Comparison of Pile Driving Equations

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ABSTRACT

In Sri Lanka, remote highway projects, driven piles are installed in large quantities mainly as a ground improvement where the soft soil thickness is very high and closer to the bridges to decrease the settlements. In building sector as well, the installation of the driven piles are very common to decrease the foundation construction time and has seen the installation of driven piles as the settlement reduction means. Recently, silent pile installation technology has increased and the Sri Lankan investors has invested large sum of money for the silent hammers.
Capacities of the piles can be estimated using the pile driving equations during installation of the piles. This is very convenient to determine the capacities of the piles without performing a pile load test. On the other hand, this can be reducing the site investigation requirements to a minimum. As the capacities of the piles are estimated during installation, it can take into account in-situ subsurface conditions. The rapidly varying ground conditions, especially in Sri Lanka, or any other location, can be captured by pile driving records. Recently, especially in Sri Lanka, the installation of the PHP piles with a hollow area at the middle of a pile section has increased. The design community multiplies the area of the pile cross section by the end bearing capacity to obtain the end bearing force whether it is a PHP pile or a solid pile.
This research will compare the pile driving equations with each other and select the best pile driving equations which predict the capacity very close to the measured capacity as an extension of the earlier research done by Thilakasiri and Jayaweera (2009). In addition the mobilization of the end bearing capacities in PHP piles with a hollow area at the middle of a pile section is compared with a solid pile and a relationship is derived to predict the capacity of the hollow area as a function of the hollow area as a percentage of the total area of the pile cross section.
Keywords: Diven piles*, pile driving equations, pile driving records, PHP pile, Capacity og the pile*

Introduction

The sound and ground vibrations are two major issues for driven piles but in Sri Lanka, where effect of these problems do not matter like remote Highway projects these piles are installed in large numbers. Large investments have gone in to the silent pile driving equipments. Fastness of construction and use of Pile driving equations and medium load carrying capacity are some of the major advantageous of driven piles. There are significant numbers of driven piles are installed in spite of the ground vibrations and noise issues during installation of driven piles.
In Sri Lanka, “Guidelines for Interpretation of site investigation data for estimating the carrying capacity of single pile for design of bored and cast in-situ reinforced concrete pile” Publication number ICTA/DEV/15 is there to guide the designer regarding bored piles but similar guidelines are not there for driven piles mainly due to lack of research done regarding driven piles in Sri Lanka. This research is done in Sri Lanka to compare the measured and theoretically determined carrying capacity of from pile driving equations. Moreover, a very recently popular PHP, mobilizations of the end bearing capacities are compared with the solid piles.
Four driven pile were installed very close to the two boreholes drilled (at the location of TP 1& TP 2, BH 7 + 669N L1 and at the location of TP 03 & TP 4, BH 7 +720L were drilled) and these four piles were tested using Pile Driving Analyzer test (PDA). The locations of the piles tested are given in Figure 1 and the borehole logs drilled at this location is given in Figure 2a and 2b. Out of the four piles tested at these locations, two piles are 300mm x 300mm precast-concrete piles (TP 01 and TP 03) and the other two piles (TP 02 and TP 04) are 400 mm diameter spun piles with the 210mm diameter hollow space at the middle of the pile crossection.

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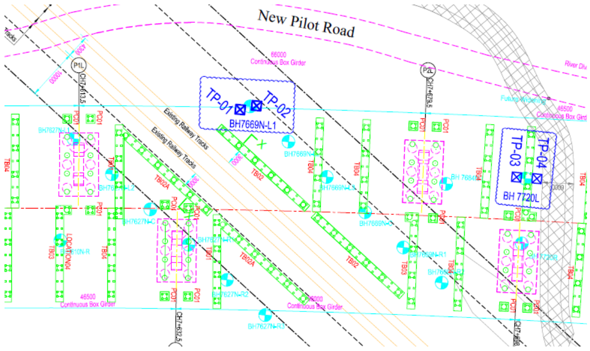

Figure 1 – The plan view of the location test piles and the borehole locations

2.0 Ground condition

Subsurface conditions at the location of TP1 and TP2 is given by BH 7 + 669NL1 and the subsurface condition of TP3 and TP 4 is given by BH 7 + 720 L. Those borehole logs are given by the Figure 2a and 2b.

