

PILE DRIVING INSTRUMENTATION OF 54-INCH PILES IN GRAVELS AT THE WIRIAGAR DEEP PLATFORM IN BERAU BAY, INDONESIA

Pua Chee Peng, Somehsa Geosciences Pte Ltd, Singapore, +65 91523149,
cppua@somehsa.com,

Murthy D.S., Somehsa Geosciences, satya@somehsa.com

Radha Rao, Somehsa Geosciences, radharao@somehsa.com

Hugo Galanes-Alvarez, BP Exploration Operating Company Ltd, Sunbury-on-Thames,
Middlesex, UK, +44 7979873712, hugo.galanes@uk.bp.com

Jeanjean P., BP America, USA, Philippe.Jeanjean@bp.com

Achmad Makmur, BP Indonesia, Jakarta, Indonesia, achmad.makmur@se1.bp.com

ABSTRACT

The paper presents the results and findings of instrumentation monitoring during the driving of six 54-inch open-ended steel piles and fourteen 30-inch conductors through dense to very dense sand and gravel layers at the Wiriagar Deep A platform in Berau Bay, Papua Barat, Indonesia. Monitoring of pile driving was carried out with a Pile Driving Analyser^R (PDA) which provided data such as energy transmitted into the pile, driving stresses and the estimated soil resistance to driving for each hammer blow. The transmitted energy was used to evaluate the hammer performance and to control the pile driving fatigue damage by adjusting the hammer efficiency. The driving stresses also helped to minimize non-uniform impact at the pile or conductor top, and to ensure that stresses within the pile were below the allowable limit, especially at the pile tip when driving through the gravel layers. Pile monitoring data was successfully acquired for all sections of all piles, delivering a high-quality continuous dataset for all piling operations. Signal matching analyses of the data from selected blows was conducted with the CAPWAPTM software which allowed for onsite evaluation of the soil resistance to driving including the shaft friction and end bearing. Comparison of the measured vs the predicted resistance was carried out in real time. Evaluation of the instrumentation data also enabled optimisation of the re-strike programme to determine the changes in pile capacity with time. A unique dataset of driving behaviour of small diameter conductors (30-in) and larger diameter piles (54-in) in gravel is now available, enabling optimised planning of future facilities in the area. A companion paper (Galanes-Alvarez et al, 2020) describes the engineering design and assurance planning for the soil conditions encountered for this platform.

Keywords: piles, gravel, pile monitoring, friction fatigue, drill-out, CAPWAP, Tangguh

INTRODUCTION

BP Berau is the operator of Tangguh LNG, which is a two-train natural gas liquefaction facility at a remote site in Berau Bay, Papua Barat, Indonesia.

The current Phase 1 of the Tangguh Expansion Project was initiated to meet additional gas production demands and involved the development of a third LNG train consisting of two new offshore gas production facilities, Wiriagar Deep A and Roabiba A and the associated pipelines.

PLATFORM DESIGN AND SOIL CONDITIONS

Details of the platform design and soil investigations are presented in Galanes-Alvarez et.al [2020].

Fig. 1 shows an image of the gravel material, Particle Size Distribution (PSD) curve of the gravel at depth 55.3 m highlighted in brown and Cone Penetration Tests (CPT) log obtained at the Wiriagar Deep A location.

