A Study on Capacity Predictions for Driven Piles

W K FUNG MSc CEng FIStructE FHKIE
Architectural Services Department, HKSAR Government
Email: fungwk@archsd.gov.hk

M K WONG MSc CEng MIStructE MHKIE
Architectural Services Department, HKSAR Government
Email: wongmk@archsd.gov.hk

C T WONG MSc CEng MICE MIStructE MHKIE
Architectural Services Department, HKSAR Government
Email: wongct@archsd.gov.hk

Since the introduction of hydraulic hammers in Hong Kong in 1995, both the local authorities and the construction industry have been trying to devise a standard method for the assessment of bearing capacity of piles driven by hydraulic hammers. This paper discusses various aspects of pile driving and presents several methods supported by site test data for the prediction of pile capacities.

Keywords: Davisson's Failure Criterion, Pile Driving Analyser (PDA), CAPWAP Analysis, Hiley Formula, Hydraulic Hammer, Pile Capacity, Driving Stress, Hammer Efficiency, Pile Settlement

Introduction

The Hiley Formula, dynamic pile tests (both PDA and CAPWAP) are commonly used in Hong Kong to evaluate the bearing capacity of piles. These are indirect methods with different degrees of accuracy. Of course, the most reliable method is the static load test, but it is costly and time-consuming. A method that is applicable to all driven piles and yet easy to use is much needed. The Hong Kong Contractor's Association (HKCA) proposed a modified Hiley Formula in 1995, to take into account of the more efficient energy transfer of the hydraulic hammer in comparison with the diesel hammer. However, its general applicability and accuracy are yet to be established. This paper will discuss the findings of a study of final sets and dynamic pile test data for over 300 Grade 55C steel H-piles (with yield strength of 430 Mpa) of size 305 x 305 x 180 kg/m driven by hydraulic hammers at 17 different sites. Predictions are then compared with 63 static load tests results. 10 of the static tests were loaded to failure in accordance with Davisson's criterion (see Appendix 1).

The objectives of this paper are:

(i) To correlate results of CAPWAP capacity predictions with static load tests;

(ii) To investigate the reliability of different pile capacity prediction methods, viz CAPWAP, Hiley Formula;

(iii) To suggest parameters and procedures to improve the accuracy of pile capacity predictions when using the Hiley Formula;

(iv) To investigate the relationship between maximum driving force and ultimate pile capacity under different site conditions;

(v) To suggest guidelines in selecting suitable hydraulic hammers.

The Correlation of CAPWAP and Static Load Test Results

Pile Bearing Capacities

The objective of this study is to investigate the reliability of CAPWAP analysis in capacity prediction as compared with the static load test. In this paper, static load tests carried out to 'failure' are as defined by Davisson's failure criterion [1]. For a meaningful comparison with the static load tests, CAPWAP results are of 'restrike' tests, rather than 'end of driving' tests. This is a logical approach as pile capacities usually change with time after installation due to soil setup or relaxation [2].

In this study, 10 steel H-piles of size 305 x 305 x 180 kg/m from 5 different Science Park Building sites were load tested to 'failure'. In order not to permanently damage the piles, the piles were loaded to Davisson's failure load or to 90% of the yield strength of the steel whichever is the lesser. Among the 10 piles tested, 7 were loaded to Davisson's failure load although 3 of them reached 90% of the yield strength of the steel before the Davisson's failure load could be identified on the load settlement curve. The results of these pile loading tests are shown in Table 1.

These results show that a good and safe correlation between CAPWAP predictions and the static load tests can be achieved.

Pile Dynamics Inc (PDI) suggests that the CAPWAP prediction may underestimate the capacity of a pile if the set per blow is small, ie less than 2.5 mm/blow [3]. The probable reason for such a phenomenon is because the soil strength has not been fully mobilised. As far as this study is concerned, the results in Table 1 show that the effect of pile capacity under-estimation for piles with set/blow less than 2.5 mm is insignificant (6 tested piles out of 8 with set/blow less than 2.5 mm have very good correlation between CAPWAP predictions and static load test results).

