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CASE REPORT

Experiences in Drivability Analysis, Testing of Open-Ended Steel Pipe Piles and Drilled Shafts at Dahej LNG Project, India

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Abstract APDPPL has constructed a coal terminal at Dahej, India. The 670-m off-shore jetty head is connected to land with 1170-m pile-supported trestle followed by 1200-m rubble mounted bund. The original plan was to construct the jetty head and approach trestle with 1200-mm concrete bored piles. However, due to site constraints, high tidal variation and to ensure timely completion, it was decided to change the jetty head piles to steel pipe piles at the jobsite. The pile diameter selected was 1422 mm and design done as per API RP2A method. The thickness of the pipe varied from 22 to 38 mm. The piles were generally planned for up to 30 m penetration into seabed and the maximum working load varied from 3228 to 5223 kN. It was required to select a hammer to drive the piles to the required depth. Options were generally limited to Delmag D100-13 or D150-42 hammer due to commercial considerations. A GRLWEAP was performed to evaluate the suitability of the hammer for driving the pile. Both the drivability and bearing graph analysis were done, and also checks were done using soil static analysis. Based on the finding, the Delmag D100-13 hammer was selected and the piles were successfully driven to the required penetration. HSDPTs were performed at EOID with 2 restrikes to confirm the long-term pile capacities due to set-up. The results gave enough confidence about the pile capacity and hammer capability to drive all the piles. Static load testing was eliminated at the project site. 10% of the steel piles, 5% bored piles and 20% integrity tests were done at the jobsite. The entire job was successfully completed, and the berths are in operation currently. The case study is an excellent example of using combination of GRLWEAP, static analysis and HSDPT towards successful completion of the entire job.

Keywords Drivability · Steel pipe pile · HSDPT · GRLWEAP · Pile integrity · Skin friction

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Introduction

Adani Petronet (Dahej) Port Private Limited (APDPPL) has constructed a coal terminal at Dahej on Western Coast of India. The port is located at the Dahej headland, on the immediate North of confluence of River Narmada and Gulf of Khambhat. Three other jetties, i.e. Petronet LNG (PLL), GCPTCL and Birla Copper are also located going from South to North. The APDPPL jetty stands in between the PLL and GCPTCL jetties as shown in Fig. 1.

The 670-m off-shore jetty head (two berths) is connected to land with 1170-m pile-supported trestle followed by 1200-m rubble mounted bund connecting landfall (refer to Fig. 1). Refer to Fig. 1 for the sketch of the terminal. The tidal variation is about 10 m, and the sea remains fairly rough throughout the year with the jetty operations closed for the period from May to September due to monsoon.

The original plan was to construct the jetty head and approach trestle with 1200-mm-diameter RCC bored piles. The approach trestle was about 1170 m long was first constructed with 200 bored piles.

However, during construction, due to site constraints, high tidal variation and to ensure timely completion, it was decided to change the jetty head piles to steel pipe piles at the jobsite. The pile diameter selected was 1422 mm and

Fig. 1 Location of APDPPL Jetty

design was carried out as per API RP2A WSD method [1]. The thickness of the pipe pile along the length varied from 22 to 38 mm. The piles were originally planned for 30 m penetration into seabed, and the maximum working load varied from 3228 to 5223 kN requiring a maximum ultimate pile resistance of approximately 14,830 kN. Once the preliminary pile selection was done by the owner based on several design, logistical and commercial requirements, the detailed geotechnical design is beyond the scope of this paper and hence not included.

It is accepted that the most reliable method of establishing the actual pile resistance for a particular site is to conduct actual pile load test, but this method holds certain limitation as it is not possible for all types of the piles due to economic reasons. Before a load test is done, the , usual practice is to predict the load-carrying capacity of a driven pile and/or determine the required hammer weight and drop height is by using pile driving formulae. These are based on rigid-body mechanics and make use of parameters according to experience in a particular soil type, pile type or driven depth. However, due to many erroneous assumptions made in pile driving formula-based predictions, professionals worldwide use pile drivability analysis modelling 1-D wave propagation in pile medium as proposed by Smith (1960). Such a method is based on a lumped mass discretization of the pile with simplified rheological models of pile-soil interaction. The GRLWEAP program that is based on such wave theory was used to study hammer, pile, soil parameters during the initial stages of the project.

Since the steel pipe pile construction is not conventional in India, there were limitations with the available equipment and rigs. The primary challenge was to identify and mobilize necessary hammer which can drive the specified pipe pile to its designed elevations. It was required to select a hammer to drive the piles to the required depth. Due to commercial considerations, the options were generally limited to a Delmag D100-13 or a Delmag D150-42 hammer (refer https://www.delmag.com/diesel-pile-hammers.html). However, before mobilizing any of the hammer out of the available options, it was essential to confirm few key aspects associated with it, i.e. suitability to drive the piles, checking adequacy of design depth, compute the long-term pile resistance and also study plugging effects. The present paper describes key highlights of the various GRLWEAP analyses carried out, procedures conducted to select the hammer, actual driving records and long-term pile capacity estimation based on obtained data.

Steel Pipe Pile Details

The piles were uniform open-ended steel pipes of 58 m length, 1422.4 mm external diameter and with wall thickness varying from 22 to 38 mm. For the purpose of GRLWEAP, a pile with 32 mm thickness up to 22.8 m and then with 30 mm wall thickness from 22.8 to 35.1 m depth below the top of the pile was considered. The pile material was API 5L, Grade B having 241 MPa yield strength, and for the purpose of analysis, it was considered that the piles will be driven in one piece and vertically. The allowable driving stress was 0.9 times the yield strength as per project

Table 1 Subsurface details and setup factor

Sr. no.	Elevation (m)	Depth into seabed (m)	Soil type	SPT N values	Setup factor
1.	0	–	Cut-off level	–	–
2.	−28.9	–	Below cut-off and water	–	–
3.	−30.4	0–1.5	Dark grey fine to medium sand	20	1.2
4.	−31.9	1.5–3.0	Very dense dark grey fine to medium sand	40	1.2
5.	−36.4	3.0–7.5	Medium dense to dense dark grey fine to medium sand	40	1.2
6.	−40.9	7.5–12.0	Stiff to very stiff dark grey clay	12	3.0
7.	−43.9	12.0–15.0	Medium dense to dense dark grey silty fine to medium sand	40	1.2
8.	−57.4	15–28.5	Very dense dark grey fine to medium sand	60	1.2
9.	<− 57.4	Up to 35 m	Hard dark grey clay	32	3.0

specifications. Total 350 steel piles were driven at the jobsite.