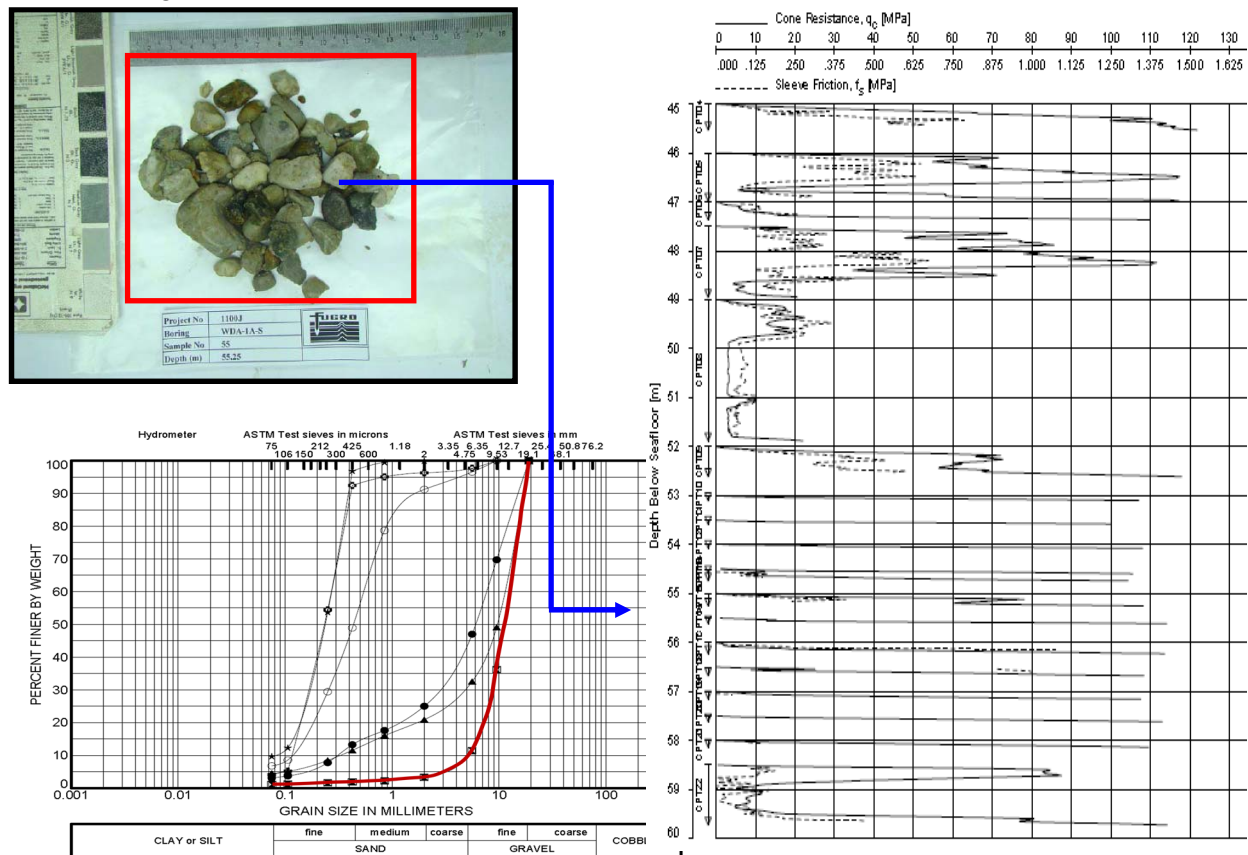


Fig. 1: Image of the gravel material, Particle Size Distribution and CPT log

FOUNDATION AND CONDUCTOR PILES

The foundation and conductor piles characteristics are provided in Galanes-Alvarez et.al [2020].

HAMMER DATA

Two Menck MHU1700 hydraulic hammers were used for the installation of the foundation piles while the Menck MHU300S and MHU800S hydraulic hammers were used for the conductor pile installation. The Menck MHU300S, MHU800S and MHU1700 hammers have a maximum rated energy of 300, 820 and 1700 respectively.

PILE INSTRUMENTATION AND DATA

A total of 12 sections for the foundation piles and 56 sections for the conductor piles were instrumented and monitored. The force-velocity data was generally of high quality for all the instrumented sections and appeared consistent from blow to blow during hammer impact.

The pile monitoring system consisted of two pairs of strain gages and accelerometers, as shown in the inset of Fig. 2, bolted diametrically opposite one another (at about 5.7 and 4.5 m below the pile top for the foundation piles and conductor piles, respectively), to record the dynamic force and acceleration during hammer impact. The “signature” of each hammer

blow is captured as time histories of force and velocity near the pile top using the Pile Driving Analyzer (PAX latest version), from Pile Dynamics Inc., of USA.

