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COMPARATIVE STUDY OF LARGE DIAMETER BORED PILE UNDER CONVENTIONAL STATIC LOAD TEST AND BI-DIRECTIONAL LOAD TEST

Vinsensius Viktor Limas[1]* & Paulus P. Rahardjo[2]

[1] *PT. Geotechnical Engineering Consultant, Jl. Lembah Sukaresmi 1 No.15, Bandung, Indonesia*
[2] *Parahyangan Catholic University, Jl. Ciumbuleuit No. 94, Bandung, Indonesia*

*Corresponding Author: *viktor_limas@yahoo.com*

Abstract: Bored pile with 1,500 mm diameter were used to support design load of 1000 tons for Tulur Aji Jangkat Bridge, Melak, East Kalimantan and tested using a single level of O-Cell near pile toe. The pile is 53.4 m long and installed through dominantly alluvial sand. The test was performed in two load cycles. The pile was reported failed at 1654 tons (±165% working load) with displacement of upper segment 41.8 mm and bottom segment 46.8 mm. The case was analyzed numerically in 2D using finite element program PLAXIS 8. The FEM model has been calibrated on the basis of the field O-Cell result. Similar material properties were also used to simulate the conventional head-down test (Kenledge) to compare the difference of soil behaviour which is under tension and under compression. There are two curves obtained from O-Cell test result, the base resistance and shaft resistance which must be converted to equivalent top-load curve. The equivalent top-load curve is used to illustrate as if the pile loaded from the pile head such as conventional head-down test. Comparison are presented between the bearing capacity of those two different pile load testing procedures using finite element method. The result shows that the bearing capacity of O-Cell test slightly lower than Kentledge test by about 11%. The differences was due to the fact that the O-Cell test has caused ground tension in upper segment.

Keywords: *Static load test, kentledge, osterberg cell, finite element modelling, bored pile, ultimate bearing capacity*

1.0 Introduction

In most standards, the bearing capacity of piles are mostly obtained by pile load tests. In fact, of various types of pile testing, not all of them can be relied upon. Pile foundations, in particular bored piles, is influenced by the quality and workmanship in construction. Bored piles construction method will vary depending on the type of soil that will make a difference in integrity and bearing capacity.

For design check on foundation of Tulur Aji Jangkat Bridge in Melak (East Kalimantan), static loading test using a two-way Osterberg Cell and dynamic load test (Pile Driving Analysis/PDA) were conducted. The location of the project is shown in Figure 1. The bridge used large bored piles with diameter of 1.5 m, and length of 53.4 m (effective length of 50 m). These bored piles use permanent steel casings as deep as 15 m prior to the construction of the bored piles.

The load test which is usually implemented is conventional static loading test (Kentledge), but since the project is located in quite remote area, it is impossible to perform testing with Kentledge method, so that bi-directional static load test was performed on this project.In the matter of the different testing methods, there are differences in load transfer mechanism where Bi-directional static load test pushes in two directions which led to soil at the upper part of cell undergo tension. In fact, soil is weak to resist tension thus the author believe that the bearing capacity conducted by bi-directional test does not reflect the actual loading conditions which ideally the entire soil should undergo compression.

Figure 1: Location of the Tulur Aji Jangkat bridge in East Kalimantan

These days, many geotechnical problems can be solved by numerical analyses with finite element calculations especially for foundation analysis. Therefore, to investigate the different behavior, numerical analyses of O-Cell test on bored pile in medium alluvial sand are modelled and calibrated to field test results to be compared with Kentledge load test. Comparisons of ultimate bearing capacity between conventional static load test and bi-directional static load test on the same pile configuration in the same soil condition will be discussed.

2.0 Project Description

Tulur Aji Jangkat bridge is located in Melak, East Kalimantan. The bridge is a cable-stayed bridge crossing over the Mahakam river with two pylon of 340 m long middle span shown in Figure 2. Due to the present of soft layers, large diameter bored piles have been selected by considering lateral required capacity to support the structure of pylons. The rest use large driven piles with 800 mm diameter.

