# DYNAMIC AND STATIC LOAD TESTING: A COST SAVINGS APPROACH

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## ABSTRACT

A test pile program was undertaken at a project site in Ain Sukhna, Egypt for an import/export oil jetty. Two 1219 mm diameter open ended steel pipe piles were evaluated at two separate test locations. Each test pile was dynamically tested during initial drive utilizing a Pile Driving Analyzer (PDA). Restrike testing was also performed to evaluate the time dependent soil setup. One static compression test and one static tension test was performed at each test location. A correlation of the static and dynamic load test results was established to develop a driving criteria for the piling across the two kilometer project. The constructability benefits of shorter piles will be discussed in more detail, given that the pile lengths were shortened by 9 to 10 meters on average. Lastly, the use of a four pile linear layout to perform both compression and tension tests will be covered.

**Keywords: Pile Driving Analyzer (PDA), Static Load Testing (SLT), Soil Set-up, Pipe Piles**

## INTRODUCTION

With the increased number of Very Large Crude Carriers (VLCC) & Ultra Large Crude Carriers (ULCC) being used to transport oil products around the world, companies and/or nations are presented with the challenge of transferring these products to and from the carriers in deep water scenarios, typically 15 to 20 meter depths, to accommodate the vessels draft. One option for loading/unloading the oil products from a VLCC or ULCC would be to transfer to/from smaller vessels several miles offshore, whereas the most economical option is to unload directly to a pipeline via a berth/jetty platform near shore. These berth platforms must be designed to withstand multiple loading scenarios while these carriers are moored and transferring their products. The use of Large Diameter Open Ended Pipes (LDOEP) piles are a common foundation choice for this offshore application. One of the drawbacks of LDOEP piles, especially across a large project site, is that there can be extreme variability in the pile driving behavior. This can be caused by either a change in soil conditions or the performance of the soil plug. Due to this variability, it is important to verify throughout the duration of the project that the piling is being installed to the correct criteria as established during the load test program. A well designed driven pile load test program, preferably with the combination of Static Load Testing (SLT) and Pile Driving Analysis (PDA), should develop a driving criteria that can allow the contractor and owner to monitor any change in driving behavior.

### PROJECT BACKGROUND

Egyptian Natural Gas Holding Company (EGAS) and Arab Petroleum Pipelines Company (SUMED) initiated the Ain Sukhna Product Hub (ASBH) project in Ain Sukhna, Egypt to further increase the nation's added value for its current and prospective clients. ASBH is located approximately 50 km south of the Suez Canal, on the north western edge of the Gulf of Suez. The facility is connected to the Sumed pipeline, which gives an alternative route for transporting oil from the Persian Gulf to the Mediterranean Sea if the Suez Canal is not passable. The ASBH project includes both onshore and offshore facilities for storage, loading, unloading and load out of Natural Gas, Fuel Oil and Liquefied Petroleum Gas (LPG). The onshore facilities include three 50000 LPG refrigerated tanks, three 35000 Fuel Oil tanks and one 20000 Gas Oil flushing tank. The offshore facilities include one Floating Storage and Regasification Unit (FSRU)/Liquefied Natural Gas (LNG) berth for natural gas import via a 170000 cubic meter FSRU vessel and an export capacity of 14.1M cubic meters of gas per day. One combined LPG/product berth to accommodate LPG carriers in the range of 5000 to 82000 cubic meters and oil tankers in the range of 25000 to 160000 Deadweight Tonnage (DWT).

The two berths for this project extend approximately 2.2 km into the Gulf of Suez to reach the water depths required for the VLCC to safely access the unloading and loading platforms. A joint venture between Besix Group and Orascom Construction PLC (BO JV) was formed to execute the construction of the berths. The project required an accelerated timeline to meet the owner requirements with the first berth needing to be operational within six months of the start of the project and the second berth would be built while live gas was being conveyed to and from tankers.

**Fig. 1: ASBH Marine Layout**

**SUBSURFACE**

A soil investigation was performed in 2015 by Fugro Middle East, which consisted of 10 soil borings arranging in depth from 50 to 60 meters, 5 CPT Borings arranging in depth from 22 to 40 meters, In-situ vane shear tests and laboratory testing to further categorize the soil stratum. Based on this investigation, the upper 1 to 6 meters is a very weak layer, underlain by alternating layers of sand, silt and clay with a high proportion of secondary soil (ie. silty and clayey sand, sandy silt, sandy clay). Figures 2 & 3 give the soil profile for CPT06 and CPT10, which correspond to test location No. 1 and 2, respectively. These borings are approximately 390 meters apart. The sea bottom elevation is approximately -13.6 and -15.5 meters for CPT06 and CPT10 with a self-penetration depth of -14.1 and -16.5 meters, respectively. Overall, the soil profile across the site cannot be generalized due to high variability in the stratum encountered during the investigation.