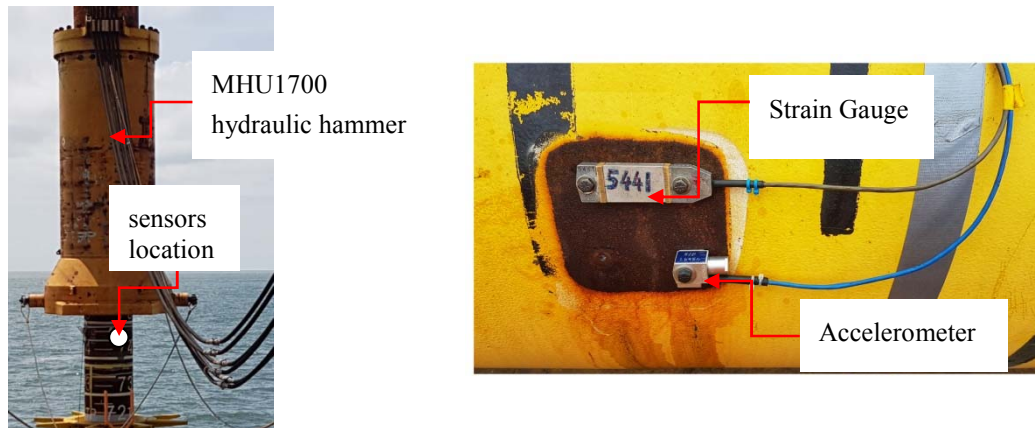


Fig. 2: Pile Monitoring Sensors and Setup

The force and velocity versus time histories of a single hammer blow are presented below on Fig. 3 for the following: (i) driving in the gravel layer at 55 m, (ii) End of Drive (EOD) at depth 72 m, (iii) Beginning of Restrike 1 (BOR 1) after 30 hours of set-up and (iv) Beginning of Restrike 2 (BOR 2) after 30 days of set-up.

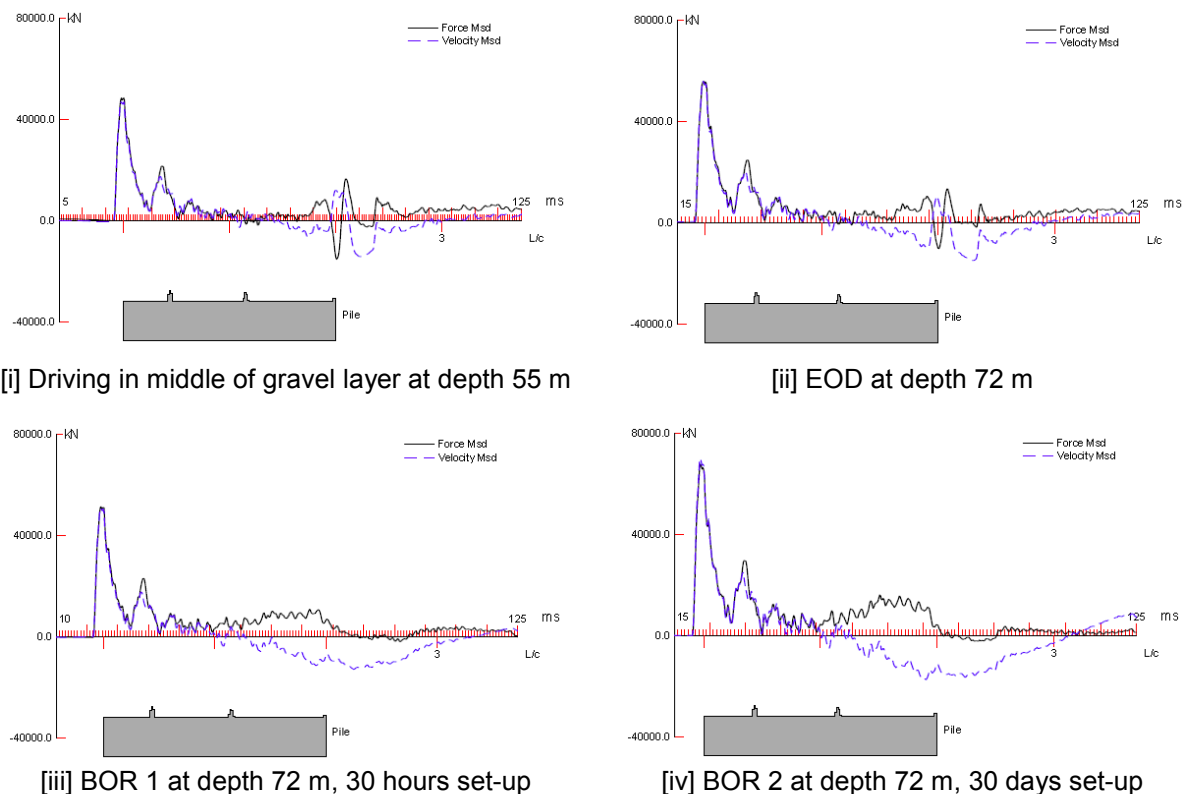


Fig. 3: Force Velocity Curves for driving in gravel, at EOD, BOR 1 and BOR 2

PILE INSTALLATION AND MONITORING

The pile monitoring results for Pile A2 which includes the restrike tests data from the PDA instrumentation and signal matching results are presented below on Fig. 4.