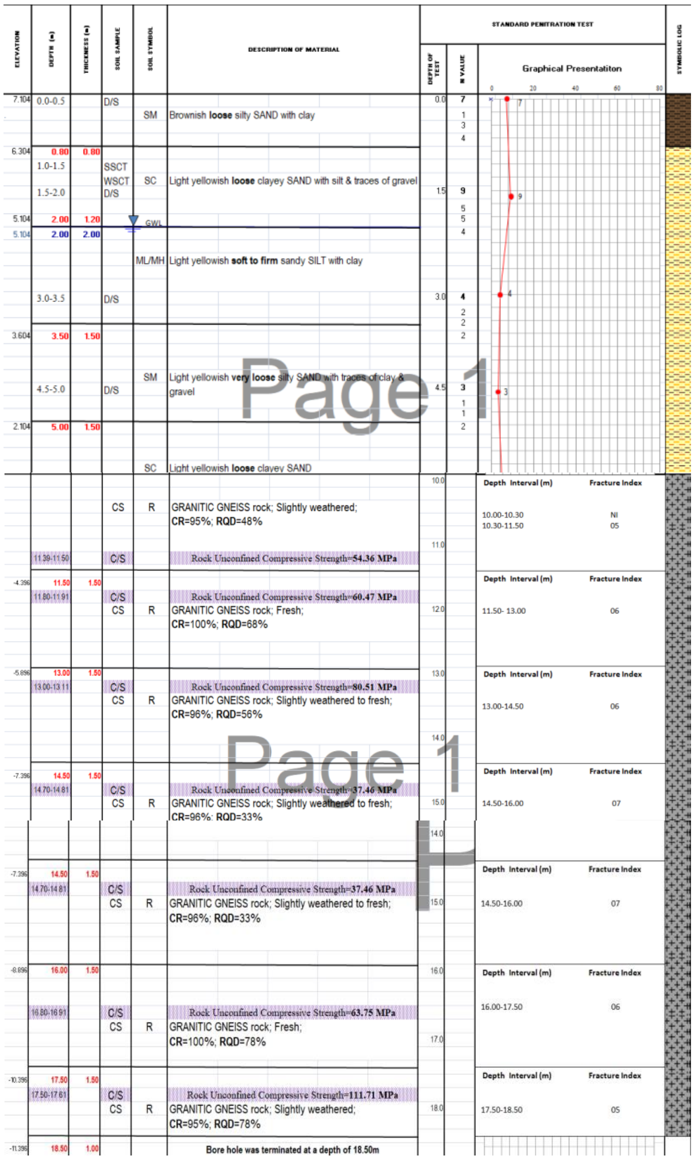

Figure 2a – Borehole log of the BH 7 + 669NL1 with the SPT blow counts

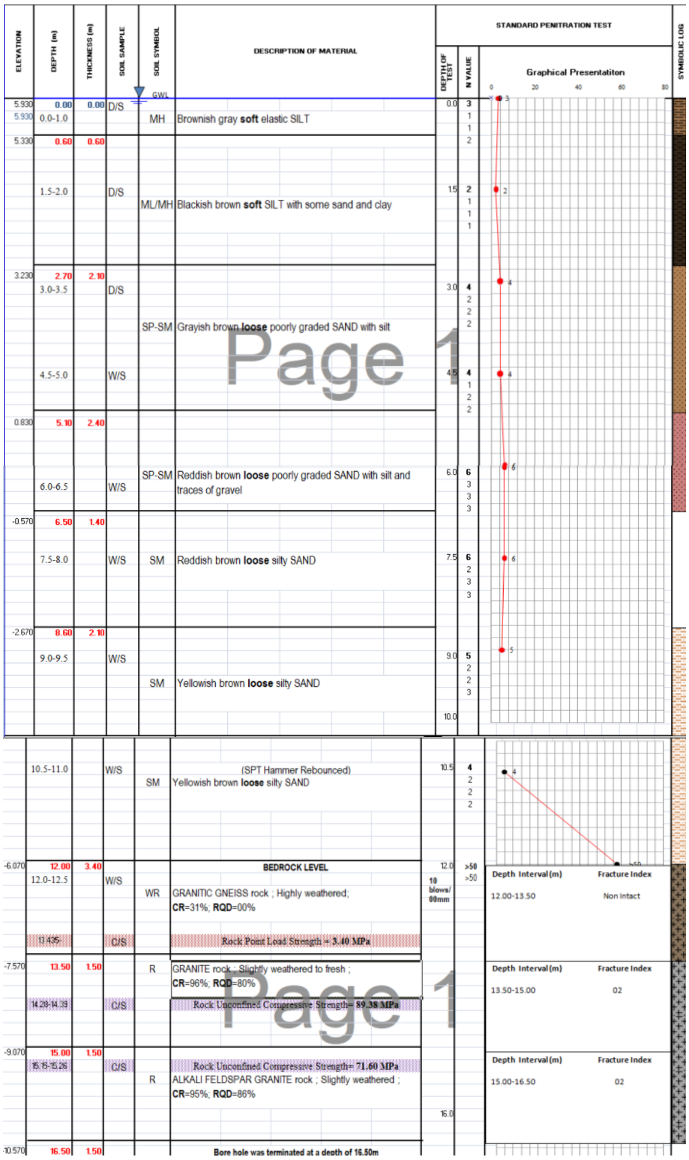

Figure 2b - Borehole log of the BH 7 + 720 L with the SPT blow counts

Based on the borehole records, the subsurface condition given in Table 1.

Table 1 – The subsurface conditions at the Borehole locations

BH 7 + 669 N L1			BH 7 + 720L		
Thickness (m)	N_{Field}	Strength properties (c_u (kPa) or ϕ')	Thickness (m)	N_{Field}	Strength properties (c_u (kPa) or ϕ')
0.80	7	$\phi' = 29$	0.60	3	$c_u = 35$ kPa
1.20	9	$\phi' = 27$	2.10	2	$c_u = 15$ kPa
1.50	4	$c_u = 20$ kPa	2.40	4	$\phi' = 25$
1.50	3	$\phi' = 23$	1.40	6	$\phi' = 26$
2.00	5	$\phi' = 24$	5.50	4 - 6	$\phi' = 23 - 25$
1.50	11	$\phi' = 27$	-		

The material strength parameters are determined from the method outlined in Bowles (1997)

The depth to the bedrock at the locations of the BH 7 + 669NL1 is 8.5m below the ground surface and the same at BH 7 + 720L is 12m. The depth of the installation of the piles TP 01 and TP 02 at the location of BH 7 + 669NL1 are 9.27m and 9.763m with the terminated at the pile penetration set of 10mm/10 blows and the 09/10 blows respectively using a hydraulic hammer with a weight of 4 tons and a stroke of 1m whereas the same quantities for the Piles T03 and T04 are at the location of at BH 7 + 720L are 15.005m and 15.541m at the 1mm/ 10 blows and 6mm/10 blows respectively. According to the pile penetration and the borehole logs, the TP 01 has penetrated into rock 0.77m (9.27 – 8.50) at 1mm per blow and TP 02 has penetrated in to rock 1.263m (9.763 - 8.5) at 0.9 per blow respectively. Same quantities for piles T03 and T04 are 3.005m (15.005-12.00) at 0.1 mm per blow and 3.541m (15.541 – 12.000) at 0.6mm per blow respectively.