Pile Settlements

The reliability of CAPWAP on settlement prediction was investigated by comparing the pile settlements at 5900 KN determined by static load test results of 63 steel H-piles of size 305 x 305 x 180 kg/m from 13 different sites with the CAPWAP predictions. The results are shown in Fig 1. The ratios of the CAPWAP predictions to the measured pile settlements vary from 0.88 to 1.14, with a mean of 1.01 and a standard deviation of 0.06.

Fig 1 shows that the settlements predicted by CAPWAP are very close to those of static load tests and can therefore give a good indication of the expected load settlement behaviour of piles.

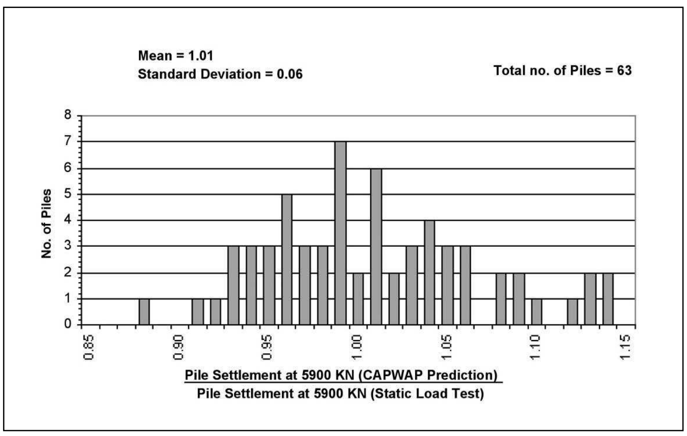


Figure 1 – Comparison of Pile Settlements Determined by Static Load Test and CAPWAP

Pile No	Embedded Length (m)	Cp + Cq (mm)	Set/Blow (mm)	Hammer Weight (W) (Ton)	Drop Height (H) (m)	$\frac{EMX}{WH}$	Ultimate Load by Static Load Test (Davisson Failure Load)	CAPWAP (KN)	$\frac{\text{CAPWAP}}{\text{Static Load Test}}$
Science Park B5, H43	21.3	37	5.7	16	1.5	0.86	> 8000 *	7500	< 0.94
Science Park B4, P186	24.0	42	2.1	16	1.5	0.95	8400	8663	1.03
Science Park B7 & B8 P800	26.5	46	0.7	16	1.2	1.02	7480	7428	0.99
Science Park B7 & B8 P519	29.2	44	1.3	16	1.2	0.96	8350	8126	0.97
Science Park B6 WP2-P1	27.6	48	3.5	16	1.8	0.72	8000	7202	0.90
Science Park B5, H75	31.1	43	2.5	16	1.5	0.85	7400	7700	1.04
Science Park B6, B2-P1	31.0	49	0.5	16	1.8	0.81	> 8800 *	8463	< 0.96
Science Park B4, P410	32.5	48	0.6	16	1.5	1.00	> 8800 *	7424	< 0.84
Science Park B9, P256	45.5	52	0.7	18	1.3	0.92	7400	7150	0.97
Science Park B9, P297	49.0	55	1.0	18	1.3	0.92	6875	7100	1.03

* The Davisson failure load was not reached at the stated load (for definition of EMX, see Eq 1).

Table 1 – Summary of Static Load Test Results

Correlation of Pile Capacity Predictions by Static Load Tests, CAPWAP, and Hiley Formula

Because of its simplicity and applicability in varied soil conditions and pile lengths, the Hiley Formula is the most commonly used dynamic formula in Hong Kong for the assessment of the pile capacity of percussive piles. The prediction of pile capacity is still subject to static load test verification. The formula is in the following form:

$$\text{Hiley Formula: } R = \frac{E_h \left(\dfrac{W + Pe^2}{W + P} \right) WH}{s + \frac{1}{2}(C_c + C_p + C_q)}$$

where
- E_h – efficiency of drop
- e – coefficient of restitution of the hammer cushion
- R – driving resistance
- W – weight of the ram
- H – drop height
- P – weight of pile and helmet
- s – set per blow
- C_c – temporary compression of cushion
- C_p+C_q – temporary compression of pile and soil

In the formula, there are two unknowns (e, E_h) while others are either known or measurable (the value of C_c is assumed to be constant, 5 mm, for the 17 sites under study).