Geotechnical Conditions/Soil Details

Sub-soil conditions were uniform r at site with respect to seabed level. Total 16 boreholes were drilled to assess the subsurface conditions. Although the soil type is briefly described in Table 1 for one representative borelog along with SPT N values, the sub-soil in general consists of medium dense to very dense dark grey fine to medium sand having SPT varying from 10 to refusal with increasing depth. The bathymetry of site indicates a gently sloping intertidal area running up to about 1700 m from the coastline. From there onwards, the seabed depth increases rather steeply approximately in a slope of 1 in 20 and reaching a depth of −20 m CD.

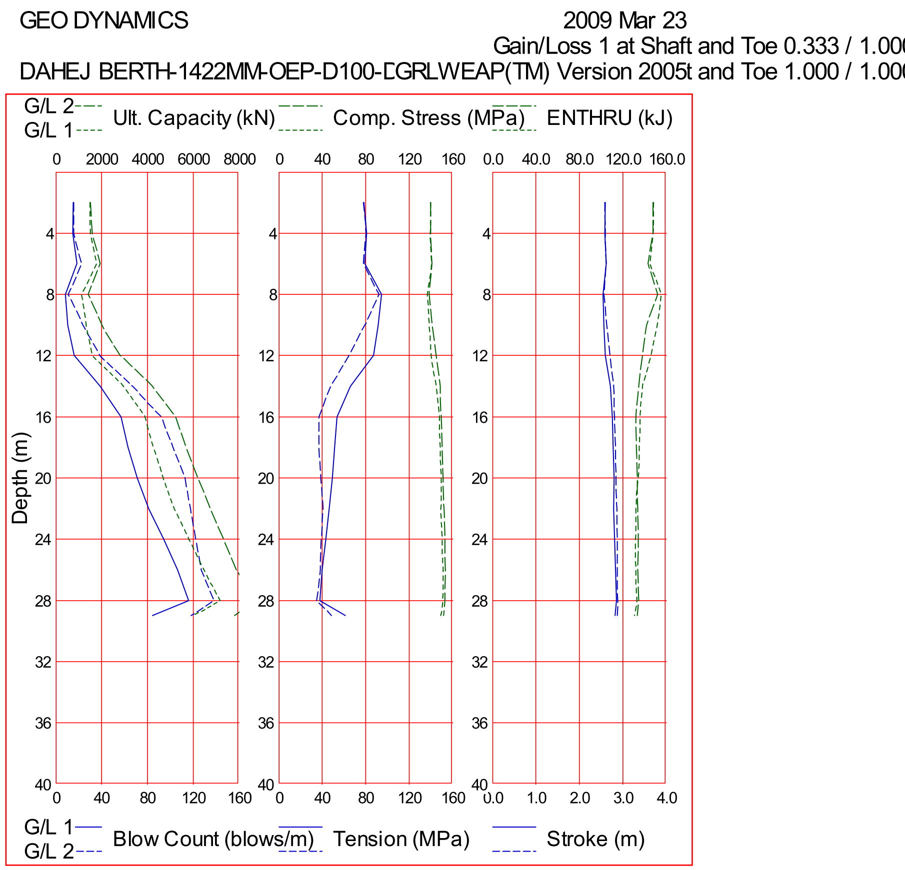
Table 2 Numerical driveability results for Delmag D100-13 hammer

Depth (m)	Ultimate capacity (kN)	Friction (kN)	End bearing (kN)	Blow count blows/m	Comp. stress (MPa)	Tension stress (MPa)	Stroke (m)	ENTHRU (kJ)
DAHEJ BERTH-1422MM-OEP-D100-DRV GRLWEAP(TM) Version 2005								
Gain/Loss 1 at Shaft and Toe 0.333/1.000								
2.0	1482.1	84.3	1397.8	15.3	139.580	−78.192	2.60	148.3
4.0	1506.3	388.1	1118.2	14.8	139.343	−81.031	2.59	147.7
6.0	1802.3	684.1	1118.2	18.6	140.620	−79.000	2.62	144.8
8.0	1122.6	1032.1	90.6	8.2	136.851	−94.689	2.54	155.7
10.0	1328.3	1237.7	90.6	10.5	138.466	−91.504	2.57	151.8
12.0	1585.0	1494.4	90.6	15.8	140.186	−87.210	2.60	146.2
14.0	2951.7	1833.4	1118.2	38.8	145.046	−65.934	2.71	138.0
16.0	3889.1	2211.8	1677.3	56.9	147.664	−53.616	2.76	135.9
18.0	4254.1	2576.7	1677.3	62.9	148.480	−51.412	2.78	135.2
20.0	4694.1	3016.8	1677.3	71.0	149.409	−49.128	2.80	134.3
22.0	5179.4	3502.0	1677.3	81.4	149.199	−46.228	2.79	131.9
24.0	5807.0	4129.7	1677.3	94.2	150.481	−43.322	2.81	131.6
26.0	6480.4	4803.1	1677.3	106.5	151.268	−39.755	2.83	132.0
28.0	7183.9	5506.6	1677.3	115.9	150.981	−37.939	2.85	132.7
29.0	5994.7	5753.2	241.5	84.5	149.311	−61.382	2.82	130.9
Gain/Loss 2 at Shaft and Toe 1.000/1.000								
2.0	1498.9	101.2	1397.8	15.6	139.567	−78.001	2.59	148.0
4.0	1583.9	465.7	1118.2	15.7	139.929	−80.566	2.60	147.9
6.0	1939.2	820.9	1118.2	22.5	140.851	−77.742	2.62	143.1
8.0	1407.5	1316.9	90.6	10.7	138.431	−92.287	2.57	151.9
10.0	2025.2	1934.6	90.6	23.6	141.569	−78.992	2.63	141.9
12.0	2796.0	2705.4	90.6	38.4	144.833	−64.767	2.70	138.1
14.0	4230.5	3112.3	1118.2	67.0	148.660	−47.625	2.79	134.7
16.0	5243.7	3566.4	1677.3	92.0	149.727	−36.980	2.81	132.0
18.0	5681.7	4004.3	1677.3	102.1	150.594	−36.816	2.83	132.6
20.0	6209.8	4532.4	1677.3	112.9	151.340	−38.765	2.84	133.4
22.0	6753.0	5075.6	1677.3	117.5	152.157	−40.916	2.86	133.9
24.0	7320.9	5643.5	1677.3	122.1	152.916	−39.185	2.87	134.1
26.0	7897.7	6220.3	1677.3	127.1	153.220	−38.104	2.87	133.8
28.0	8741.9	7064.6	1677.3	137.9	152.785	−34.848	2.89	134.5
29.0	7803.3	7561.7	241.5	118.1	151.668	−48.633	2.87	133.2

Gain/Loss 1: total continuous driving time 36.00 minutes; total number of Blows 1406

Gain/Loss 2: total continuous driving time 52.00 minutes; total number of blows 1999

Fig. 2 Driveability plots for Delmag D100-13 hammer



GRLWEAP Considerations

As described above, out of the several hammer options available, it was decided to select either a Delmag D100-13 or a Delmag D150-42 hammer due to commercial considerations. The Delmag D150-42 appeared to be a more suitable option based on preliminary studies and based on WEAP calculations provided by the distributor of the hammer. The analysis by the distributor showed a blow count of 500 blows/m with a Delmag D100 hammer which obviously indicated hard driving and a possibility that the hammer is not suitable and the Delmag D150-42 which shows a blow count of 266 blows/m for the same capacity should be considered.