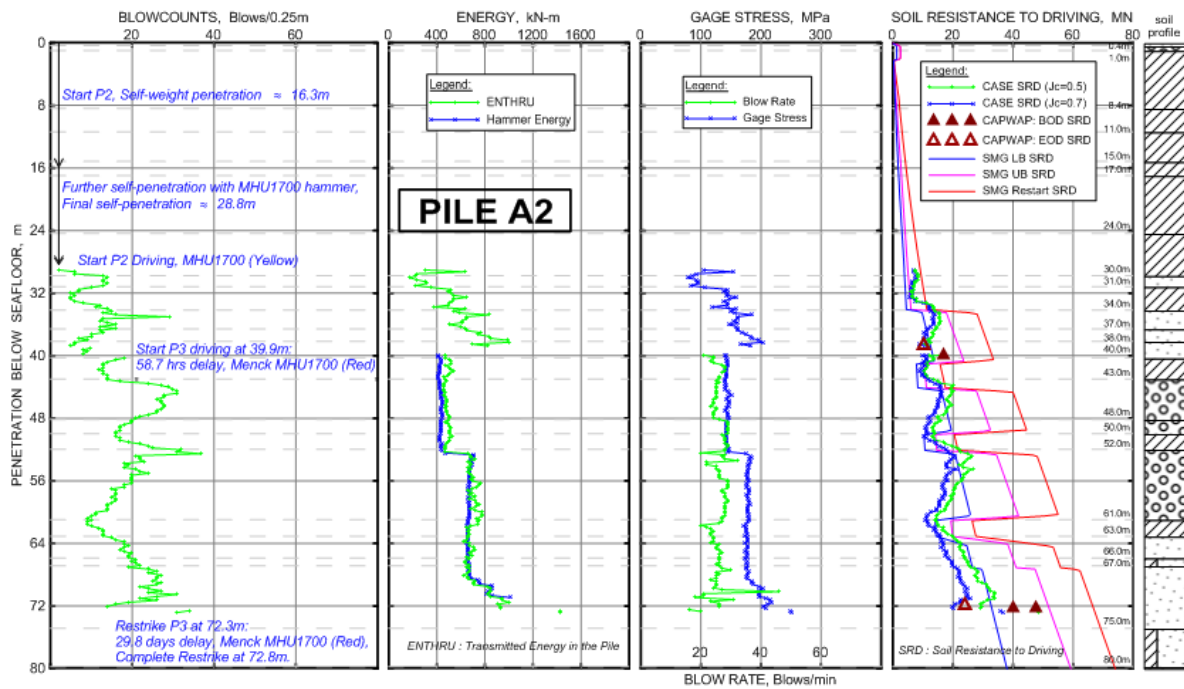


Fig. 4: Pile Monitoring Results for 54-inch diameter Foundation Piles

Observed Blowcounts

The observed blow counts for both the foundation piles and conductors are presented on Fig. 5.