Traditionally, the values of e and E_h are adopted from the British Code of Practice for Foundation – CP4, which reflected the technology in the early fifties. The e values commonly adopted are 0.32 - 0.4 and E_h 0.8 - 0.85 depending on the types of equipment.

With hydraulic hammers of the present technology, we can use higher values of 'e' and 'E_h'. The drop efficiency for most of popular brands of hydraulic hammers is about 95% as claimed by the manufacturers. From Steel Bearing Piles Guide by A R Biddle, SCI publication No P156 [4], e = 0.8 with Micarta plastic cushions, and the E_h for hydraulic hammers is 1.0, both values are quite high compared with those used for traditional diesel or drop hammers. Some cushions are claimed to have even higher e values, eg 0.92 for a new high stiffness plastic Monocast MC 904 cushion (this type of cushion was used for all the 17 sites under study). The e values may be verified in the laboratory by using the method suggested by the 'Standard Testing Method for Deflection Characteristics of Pile Driving Cushion Material' published by the Deep Foundations Institute [5].

For the verification of E_h , some hydraulic hammer manufacturers have carried out tests using magnetic sensors. These tests do need improvement because results show considerable scatter.

Questions are often asked as to whether the Hiley Formula is still appropriate for piling today as both materials and equipment have undergone great changes. Further questions also arise on what the appropriate parameters (e and E_h) are and how accurate the Hiley Formula is. With the questions in mind, we have carried out tests and studies described as follows:

Case 1 – Sites with Static Load Tests

Static load tests were carried out in 5 different Science Park Building sites to determine the Davisson failure load for 10 steel H-piles of size 305 x 305 x 180 kg/m. For each site, the Davisson failure load was then substituted into the Hiley Formula from which combinations of drop efficiency E_h and coefficient of restitution of hammer cushion e were back calculated (see Table 2). These parameters so obtained were used in the Hiley Formula for the prediction of the capacity of other piles installed by the same hammer on the same site. In order to check the reliability of the Hiley Formula, the capacities so calculated (totally 67

Project Title	No of Piles Studied	Average Embedded Length (m)	Average CAPWAP Capacity (KN)	Average EMX / WH	Back Analysed Parameters	
					Correlated (e)	Correlated (E_h)
Science Park Building 5	9	25.9	7997	0.82	0.76	0.95
Science Park Building 7 & Building 8	16	27.9	7543	0.96	0.92	0.98
Science Park Building 6	13	28.9	7902	0.76	0.88	0.90
Science Park Building 4	15	32.8	7786	0.93	0.90	0.95
Science Park Building 9	14	51.6	7128	0.93	0.92	0.98

Table 2 – Results of Correlation of e and E_h by Static Load Tests (For Definition of EMX, See Eq 1)

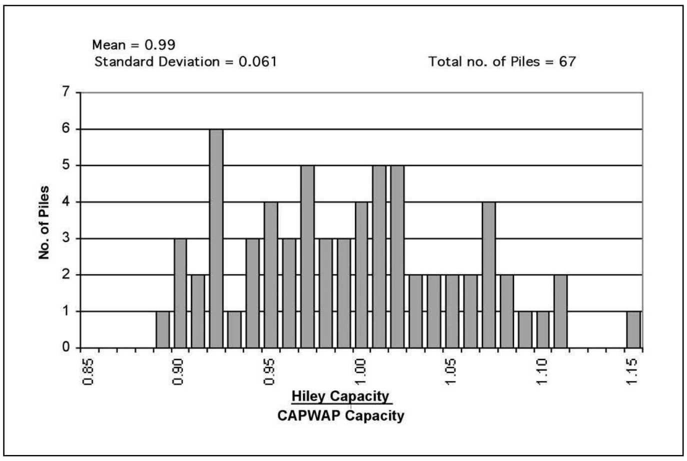


Figure 2 – Comparison of CAPWAP Capacity and Hiley Capacity Calculated Using the Correlated e and E_h Values by Static Load Tests

piles) were compared with CAPWAP predictions and the results are summarised in Fig 2. The results from the 67 piles show good agreement between the capacities obtained by the Hiley Formula and those by CAPWAP analysis, as evidenced by the ratio of Hiley Capacity/CAPWAP Capacity varying from 0.89 to 1.15, with a mean of 0.99 and a standard deviation of 0.061 only.