It was the decision of the owner to have a review WEAP analysis based on the preliminary findings of the distributor of the hammer. Hence it was decided to evaluate all the hammer, pile, soil parameters in detail before deciding on hammer selection including both drivability and bearing graph analysis. Thus both the hammers were to be evaluated before arriving at a final decision by conducting a revised wave equation analysis.

The GRLWEAP input includes not only pile and hammer details but also a soil model and broad set-up of the soil. Based on the soil data available and experience of soil marine properties, the set-up factor considered was 1.2 for dark grey fine to medium sand and 3.0 for stiff to hard dark grey clay. These factors could however be modified once actual field data are available. The setup factors used during GRLWEAP analysis are also defined. The WEAP typically assigns the highest factor (most sensitive layer (i.e. clay in current situation) for strength reduction during driving). For less sensitive layers (sand in current situation), the reduction of resistance would be proportionate to the ratio of set-up factors. Set-up is time dependent increase in pile capacity. Set-up is higher in fine grained soils, i.e. silts and clays and lower for coarse grained soils such as sands.

In order to model the SRD, i.e. the static resistance to driving, a Gain/Loss Factor of 0.33 (full loss of resistance) and 1.0 (no loss of shaft resistance, i.e. full long-term resistance or restrike situation) were considered. As per WEAP guidelines, Gain/Loss factor shall be inverse of the highest set-up factor. It was also considered that there will be no change in end bearing with time, and hence, analysis was done with a toe Gain/Loss Factor of 1.0 for both analyses.

Since the pile is of larger diameter of 1422 mm, it was assumed that pile will not plug and end bearing will only act against the steel annulus of the pile bottom. Internal

Table 3 Numerical driveability results for Delmag D150-42 hammer

Depth (m)	Ultimate capacity (kN)	Friction (kN)	End bearing (kN)	Blow count blows/m	Comp. stress (MPa)	Tension stress (MPa)	Stroke (m)	ENTHRU (kJ)
DAHEJ BERTH-1422MM-OEP-D150-DRV GRLWEAP(TM) Version 2005								
Gain/Loss 1 at Shaft and Toe 0.333/1.000								
2.0	1482.1	84.3	1397.8	9.4	147.499	−76.532	2.33	226.3
4.0	1506.3	388.1	1118.2	8.9	147.531	−79.708	2.32	227.2
6.0	1802.3	684.1	1118.2	11.4	149.417	−78.804	2.36	219.7
8.0	1122.6	1032.1	90.6	5.4	139.141	−89.914	2.23	241.9
10.0	1328.3	1237.7	90.6	6.7	144.446	−88.914	2.29	239.1
12.0	1585.0	1494.4	90.6	9.0	148.189	−86.010	2.33	225.8
14.0	2951.7	1833.4	1118.2	24.1	156.285	−67.038	2.47	201.1
16.0	3889.1	2211.8	1677.3	34.0	160.077	−54.489	2.54	196.8
18.0	4254.1	2576.7	1677.3	37.8	161.453	−52.079	2.56	196.1
20.0	4694.1	3016.8	1677.3	43.0	162.832	−49.580	2.59	194.9
22.0	5179.4	3502.0	1677.3	49.3	164.350	−47.348	2.61	193.8
24.0	5807.0	4129.7	1677.3	57.5	166.222	−43.871	2.64	192.2
26.0	6480.4	4803.1	1677.3	65.7	167.534	−39.968	2.67	190.1
28.0	7183.9	5506.6	1677.3	76.2	167.769	−36.950	2.70	188.2
29.0	5994.7	5753.2	241.5	53.8	164.908	−58.868	2.65	190.2
Gain/Loss 2 at Shaft and Toe 1.000/1.000								
2.0	1498.9	101.2	1397.8	9.5	147.532	−76.433	2.33	225.7
4.0	1583.9	465.7	1118.2	9.5	147.875	−79.418	2.33	224.4
6.0	1939.2	820.9	1118.2	12.5	150.301	−77.952	2.37	216.4
8.0	1407.5	1316.9	90.6	6.7	145.030	−90.216	2.29	238.6
10.0	2025.2	1934.6	90.6	13.7	151.538	−79.509	2.39	214.7
12.0	2796.0	2705.4	90.6	24.0	156.041	−65.784	2.47	201.3
14.0	4230.5	3112.3	1118.2	40.6	162.005	−48.704	2.58	195.5
16.0	5243.7	3566.4	1677.3	56.1	165.128	−36.764	2.64	192.5
18.0	5681.7	4004.3	1677.3	61.8	166.348	−34.834	2.66	190.5
20.0	6209.8	4532.4	1677.3	69.2	167.625	−34.856	2.68	188.6
22.0	6753.0	5075.6	1677.3	77.7	167.791	−37.304	2.68	186.6
24.0	7320.9	5643.5	1677.3	84.2	169.190	−38.654	2.69	187.4
26.0	7897.7	6220.3	1677.3	90.6	169.998	−37.697	2.71	188.1
28.0	8741.9	7064.6	1677.3	99.7	170.079	−32.109	2.74	189.4
29.0	7803.3	7561.7	241.5	84.1	168.025	−44.382	2.70	186.0

Gain/Loss 1: total continuous driving time 21.00 minutes; total number of blows 865

Gain/Loss 2: total continuous driving time 33.00 minutes; total number of blows 1305

friction was modelled as per the GRLWEAP [2] manual recommendations. The plugging phenomenon was evaluated in detail by studying available literature [3], past experience [4] and the manual which states that piles above 900 mm are unlikely to plug. The soil model input inside the programme also requires input of damping and quake values. Any error in selection of these values may have a considerable impact on the final conclusions. Thus, a shaft damping factor of 0.226 s/m and a toe damping factor of 0.49 s/m were considered based on the soil type, GRLWEAP recommendations and some conservatism. Shaft quakes and toe quakes were set to 2.54 mm which are standard assumptions for open ended pipe piles. The experience from the original developer of the program was also sought as the GRLWEAP program does not provide direct inputs for modelling plugging and selection of several parameters can be subjective. In general, it is always difficult to determine if pile will be plugged in real scenario unless it is verified by physical measurement.