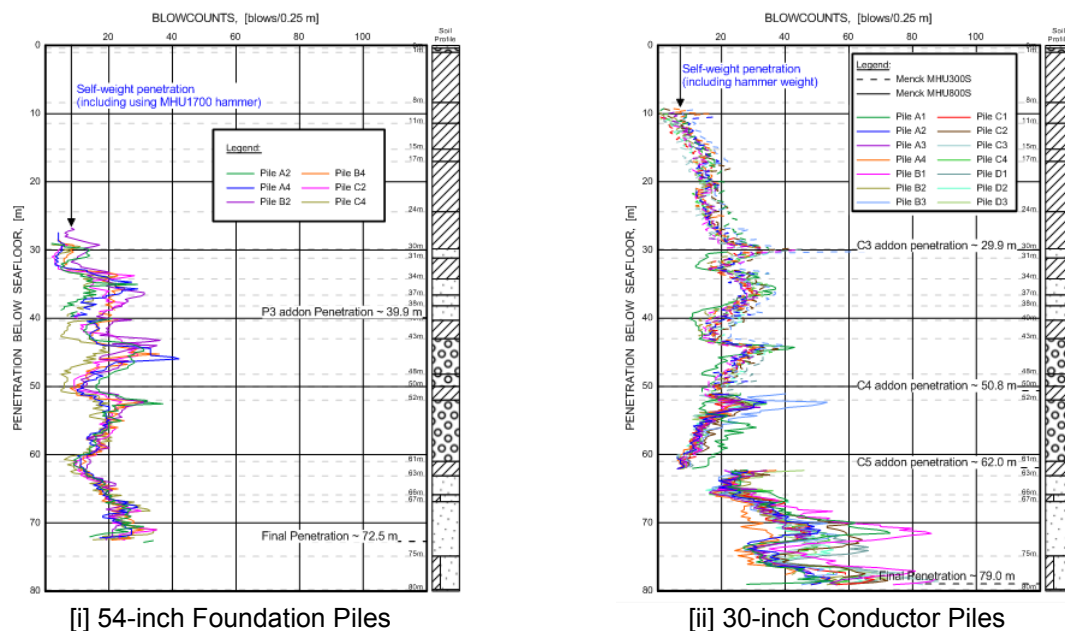


Fig. 5: Observed Blowcounts for the Foundation and Conductor Piles

Pile Driving Fatigue Assessment and Hammer Performance

For the foundation pile installation, the hammer energy setting was governed primarily by the risk of fatigue damage. Hence, the hammer energy setting and blow-count had to be optimized based on an industry-practice based calculation (such as DNV (2014)) to maintain the Design Fatigue Factor (DFF) above a minimum value of 10. Based on the upper bound

hammer rated energy proposed during the design stage, the DFF was about 11. During the installation, however, lower hammer energies were used. The measured energies and driving stresses (from pile monitoring) together with the observed blow-counts gave a DFF of about 14. Hence, the fatigue life of the piles due to pile driving is expected to be better than planned.

In general, the measured transmitted energy in the pile (ENTHRU) ranged from 150 to 500 kJ during driving of the P2 sections. There were some instances where higher energies (up to 760 kJ) were measured, notably towards the end of driving of the first few P2 sections to help optimize the P3 driving.

During the driving of the P3 sections to about 67 m penetration, the measured energy generally ranged from 350 to 700 kJ. Below 67 m penetration, higher energies were noted when driving the piles through the dense to very dense sand layer, till the target penetration of 72 m. The measured energy within these depths ranged from 800 to 1000 kJ.

The first restrike test was carried out after a delay of about 1.3 days (30 hours) on Pile A2, with the MHU1700 hammer. The pile penetrated about 4 inches (10 cm) after about 20 blows while being driven at an average measured energy of about 800 kJ.

The second restrike test, was carried out on the same pile (Pile A2) after a delay of nearly 30 days with the same MHU1700 hammer. In order to mobilize the full skin resistance due to the 30-day set up, the hammer was set at its full rated energy. The pile penetrated about 20 inches (50 cm) after about 67 blows while being driven at an average measured energy of about 1,400 kJ and the test was terminated.

The hammer energies, as delivered to the pile head by the hammer, are plotted against depth, together with the corresponding measured energy in the pile (ENTHRU) on Fig. 4. The hammer energy readings compared reasonably well with the ENTHRU, suggesting that energy transfer with the MHU1700 hammer was generally good, with minimal losses to the pile at impact.

Pile Driving Stresses

The impact stress near the pile top was measured directly by the gages while the maximum stress within the pile was determined from a review of the stress-wave response from the soil (also provided by CAPWAP). The maximum driving stress along the pile length was as high as 220 MPa during the driving of all the piles and was as high as 260 MPa during the restrike tests on Pile A2. These correspond to 53 and 63 percent of F_y respectively, where F_y is the nominal yield strength of the steel (414 MPa). These stresses are lower than 80 percent of F_y and hence within the allowable driving stress as per API RP2A (2014) Cl. 9.10.5.

The measured stresses at the gage location versus pile penetration are also plotted on Fig. 4, together with hammer and measured energy as well as observed blowcounts.

Soil Resistance to Driving

The soil resistance to driving (SRD) was obtained in real time during the pile installation, using a simplified CASE Method approach (RMX with $J_c = 0.5$ and 0.7). This soil resistance to driving also referred to as CASE SRD allows for a quick and simple calculation of soil resistance for uniform piles. The CASE SRD's were also compared against the predicted SRD on Fig. 4 and appear reasonable. Subsequently, in a post driving exercise, the CASE SRD was calibrated against the CAPWAP signal matching analyses. While the CASE SRD measurements helped in evaluating changes in soil resistances during driving, the final

interpretations for the pile adequacy assessment are based on the results from the signal matching analyses.

The analyses results include total, shaft and toe resistances as well as the related dynamic soil properties. For the sake of validating the computed static pile capacity (as part of the pile adequacy check), the shaft and toe resistances are also presented as equivalent “skin friction” or “end bearing” merely for simplicity and for minimizing confusion.