All the piles have penetrated some distance in to the bedrock and are sitting on the bedrock. Penetration of the pile to bedrock at the location of TP 01 and TP 02 having CR 83, RQD 23 and unconfined compression stress of 42.73 MPa. The bedrock is identified as slightly weathered granitic gneiss. The location of TP 03 and T P04, the bedrock is having highly weathered granitic gneiss rock having CR 31, RQD 00 and unconfined compression stress of 3.40 MPa (from the point load index tests) from 12.0m to 13.5m. Below that level, slightly weathered to fresh bedrock is present with CR 96 and RQD 80 with the UCS equal to 89.38MPa. Penetration of the piles 1.505m and 2.041m into this rock cannot be anticipated if the ground conditions are different than this at the locations of pile installation or the pile is broken at the tip.

3.0 PDA Results

A summary of the PDA results of the four piles are shown in Figure 3a and 3b respectively for the pile TP 01 & TP 02, and TP 03 & TP 04 respectively

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CAPWAP SUMMARY RESULTS

Total CAPWAP Capacity: 2971.7; along Shaft 1588.8; at Toe 1382.9 kN

Soil Sgmnt No.	Dist. Below Gages m	Depth Below Grade m	Ru kN	Force in Pile kN	Sum of Ru kN	Unit Resist. (Depth) kN/m	Unit Resist. (Area) kPa
				2971.7			
1	4.2	3.0	146.3	2825.4	146.3	49.39	41.16
2	6.3	5.1	205.4	2620.0	351.7	98.00	81.66
3	8.4	7.2	492.7	2127.3	844.4	235.07	195.89
4	10.5	9.3	744.4	1382.9	1588.8	355.15	295.96
Avg. Shaft			397.2			171.76	143.14
Toe			1382.9				15365.56

Soil Model Parameters/Extensions Shaft Toe

CAPWAP SUMMARY RESULTS

Total CAPWAP Capacity: 2627.0; along Shaft 1560.9; at Toe 1066.1 kN

Soil Sgmnt No.	Dist. Below Gages m	Depth Below Grade m	Ru kN	Force in Pile kN	Sum of Ru kN	Unit Resist. (Depth) kN/m	Unit Resist. (Area) kPa	Quake mm
				2627.0				
1	2.1	1.4	61.1	2565.9	61.1	43.46	34.58	3.7
2	4.2	3.5	110.1	2455.8	171.2	52.78	42.00	3.7
3	6.3	5.6	221.0	2234.8	392.2	105.94	84.31	3.7
4	8.3	7.7	456.5	1778.3	848.7	218.84	174.15	3.7
5	10.4	9.8	712.2	1066.1	1560.9	341.42	271.69	3.4
Avg. Shaft			312.2			160.09	127.40	3.5
Toe			1066.1				8483.75	2.7

Soil Model Parameters/Extensions Shaft Toe

Figure 3a– PDA results of pile TP 01 & TP 02

CEP SECTION 1 (04-05-2022); Pile: TP-03_1 Test: 04-May-2022 11:16
300X300; Blow: 20 CAPWAP(R) 2014-3
ELS (Pvt) Ltd OP: AMILA

CAPWAP SUMMARY RESULTS

Total CAPWAP Capacity: 2996.0; along Shaft 1736.5; at Toe 1259.5 kN

Soil Sgmnt No.	Dist. Below Gages m	Depth Below Grade m	Ru kN	Force in Pile kN	Sum of Ru kN	Unit Resist. (Depth) kN/m	Unit Resist. (Area) kPa	Quake mm
				2996.0				
1	3.1	2.6	84.7	2911.3	84.7	32.98	27.49	7.1
2	5.2	4.6	101.7	2809.6	186.4	49.08	40.90	7.1
3	7.3	6.7	203.9	2605.7	390.3	98.41	82.01	7.1
4	9.3	8.8	220.9	2384.8	611.2	106.61	88.84	7.1
5	11.4	10.9	240.9	2143.9	852.1	116.26	96.89	7.1
6	13.5	12.9	301.2	1842.7	1153.3	145.37	121.14	6.4
7	15.5	15.0	583.2	1259.5	1736.5	281.47	234.56	5.4
Avg. Shaft			248.1			115.77	96.47	6.4
Toe			1259.5				13994.44	5.4