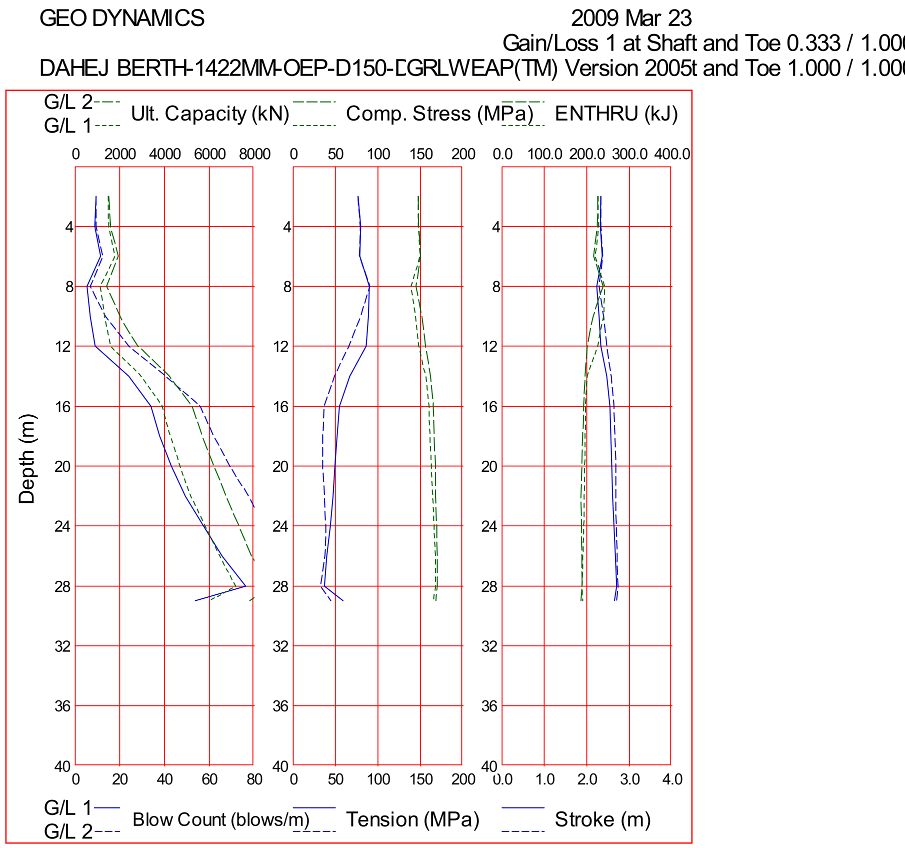


Fig. 3 Driveability plots for Delmag D150-42 hammer

The GRLWEAP program allows both the drivability analysis and a bearing graph output. The drivability analysis provides information about the possible blow count for a certain capacity and depth of the pile. It also provides information on likely stresses inside the pile at the time of driving. The bearing graph analysis provides information on the capability of the hammer to drive the pile for a certain load which was 14,830 kN in this case. Both the analyses were conducted to assess various possibilities that may arise due to selection of a particular hammer. The results are presented below:

Drivability Analysis Results

The results indicate that driving the pile up to 29 m depth below mudline (i.e. elevation of—57.9 m) for an ultimate capacity of 6000 kN is easy, considering the friction losses of 67% in the clay and 17% in the sands. The blow count for a capacity of 6000 kN was calculated to be 84 blows/m or 21 blows/0.25 m. If prolonged driving interruptions occur, then the blow count at 29 m depth is expected to reach 120 blows/m (30 blows/0.25 m). Refer to Table 2 and Fig. 2 for details.

Obviously driving the pile to same depth with the Delmag D150-42 hammer was even easier. The blow count was 54 blows/m, and if prolonged driving interruptions occur, then the blow count is expected to reach 84 blows/m for driving the pile at the same depth. The maximum compression stress with the D100-13 hammer was 152 MPa, whereas it was 170 MPa with the Delmag D150-42 hammer. In both the cases, the stresses were very much within the allowable limit of 217 MPa (i.e. 0.9 times yield strength). The hammers were considered in a normal state of maintenance. Refer to Table 3 and Fig. 3 for the tabular and graphical output of GRLWEAP. Thus, the pile can be easily driven to the estimated depth even with a lower fuel setting of the Delmag D100-13 hammer considering plugging will not occur.

However, static analysis data were not yet available, and the maximum expected ultimate load was 14,830 kN. Hence it was decided to conduct a bearing graph analysis for both the hammers to check if the pile can be driven to the required ultimate capacity.

Bearing Graph Analysis Results

The bearing graph for the Delmag D100-13 showed that it should be possible to use the hammer to measure capacity up to 16,000 kN (driving up to of 350 blows/m) even if the pile was to reach refusal due to plugging. Driving may get

Table 4 Bearing graph table for D100 & D150 hammers

Ultimate capacity (kN)	Maximum compression stress (MPa)	Maximum tension stress (MPa)	Blow count blows/m	Stroke (m)	Energy (kN-m)
DAHEJ BERTH-1422MM-OEP-D100-bg GRLWEAP (TM) Version 2005					
2000.0	141.70	90.81	24.5	2.64	140.48
4000.0	147.39	75.96	52.5	2.78	135.27
6000.0	149.60	60.45	91.4	2.83	131.12
8000.0	151.04	46.17	124.1	2.88	133.31
10,000.0	152.60	33.48	155.5	2.92	135.06
12,000.0	155.21	23.65	196.2	2.98	138.20
14,830.0	157.72	26.88	290.2	3.03	141.10
16,000.0	158.40	29.09	351.9	3.05	141.70
18,000.0	158.91	34.91	510.9	3.05	141.88
20,000.0	158.97	40.64	745.9	3.04	141.35
DAHEJ BERTH-1422MM-OEP-D150-bg					
2000.0	148.23	87.61	11.7	2.38	214.01
4000.0	157.16	70.55	31.5	2.55	194.68
6000.0	162.96	54.24	58.4	2.67	187.56
8000.0	165.15	39.52	89.8	2.72	184.71
10,000.0	167.38	28.32	112.2	2.77	187.99
12,000.0	170.18	30.55	139.5	2.82	191.80
14,830.0	173.88	35.67	196.4	2.90	197.31
16,000.0	174.87	37.06	232.7	2.92	198.56
18,000.0	175.99	39.94	328.8	2.94	199.78
20,000.0	176.96	43.93	518.7	2.95	200.54
10,000.0	167.38	28.32	112.2	2.77	187.99

harder beyond this capacity. At 14,830 kN which is the required ultimate capacity, the blow count is reasonable at 300 blows/m (75 blows/0.25 m). The maximum compressive stress in the pile is 158 MPa and the maximum tension stress is 90 MPa, respectively, and is within the limits for the grade of steel.