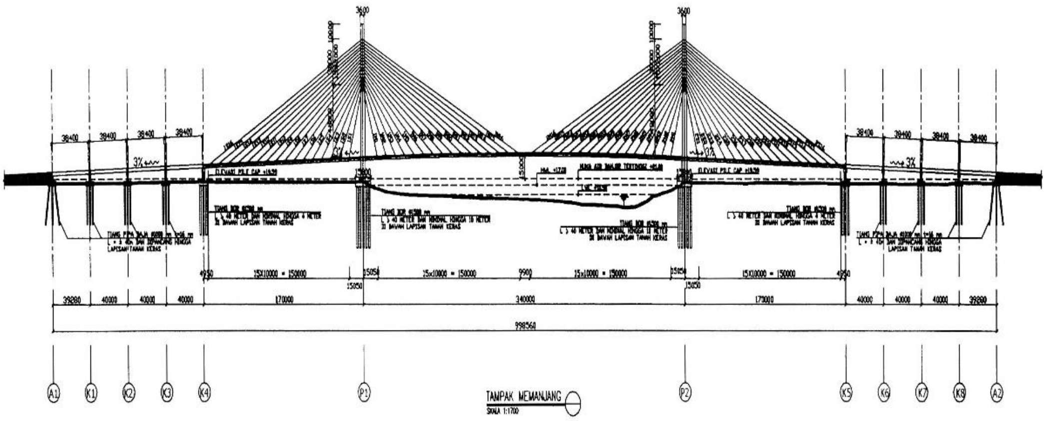


Figure 2: Longitudinal cross section of Tulur Aji Jangkat Bridge at Melak, East Kalimantan

3.0 Subsoil Condiion and Site Layout

Figure 3 shows the locations of the bore holes for soil investigation. The soil investigation consists of 6 bore holes drilled to 60 m depth. Bore holes BH-1 and BH-2 represent of the south side while BH-4 and BH-5 represent of the north side.

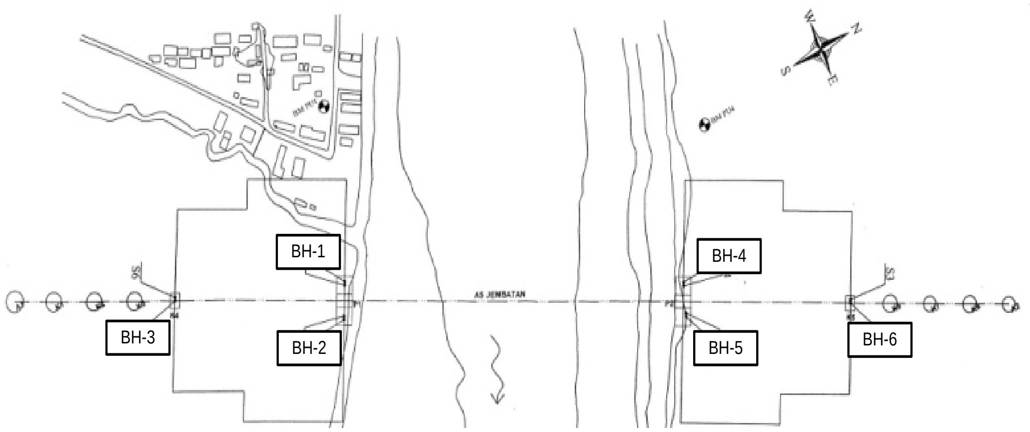


Figure 3: Plan view of the test site with the locations of site investigations

While Figure 4 shows the geological condition of the project site. The soils on site consist of deep sediment from Mahakam river. In the upper layer, the soils are dominated by very soft to soft silty clays and loose to medium sandy soils with fine to coarse particles, uniform gradation in the deeper layer.

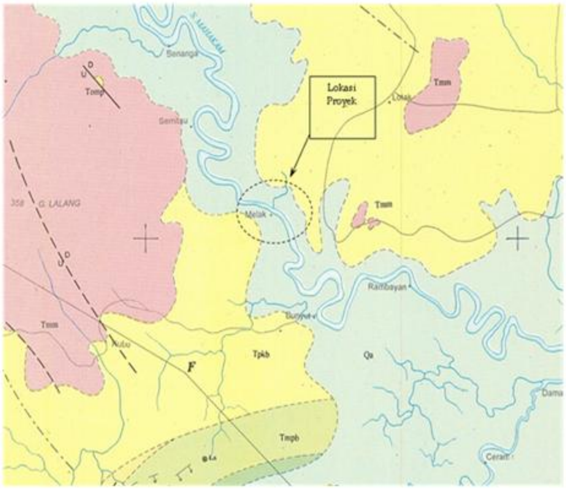


Figure 4: Geological condition of the project site

The bored pile which is being investigated located on south side (near BH-1 and BH-2), consist of very soft to soft high plasticity silty clay on the surface, and dominantly sandy soil below it. The soil condition can be seen in Figure 5.

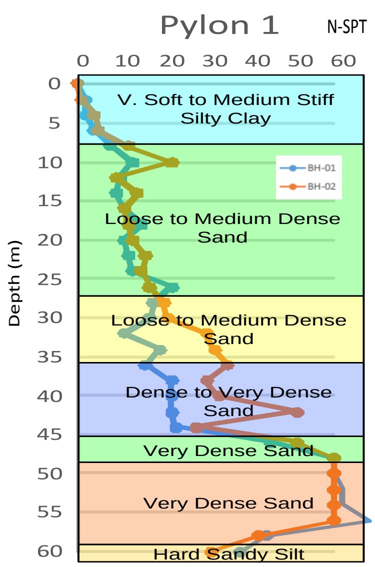


Figure 5: Soil condition at the pile test location

4.0 Bi-directional Static Load Test Method

The bi-directional static load test is conducted on bored pile with 1500 mm diameter and 50 m effective length. The proposed working load is 1000 tons and the test load is 2000 tons. The test was executed using single level O-Cell, hence the pile will be divided into 2 segments. The hydraulic jack assembly consist of 2 nos of 600 tons symmetrically which in combination delivers loads of 1200 tons in upward and downward direction. Hence, the total load capacity is 2,400 tons. Figure 6 shows the schematic of the pile load test installation.