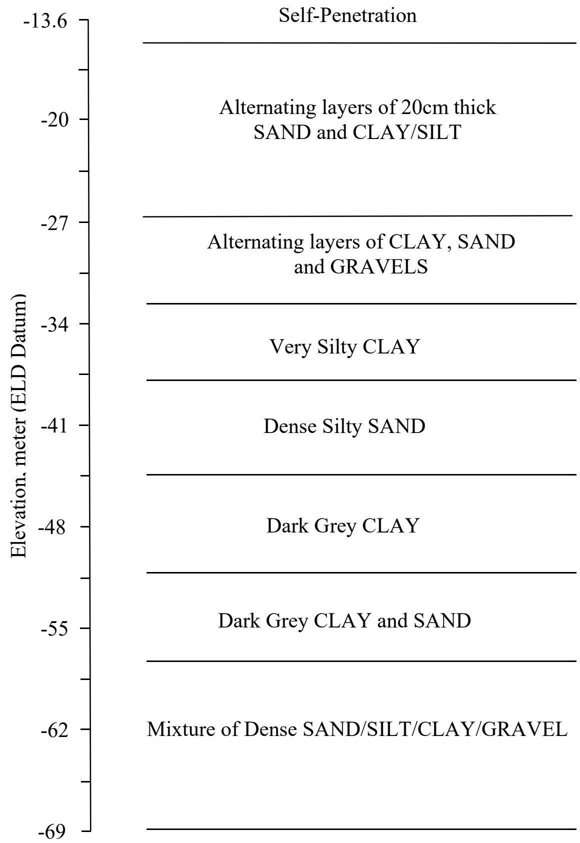


**Fig. 2: Soil Profile – CPT06**

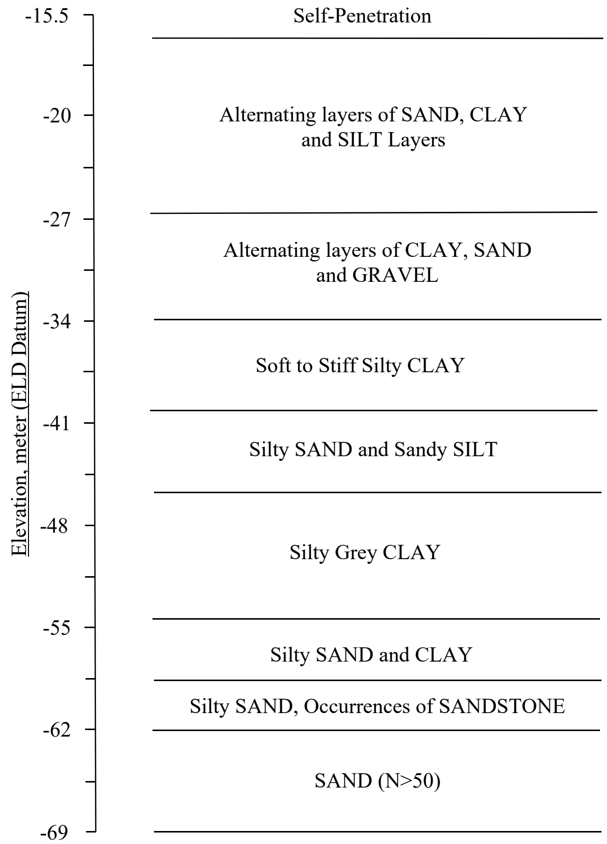


**Fig. 3: Soil Profile – CPT10**

**PILE DESIGN**

The soft upper layer indicated during the soil investigation has been neglected and the depth of the competent layer is summarized in Table 1.

**Table 1: Depth of Competent Layer**

| CPT Boring | Test Location | Thickness of Very Soft Layer, m | Depth of Competent Layer (m, ELD) |
|---|---|---|---|
| 6 | 1 | 1.5 | -17.0 |
| 10 | 2 | 3.0 | -23.0 |

The calculated undrained shear strength, $c_u$, was then utilized to calculate the ultimate bearing capacity in compression and tension with the API formula. A global safety factor of 2.0 and 2.5 were applied to the ultimate bearing capacity in compression and tension, respectively, for the operational conditions. Table 2 is the required penetration into the competent layer, as defined above, of a 1.2 meter outer diameter pile for varying ultimate bearing capacities in compression and tension.