Case 2 - Sites without Static Load Tests

Studies were conducted on 12 other sites where static load tests had not been carried out. As such, the bearing capacities predicted by CAPWAP analysis were taken to be the failure loads. For each site, the coefficient of restitution e and drop efficiency E_h were obtained by back analysis such that the average of pile capacity predicted by the Hiley Formula equal to the average of the capacity predicted by the CAPWAP analysis. We can call the back calculation a correlation process and the e and E_h are termed 'correlated' values (see Table 3).

The capacities obtained by the Hiley Formula (using the correlated e & E_h for each site) were compared with CAPWAP predictions and the results are summarised in Fig 3. Again, the results from 246 piles show good agreement between the capacities obtained by the Hiley Formula and those by CAPWAP analysis. The ratio of Hiley Capacity/CAPWAP Capacity varies from 0.83 to 1.17, with a mean of 1.0 and a standard deviation of 0.059. The results show that most of the bearing capacity of piles obtained by the Hiley Formula deviate from their corresponding CAPWAP capacities by less than ± 10%.

While the parameters obtained in this way may not be the exact physical properties of the driving system, we can at least conclude that when these parameters are applied to the Hiley Formula, they give pile capacity predictions close to the static load tests or CAPWAP results, as noted from the results of 313 no of piles from 17 different sites. On the other hand, further research is still needed to determine the actual physical properties. Notwithstanding the comment above, these parameters are in the common range as quoted by A R Biddle and the manufacturers of hammers and cushions. It is also noted that there are variations in the E_h as claimed by different hammer manufacturers and those observed in actual performance.

In most cases, the correlated coefficients of restitution e and drop efficiency E_h are high values (refer to Results of Correlations in Table 2 and Table 3). But, in the sites in Kowloon Bay (1) and West Kowloon, the correlated parameters appear to be low. This can be explained by the fact that the Energy Transfer Efficiency of the driving system, EMX/WH, is very low for these two projects (0.74 and 0.66 respectively), (for definition of EMX/WH, see Eq 1). Therefore, the low or high values adopted should reflect the actual performance of the driving system.

The coefficient of restitution e of the hammer cushions decreases due to sustained use and the rate of aging is also affected by the way the cushion is used (a cushion used for 30 days for say 10 hours a day would deteriorate more than one used for 100 days for 3 hours a day). The results in Tables 2 and 3 show that correlated e values range from 0.76 to 0.99. The spread of e values can be explained by the fact that condition of cushions used for the 17 sites are different, therefore, correlated e with different values are expected. Some correlated e values are high (even higher than the value claimed by the manufacturer). This may be due to the actual input energy being higher than what used in the calculation as explained in the following paragraph.

It can be concluded from above studies that, provided appropriate e and E_h values are used, the Hiley Formula can be applied for the assessment of pile bearing capacities with good accuracy when hydraulic hammers are used.

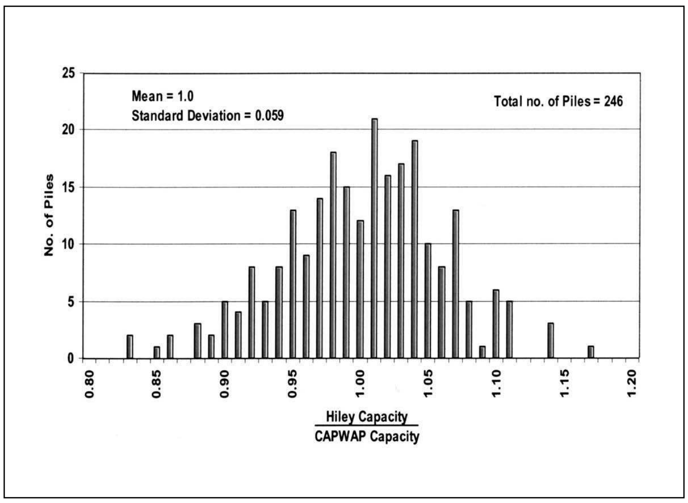


Figure 3 – Comparison of CAPWAP Capacity and Hiley Capacity Calculated Using the Correlated e and E_h Values by CAPWAP

