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Investigation of the Accuracy of the Dynamic Methods of Capacity Estimation of Piles

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Abstract: Capacity estimation of piles using dynamic methods is considered in this paper. Commonly used dynamic methods in Sri Lanka, high strain dynamic load testing and pile driving equations are considered in detail. The accuracy of the CAPWAP method of capacity prediction was discussed considering the results of the available comparison studies. Considering the CAPWAP predicted capacities and the capacities estimated from the Case method, the applicability of the commonly used Case damping factor of 0.5 was investigated. Furthermore, Case damping factors to be used in the field high strain dynamic load testing are also suggested. The capacities estimated from the CAPWAP analysis of the dynamic load test data and the measured set of the pile during high strain dynamic load testing are used to evaluate the accuracy of the capacity predicted by pile driving equations. Based on the data collected, the accuracy of each pile driving method is discussed. Furthermore, the factors affecting the accuracy of the pile driving equations are also investigated. Moreover, the factors of safety to be used with different methods are also presented.

Keywords: Pile driving equations, High strain dynamic testing, Case method, Statnamic testing,

1. Introduction

Dynamic methods are very often used to estimate the carrying capacities of piles. In the dynamic methods of carrying capacity estimation, a pile is subjected to a dynamic load, very often to a transient impact using a heavy hammer, and the static capacity of the pile is estimated. The dynamic methods that are commonly used in the capacity estimation of piles can be categorized into the following categories:

i. High strain dynamic load testing;
ii. Rapid load testing; and
iii. Other empirical methods, such as pile driving equations.

At the outset, it would be prudent to highlight the fundamental differences between the static methods and the dynamic methods of capacity estimation. First major difference between the two methods is the rate dependent viscous resistive forces from the surrounding medium during the dynamic loading. In the static methods of capacity estimation, the load on the pile is slowly increased and the rate dependent viscous resistive forces from the surrounding medium are negligible. On the other hand, when a transient dynamic load is applied on a pile, it moves at a considerably high velocity and as a result, the rate dependent viscous resistive forces from the surrounding medium become significant. However, when a pile supporting a normal structure is considered, the load on the pile is increased very slowly and the rate dependent viscous resistive forces are almost nonexistent. Therefore, if it is required to obtain the static capacity from a dynamic load applied on a pile, the rate dependent viscous resistive forces should be removed from the mobilized capacity.

The second major difference between the two methods is the duration of the applied load on the pile. In the case of static loading, the duration of the applied load on the pile is very large and the entire pile is stressed at the same time. But when a dynamic load is applied at the top of the pile it travels through the pile at a certain velocity, commonly referred to as the wave velocity (c). The wave that passes through a pile of length L is reflected at the pile toe and returns back to the pile top after $2L/c$ time after the initial impact on the pile top. The relative duration (T_r) is defined as the ratio between the duration of the stress pulse (T_i) and the wave return period. If the relative duration (T_r) is less than unity, the entire pile is not stressed at the same time and therefore, wave propagation becomes the form of stress propagation through the pile.

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The high strain dynamic load tests are carried out by applying a transient dynamic impact on the pile top by a drop hammer or a pile driving hammer. The relative duration (T_r) for a average pile is less than unity and the acceleration of the pile during the hammer blow is in the rage of 500 - 1000g. As a result, viscous resistance developed by the surrounding soil and the wave propagation through the pile are significant. On the other hand, rapid loading on the pile are applied during statnamic load testing, where a pile is loaded due to burning of solid fuel within a pressure chamber, which is directly in contact with the top of the pile.

The peak acceleration of the pile during statnamic load testing ranges between 0.2 to 1g, whereas the relative duration varies between 10 and 50. As a results, the viscous resistive forces and the wave propagation effects during statnamic load testing is relatively low. Therefore, pseudo-static methods such as unloading point method [9] may be used to obtain the static capacity. Eventhough there are large number of studies conducted in other countries to prove the accuracy of the statnamic load test method ([6], [8], [4], and [12]), as this method is yet to be introduced to Sri Lanka, it is not further considered in this paper.

Pile driving equations are used to estimate the carrying capacity of the pile based on the permanent penetration of the pile during a hammer blow. Eventhough a transient dynamic load is applied on the pile head during driving, pile driving equations give no consideration to the viscous resistance of the soil nor the wave propagation through the pile during driving. Simply pile is assumed to be a rigid body penetrating the surrounding soft medium. Therefore, the theoretical basis of the pile driving equations is very weak. However, it is observed that the pile driving equations are very often used in practice to estimate the carrying capacity of piles. There are various reasons for the popularity of the pile driving equations. Among them; simplicity; economy; and practicability are the main reasons

2. Accuracy of the high strain dynamic load testing results

High strain dynamic load tests are conducted by applying a transient impact load on the pile top while monitoring the strain and acceleration at the pile top. The data thus obtained are used to obtain the force and the velocity time history at the pile top during the impact loading. The results can be used to obtain an approximate capacity in the field using the Case method or some other similar method. The data obtained during dynamic load testing may be subjected to further rigorous signal matching process, such as CAPWAP, DLTWAVE, SIMBAT, to obtain the static capacity and the static load - settlement curve. Based on the results of already conducted comparison studies, the accuracy of the results obtained from signal matching the dynamic load test data are discussed in section 2.1. Accuracy of the capacity estimated from the Case method in relation to the signal matching techniques is considered in section 2.2.