The shaft resistance (acting over the perimeter area of a pile segment on the outside of the pile) is needed to compare with or to estimate the unit skin friction expected from static pile capacity calculations. However, during unplugged driving, the shaft resistance is measured on both the outside and inside of the pile, so it is necessary to know the distribution of external and internal soil resistance. While a simple distribution can be estimated for most of the pile length, the distribution near the pile tip, however, can be influenced by the resistance near the pile tip.

Driving in Gravel

A total of 14 signal matching analyses with CAPWAP were carried out for the six foundation piles and 20 analyses were carried out for the 14 conductor piles to determine the soil resistance during driving, particularly, in the gravel and the dense to very dense sand layers below 50 m.

The unit shaft resistance profiles obtained from signal matching analyses of blows at or near the final penetration (of 72.5 m) for all the foundation piles are plotted together and presented on the first plot of Fig. 6.

For the driving conditions at the final pile depth, an external soil resistance factor of 70% was assumed for most of its length. This factor was based on a review of all the blow records as the piles drove through the various soil layers. These “unit skin frictions” are plotted on the second plot of Fig. 6.

The third plot is a comparison of the above CAPWAP external unit shaft resistances with the unit skin frictions obtained from the various CPT-based methods (in the commentary section of the API RP 2GEO).

From a comparison of these plots, especially within the gravel layer between 52 and 61 m, the CAPWAP external unit shaft resistances are clearly much lower than the unit skin frictions obtained from the various CPT-based methods. They are also lower than 115 kPa, the current API RP2A (WSD 2000) recommended value for dense gravel. These observations suggest that the current procedures for estimating relative density based on CPT (in granular soils) may not be appropriate for gravel. Jeanjean et al (2015) also reported similar lower-than-anticipated unit skin friction in gravel layers based on pile driving monitoring with the PDA and CAPWAP signal matching analyses.

Furthermore, there was yet another interesting observation. In the middle plot of Fig 6, the unit shaft resistances below 61 m (with more sand than gravel) are much higher than the resistances in the gravel layers above, both for continuous and restrike driving. So gravel behavior is clearly different from sand.

CAPWAP analyses of the conductor piles, at their final penetration of 79 m, produced a similar observation as the foundation piles, with unit skin friction within the same gravel layer being lower than that obtained from the CPT methods for the conductor pile. The unit skin friction curves obtained from CAPWAP analyses and CPT Methods are presented on Fig. 7.