The results were obviously more generous for the Delmag D150-42 hammer and showed that it should be possible to use the hammer to measure capacity up to 18,000 kN (driving up to of 330 blows/m) even if the pile were to reach refusal due to plugging. Driving may get harder beyond this capacity. At 14,830 kN which is the required ultimate capacity, the blow count is reasonable at 200 blows/m (50 blows/0.25 m). Refer to Table 4 and Fig. 4 for the numerical and graphical output from GRLWEAP for both the hammers.

The bearing graph analysis of the reseller showed a blow count of 500 blows/m with a Delmag D100 hammer which obviously indicated hard driving and a possibility that the hammer is not suitable and the Delmag D150-42 which shows a blow count of 266 blows/m for the same capacity should be considered.

Static Analysis Considerations

The initial WEAP was based on the soil input as per the internal program of GRLWEAP. It under-predicted the required ultimate test load of 14,830 kN likely to be encountered for a few piles. Hence some concerns still remained even after the original drivability and bearing graph analysis was available that whether the hammer can still be driven to the required load and depth. A few weeks later once the static analysis data were available in terms of friction and end bearing values at every 2 m, it was decided to conduct additional drivability analysis for further verification and confirmation that the Delmag D100-13 is yet suitable to drive the pile.

The drivability and bearing graph analysis for the D100-13 hammer with static analysis input showed that the pile is capable of being driven to 29 m with a blow count of 126 blows/m. However, if frequent interruptions were to occur or if long-term ultimate capacity was to be monitored, then driving would be hard and the blow count may reach 335 blows/m at 22 m akin to refusal. Refer to Table 5 for the GRLWEAP numerical output. Driving may

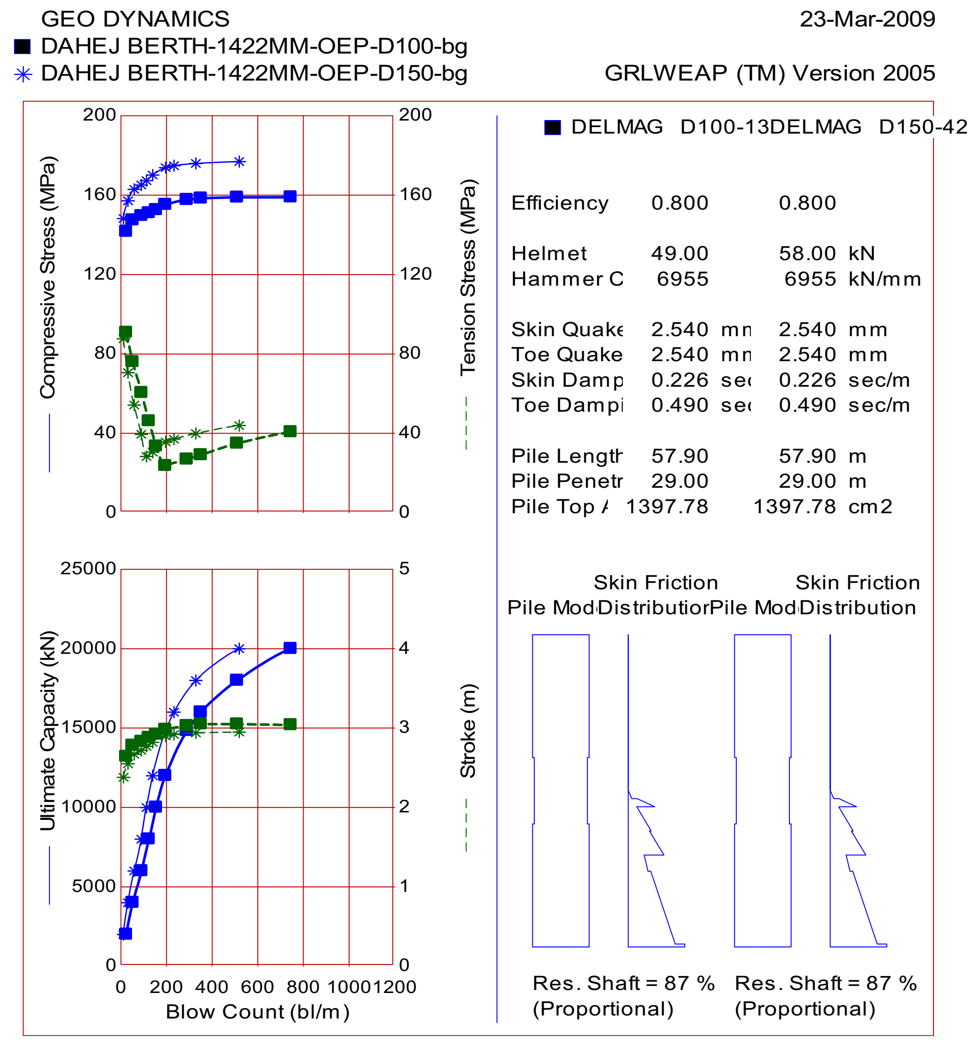


Fig. 4 Bearing Graph For D100 & D150 hammers

be hard beyond that up to 29 m. However, long-term capacity analysis was analysed only as an extreme conservative approach. Hence it was decided to ignore such a situation as it was very unlikely with the modern jack-up platforms available at site and back up hammer also planned.

Based on all the available analysis data, it was decided to ignore the reseller WEAP, and a decision was taken to procure the Delmag D100-13 hammer. It was planned to do the high strain dynamic tests on the first few piles at the job site to validate the GRLWEAP findings and pile capacity.