2.1 Investigation of the accuracy of the results obtained from signal matching of high strain dynamic load test data

The high strain dynamic method of capacity estimation has become very popular through out the world due to its low cost and the other advantages compared to static load testing. However, due to the indirect nature of the data interpretation involved in obtaining the static response of piles, large number of researches have investigated the accuracy and the reliability of the results of the high strain dynamic load test by comparing with the static load test results ([9], [3], [14], [9], [7], [5], and [15]). Almost all the comparison studies mentioned above confirm the reliability and accuracy of the high strain dynamic load test results. However, one should be very mindful that the above statement is valid only if the results are analysed by well qualified geotechnical engineers.

Dynamic load testing of piles was introduced to Sri Lanka in the late nineteen nineties and by now it has almost become the main method of pile load testing in the country. However, only very few studies were conducted to investigate the accuracy of the data interpretation methods performed in Sri Lanka. Eventhough one could argue that the accuracy of the interpretation methods is independent of the country, it may not be true as the accuracy level depends on the personal involved in testing and interpretation, general subsurface condition, construction methodology of piles, load carrying mechanism of piles etc. Thilakasiri et al. (2006) investigated the accuracy of the interpretation of the results of the dynamic load tests by comparing the load - settlement curves obtained by testing the same pile with static and dynamic methods. Due to the space limitation, only the settlement of the piles from the static and dynamic methods at the working load and the test load of the piles considered in the comparison study are given in Table 1.

Table 1 - Comparison of settlement from static and CAPWAP [16].

Case stud y	Settlement at working load (mm)		Settlement at 1.5 x working load (mm)	
	Static	PDA	Static	PDA
I	4.29	3.91	8.26	7.86
II	1.64	2.43	4.10	3.67
III	3.14	4.00	5.48	6.15
IV	5.59	4.90	11.81	11.81
V	10.92	9.00	28.60	*
VI	3.93	4.95	9.20	8.40

* Pile was not loaded upto 1.5 x working load.

But Thilakasiri et al. (2006) showed that the collection of data and the analysis of PDA data should be carried out carefully by qualified geotechnical engineers considering not only the match quality but also subsurface condition at the site, dynamic soil properties, and the measured and predicted blow counts.

3.2 Accuracy of the capacity estimated using the Case method

Case method of capacity estimation is a very important tool used in the field during high strain dynamic load testing to obtain an approximate capacity of the tested pile. The pile testing engineer decides to stop the test when the capacity predicted by the Case method exceeds the test load. Eventhough there are different methods of estimating the capacity from the Case method, such as: RSP, RMX and Auto methods (Model L(PAL) User Manual,1999), RMX method is very often used with a Case damping factor of 0.5 to obtain the capacity of piles in the field. Capacities obtained from the RSP and RMX methods depend on a dynamic pile-soil parameter commonly referred to as the Case Damping factor (J_c). In most cases, the high strain dynamic load test results are analyzed to obtain more accurate results using more rigorous signal matching techniques such as CAPWAP method. It is often a problem that when a high strain dynamic test is terminated based on the approximate capacity from RSP or RMX methods based on an assumed J_c factor, the capacity from more accurate CAPWAP estimation shows that the pile is not loaded upto the required test load.

Both Case method and CAPWAP results of high strain dynamic load tests were collected to investigate the accuracy of Case method in comparison to the CAPWAP method. Table 2 shows the capacities estimated by the CAPWAP method and the Case damping factors required to get the CAPWAP capacities using RSP and RMX methods.

Table 2 - Capacities estimated by the CAPWAP method and the Case damping factors required to get the CAPWAP capacities using RSP and RMX methods.