**Table 2: Required Penetrations for varying Ultimate Bearing Capacities**

| Ultimate Bearing Capacity, kN | Compression | Tension |
|---|---|---|
| | Required Penetration, m | Required Penetration, m |
| 4000 | - | 30 |
| 6000 | 34 | 36 |
| 8000 | 40 | 42 |
| 10000 | 46 | 47 |
| 12000 | 50 | - |

The required allowable load was indicated to be 5000 and 4000 kN for compression and tension, respectively. With the above mentioned global safety factors, the required ultimate bearing capacity is 10000 kN for both compression and tension. Therefore, based on Table 2, 46 to 47 meters of penetration into the competent layer is required to achieve an ultimate bearing capacity of 10000 kN.

**SOIL SET-UP**

In certain soil types, driven piles can exhibit a higher capacity several hours, days or months later when compared to their capacity during initial installation (Fellenius et. al. 1989, Komurka 2004). Soil set-up is a phenomenon that is defined as an increase in shaft resistance that develops over a certain amount of time after installation. For the defined soil types on this project, this set-up is most likely caused by a combination of the remodeling of disturbed soil and an increase in soil strength as the excess pore water pressure dissipated. The rate of soil set-up can vary from site to site. Determining the EOD capacity along the set-up gain during a short-term (2 to 48 hours) and a long-term (5 to 50 days) restrike is helpful in evaluating the long term static capacity of the installed pile.

**DYNAMIC LOAD TESTING**

Dynamic Load Testing (DLT) using a Pile Driving Analyzer® (PDA) was performed on the compression and tension test piles at test location No. 1 and 2. The purpose of the DLT was to monitor hammer performance, assess pile structural integrity, calculate pile driving stresses, and evaluate bearing capacity. The bearing capacity for each testing scenario was further evaluated with CAPWAP®. CAPWAP allows for the computation of soil resistance forces and their distribution, ie. separation between the skin friction and end bearing. DLT measurements were taken using strain gages and accelerometers attached to diametrically opposite sides of the pile approximately 3 meters below the top of each pile under pile hammer impacts.

A total of 8 piles were installed: 4 reaction piles and 4 static load test piles. The test piles were 1219 mm O.D. x 22/18 mm open ended steel pipe test piles with a wall thickness of 22 mm in the upper 12 meters of the pile, reducing to 18 mm of thickness for the remainder of the pile. The total test pile lengths were 61 to 62 meters and were reported to have a minimum yield strength of 400 MPa. DLT was performed during initial drive (EOD) and during a short-term restrike (BOR) typically 24 to 48 hours after initial driving. Long-term restrikes were then conducted on the test piles 11 to 38 days after EOD. The piles were driven using either an IHC S150 or IHC S200. According to the manufacture's literature, the IHC S150 and S200 have a 74 and 98 kN ram and a maximum rated energy of 149 and 198 kN-m, respectively. Table 3 summarizes the calculated setup ratio based on the CAPWAP calculated EOD shaft resistance and subsequent shaft resistance values for short and long-term restrikes.

**Table 3: Setup Ratio**

| Pile | Shaft Resistance (kN) | | Time (days) | Setup Ratio | Embedment Depth* (m) |
|---|---|---|---|---|---|
| | EOD | BOR / BOR2 | | | |
| Tension Pile 1 | 2200 | 7400 / 9500 | 0.9 / 11 | 3.4 / 4.3 | 38.25 |
| Compression Pile 1 | 2100 | 8200 / 10000 | 1.8 / 12 | 3.9 / 4.8 | 38.25 |
| Tension Pile 2 | 1700 | 7400 / NA | 1.2 / NA | 4.4 / NA | 29.80 |
| Compression Pile 2 | 1500 | 6800 / 8800 | 1.0 / 38 | 4.5 / 5.9 | 29.80 |

*Embedment Depth based on penetration into competent soil layer

## STATIC LOAD TEST PROGRAM

Test location No. 1 was located approximately 800 meters from shore along the access trestle and test location No. 2 was located in the FSRU platform approximately 400 meters northeast of test location No. 1. For each of the test locations, four piles were driven in a linear configuration, two reaction piles, one compression test pile and one tension test pile. Each pile was installed with a spacing of approximately 4.5 meters. The load was applied with two 7000 kN jacks connected to a manifold. The applied load was monitored with two sets of bending compensated strain gages (three strain gages attached in a triangular pattern 120 degrees apart). The two sets were placed to assure accuracy and backup information in case of instrumentation problems. The applied load was also monitored via two manometers, however, the presented applied loads are based on the strain measurements. Four displacement measurement readers (LVDTS and Digital Dial Gages) were placed at 90 degrees to measure displacement on the test pile. Additional instrumentation was attached to the closest reaction pile to monitor the load and displacement.