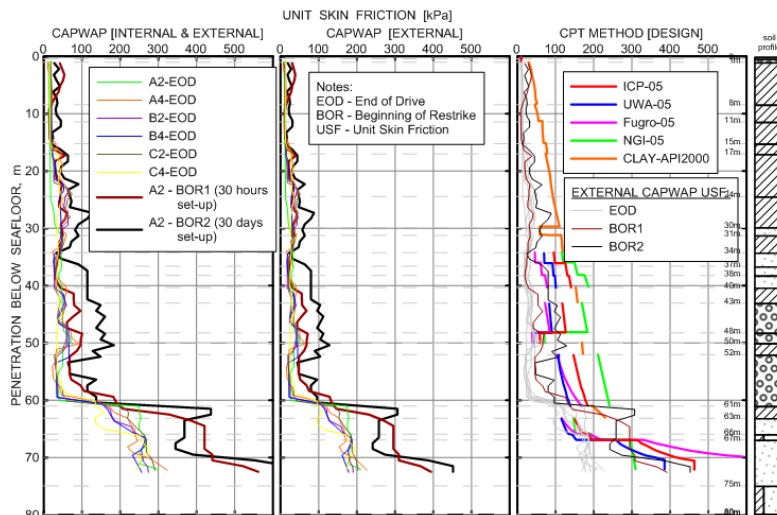


Fig. 6: Comparison of USF from CAPWAP and CPT Methods for Foundation Piles

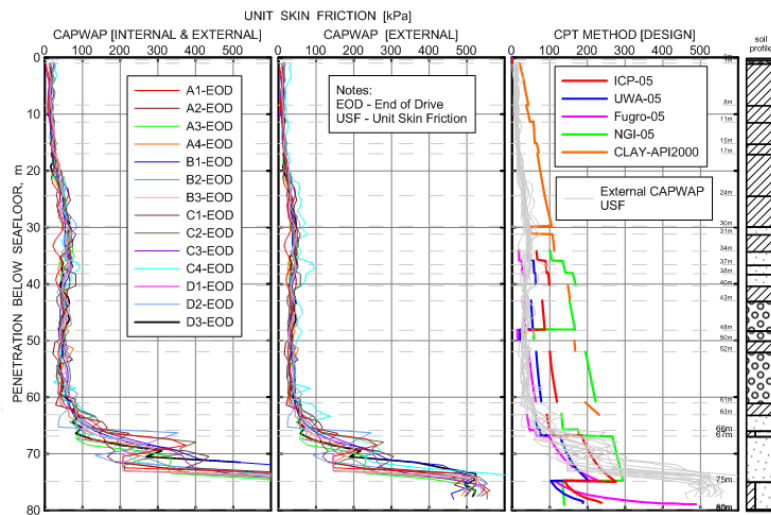


Fig. 7: Comparison of USF from CAPWAP and CPT Methods for Conductor Piles

Restrike Tests on Pile A2

Two restrike tests were carried on Pile A2 which was the first foundation pile driven to the target penetration of 72 m. Initially, only one restrike test was planned to be conducted after the installation of all the conductor piles. However, due to the anticipated delay of several weeks for the conductor installation, there was a concern that the MHU1700 hammer may not be able to fully mobilize the increased soil resistance due to set-up. Therefore, an advance restrike test was proposed and conducted after about 30 hours from the end of initial driving. The second restrike test was conducted with the same hammer after nearly 30 days.

CAPWAP analyses were carried out for the end of initial driving (EOD) and the two restrike tests (BOR1 and BOR2). The total skin friction from the CAPWAP analyses for EOD, BOR1 and BOR2 are 21.8 MN, 35.7 MN and 44.3 MN, respectively. The corresponding set-up factors are 1.64 after 30 hours and 2.0 after 30 days.

Friction Fatigue in Gravel Material

According to Randolph et al (2011) and Schneider et al (2010), as driving progresses, the process of reduction in shaft resistance with increasing distance behind the pile tip is caused by the reduction in horizontal stress acting on the pile shaft and this phenomenon is described as friction fatigue.

For the purpose of assessing friction fatigue and the associated localized degradation of horizontal stress as the pile penetrated deeper, additional CAPWAP analyses were carried out at a shallower depth with particular emphasis on the gravel layer between 52 and 61 m.

In order to minimize the influence of toe resistance on the shaft resistance within the gravel, these additional analyses were carried out at a depth of 59 m for all the foundation piles. These results were then compared with the previous CAPWAP analyses at the target depth of 72.5 m to evaluate friction fatigue.

For illustration, the unit shaft resistances at about 55 m within the gravel layer from the CAPWAP results at the two analyses depths (59 m and 72 m), were selected for friction fatigue assessment. The change in the unit shaft resistance and the corresponding blow cycles (additional hammer blows from 59 to 72.5m) are presented in Table 1.

Table 1: Unit Shaft Resistance at 55 m from CAPWAP results at depths 59 m and 72 m

Pile	CAPWAP Analyses [m]	CAPWAP Blow No	Unit Shaft Resistance [kPa]	Reduction in Unit Shaft Resistance		Hammer Blow Nos
				[kPa]	[%]	
A2	59	1601	92	57	62	943
	72.5	2544	35			
A4	59	1421	93	69	74	965
	72.5	2386	24			
B2	59	1604	84	53	63	973
	72.5	2577	31			
B4	59	1455	96	64	66	1009
	72.5	2464	32			
C2	59	1396	116	84	72	1024
	72.5	2420	32			
C4	59	1065	59	24	41	968
	72.5	2033	35			
Average	59		90	58	63	980
	72.5		32			

In general, the data for all the piles, with the exception of Pile C4, indicates a reduction of unit shaft resistance of about 65 percent after an average of nearly 1,000 hammer blow cycles for the driving between 59 and 72.5 m. The effect of friction fatigue is quite apparent from the unit skin friction profiles presented on Figs. 6 and 7 and is more obvious for the conductor piles on Fig. 7.

Conductor Drill-Out

After Conductor Pile A1 was installed to about 50.7 m penetration (A1C3 section), the soil column inside was drilled out to 49 m (slightly above the conductor tip) to mitigate potential refusal when driving through the deeper gravel layers. However, the soil resistance at the restart of the next section, A1C4, was significantly lower-than-expected even after 49 hours of set up. Furthermore, driving through the gravel layer between 52 and 61 m was also relatively easy. Based on these observations, an on-site decision was made to not proceed with the planned drill-out for the next section (A1C5).