Level Reference	Level Description	Depth RL (m)	Depth (m)
GL	Ground level	0.00	0.00
COL	Cut-off level	-3.60	3.60
J1	Hydraulic jack assembly (2 nos x 600 tonnes)	-48.60	48.60
PT	Pile toe	-53.40	53.40

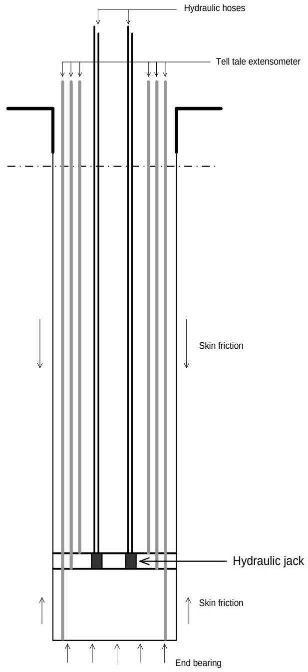


Figure 6: Schematic of pile load test installation (Soil Dynamics Sdn Bhd, 2011)

The ground level elevation is at RL 0.00, while the O-Cell installed at RL -48.60m, and the toe level is at RL -53.40 m. The drilling process of bored pile was under instruction and supervision of the engineer and the bottom elevation was also cleaned. The hydraulic jack installation, both hydraulic supply and instrumentation were set up to the hole attached to the steel cage. Hydraulic jack assembly inside the cage used angle bar or directly welded to the cage. Concrete casting is done by using appropriate size tremie pipe with sufficient length to extend beyond the O-Cell until the pile toe.

Sufficient sizes of opening were provided in the hydraulic jack steel bearing plates for the tremie pipe to pass. The concrete mix can bring through maximum workability (slump 180-200 mm) and contain with sufficient retarding admixtures to maintain workability for a minimum 3 hours (Soil Dynamics Sdh Bhd, 2011).

The loading is done by 2 cycles, the first cycle is loading to 100 percent working load and the second test is to 200 percent working load. The load is increased at intervals of 25 percent and the reading is maintained for 30 minutes. Meanwhile, for unloading condition, the reading is taken for 15 minutes.

The pile head movements were obtained directly using displacement tranducers which installed on the reference beam with telltale rods attached to the pile head. While the top and bottom of O-Cell and pile toe movement were measured by using displacement tranducers which connected to extensometers. Eight (8) displacement tranducers were used to measure all movement at the designated telltale locations. All the displacement tranducers performed well during the duration of the test.

4.0 Result of Bi-directional Static Pile Load Test

Load testing initiated by applying hydraulic pressure to the hydraulic jacks using an air-driven hydraulic pump. A high-pressure Bourdon gauge as well as well-calibrated pressure transducer were used to control the pressure. The displacement transducers which supported by the reference frame were used to measure relative movement at the designated telltale locations.

It should be noted that the result has not reflected the actual loading condition as the top cell which applies upward pressure is actually weighed by the buoyant weight of upper pile segment so it needs to be corrected by a reduction in pile buoyant weight. The bi-directional load test results has already corrected and is shown in Figure 7.

At 50% load (250 ton), almost no movement happened to the upper and lower segment which indicated that the soil is still behave elastic. At 100% load (500 ton), the lower segment start to move about 20 mm. It is a quite significant movement compared to the above segment which is still elastic. It shows that when 150% of loading was executed, the displacement goes very high and the attempt to increase the load to 175% of working load reach to a failure state because the pile had large displacement and the load cannot be sustained. It can also be seen that the pile tip response has not reached its ultimate capacity yet but the upper segment might have failed.

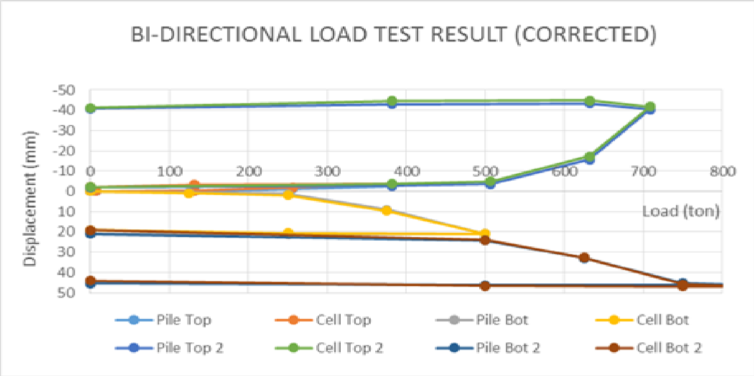


Figure 7: Results of Birectional Static Load Test

During cycle 1, the maximum pile top movement was 2.6 mm and maximum cell top movement was 3.6 mm. The maximum cell bottom movement was 20.9 mm and maximum pile bottom/toe movement was 20.9 mm at the applied load of 500 tons which equivalent to the effective bi-directional load of 1,000 tons (100% working load).