No	CAPWAP capacity (kN)	RSP J_c for CAPWAP capacity	RMX J_c for CAPWAP capacity	No	CAPWAP capacity (kN)	RSP J_c for CAPWAP capacity	RMX J_c for CAPWAP capacity
1	3436	0.21	0.66	45	1519	0.11	0.48
2	5263	0.25	0.34	46	4737	0.37	0.37
3	2193	0.75	0.80	47	4089	0.37	0.37
4	3953	0.60	0.72	48	6852	0.45	0.45
5	2388	0.12	0.13	49	3240	0.26	0.31
6	4012	0.36	0.37	50	3862	0.43	0.43
7	2905	0.29	0.32	51	5009	0.45	0.45
8	4206	0.43	0.66	52	4100	0.45	0.45
9	1209	0.68	0.68	53	11790	0.27	0.27
10	1410	0.74	0.74	54	12155	0.03	0.03
11	5079	0.64	0.66	55	4495	0.59	0.63
12	4890	0.56	0.56	56	8731	0.24	0.28

13	6102	0.46	0.46	57	3706	0.31	0.32
14	1705	**0.48**	**0.48**	58	3512	0.41	0.41
15	13,474	0.35	0.39	59	3235	0.40	0.62
16	13,963	0.15	0.80	60	3881	0.51	0.51
17	13,975	0.35	1.00	61	3968	0.59	0.59
18	14,214	0.33	0.33	62	4171	0.30	0.30
19	8710	0.32	0.32	63	3983	0.60	0.60
20	7440	0.37	0.37	64	3811	0.33	0.33
21	4607	0.62	0.62	65	3204	0.30	0.30
22	7,142	0.42	0.42	66	3258	0.63	0.63
23	9,737	0.34	0.34	67	2842	0.47	0.47
24	5,025	0.48	0.48	68	3781	0.24	0.24
25	10,389	0.28	0.30	69	3590	0.42	0.42
26	5,150	0.70	0.70	70	3266	0.43	0.44
27	8.53	0.63	0.63	71	3607	0.58	0.58
28	10,480	0.61	0.61	72	3244	0.36	0.36
29	4,915	0.58	0.58	73	17516	0.33	0.63
30	2,844	0.27	0.27	74	17,660	0.53	0.53
31	5484	0.48	0.58	75	16,456	0.52	0.52
32	3304	0.15	1.00	76	24,406	0.56	0.56
33	7787	0.04	0.12	77	21,923	0.21	1.00
34	8800	0.53	0.53	78	3294	0.42	0.42
35	7580	0.43	0.45	79	9920	0.30	0.30
36	5452	0.44	0.65	80	3511	0.05	0.31
37	5628	0.53	0.56	81	7805	0.13	0.15
38	7405	0.50	0.50	82	5949	0.63	0.63
39	8127	0.37	0.37	83	5901	0.53	0.60
40	7041	0.46	0.46	84	3783	0.60	0.60
41	4429	0.71	1.00	85	5938	0.58	0.59
42	2502	0.39	0.69	86	4098	0.63	0.63
43	4076	0.48	0.48	87	3599	0.54	0.54
44	3702	0.36	0.36	Mean		0.42	0.50
				Standard deviation		0.17	0.19

Mean (χ) of the J_c factors for RSP and RMX methods are 0.42 and 0.50 respectively while the standard deviations (σ) are 0.17 and 0.19 respectively. It is observed that, the capacity from the case method decreases with the increase in the J_c. Therefore, when a Case damping factor of 0.5 is used RMX and RSP methods over predict the capacity 50% and 32% of the times respectively, assuming a normal distribution. If the testing engineer terminates the test, when the RSP capacity exceeds the test load with the Case damping factor 0.5, there is a probability of 32% that the CAPWAP capacity is less than the test load and the pile is not loaded upto the test load. Similarly, with the RMX method there is a probability of 50% that the pile is not loaded upto the test load.

If a J_c factor of mean plus the standard deviation of the RSP method, $\chi + \sigma = 0.59 \approx 0.6$, is used and the test is terminated based on the RSP capacity, there is only about 14% probability that the CAPWAP capacity may be less than the test load. On the other hand, if a J_c factor of mean plus the standard deviation of the RXP method, $\chi + \sigma = 0.69 \approx 0.7$, is used and the test is terminated based on the RSP capacity, there is only about 14% probability that the CAPWAP capacity may be less than the test load.

3. Accuracy of the capacity prediction by pile driving equations

Due to its popularity and the wider application of the pile driving equations, it is prudent to investigate the accuracy of the capacities estimated from pile driving equations in detail.

3.1 Investigation methodology adopted

Large number of researches all over the world has carried out various investigations related to the accuracy of the pile driving equations. In these investigations mostly carrying capacity of the piles determined from the static load tests had been considered. However, it should be noted here that there is a time gap between driving and static load testing the pile. It is proved through research that there is capacity gain after driving and the rate of increase of the capacity is high immediately after driving the pile. As a result, the carrying capacity obtained from static load testing is not equal to the capacity of the pile during driving.

In the present study, the set measured during the dynamic load testing is used to estimate the carrying capacity of the pile from pile driving equations. The actual mobilized capacity of the pile is obtained from analysis of the dynamic load test data using CAPWAP signal matching technique. As such there is no time gap between the driving the pile and testing the pile to obtain the carrying capacity.