Loading specifications required that the compression test piles be loaded to 10000 kN (200% of the design load) during the first cycle. After this load was achieved and failure had not occurred for compression test pile 1, the load was increased up to a target load 12500 kN (250%) during the second cycle. As shown in Figure 4 & 6, the maximum test load for compression pile 1 and 2 was 11600 and 8900 kN, respectively. At these points, the pile could not hold the load and geotechnical failure occurred. If using Davisson Criterion for failure load determination it is observed that the obtained failure load is 11600 and 8500 kN for compression test pile 1 & 2, respectively.

For the tension test piles, the first cycle had a target load of 10000 kN (250% of the design load). There was a contingency for a second cycle to 12500 kN (300%) if failure did not occur after the first cycle. As shown in Figure 5 & 7, the maximum test load for tension pile 1 and 2 was 9500 and 9200 kN, respectively. At these points, the pile could not hold the load and geotechnical failure occurred. If using a tangent criterion for failure load determination it is observed that the obtained failure load is 9500 and 8500 kN for tension test pile 1 & 2, respectively.

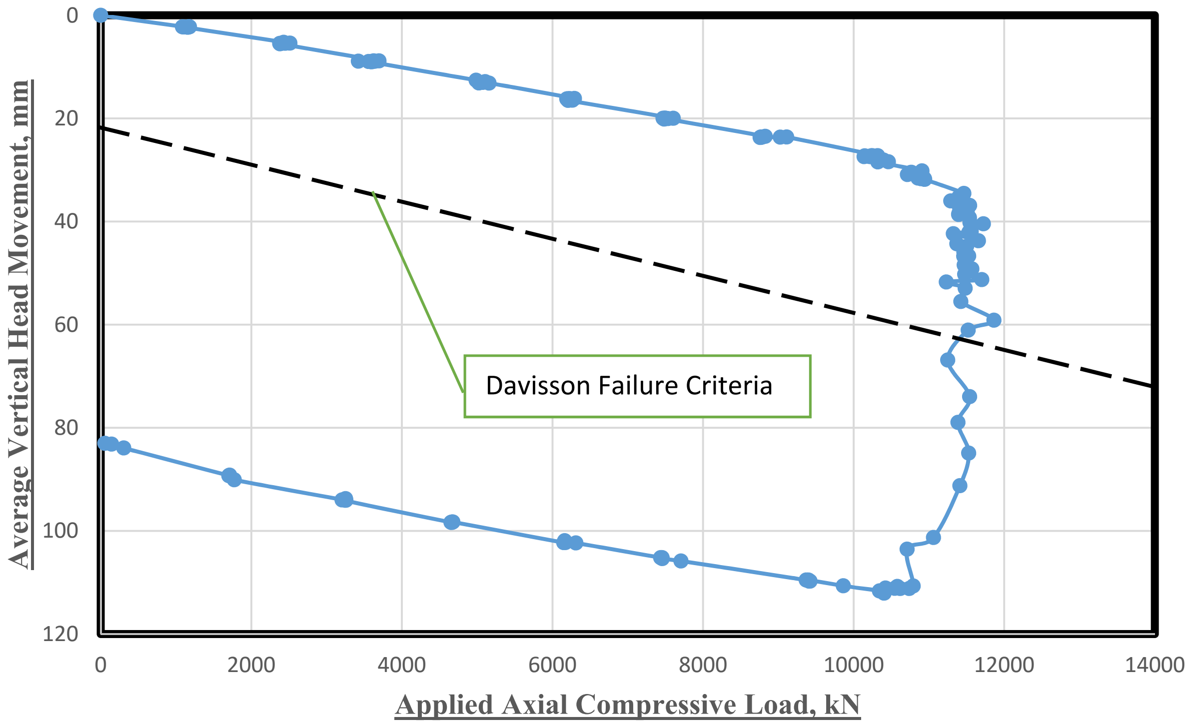


**Figure 4: Compression Pile 1 – Load vs. Vertical Movement**

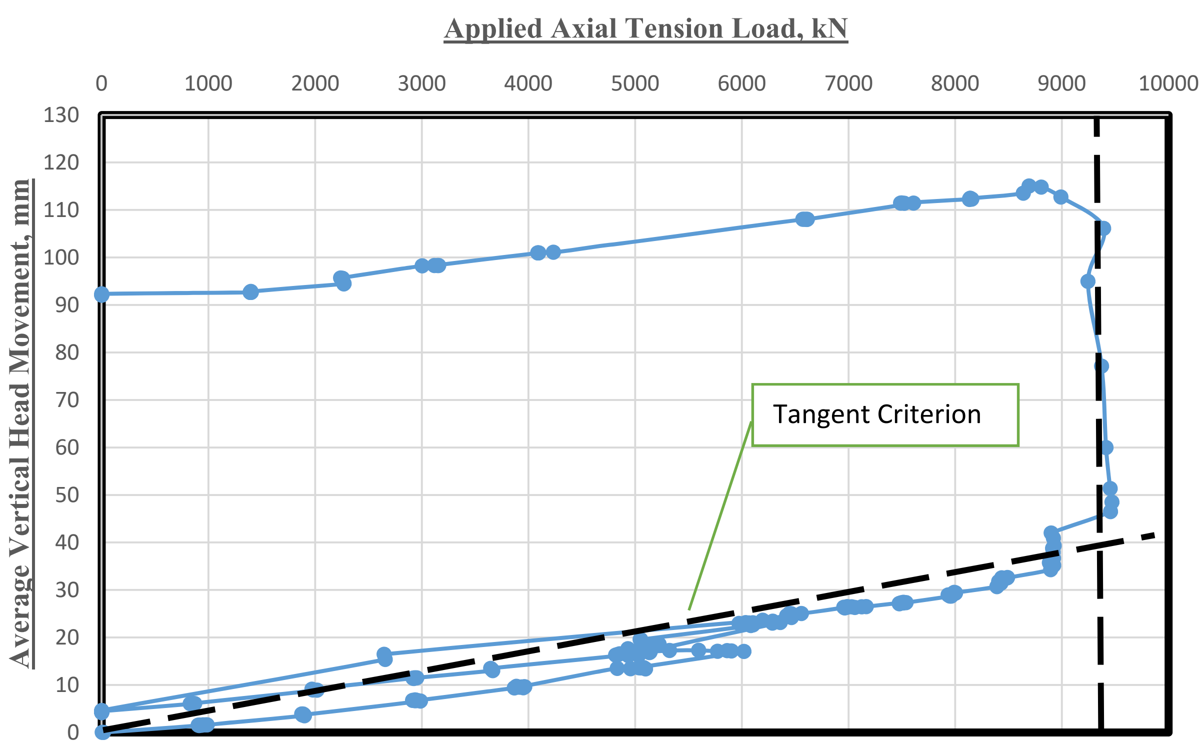


**Figure 5: Tension Pile 1 – Load vs. Vertical Movement**

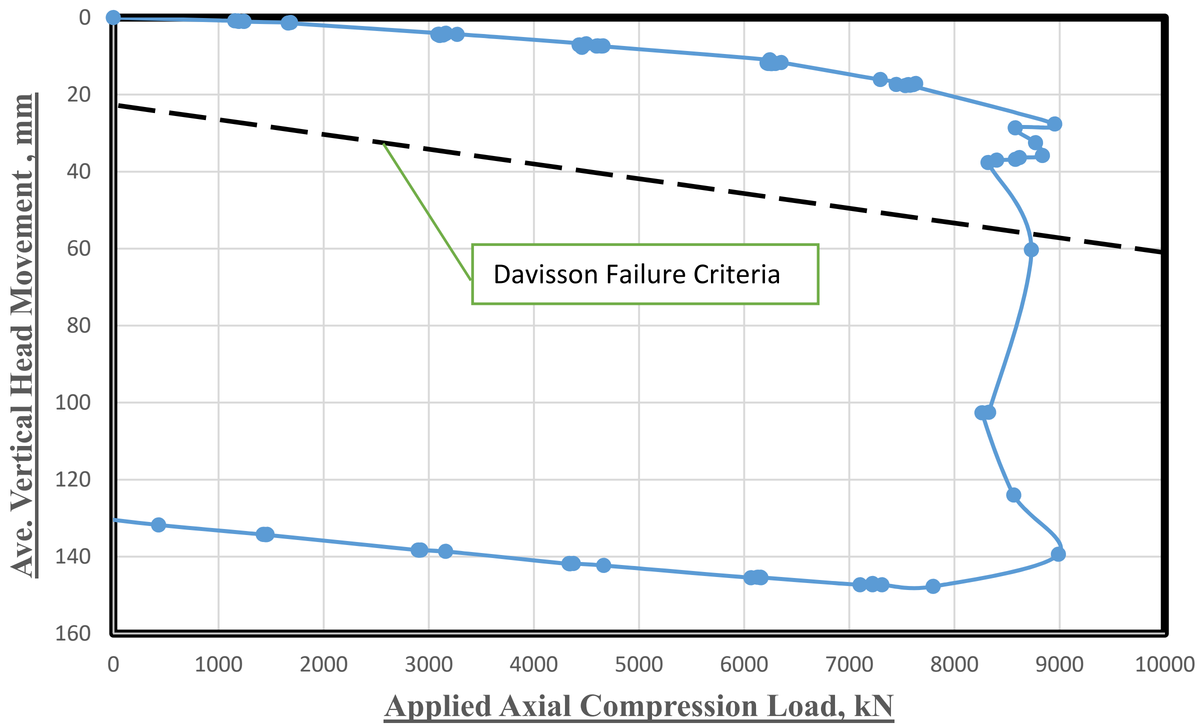


**Figure 6: Compression Pile 2 – Load vs. Vertical Movement**

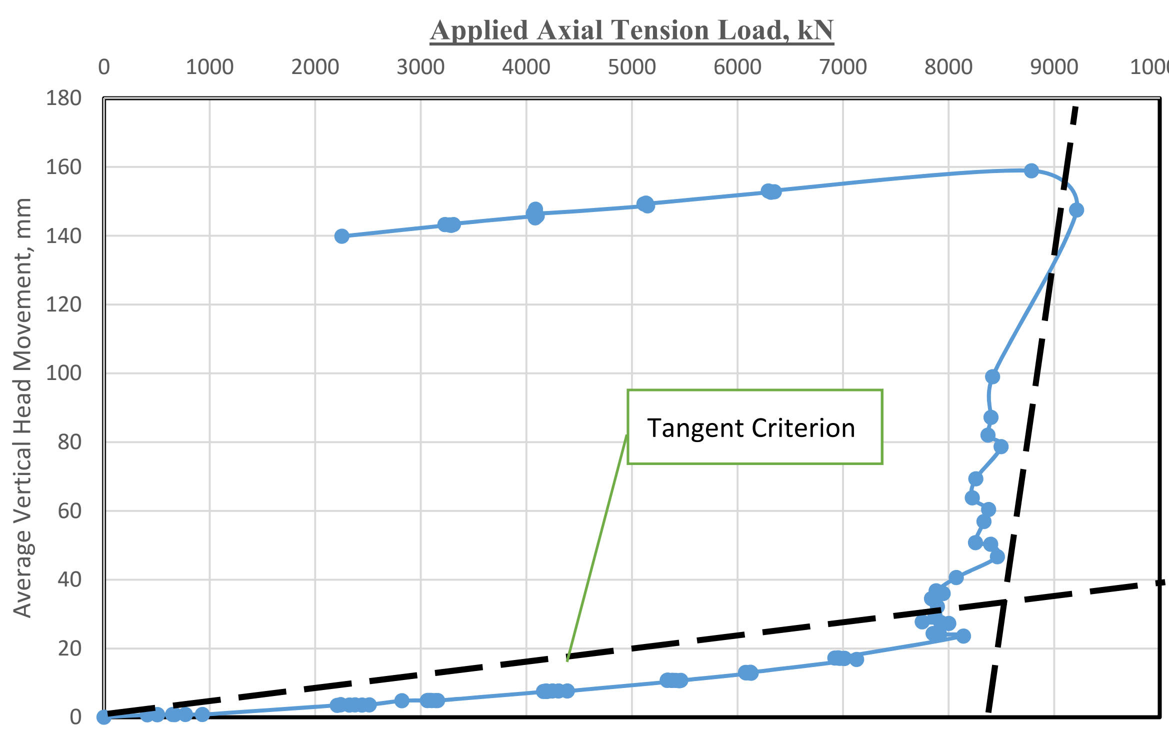


**Figure 7: Tension Pile 2 – Load vs. Vertical Movement**

**CORRELATING DLT & SLT RESULTS**

As evidenced for compression test pile 1, the shaft friction setup factor obtained when comparing the shaft friction at the end of initial drive (2100 kN) versus the shaft friction obtained during the static load test (10600 kN) generates a shaft friction setup factor of 5.0. The end bearing being was assumed to be 1000 kN, as was calculated during DLT testing. This implies an overall pile resistance setup factor (including end bearing) of 4.0 (11600kN/2900kN). Figure 8 presents on a log scale the estimated shaft friction vs elapsed time. The initial rate of shaft friction increase is considerably fast, but then slows down with time. A majority of the soil setup is gained in the first 10 days after initial pile installation. Both DLT and SLT results are consistent. The predicted failure load of compression test pile 1 during DLT was predicted to be 10500 kN after an elapsed time of 11 days after EOD, whereas the failure load during SLT was predicted to be 11600 kN after an elapsed time of 42 days after EOD. With this agreement, no adjustments are necessary to be performed to the DLT results to correlate with the SLT results. Based on Figure 8, a conservative estimate of the long term capacity is approximately 1000 kN higher than at the time of testing, however, it was decided to utilize this additional resistance as a conservative approach for the pile length determination.