During cycle 2, the maximum pile top movement was 43.8 mm and maximum cell top movement was 44.8 mm. The maximum cell bottom movement was 46.8 mm and maximum pile bottom/toe movement was 46.1 mm at the applied load of 825 tons that was equivalent to the effective bi-directional load of 1,650 tons. (165% working load)

The failure can also be seen from Figure 8 and Figure 9. Time-Load graph in Figure 8 shows that the loading failed at ± 900 minutes since the start of cycle 1 with applied load of 825 tons. Meanwhile, Figure 9 shows time-displacement. In this graph, it can be seen that upper segment of pile (the dashed line shows pile top and cell top) had quite a big sudden displacement incremental at cycle 2 without additional load which prove that the pile has reached its ultimate capacity.

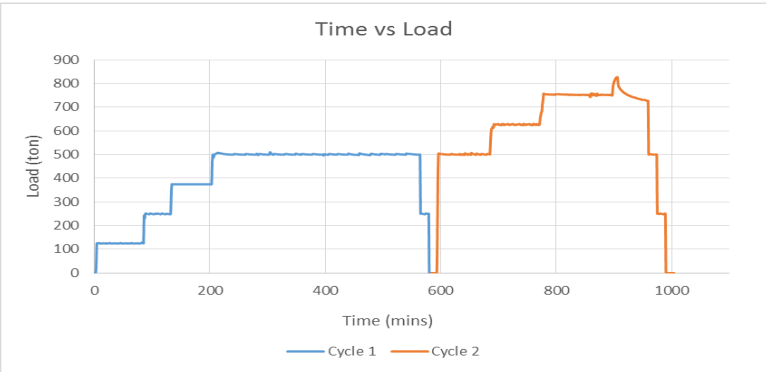


Figure 8: Time-Load Graph

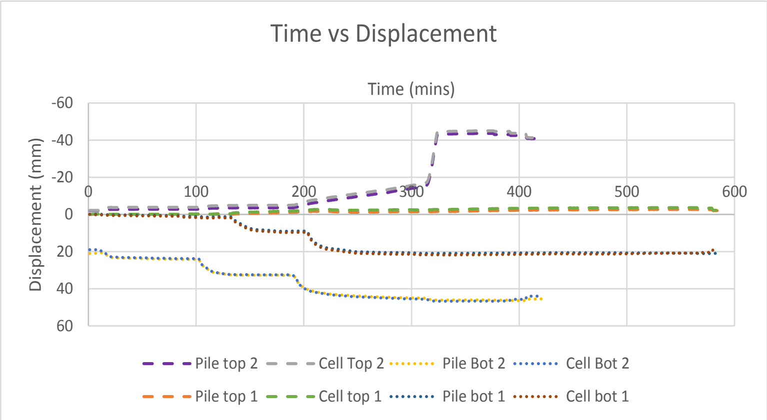


Figure 9: Time-Displacement Graph

It has to be understood that the upward jack load include the response of the soil friction and the buoyant weight of the upper pile segment. The test results should be used to compute the equivalent load settlement curve for simulating the load applied at the top of the pile. The main steps to construct the equivalent top load curve are as follows :

- Select a displacement value. This selected value will be used for both top and bottom cell because the pile is assumed as rigid pile. For bored concrete piles, the compression of the pile is typically 1-3 mm at ultimate load (Osterberg, 1998)
- Draw a line from the selected value until it meets the load-displacement curve thus the o-cell load will be obtained for both "up" and "down" curve.
- Sum the corresponding loads to obtain the total load which is equivalent to the load on pile head.
- Repeat those procedures to construct the equivalent top-load curve.
- To simulate the real condition, modify the curve to account the elastic shortening of pile (shaft compression).

The results of equivalent top load is presented in Figure 10.