Soil Model Parameters/Extensions Shaft Toe

CAPWAP SUMMARY RESULTS

Total CAPWAP Capacity: 2190.0; along Shaft 1336.6; at Toe 853.4 kN

Soil Sgmnt No.	Dist. Below Gages m	Depth Below Grade m	Ru kN	Force in Pile kN	Sum of Ru kN	Unit Resist. (Depth) kN/m	Unit Resist. (Area) kPa	Smith Damping Factor s/m
				2190.0				
1	3.1	2.8	41.3	2148.7	41.3	14.96	11.91	0.53
2	5.1	4.8	44.5	2104.2	85.8	21.81	17.36	0.53
3	7.1	6.8	56.1	2048.1	141.9	27.50	21.88	0.53
4	9.2	8.9	67.2	1980.9	209.1	32.94	26.21	0.53
5	11.2	10.9	173.1	1807.8	382.2	84.85	67.52	0.53
6	13.3	13.0	375.7	1432.1	757.9	184.17	146.56	0.53
7	15.3	15.0	578.7	853.4	1336.6	283.67	225.73	0.56
Avg. Shaft			190.9			89.11	70.91	0.54
Toe			853.4				6791.14	0.27

Soil Model Parameters/Extensions Shaft Toe

Figure 3b – PDA results of piles TP 03 & TP 04

In the bedrock the piles TP01 and TP02 skin frictions are mobilized at 7.2m depth below the grade 195.89 kPa and at 7.7m depth below the grade 174.15 kPa respectively whereas in the bedrock of TP 03 and TP 04 mobilizes skin friction mobilized at 12.9m below the grade is equal to 121.14 kPa and at 13m below the grade 146.56 kPa respectively. Therefore, the skin friction of the weathered rocks or soils may vary from 121.14 kPa to 195.89 kPa.

4. Pile Driving Records

The pile penetration record is shown in Figure 4.

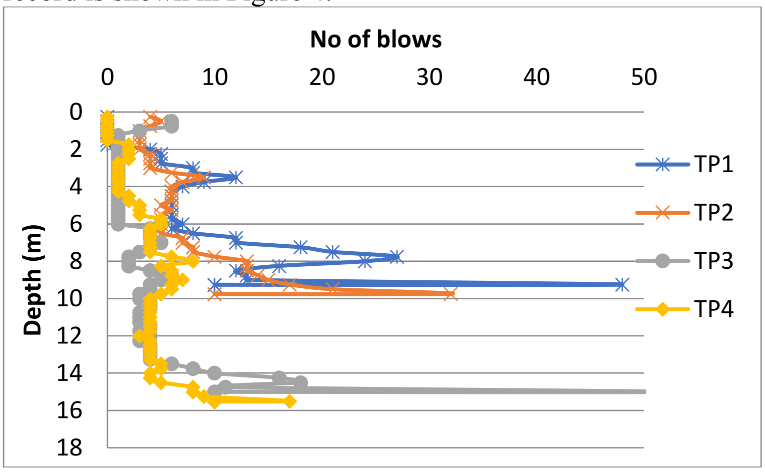

Figure 4 – Pile driving record

5.0 Static capacity estimation

To estimate the skin friction (SF) of pile (f_s) for clayey soils was initially proposed by Tomlinson (1971) as $f_s = \alpha c_u$ (units of c_u)

where α = Coefficient from Figure 5 (Re-produced by Bowles (1997)

c_u = average cohesion (or s_u) for the soil stratum of interest

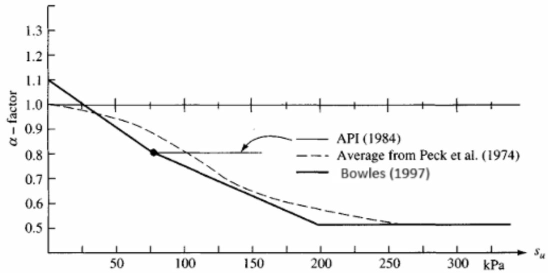

Figure 5 - Relationship between the adhesion factor α and undrained shear strength s_u