For the successful application of the proposed methodology, mainly two conditions should be satisfied:

(i) the capacity obtained from the CAPWAP analysis should be accurate; and

(ii) the behaviour of the bored piles considered in the analysis should be similar to driven piles.

The accuracy of the CAPWAP results were assessed following the methodology proposed by Thilakasiri et al. (2006), as given in section 2.2. The dynamic load test results given in the test reports, which do not give a reasonable skin friction distribution, dynamic soil parameters applicable to the subsurface, and a reasonable blow count match were not considered in the present study. The dynamic test results satisfying the above conditions are assumed to be accurate, as shown by Thilakasiri et al. (2006).

The main difference between driven and bored pile is the variability of the pile cross sectional area. Preformed driven piles are having uniform cross sectional area or systematic variation of the cross sectional area. But depending on the subsurface condition along the pile shaft, bored piles may show necking and/or buldging. However, the CAPWAP simulation results give the variation of the impedance of the pile shaft with depth. If it is assumed that the properties of the concrete along the pile shaft is approximately uniform, the impedance variation may represent the variation of the pile cross sectional area. To minimize the difference between the behaviour of bored piles and the driven piles during driving, only the piles having uniform impedance profiles from the CAPWAP simulation are considered in the present study.

Having established the accuracy of the HSDT of the piles, the results of the HSDT of piles are used to investigate the accuracy levels of the pile driving equations, as the set of the pile is also measured during high strain dynamic testing of piles. Furthermore, the efficiency of the hammer blow obtained from the HSDT is used with the relevant equations to remove any error due to the assumed efficiency factor of the hammer. Commonly used pile driving equations such as, Engineering News Record (ENR), Hiley method, Janbu method, Gates method and the Danish method are investigated in this study. The capacities obtained from the HSDT are compared with the same estimated from different pile driving equations. The effects of the pile length, diameter, skin friction developed along the pile shaft are investigated. Based on the results of this study, factor of safety to be used with the different methods are proposed.

3.2 Overall accuracy of different pile driving equations

Data related to the present study were collected from the various engineering institutions in Sri Lanka. The collected HSDT data was subjected to thorough screening and data satisfying the criteria set out in Thilakasiri et al. (2006), totaling 33 no of precast piles and 125 number of bored and cast in-situ piles were considered for the present analysis. The pile driving equations namely, Engineering News Record

(ENR), Hiley, Janbu, Danish and Gates methods as given in Table 3 were considered in this study. The assessment of the accuracy of the different pile driving equations are evaluated based on coefficient of determination (R^2) value; and one measure of effectiveness: the goodness-of-prediction (G). The mathematical representation of the G ([1], and [17]) is shown in Eq. [1].

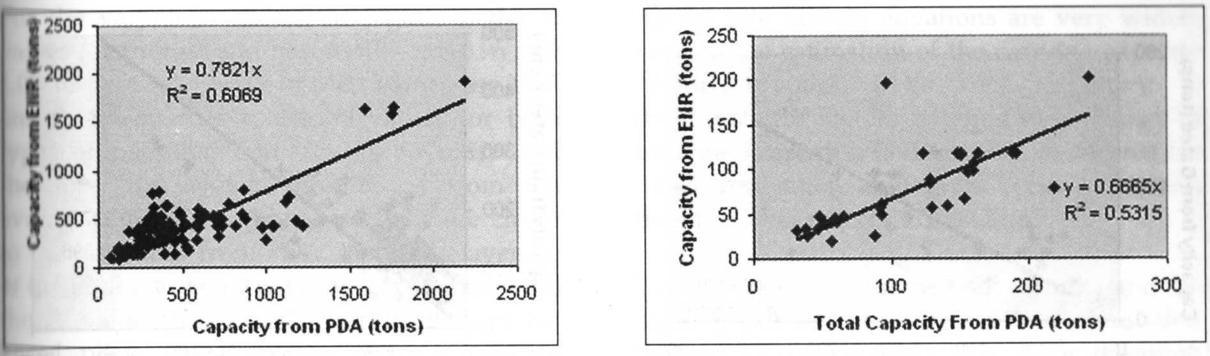
$$G = \left[1 - \left\{ \frac{\sum_{i=1}^{n} \left[z(x_i) - z'(x_i) \right]^2}{\sum_{i=1}^{n} \left[z(x_i) - Z \right]^2} \right\} \right] \tag{1}$$

Where $z(x_i)$ and $z'(x_i)$ are the observed and predicted values at assessment points and Z is the average value of the parameter being measured.

The measured capacity vs. predicted capacity from bored and cast in-situ piles for ENR, Hiley, Janbu, Danish, and Gates methods are shown in Figures 1(a) to 5(a) and the same variation for driven precast piles are shown in Figures 1(b) to 5(b). The trend lines passing through the origin are also shown in Figures 1 to 5 together with the R^2 value and the equation of the trend lines. Table 4 shows the R^2 values, the slope of the trend lines (m), and goodness of prediction (G) for different pile driving equations for both precast and bored piles.