High Strain Dynamic Load Tests

Steel Pipe Piles

As a check on the drivability analysis, bearing graph analysis, project requirements and to understand pile behaviour, plugging effects, etc., it was planned that at least 10% of the piles shall be subjected to High Strain Dynamic tests [5, 6]. Similar studies were done worldwide successfully [7, 8]. Testing was done on more piles in the first few days of driving, and then, it was done intermittently based on stratum variation and critical locations. Pile No. G92 was one of the first few driven piles. The pile was 57 m long and was driven to 30.3 m into seabed. The actual working load was 4509 kN, and the test load was 9671 kN. The pile thickness varied from 28 to 32 mm, and the last 12 m pile length was 32 mm thick. The pile was driven successfully to the required depth using the Delmag D100-13 hammer. The blow count was 220 blows/m which was more than the anticipated blow count, yet the driving was comfortable and was at a lower fuel setting implying that a higher setting might have reduced the blow count. The pile capacity at end of drive was 7552 kN which was significantly more than the required working load, although less than the target ultimate compression load. Refer to CAPWAP analysis output in Fig. 5. However, it was expected that the pile capacity will be significantly higher

Table 5 Numerical driveability results using static analyses parameters

Depth (m)	Ultimate capacity (kN)	Friction (kN)	End bearing (kN)	Blow count blows/m	Comp. stress (MPa)	Tension stress (MPa)	Stroke (m)	ENTHRU (kJ)
DAHEJ BERTH-1422MM-OEP-D100-DRV GRLWEAP(TM) Version 2005								
Gain/Loss 1 at Shaft and Toe 0.333/1.000								
2.0	52.3	13.2	39.1	0.0	0.000	0.000	3.67	0.0
4.0	252.9	74.8	178.1	0.0	0.000	0.000	3.67	0.0
6.0	480.0	207.0	273.0	0.0	0.000	0.000	3.67	0.0
8.0	547.9	409.6	138.3	0.0	0.000	0.000	3.67	0.0
10.0	923.4	785.1	138.3	7.9	134.433	−88.907	2.52	159.3
12.0	1436.6	1298.3	138.3	15.0	139.699	−81.334	2.60	148.3
14.0	2748.7	1811.5	937.2	37.3	144.317	−65.008	2.69	138.2
16.0	3489.5	2381.9	1107.6	48.8	146.702	−58.994	2.74	136.8
18.0	4323.1	3045.1	1277.9	63.9	148.370	−51.791	2.78	134.7
20.0	5228.2	3779.8	1448.3	83.5	149.174	−44.251	2.80	131.8
22.0	6122.4	4586.1	1536.3	104.4	150.625	−39.738	2.83	132.5
24.0	6949.1	5412.7	1536.3	115.0	151.613	−41.996	2.85	133.3
26.0	7813.7	6277.3	1536.3	123.1	152.441	−43.032	2.86	133.9
28.0	8785.1	7248.7	1536.3	135.1	153.155	−42.076	2.88	134.6
29.0	8212.9	7773.0	440.0	125.7	152.723	−44.042	2.87	134.1
Gain/Loss 2 at Shaft and Toe 1.000/1.000								
2.0	78.7	39.6	39.1	0.0	0.000	0.000	3.67	0.0
4.0	402.8	224.7	178.1	0.0	0.000	0.000	3.67	0.0
6.0	894.6	621.5	273.0	7.0	133.361	−92.817	2.50	158.6
8.0	1368.3	1230.0	138.3	10.0	138.062	−93.941	2.56	154.6
10.0	2496.0	2357.7	138.3	32.8	143.461	−67.981	2.67	139.3
12.0	4037.2	3898.9	138.3	68.2	148.248	−40.553	2.78	135.7
14.0	6377.2	5440.1	937.2	123.0	151.166	−34.163	2.85	134.2
16.0	8260.4	7152.8	1107.6	146.8	153.049	−42.099	2.89	136.2
18.0	10,422.5	9144.6	1277.9	180.8	154.500	−43.033	2.93	138.1
20.0	12,799.2	11,350.9	1448.3	235.7	156.448	−41.060	2.97	140.0
22.0	15,308.3	13,772.0	1536.3	335.3	157.836	−43.606	3.00	141.7
24.0	17,790.8	16,254.5	1536.3	480.4	159.264	−44.659	3.03	143.0
26.0	20,387.2	18,850.9	1536.3	661.5	160.077	−49.076	3.04	143.3
28.0	23,304.3	21,768.0	1536.3	1106.1	161.017	−52.662	3.07	144.6
29.0	23,782.2	23,342.2	440.0	1408.7	160.875	−52.636	3.07	144.5

Gain/Loss 1: total continuous driving time 38.00 minutes; total number of blows 1462

Gain/Loss 2: total continuous driving time 185.00 minutes; total number of blows 6927

with a suitable wait period. This was also demonstrated during the GRLWEAP analysis by using suitable Gain/Loss factors. The compression stress in the pile was 154 MPa and the maximum tension stress was 25.7 MPa which was much below the permissible stresses for the grade of steel adopted at site. Thus the driving program and the hammer selection was deemed successful, and there was reasonable confidence to justify that the hammer is capable of driving all the balance steel pipe pile at various locations of the terminal.

A restrike test was possible and was conducted on this pile after a wait period of 49 days indicated a capacity of 13,309 kN with a blow count of 1000 blows/m which is significantly more than the required test load. Refer to Fig. 6 for the CAPWAP graphical output. The blow count implied that the pile had even more capacity that was not measured at the time of testing. The friction and end bearing values during end of drive and restrike are as given in Table 6. The set-up factor was 1.76 if the total increase in capacity with time is considered. There was not much change in end bearing with time although full end bearing