Based on the tension test pile 1 results, the predicted failure load of 9500 kN was achieved after an elapsed time of 42 days after EOD. This implies that the uplift pile resistance is close to 90% of the measured compression shaft friction. Typically, a general assumption is that the compression shaft friction is reduced by 80% to calculate the uplift resistance. For these soil types in which most of the shaft friction is developed from cohesion, as evidenced by the large setup factor (5.0), a 90% reduction factor seems appropriate.

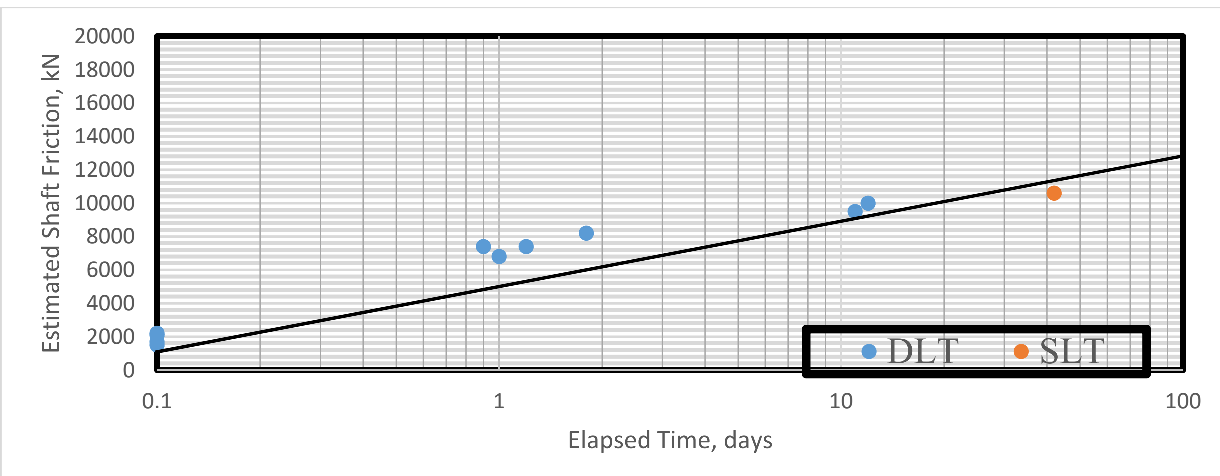


**Figure 8: Shaft Friction vs. Log Scale Elapsed Time**

**DRIVING CRITERIA**

Based on the obtained overall soil resistance setup factors from testing location No. 1 and 2, a driving criteria recommendation was established for the piles to be installed. The soil resistance setup factor was estimated to be 4.0 and thus the driving criteria was developed for EOD loads of 25% of the required ultimate load. The additional 75% of the resistance will develop with time after initial pile installation as soil setup occurs. The GRLWEAP® program was used to create a refined Wave Equation Analysis (WEAP) which creates a model that calibrates to the field testing that was performed. As shown in Table 4, the refined WEAP provides the required blow count for select ultimate bearing capacities for the IHC S150 at varying hammer energies. The driving criteria assumes a 62 meter long 1209 O.D. x 18 mm open ended pile with an embedment depth of 40 meters, without consideration of the competent layers as Table 1.

Three hammer settings were assumed; 100% (150 kJ) of the hammer, 80% (120 kJ) and 60% (90kJ) of the hammer. The driving criteria also considers that the piles will be installed in either a vertical orientation, or inclined on a 1:3 or 1:4 ratio. Driving criteria was also developed for the S90 and S200 hammers, but are not presented.