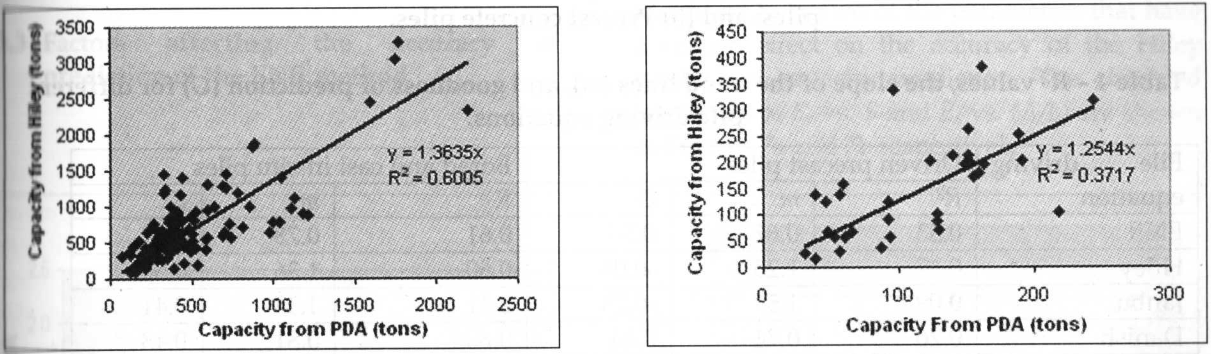
Table 3 - Pile driving equations considered in the study.

Name	Equation	Symbols
Engineering News [13]	$R_{ult} = \frac{WH}{S+C}$ C = 1.0 in. for drop hammers 0.1 in. for steam hammer $0.1\frac{W_p}{W}$ in. for steam hammer on very heavy piles	W - weight of the Hammer H - height of drop of the hammer W_p - Weight of the pile A - cross section of the Pile E - elastic modulus of pile material e_f - efficiency of the hammer S - Set (penetration of the pile per hammer blow) L - Length of the pile n - Coefficient of restitution.
Janbu [13]	$R_{ult} = \frac{1}{K_u}\frac{WH}{S}$ Where $K_u = C_d\left(1+\sqrt{1+\frac{\lambda}{C_d}}\right)$ $C_d = 0.75 + 0.15\frac{W_p}{W}$ $\lambda = \frac{WHL}{AES^2}$	
Gates [2]	$R_{ult} = 4.0\sqrt{e_f WH}\left(\log_{10}(\frac{25}{S})\right)$ Units are metric tons (1000 kg) and centimetres	
Danish [13]	$R_{ult} = \frac{e_f WH}{S + \sqrt{\frac{2e_f WHL}{AE_p}}}$	
Hiley [13]	$R_{ult} = \frac{e_f WH}{S + \frac{(C_1+C_2+C_3)}{2}}\left(\frac{W+n^2W_p}{W+W_p}\right)$ Refer Tables 2.2, 2.3 and 2.4 for the values of e_f, C_1, C_2, C_3 and n.	



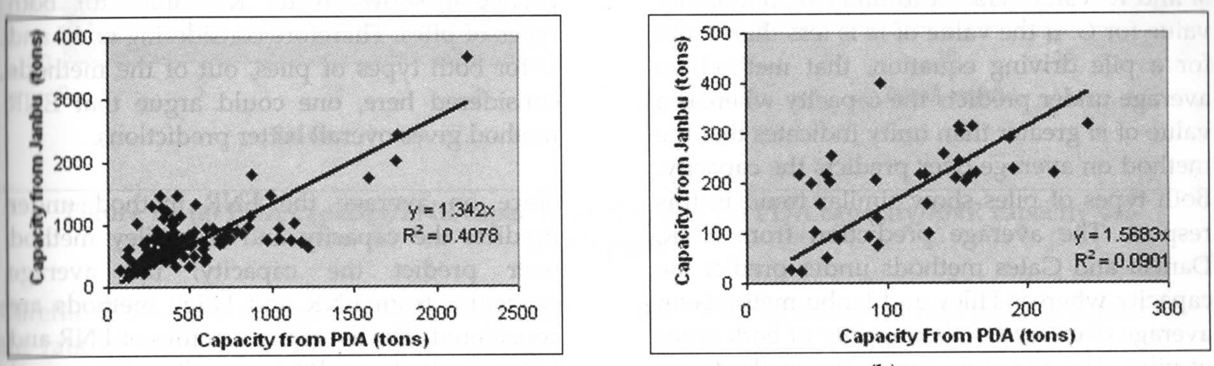
(a) (b)

Figures 1 - Capacity predicted from ENR vs. capacity from PDA for: (a) bored and cast in-situ piles; and (b) Precast concrete piles.