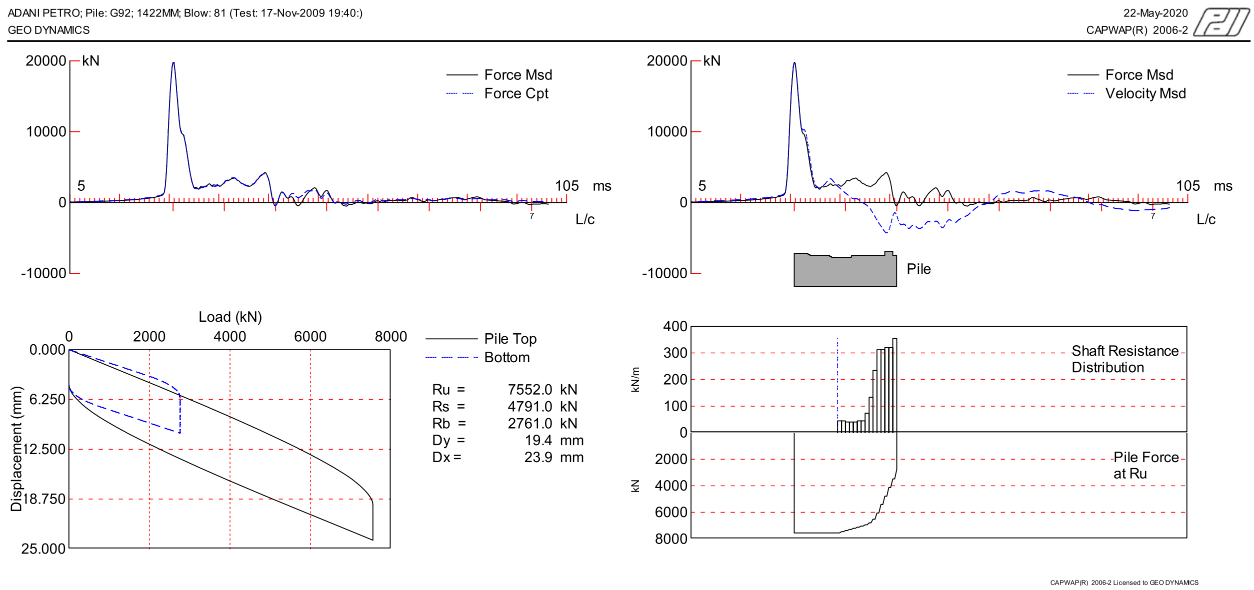


Fig. 5 HSDPT results—graphical output—EOID

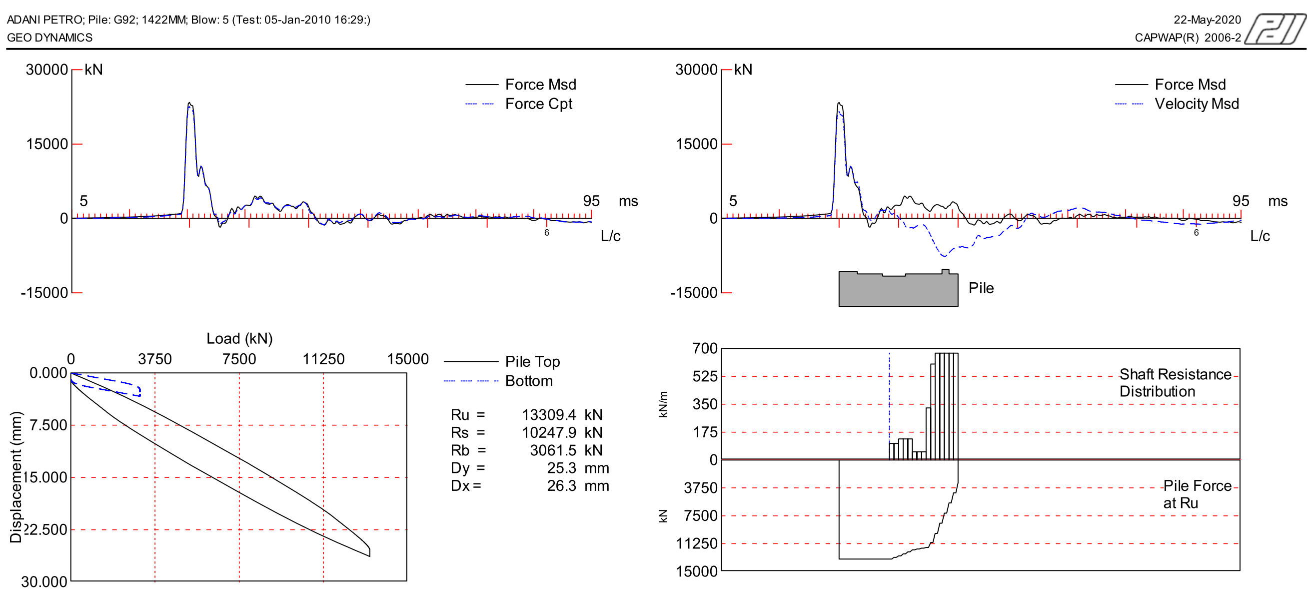


Fig. 6 HSDPT results—graphical output—restrike

Table 6 Summary of HSDPT results—EOID and restrike

Pile No. G92	EOID	Restrike	Setup Factor
Pile capacity (kN)	7552	13,309	1.76
Skin friction (kN)	4791	10,248	2.13
End bearing (kN)	2761	3061	-

was not mobilized during the restrike test. The set-up factor was at least 2.1 for the friction component based on CAPWAP. Thus the original assumptions about end bearing and gain/loss factors seem adequate. A total of 16 high strain tests were conducted for end of drive, and two restrike tests were also conducted to confirm the long term capacity.

Findings of Testing on Drilled Shafts

A total of 200 drilled shafts were installed for the approach trestle. The original diameter was 1 m; the pile depth was generally 42 m and penetration into seabed was approximately 35 m. Later due to engineering requirements,