The Practical Approach to Pile Capacity Prediction

In practice, Hiley Formula and CAPWAP analysis can be used hand in hand to control the piling works; their combined use is simple in application and gives more confidence. At the initial stage of piling works, trial/preliminary piles should be driven to enable appropriate values of e and E_h of the driving system to be determined from the ultimate load capacity predicted by the CAPWAP analysis, if static load tests have not been

Project Title	No of Piles Studied	Average Embedded Length (m)	Average CAPWAP Capacity (KN)	Average EMX / WH	100% CAPWAP Capacity		85% CAPWAP Capacity	
					Correlated (e)	Correlated (E_h)	Correlated (e)	Correlated (E_h)
Schools in Fanling	22	28.3	8630	0.91	0.80	0.93	0.55	0.90
Project in Shatin	20	30.6	8261	0.99	0.99	0.99	0.80	0.95
Schools in Tung Chung	14	34.7	8596	0.91	0.94	0.99	0.76	0.95
School in San Po Kong	15	40.0	6936	0.94	0.79	0.95	0.62	0.90
Schools in Kowloon Bay (1)	14	41.4	6298	0.74	0.83	0.75	0.55	0.75
Schools in Tin Shui Wai	18	43.2	7956	0.87	0.79	0.95	0.60	0.90
Schools in West Kowloon	14	44.7	6529	0.66	0.80	0.72	0.52	0.72
Schools in Kowloon Bay (2)	15	44.9	6761	0.90	0.85	0.95	0.67	0.90
Schools in Lai Chi Kok	20	45.7	6737	0.99	0.88	0.95	0.71	0.90
Project in Tin Shui Wai	44	49.7	7665	0.94	0.92	0.98	0.72	0.95
Schools in Tokwawan	17	50.2	6810	0.95	0.90	0.95	0.64	0.95
School in Tseung Kwan O	33	53.0	7402	0.97	0.92	0.95	0.70	0.95

Table 3 – Results of Correlation of e and E_h by CAPWAP

carried out. It is also recommended that 85% of the CAPWAP ultimate bearing capacity be used instead of the full value. This factor of 85% accounts for the possible variation of CAPWAP predictions with the static load test results and the decrease in efficiency of the driving system due to the deterioration of the condition of hammer cushion (the e value of cushion will decrease due to sustained use and the efficiency of the driving system will be lower as compared with that during the trial pile installation). Table 3 shows values of e and E_h established on this basis. For practical reasons, the e and E_h values used should not be higher than 0.65 and 0.98 respectively.

In special ground conditions piles may fail to comply with the Hiley Formula with the chosen e and E_h values following prolonged driving. There are situations where the Hiley Formula gives odd results even with e and E_h determined when measured $C_p + C_q$ and final set values are substituted into the equation. This means that the Hiley Formula falls outside the range of application. In these cases, PDA tests and CAPWAP analyses should be used. At least one of the piles with the lowest CAPWAP capacity should be load tested for verification and acceptance.

Before the start of pile driving, visual inspection of the type and quality of the hammer cushion is essential. PDA tests should be carried out for the trial piles (3% of the piles or 5 nos whichever is greater) and the Energy Transfer Efficiency of the driving system, EMX/WH, should be recorded, checked and reviewed. PDA tests should be carried out regularly during the pile construction period and changes of the Energy Transfer Efficiency should be closely monitored. This will provide a signal that the efficiency of the driving system has changed.

Normally the set measured at restrike should be less than that at final set due to build up of soil resistance. If the set values of the restrike tests are larger than those obtained during the final set, it could mean that the pile had been driven with reduced energy towards final set and an investigation should be conducted accordingly.