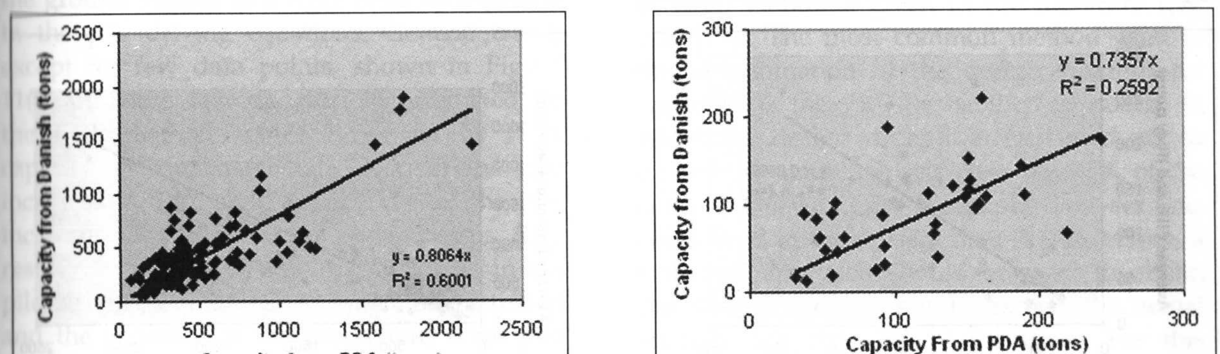
(a) (b)

Figures 2 - Capacity predicted from Hiley vs. capacity from PDA for: (a) bored and cast in-situ piles; and (b) Precast concrete piles.



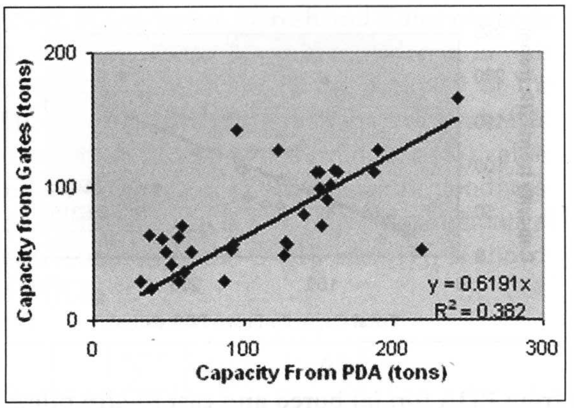
(a) (b)

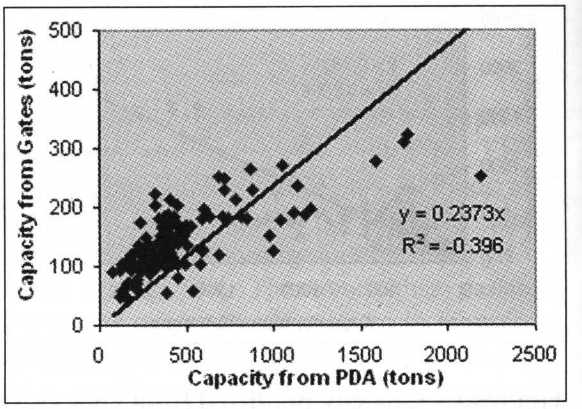
Figures 3 - Capacity predicted from Janbu vs. capacity from PDA for: (a) bored and cast in-situ piles; and (b) Precast concrete piles.



(a) (b)

Figures 4 - Capacity predicted from Danish vs. capacity from PDA for: (a) bored and cast in-situ piles; and (b) Precast concrete piles.





(a) (b)

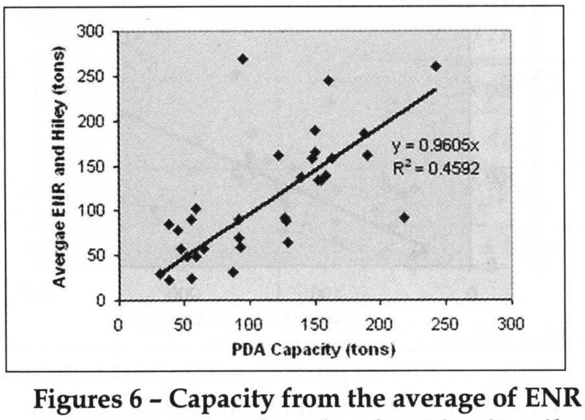
Figures 5 - Capacity predicted from Gates vs. capacity from PDA for: (a) bored and cast in-situ piles; and (b) Precast concrete piles.