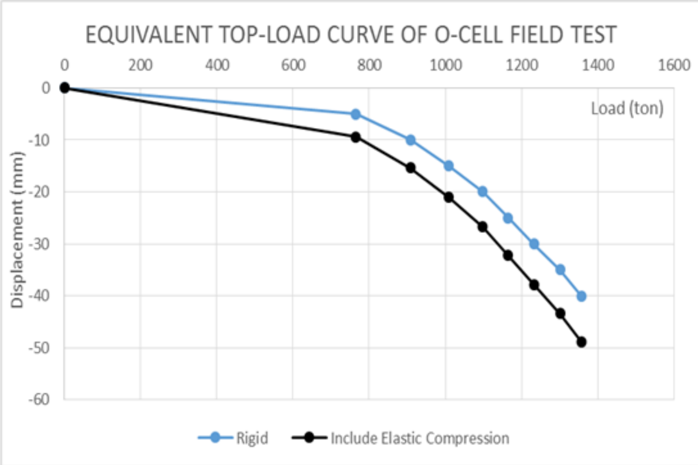


Figure 10: Computed Load Settlement Curve

5.0 Modelling for Simulations of Pile Test

The case is modelled and analyzed using finite element program PLAXIS 8 as axisymmetry model with geometry dimension of 40m x 66.6m. The soil is modelled as Mohr-Coulomb material with 15-nodes elements and classified into 7 layers as shown in Figure 11. The soil stratification is modelled based on the average N-SPT values. It consists of soft silty clay in the upper layer with 8m thick with N=3, the second until fourth layer is medium sand of 19m, 9m, and 9m thickness with N=12, N=19, and N=25 consecutively. While the fifth layer consist of dense sand of 3m thickness with N=34, then followed by a layer of very dense sand with N=79.

The bottom layer consist of sandy silt and assumed to be continuous until the boundary with N=35 as it does not have much impact around the pile. The pile is modelled as linear-elastic material with radius of 0.75m. To simulate the loading test, a same amount of distributed load is applied on top and bottom of O-Cell plate position. When the O-Cell began to work, the material between the plates is filled with elastic material with a very low elasticity modulus in order to minimize the interaction between upper and bottom segment.

To improve the accuracy of the calculation, the mesh in area of 10m x 58m around the pile is refined to fine coarseness. Groundwater table is located at 5.5m from the surface according to the borelogs. Laboratory data is used for engineering properties of soil materials. Some samples are not tested in laboratory, therefore the density values can be obtained from Lambe's correlation (1962). While the ϕ' values are obtained from correlation between $N_{1(60)}$ and ϕ' (Peck, 1953). The back-analysis is done by changing the stiffness and interface value to calibrate the load-displacement curve from numerical analysis with the field O-Cell test result.

After the parameter has been calibrated, it is found that the Young Modulus is in correlation range of 1-4 N_{SPT} (MPa) and the R interface = 0.54-0.57 which shows the interaction between structure and the soil. The soil properties are shown in Table 1.