Based on the standard penetration test (SPT), following relationships are presented in Bowles (1997). Accordingly,

(i) Meyerhof (1956, 1976) suggested obtaining skin friction (F_s) as: $f_s = \chi_m N_{55}$ (kPa)

Where χ_m = 2.0 for piles with large-volume displacement
χ_m = 1.0 for small-volume piles
N_{55} = Statistical average of the blow count in the stratum (and with any corrections)
(ii) Shioi and Fukui (1982) suggested the following:
For driven piles: $f_s = 2N_{S,55}$ for sand; $= 10N_{c,55}$ for clay
For sandy soils for driven piles, skin friction is given by $f_s = 2N_{S,55}$.
Using the above relationships the SF of the soil is calculated. However, the piles are penetrated into rocks as well. The rock's SF and end bearing (EB) capacities are determined from the PDA results. Accordingly, EB capacities of the 300 x 300mm square piles are taken as 13994 kPa (Lowest value of EB capacity mobilized) whereas same for the spun files are determined to be 6791 kPa. Similarly, the skin friction capacity value is taken as 225 kPa (Smallest value of the mobilized SF of the final element). Taking those SF and EB capacities, the static capacities of the piles were determined.

5 **Comparison of predicted capacities**

The Pile driving equations are used to determine the capacities of the pile. The capacity of the pile determined were compared with the measured capacities of the pile in are shown in Table 2. It should be noted here that the pile driving equations and the parameters were obtained from Poulos and Davis (1980)
Table 2 – Capacity measured and capacity predicted

Capacity estimation method	Capacity (kN)	Pile considered	Measured capacity (kN)	Factor of safety (FoS) with respect to the measured capacities
Hiley pile driving equation	2090	TP 1	2971	0.703
Gate pile driving equation	1052			0.354
Danish pile driving equation	1414			0.476
ENR pile driving equation	1503			0.506
Janbu pile driving equation	2449			0.823
Static capacity using soil properties	2056			0.692
Hiley pile driving equation	1961	TP 2	2627	0.746
Gate pile driving equation	1136			0.432
Danish pile driving equation	1456			0.554
ENR pile driving equation	1503			0.506
Janbu pile driving equation	2450			0.930
Static capacity using soil properties	1774			0.676
Hiley pile driving equation	1954	TP 3	2996	0.652
Gate pile driving equation	1253			0.418
Danish pile driving equation	1478			0.493
ENR pile driving equation	1503			0.506
Janbu pile driving equation	2323			0.775
Static capacity using soil properties	2104			0.702
Hiley pile driving equation	1935	TP 4	2190	0.883
Gate pile driving equation	1100			0.502
Danish pile driving equation	1442			0.658
ENR pile driving equation	1503			0.506
Janbu pile driving equation	2423			1.106
Static capacity using soil properties	3480 -			1.588

7.0 Data Analysis

The static capacity estimation method gives a factor of safety (FoS) of 0.696 – 1.588 with respect to the measured capacities. Few observations are made based on the data resented in this paper. First it is shown that the Hiely formula is the closest conservative one to the measured capacity with a factor of safety ranges from 0.652 – 0.883. Even though Janbu method of capacity estimation method gives closer to measured value values than Hiely method for three cases, the other pile capacity slightly estimated over the measured capacity with a factor of safety of 0.775 – 1.106. However, it is noted that a FoS that goes with