[i] Pile top drilling rig on Conductor Pile A1



[ii] Drill bit

Fig. 8: Pile top drilling on Conductor Pile A1 at depth 50.7 m and drilling equipment

CAPWAP analyses were performed for one blow near the End of Drive (EOD) of A1C3 (at about 49 m, just before the PDA sensors were removed) and two blows at the Beginning of Drive (BOD) of A1C4 (blow nos. 6 and 21). The plots as presented on Figs. 9 and 10 were used to evaluate the **external** soil resistance set-up of this drilled-out conductor as well as pile tip response due to a short, 2-m soil plug.

Of the three CAPWAPS shown on Fig. 9, the BOD Blow 6 shows a significantly higher soil resistance near the pile tip starting from about 46 m, suggesting that it may also be plugged. After just a few blows, BOD Blow 21 shows a sharp drop in unit skin friction or shaft resistance below 46 m and, as seen on the third plot of Fig. 9, the pile is likely unplugged from the pile tip response, which is also similar to first plot of the EOD blow.

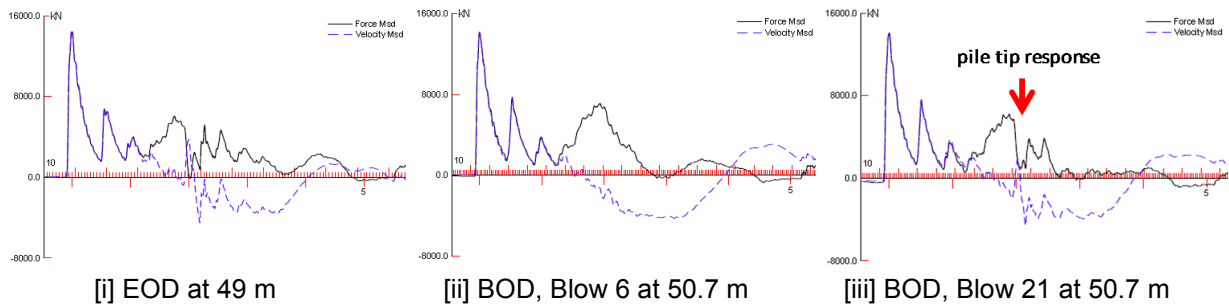


Fig. 9: Force Velocity Curves at EOD and BOD after drill-out to 49 m

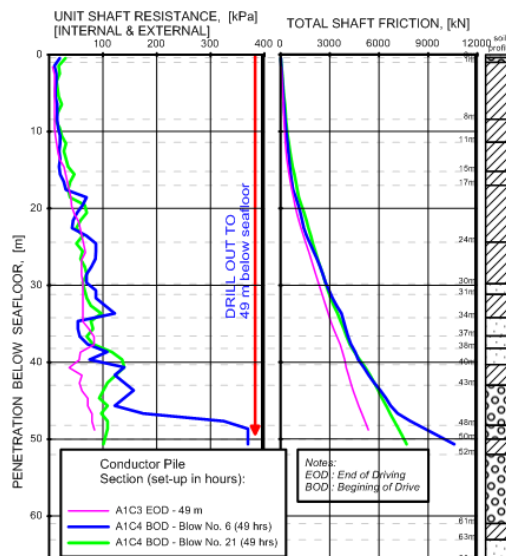


Fig. 10: Unit Shaft Resistance and Total Shaft Resistance at 50.7 m before and after drill-out

CONCLUSIONS

This installation confirmed the findings of previous studies about gravel layers that

- (i) there are difficulties in characterizing the in-situ relative densities with CPT,
- (ii) toe resistance in gravel is lower than expected for dense sand,
- (iii) shaft resistance during continuous driving as well as after delays is also significantly lower than expected, and
- (iv) the current design values for axial capacity may be unconservative.

In addition, pile instrumentation and monitoring on this project proved to be very useful in:

- (a) optimizing the installation (by comparing measured soil resistance during driving in real time against prediction; increasing confidence and thereby reduced the use of drill-drive with good assurance on pile design and installation),
- (b) optimizing hammer performance (by minimizing energy losses due to non-uniform impact),
- (b) improving the pile fatigue life (by optimizing the hammer energy and driving stress,
- (c) minimizing the risk of pile tip damage (by monitoring pile tip response during driving),
- (e) using conductor monitoring data to better understand soil plug resistance in the different layers, and
- (f) verifying axial capacity (in the short and long term through re-strike tests).

More research needs to be carried out to incorporate friction fatigue into the current methodologies for the development of soil resistance in gravels. This will help in optimizing the pile size, stick-up length and wall thickness as well as sizing of hammers for efficient pile installation while also minimizing pile damage due to fatigue or tip buckling.

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