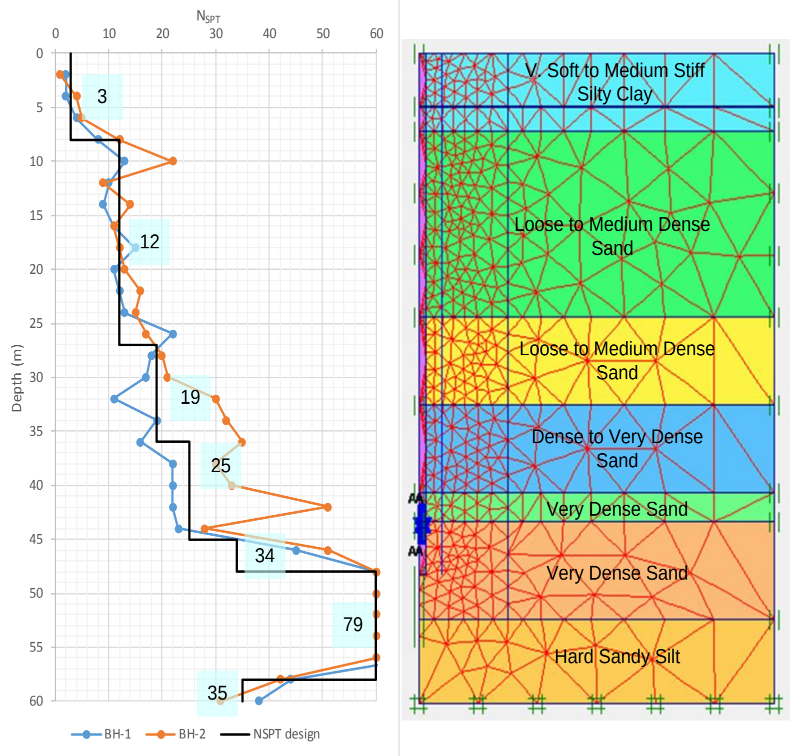


Figure 11: Modeling of O-Cell Test

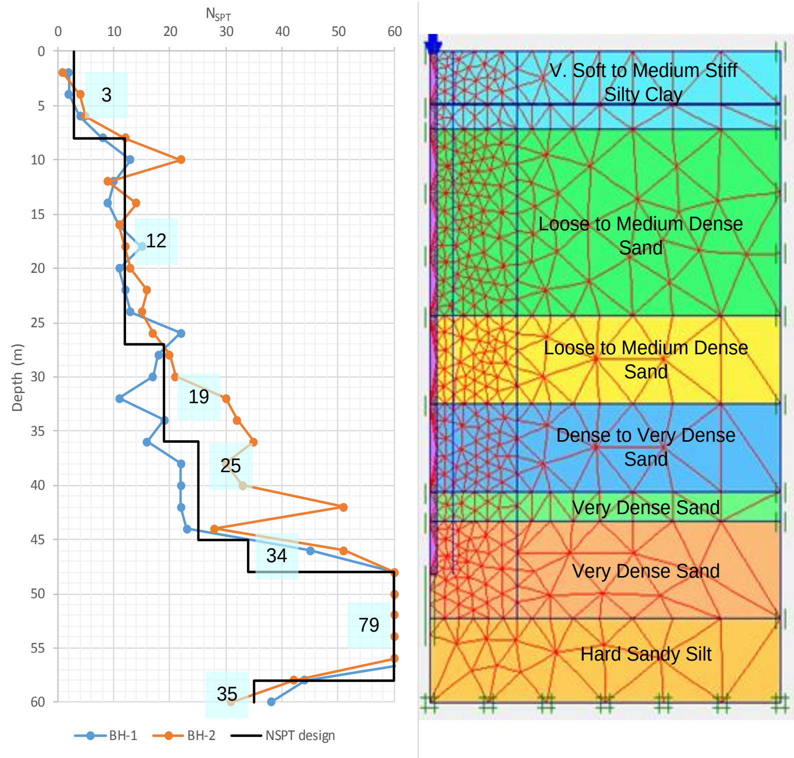


Figure 12: Modeling of Kentledge Test

Table 1: Material Parameters

Name	Yunsat	Ysat	v	E_ref	c_ref	ϕ	R_inter
	[kN/m^3]	[kN/m^3]	[-]	[kN/m^2]	[kN/m^2]	[°]	[-]
1. SILTY CLAY	14	15.89	0.35	3000	18	0	0.54
2. SAND	18	19	0.25	48000	0	30	0.54
3. SAND	18	19	0.25	76000	0	30	0.54
4. SAND	18	19	0.2	100000	0	30	0.54
5. SAND	18	19	0.2	136000	0	30	0.54
6. SAND	18	19	0.15	160000	0	34.5	0.57
7. SANDY SILT	18	19	0.3	70000	50	30	0.57

6.0 Analysis Results

The calculation was conducted with 10-phases analysis namely :

1. The drilling and casting of bored pile
2. Apply load of 1 kN/m2 on top and bottom plates of O-Cell
3-10. Stage loading is applied with increment of 25% load until 200%

From the back-analysis, it also shown that the failure occured at ±165% working load. Figure 13 shows the displacement and shear stress concentration at the point of application of the load. It is shown that the pile tip has moved substantially and the failure shape in the form of bulb strains or stresses about 3.5 diameter below the pile tip. It can also be seen that the dotted lines in the shear stress graph has shown which indicate that the pile has reached its full shear resistance. From the output of displacement at each stage of loading, the load-displacement curve can be plotted as shown in Figure 14.

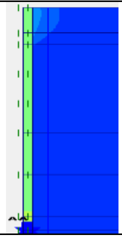
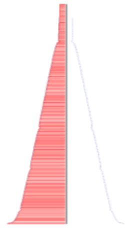
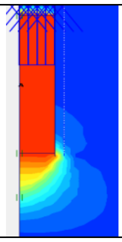
	Displacement Shadings	Shear Stress
Upper Segment		
Max.	32.61 mm	81.69 kN/m^2
Bottom Segment		
Max.	59.69 mm	93.84 kN/m^2

Figure 13: Displacement and shear stress concentration close to the point of load application

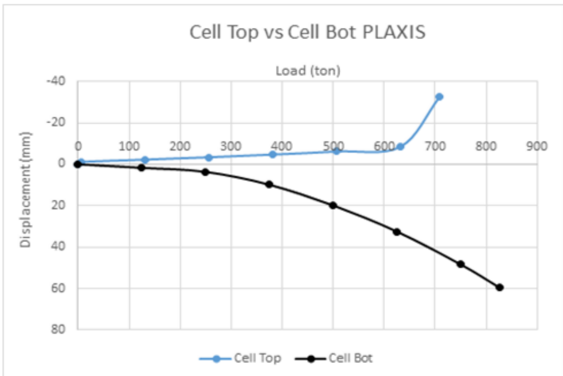


Figure 14: Load-Displacement Curve of O-Cell Test (PLAXIS)

The load-displacement curve of O-Cell from PLAXIS calculation is also compared with the curve from field testing and the result is quite similar. It can be seen in Figure 15. In order to obtain the bearing capacity, the curve needs to be converted to equivalent top load curve and it is shown in Figure 16.