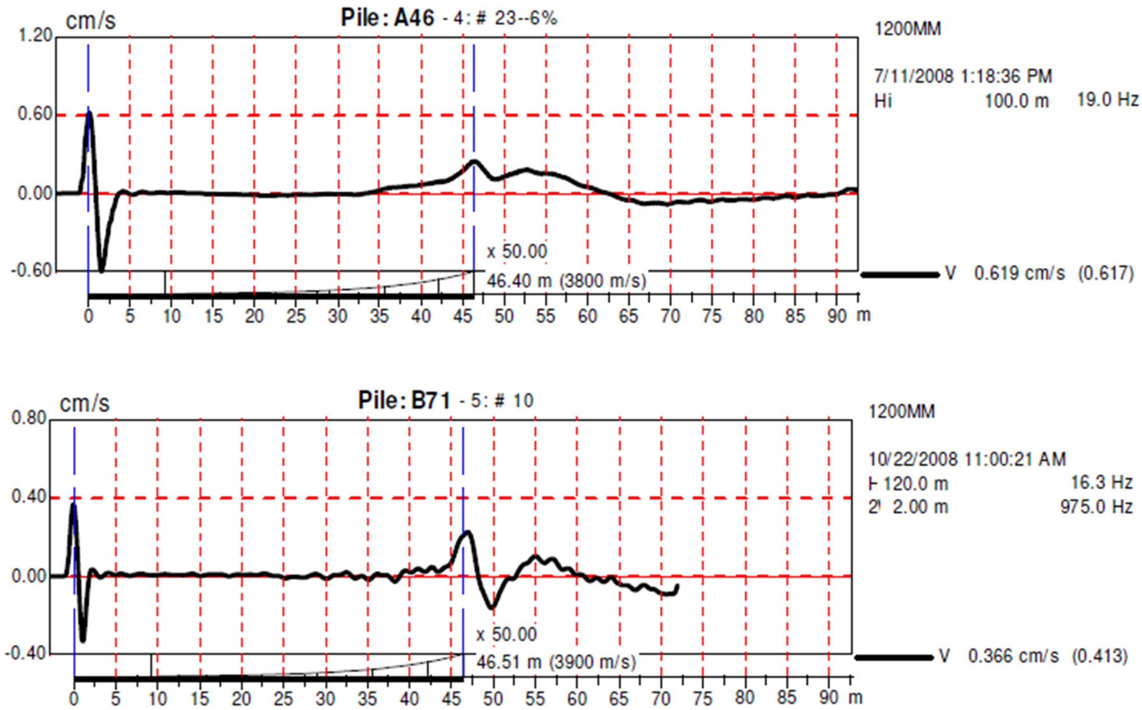


Fig. 7 PIT results

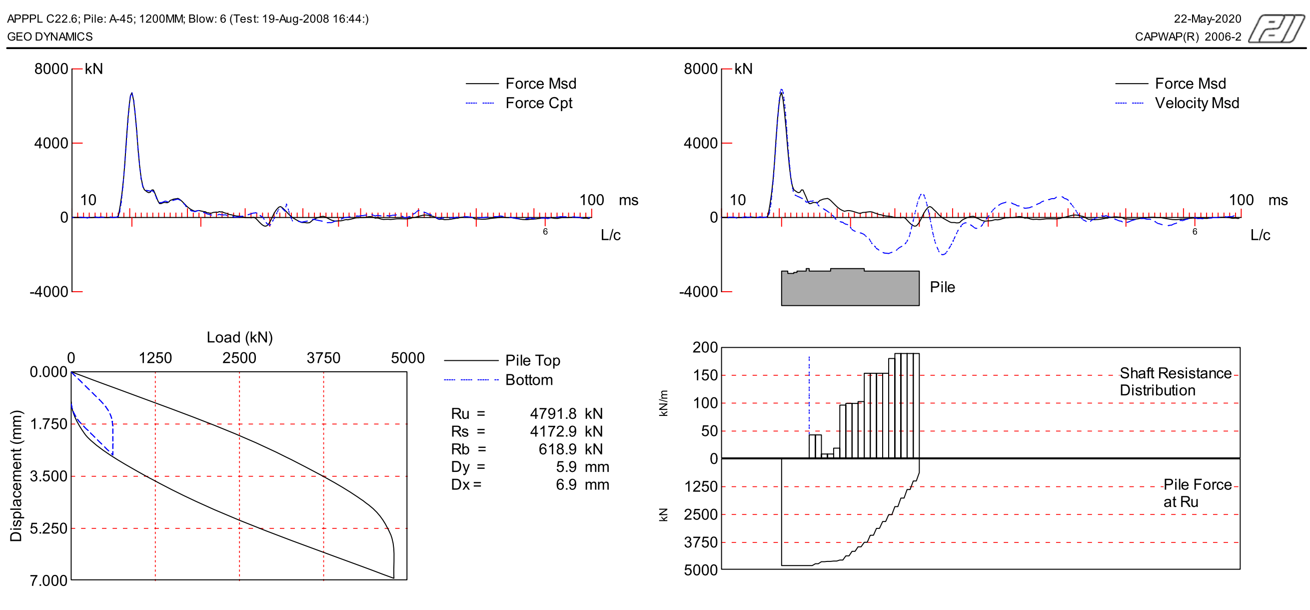


Fig. 8 HSDPT results—graphical output—drilled shaft

changes in loads, etc., the pile diameter was modified to 1200 mm and the pile depths extended to 48 m. The design load for the piles was 3000 kN, and the test load was 4500 kN. One initial pile load test was conducted on land before commencement of the job. However, it was planned to conduct only high strain dynamic routine load tests on the working piles as previous references were available for reliability of high strain tests on drilled shafts [10]. A total of 44 low strain pile integrity tests were conducted, and 10 high strain dynamic load tests were conducted for the entire approach trestle. 2% static load tests were replaced by 5% dynamic load tests to ensure more quality control. There was some apprehension [9] if reasonable data could be obtained for 40–48 m pile lengths with the PIT. Refer to Fig. 7 for the PIT test results for 2 piles. As evident, a clear response from the pile bottom seemed evident. Based on

Fig. 9 A view of the partially completed Jetty

similar response for other piles, no major integrity problems were reported and the piles were classified as acceptable.

High strain dynamic load tests on the piles would have required at least 100 kN hammer for such a deep pile. However, with the current site arrangements it was not possible to arrange a suitable crane to lift the heavy hammer, and eventually it was decided to test with a 70 kN hammer. Refer to Fig. 8 for the high strain dynamic test results on a typical pile. The test loads achieved were in the range of 3900 kN to 5000 kN with the limited hammer weight and drop height possible. Since no major settlement was noticed at these loads, the piles were deemed capable of taking the required load of 4500 kN in all the cases. A view of partially completed jetty is presented as Fig. 9.

Conclusions

1. GRLWEAP and HSDPT helped at every stage from selection of the hammer, deciding termination criterion to estimation of the long-term capacity. All the conditions like unplugged, plugged, static analysis data obtained from the client were considered during the GRLWEAP analysis. Both drivability and bearing graph analysis were conducted to evaluate hammer, pile and soil.
2. The judgment that the Delmag D100-13 hammer should be sufficient was proven by actual driving of piles at the jobsite. The selection of D100-13 instead of D150-42 hammer saved significant costs for the project.
3. It also proved that the use of Gain/Loss factors and other soil parameters were appropriate. The assumption of internal and external friction was proved reasonably correct. A set-up factor of at least 1.7 can be attributed to significant gain in internal and external friction for the steel pipe piles.
4. The pile capacity computed using GRLWEAP program was more than the static analysis done for friction and end bearing. The actual capacity and the friction computed by PDA/CAPWAP system was more than all the cases indicating conservative assumptions during the analysis stage.
5. Since the blow count was as high as 1000 blows/m during restrike dynamic testing, it was evident that the soil had substantially remoulded with time. The end bearing might be much higher than computed from HSDPT as it is likely that the pile may behave like a plugged pile under static loading. Driving stresses as measured during testing showed reasonable agreement with stresses predicted by GRLWEAP. The variation was 20–25% with the GRLWEAP predicting higher values as is the norm. They were also below the acceptable limits as anticipated by GRLWEAP and confirmed later by HSDPTs.
6. Modelling with GRLWEAP and subsequent testing and analysis using the PDA/CAPWAP system requires significant expertise and understanding of the hammer/pile/soil behaviour. Thus, selection of an experienced and independent analyst is a prerequisite before accepting the analysis. Any laxity on the part of clients/consultants in selecting of testing company may also result in serious errors and delays and additional costs.
7. Low strain integrity tests and HSDPT helped ascertain the integrity and capacity of pile shafts in marine conditions. The results also demonstrated that LSIT can be used for longer piles. HSDPT was done on 5% of the piles at significantly lower costs than static load tests and helped save both money and time for the project. It was apparent that the piles had much higher capacity than measured at site, but measurement was limited as heavier hammer could not be used due to site limitations. Since the set per blow was nominal, full end bearing was not mobilized.

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