3) From the results of analytical and empirical methods, it is observed that the differences between estimated axial bearing capacities are remarkable, hence these methods more specifically analytical methods individually shouldn't be considered as the only source of pile design.

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