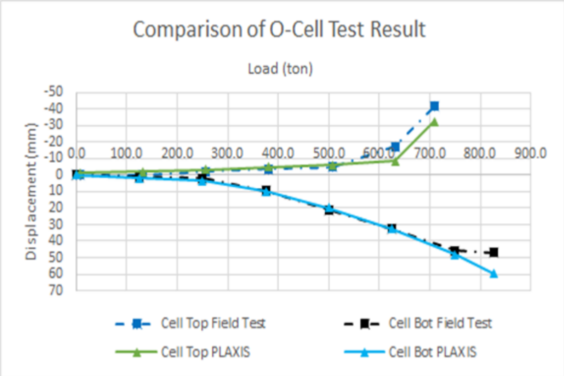


Figure 15: Comparison of O-Cell load-displacement curves between PLAXIS and field test

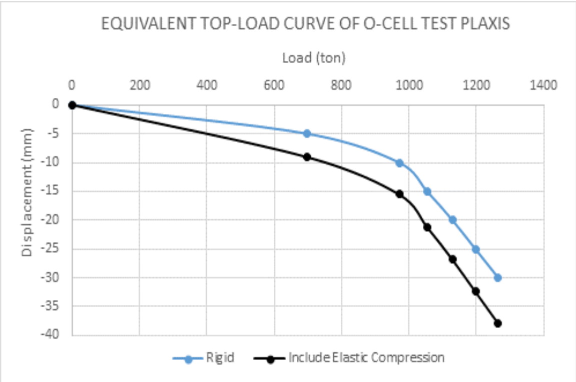


Figure 16: Equivalent Top-Load Curve of O-Cell Test (PLAXIS)

After analyzing the O-Cell test, the Kentledge Test is also analyzed. Unlike the O-Cell test, the Kentledge test shows that it has not failed yet until 200% working load. Figure 17 shows the movement of pile with maximum of 87.46 mm and the maximum shear stress is 68.05 kN/m2.

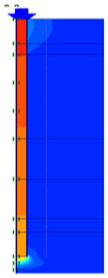
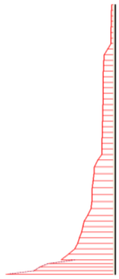
Displacement Shadings	Shear Stress
	
87.46 mm	68.05 kN/m^2

Figure 17: Displacement and shear stress along the upper segment of the pile

From the output of displacement at each stage of loading, the load-displacement curve can be plotted as shown in Figure 18.

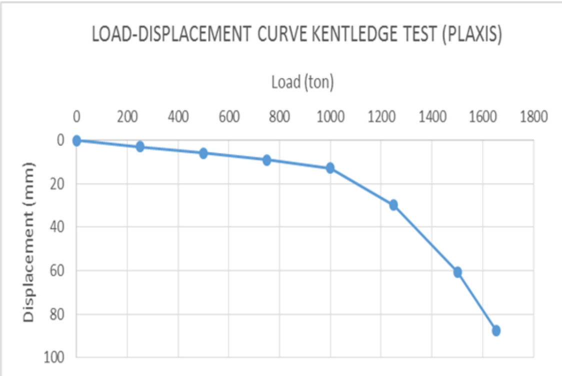


Figure 18: Load-Displacement Curve of Kentledge Test (PLAXIS)

Finally, Figure 19 shows the comparison among the equivalent top-load curves obtained by field measured O-Cell test, numerical simulation O-Cell test and Kentledge test. It shows that the curve from Kentledge test higher than O-Cell test which has more potential to have higher bearing capacity.

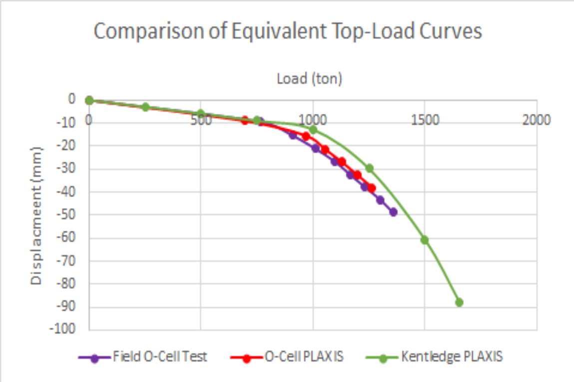


Figure 19: Comparison of Equivalent Top-Load Curves from O-Cell versus Kentledge Test

7.0 Result Interpretation

After getting all the load-displacement curves, the ultimate bearing capacity can be calculated. The ultimate bearing capacity is defined as the load when the pile plunges or settles rapidly under sustained load.

Ideally, the failure definition should be based on mathematical rule. In this research, Davisson (1972), Mazurkiewicz (1972), and Chin (1970,1971) methods are used to obtain the bearing capacity of the pile. But, it turns out that Davisson method can not be used because the pile diameter is too large so that the load-displacement curve does not intersect with the limit line. Therefore, only Mazurkiewicz and Chin method can be used as shown in Figure 20 and Figure 21.