The Relationship between the Maximum Driving Stress and the Ultimate Pile Capacity

The maximum driving force, hence maximum driving stress on a pile during final set, is a good indicator of the ultimate pile capacity. This is because higher driving stress must come from higher pile/soil resistance, and hence give higher pile ultimate capacity. Since the maximum driving stress of a pile during final set can be measured by the PDA test directly, we have compared the driving force with the CAPWAP capacity on 272 no of piles (305 x 305 x 180 kg/m) and the results are shown in Fig 4. We can see that the ratio CAPWAP Capacity/Maximum Driving Force varies from about 1.0 to 1.2 as the nature of resistance changes from end-bearing to friction.

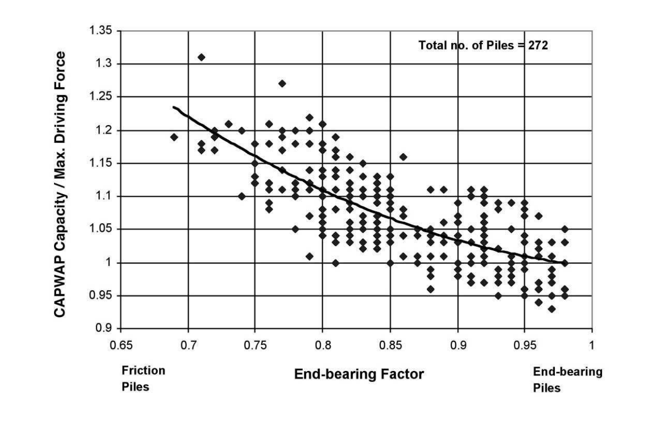


Figure 4 – The Relationship between the Ratio CAPWAP Capacity/ Maximum Driving Force and the End-bearing Factor

In Fig 4, the term End-bearing Factor is defined as follows:

$$\text{End-bearing Factor} = \frac{\text{Average Axial Force Along the Pile}}{\text{Axial Force at the Pile Head}}$$

The above relationship is established from piles driven to small values of final set (typically 3.0 mm per blow or less).

What is an Efficient Hammer?

A pile driving system is defined as a combination of pile driving hammer, pile, helmet and hammer cushions. The performance of a pile driving system is governed not only by the drop efficiency but also by the individual and combined effects of each of these components [6].

The efficiency of a hammer can be measured by using PDA methods with the Energy Transfer Efficiency (ETR) defined as:

$$ETR = EMX/WH \qquad \text{Eq 1}$$

where EMX is the maximum energy transmitted past the transducers (at pile head) and is calculated by the PDA from dynamic measurements (velocity and strain in the steel, and hence stress), W is the ram weight and H is the drop height.

Normally, the drop efficiency, E_h, has the greatest effect on ETR.

$$E_h = \frac{\frac{1}{2} mv^2}{WH} \qquad \text{Eq 2}$$

where m is the mass of the ram, v is the ram velocity just before impact.

The ETR is a measure of the 'pile driving system' overall performance and not just of the hammer. ETR is closely related to the coefficient of restitution e and the drop efficiency E_h (refer to Results of Correlations in Table 2 and Table 3).

Sometimes, the ETR measured may appear to be unreasonably high. This is because the actual energy input may be larger than that used in the calculation due to the following reasons:

(i) During final set, the ram is raised to a position higher than the required level (it is very difficult to raise it to the exact position).

(ii) The temporary compression of the pile, soil and hammer cushion ($C_p + C_q + C_c$) and the permanent set allow an extra distance for the ram to travel.

Due to (i) and (ii) above, the actual drop height of the ram may be 5 to 10% higher than that assumed in the calculation.

In Table 2 and Table 3 above, we can see that hammers used in over 70% of the sites had an ETR greater than 90%. It is also worth noting that the variation of ETR among hammers is large, from 66% to 99%. Therefore, it is essential that each set of driving equipment be assessed, to determine the appropriate values of e and E_h.

How to Choose a Suitable Hammer for a Piling Job?

It is important to use a hammer with suitable weight and drop height to successfully drive a pile. A heavy hammer may damage short piles while a hammer with inadequate energy cannot drive long piles to the required depth and capacity. The hammer chosen should be compatible with the size and length of the pile.