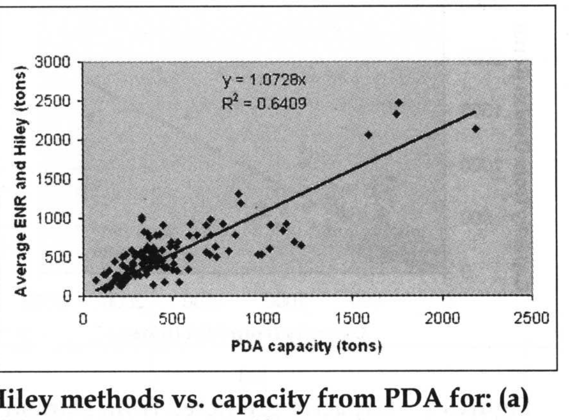
Table 4 - R^2 values, the slope of the trend lines (m), and goodness of prediction (G) for different pile driving equations.

Pile driving equation	Driven precast piles			Bored and cast in-situ piles		
	R^2	m	G	R^2	m	G
ENR	0.53	0.67	0.38	0.61	0.78	0.44
Hiley	0.37	1.25	-0.08	0.60	1.36	0.52
Janbu	0.09	1.57	-0.23	0.41	1.34	0.41
Danish	0.26	0.74	0.44	0.60	0.81	0.48
Gates	0.38	0.62	0.53	-0.40	0.24	-0.81

The most accurate method will have both the m and R^2 values closest to unity with a higher value for G. If the value of m is less than unity for a pile driving equation, that method on average under predicts the capacity whereas a value of m greater than unity indicates that the method on average over predicts the capacity. Both types of piles show similar trend in this respect. The average prediction from ENR, Danish and Gates methods under predict the capacity whereas Hiley and Janbu methods on average over predict the capacity of both types of piles. The R^2 values for all the methods are relatively low for both the types of piles indicative of scattered data. Considering both types of piles, ENR and Hiley methods show relatively better R^2 values and ENR in particular shows better R^2 values for both types of piles. Therefore considering m, R^2 and G for both types of piles, out of the methods considered here, one could argue that ENR method gives overall better predictions.

Since on average the ENR method under predicts the capacity and the Hiley method over predict the capacity, the average capacities from ENR and Hiley methods are considered. The average capacities of ENR and Hiley methods vs. PDA capacities for precast and bored piles are shown in Figures 6(a) and 6(b) respectively.





Figures 6 - Capacity from the average of ENR and Hiley methods vs. capacity from PDA for: (a) bored and cast in-situ piles; and (b) Precast concrete piles.

For the variations shown in Figure 6, the m values for precast and bored piles are 0.96 and 1.07 respectively while the R^2 values are 0.46 and 0.64 respectively. The m values for both types of piles has come closer to unity and therefore, the average predictions from the average of ENR and Hiley methods are closer to the capacities from PDA. When the average of the ENR and Hiley capacities are considered, the R^2 value shows a slight improvement for bored piles. Therefore, the average capacity estimated from the average of the ENR and the Hiley method may give capacity closer to the PDA capacity.

3.3 Factors affecting the accuracy of prediction of the ENR method

As the pile driving equations are very widely used in the estimation of the carrying capacity of driven piles, it is very important to investigate the factors affecting the accuracy of estimated capacity. ENR method is selected for this investigation as it gives better prediction than the other methods considered.

The ratio (E_r) between the ENR capacity and the capacity predicted by the CAPWAP simulation is used for this investigation. After thorough analysis of the data available, the set (S) of the pile, and the ratio between the pile cross sectional area (A) and the length (L) are identified to be two of the parameters that have a certain effect on the accuracy of the Hiley method of capacity prediction. The observed variations of E_r vs. S and E_r vs. (A/L) are shown in Figures 7a and 7b respectively.