**Table 4: Driving Criteria – S150 Hammer**

| Required Ultimate Capacity | Required BLC - Energy 60% | Required BLC - Energy 80% | Required BLC - Energy 100% |
|---|---|---|---|
| MN | blows/25cm | blows/25cm | blows/25cm |
| 11 | 26 | 22 | 18 |
| 10 | 23 | 19 | 16 |
| 9 | 22 | 17 | 14 |
| 8 | 19 | 15 | 13 |
| 7 | 16 | 13 | 11 |
| 6 | 14 | 12 | 9 |
| 5 | 11 | 9 | 8 |
| 4 | 9 | 8 | 7 |
| 3 | 7 | 6 | 5 |

## CONSTRUCTION BENEFITS

The pile driving operations were facilitated with jack-up barges and adjustable side mounted pile templates. Based on the initial design of the piling, it was assumed that a majority of the piles would be 71 to 72 meters in total length, however, after the load test program, the total pile length was optimized to 62 meters. The following benefits significantly aided in keeping the project ahead of the accelerated schedule, on budget, and avoiding costly delays with the potential for deadline penalties.

- The reduction in length was a significant cost savings when applied to 400+ piles (~3600 meters of piling length reduction)
- The contractor was able to mobilize a third jack-up barge to aid in installing piles. This third jack-up was not included in the initial construction plan because it did not have the configuration to handle piles over 70 meters.
- The decrease in total pile stick up, especially for the battered piles, reduced the bending and strain induced on the pile template during driving and thus saved down time that would have been required for maintenance and repairs.
- The jack-ups spent less time getting the platform to the proper elevations because of the reduced pile stick-up.
- The total number of blows required to install the piling was reduced.

## FOUR PILE LINEAR LOAD TEST

Onshore static load testing generally uses a linear layout of test piles and reaction piles with the reference beams supported without the use of piles, but offshore testing typically relies on piling installed orthogonal to the test piles to support the reference beams. The setup for these static load tests utilized a four pile linear layout with the tension and compression test piles installed next to each other and the outer most piles acting as the reaction piles. The reference frame was then cantilevered from the non-test pile, as depicted in Figure 9. The reference frame was designed to be as stiff as possible, however, there was relative motion that was observed in the dial gage readings. This motion (~1 mm) was determined to be minute compared to the total displacement that was observed throughout testing.

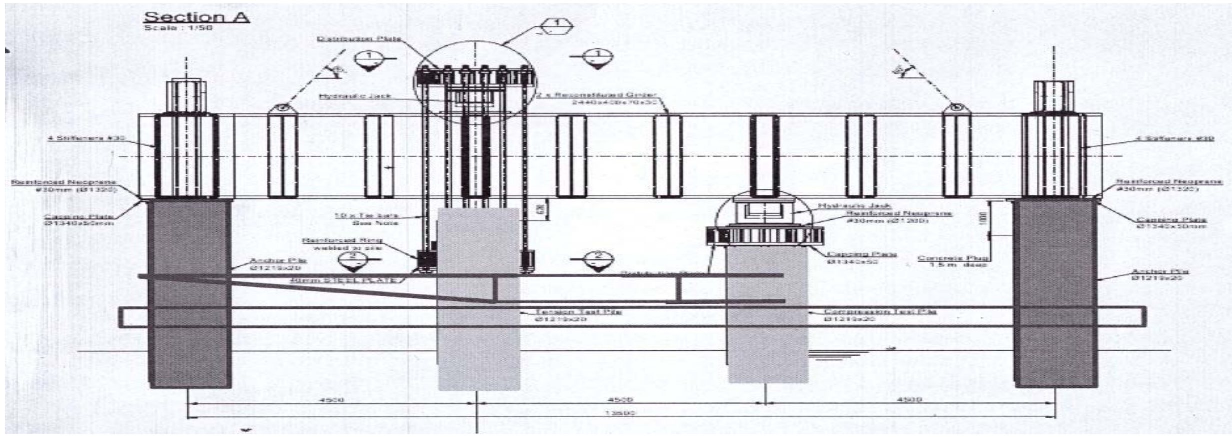

Figure 9: Four Pile Linear SLT Layout

**CONCLUSIONS**

Given the required accelerated timeline for this project, some may have foregone the load test program in favor of making progress. However, based on the benefits of shorter piles and additional equipment assisting in installing piles, the load test program was successful in providing significant cost savings to the project along with a quality control mechanism that increases the owner's confidence in the installed foundation. Furthermore, it was concluded that the dynamic load testing and static load testing results were very comparable for this site. The tension load tests indicated the pile uplift resistance can be assessed as 90% of the measured compression resistance obtained from the dynamic testing. A friction setup factor of 5.0 was obtained a combination of testing, yielding an overall setup factor (including end bearing) of 4.0.

**ACKNOWLEDGEMENTS**

The authors gratefully acknowledge Besix Group for the release of the design documents, load test program results and production pile DLT results presented in this paper.

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