these capacity estimation methods of 3.0, the over prediction shown by Janbu method is negligible. It is noted that the Janbu method of capacity prediction using pile driving equation is always more closer to the measured capacity than static capacity prediction using soil properties,. The Engineering News Record (ENR) method even with a simple method of calculation, yields a FoS of 0.506. The Danish pile driving equation with a FoS of 0.476 to 0.658. The Gate's pile driving method under predict the measured capacities with a FoS of 0.354 – 0.502.
In the bedrock the piles TP01 and TP02 end bearings mobilized are 15365.56 kPa and 8483.75 kPa respectively whereas in the bedrock of TP 03 and TP 04 mobilized end bearing capacities are equal to 13994.44kPa and 6791.41kPa (for TP 2 and TP 4, area of the entire pile section without considering the hollow area ($\pi x 0.4^2/4$)) respectively. Unlike in SF, even though the cross sectional areas of solid piles and the PHP piles 90,000mm^2 and 91,027 mm^2 are approximately equal, probably because of the middle hollow area of the PHP piles, it consistently mobilized the lower end bearing capacities considering the actual cross sectional areas of the piles 91,027mm^2. In the bedrock, the end bearing capacities mobilized for solid piles varies from 15365 kPa to 13994 kPa.

8 Conclusions

Even though pile capacities of the driven piles can be determined using pile driving equations, despite some theoretical drawbacks, is easy way of determining capacities. It is proven by the capacities measured and the capacities estimated in various pile driving equations are given in Table XX, some method predicts closer than other methods to the measured capacities. That shows the importance selection of pile driving equation method for the problem you are working on. From this research the best pile driving method has immerged as the method proposed by Janbu with a Factor of Safety (FoS) 0.775 – 1.102 with the measured capacities. Hiely method is the conservative method of capacity prediction with a FoS of 0.652 – 0.883 with the measured capacity. The other pile driving equations like ENR method or Danish methods have a factor of safety around 0,5, according to this study, are not suitable to determine the driven pile capacities. The Gates method over predict the capacity,
The other conclusion can be made that the PHP piles with a hollow area at the middle of the pile cross section it consistently shows that the measured end bearing capacities are significantly lower than the end bearing capacities of the solid piles without the hollow area at the middle of the pile cross section. When four piles are considered, end bearing capacities mobilized without a hollow area in the pile cross sections are 15365 and the 13994 kPa, and with the hollow area at the middle of the pile cross section are 11711.9 kPa and 9371.9 kPa (considering actual cross sectional area of the pile = 91027 mm^2). It can be speculated that about 66.9 to 76.2 prcent of the capacities are mobiles, if the pile cross section to the hollow area cross section is 25%. The other conclusion it can be drawn from this study is the even though presence of a hollow area in the middle of the pile cross section affects the end bearing capacity of the pile, the skin friction is not affected.

9 References

1. Boles, J. E. (1997), Foundation Analysis and Design, International Edition, McGraw-Hill,
2. Meyerhof, G. G. (1956), Penetration Tests and Bearing Capacity of Cohesionless Soils. JSMFD, ASCE, vol. 82, SM l,pp. 1-19.
3. Meyerhof G. G. (1976), Bearing Capacity and Settlement of Pile Foundations, JGED, ASCE, vol. 102, GT 3, March, pp. 195-228 (Terzaghi Lecture).
4. Poulos, H. G. and Davis E, H. Foundation Analysis and Design, 1980, Rainbow-bridge Book co.
5. Shioi, Y. and J. Fukui, (1982), Application of N-Value to Design of Foundations in Japan, 2nd ESOPT, vol. l, pp. 159-164.
6. Skempton, A. W. (1986), Standard Penetration Test Procedures , Geotechnique, vol. 36, no. 3, pp. 425-447.
7. *Thilakasiri, H. . and Jayaweera, R.*, (2009), Investigation of the Accuracy of the Dynamic methods of Capacity Estimation of Piles, *Engineer, J. of Inst. of Engineers, Sri Lanka, Vol 42, No 04, 2009*, pp. 75 – 85.