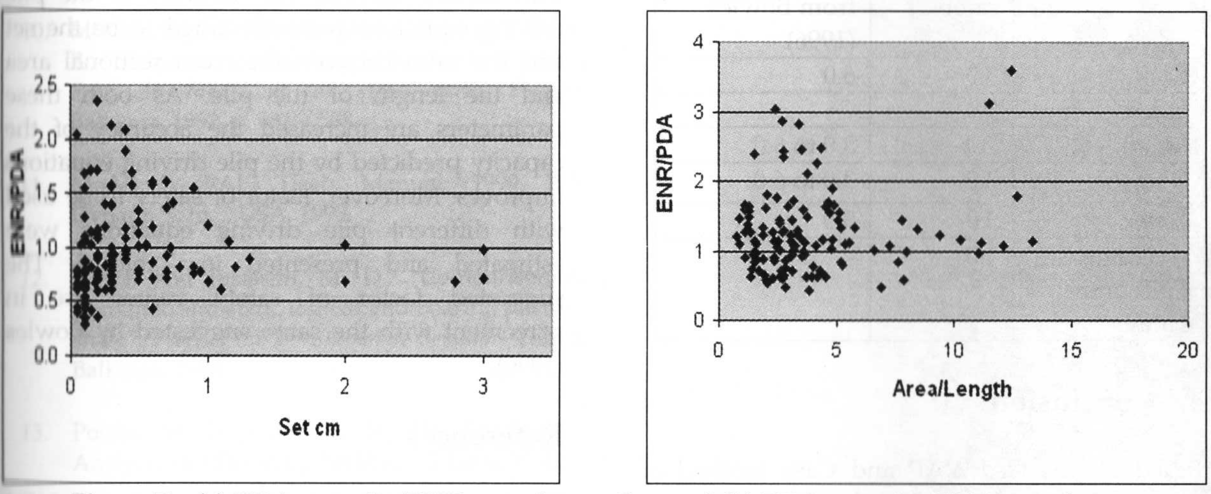


Figure 7 - (a) PDA capacity/ENR capacity vs. Set; and (b) PDA capacity/ENR capacity vs. area/length.

Careful observation of Figure 11(a) shows that the ratio between the ENR and PDA capacities comes closer to unity as the set (penetration of the pile per hammer blow) increases. This is expected as the set increases the pile penetrates the ground similar to a rigid body as assumed in the pile driving equations. General trend, except for few data points, shown in Figure 11(b) indicates that the capacity predicted by the ENR method comes closer to the PDA capacity as the area/length ratio of the pile increases. As the area/length ratio of the pile increases, the rigidity of the pile increases. As a result, the rigid body assumption made in the pile driving equations is somewhat satisfied and the accuracy of the predictions from pile driving equations improves.

3.4 Factor of safety for pile driving equations

In the estimation of the factor of safety to be used in field applications, the capacities of the piles were estimated with the efficiency factor of drop hammers given in the literature ([2], and [13]). The most common method used in the determination of the design strength (or capacity) is the 95% probability approach, in which the design strength is estimated not to exceed the actual capacity less than 5% of the cases. However, only a sample data set was considered in the present data set. Therefore, a statistical approach should be used to obtain the design strength not to exceed the actual strength less than 5% of the times. For this purposed, a normal distribution is considered.

The ratio ($1/E_r$) between PDA capacity and the capacity from each method and the is considered for the statistical analysis. The standard deviation and the mean of the E_r for each method were estimated. The estimated standard deviation and the mean for each method together with the probability density function of the normal distribution were used to estimate the $1/E_r$ for each capacity estimation method which has a probability of exceeding 95% of the time. Reciprocal of that $1/E_r$ is the factor of safety that should be applied against the capacity estimated by that particular method. The estimated factor of safeties are given in Table 5.

Table 5 - Factor of safety to be used for the estimated capacities from different methods.

Method	Factor of safety	Range of FoS from Bowles (1996)
ENR	3.0	6.0
Hiley	5.0	-
Janbu	7.0	3.0 to 6.0
Danish	3.0	3.0 to 6.0
Gates	3.0	3.0
Average of ENR and Hiley	4.0	-

4. Conclusion

Based on the CAPWAP and Case method of analysis of HSDT results, the Case damping factor (J_c) required to achieve the CAPWAP capacity was obtained. Mean (χ) of the J_c factors for RSP and RMX methods are 0.42 and 0.50 respectively while the standard deviations (σ) are 0.17 and 0.19 respectively.

If a J_c factor of mean plus the standard deviation for the RSP method, 0.6, is used and the test is terminated based on the RSP capacity, there is only about 14% probability that the CAPWAP capacity may be less than the test load. On the other hand, if a J_c factor of mean plus the standard deviation of the RXP method, 0.7, is used and the test is terminated based on the RSP capacity, there is only about 14% probability that the CAPWAP capacity may be less than the test load. Therefore, a Case damping factor of 0.6 with the RSP method of a Case damping factor of 0.7 may be used with the RMX method to ensure that the CAPWAP capacity is more than the test load for a reasonable number of tests.

The investigation of the accuracy of different pile driving equations revealed that the average prediction from ENR, Danish and Gates methods under predict the capacity whereas Hiley and Janbu methods on average over predict the capacity of both types of piles. Eventhough the correlation data between the CAPWAP capacity and the capacity from pile driving equations yield scattered data with lower R^2 values, ENR and Hiley methods are slightly better than other methods. Furthermore, the capacities from the average capacities from ENR and Hiley methods show a better correlation with the CAPWAP estimated capacities.

Two factors affecting the accuracy of the pile driving equations were identified to be the set and the ratio between the cross sectional area and the length of the pile. As both these parameters are increased the accuracy of the capacity predicted by the pile driving equations improves. Moreover, factor of safety to be used with different pile driving equations were estimated and presented in Table 5. The suggested factor of safety values are in agreement with the same suggested by Bowles (1996).

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