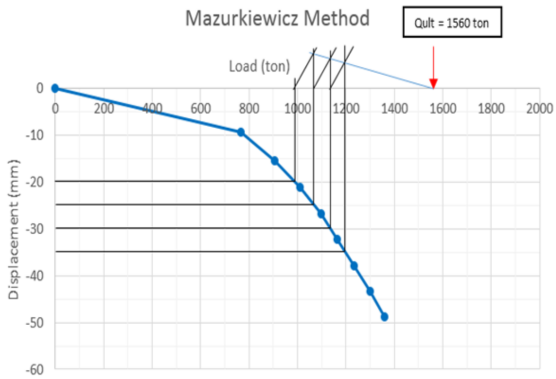


Figure 20: Typical interpretation result with Mazurkiewicz method

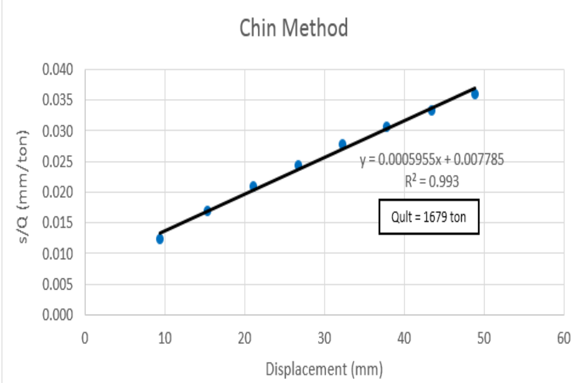


Figure 21: Typical interpretation result with Chin method

Then, equation from Chin (1970) is used to obtained the load-displacement parabolic curve namely s/Q = C1 s +C2 where s = settlement of pile at pile load Q ; C1 and C2 = slope and Y-axis intercept of the straight line, respectively, and it is plotted together with equivalent top-load curve. The comparison shows that the curves are quite similar which shown in Figure 22.

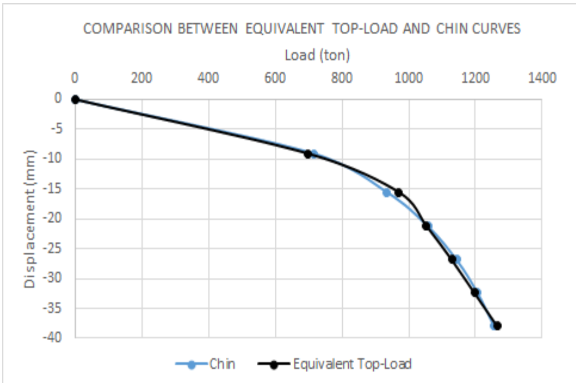


Figure 22: Typical comparison result between equivalent top-load and Chin curves

Besides the numerical calculations, manual calculations were also carried out using Reese & Wright (1977) and Kulhawy (1991) method. The results are shown as in Table 2 below.

Table 2: Bearing capacity result from manual calculation

End Bearing Capacity (ton)	Ultimate Friction Capacity (ton)		Weight of Pile (ton)	Ultimate Bearing Capacity (ton)	
	Reese & Wright	Kulhawy		Reese & Wright	Kulhawy
707	1435	1908	142	2000	2473

Then, all the bearing capacity obtained from interpretation of equivalent top-load curves and manual calculation is tabulated in Table 3. According to Terzaghi (1942), the ultimate bearing capacity is reached when the pile settlement is 10% of pile diameter, so it is also calculated by using the equation of Chin method.

Table 3: Bearing capacity resume of all analyses both Kentledge and O-Cell Test

	Kentledge				
	Manual Calculation		PLAXIS		
	Reese & Wright	Kulhawy	Mazurkiewicz	Chin (when s = 10%D)	Chin (when s = ∞)
Qu (ton)	2000	2473	1800	1753	1942

	O-Cell					
	Field Test			PLAXIS		
	Mazurkiewicz	Chin (when s = 10%D)	Chin (when s = ∞)	Mazurkiewicz	Chin (when s = ∞)	Chin (when s = 10%D)
Qu (ton)	1560	1545	1679	1600	1527	1647

8.0 Conclusions

i. The ultimate bearing capacity from O-Cell test is slightly lower than Kentledge test. In this study case, the ultimate bearing capacity is lower about 11% than Kentledge test. It shows that the behavior of bored piles tested using bi-directional static load test is different than conventional static test using kentledge system because the point of application is down below, where the pile tip is close to the point of load application. In conventional static load test, the friction is normally mobilised prior to the tip, but in the bi-directional test method, the pile tip may be mobilised prior to the friction.

ii. It is important to note that the actual behavior of the pile under bi-directional load is different than the kentledge system. Hence, the calculation should be conducted to simulate the equivalent top-load curve of the bi-directional test results by considering pile elastic compression as well as the load transfer when the load is applied at the top, rather than from the bottom. In this research, the elastic compression of the pile is about 8 mm.

iii. Test piles with targeted capacity of 1000 tons can not be satisfied based on the results of bi-directional static load test. The maximum ultimate bearing capacity proposed is 1650 tons, which means that the allowable load is 825 tons. For practical purposes, additional pile may be added for instance.

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