From our experience of driving steel H-piles with hydraulic hammers, a maximum driving stress between 280 MPa (0.65 fy) and 350 MPa (0.8 fy) for grade 55C steel H-pile during the final set will give the desired results. Too high a stress may damage pile while too low a stress implies the pile has not been driven to the resistance commensurate with the required bearing capacity.

A plot of the embedded pile length vs EMX for predominantly end-bearing piles (305 x 305 x 180 kg/m) with maximum driving stresses between 280 and 350 MPa during the final set is shown in Fig 5. The case for predominantly friction piles (305 x 305 x180 kg/m) is shown in Fig 6. These stresses are calculated from the strains measured during final set, multiplied by the elastic modulus of steel.

In Fig 5, we can see that a 16 Ton hammer, a 1.5 m drop with 95% Energy Transfer Efficiency (ie EMX = 228 KN-m) is suitable to drive predominantly end-bearing piles of 2950 KN working load with lengths between 36 m and 46 m. Fig 6 reveals that the same hammer is suitable to drive predominantly friction piles with lengths between 29 m and 42 m. Predominantly end-bearing piles may be defined as piles with an End-bearing Factor equal to or greater than 0.9 and friction piles are piles with an End-bearing Factor equal to or less than 0.85.

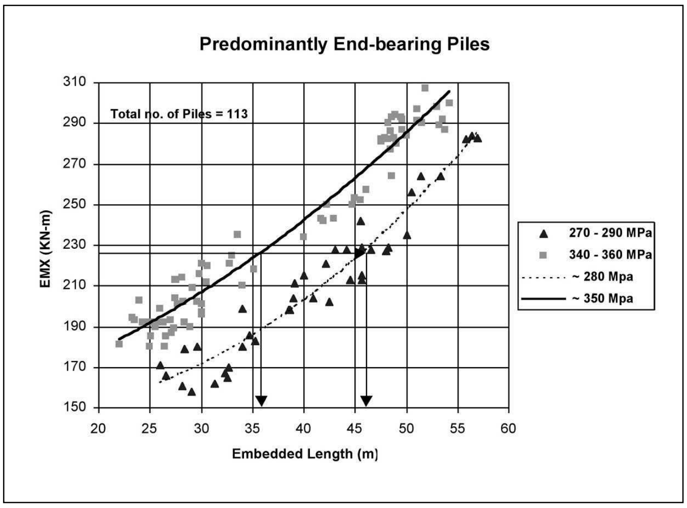


Figure 5 – Relationship between Embedded Pile Length and Energy Delivered to the Pile (End-bearing Piles)

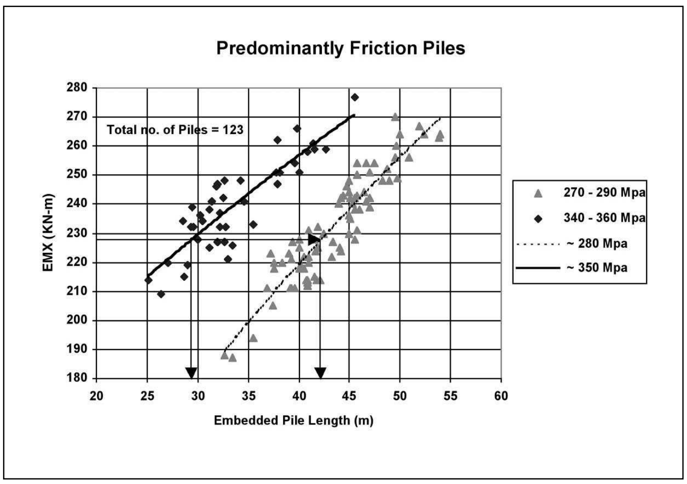


Figure 6 – Relationship between Embedded Pile Length and Energy Delivered to the Pile (Friction Piles)

Fig 7 shows the superimposition of Fig 5 and Fig 6. The results indicate that for a given embedded pile length and hammer energy, the driving stresses in end-bearing piles are higher than that in friction piles.

The Relationship among $C_p + C_q$, Embedded Pile Lengths (EL) and Maximum Driving Stress

Observations from site measurements indicate that the value of temporary compressions $C_p + C_q$ depends on the pile length, the maximum driving stress and the nature of resistance to driving. The ratio $C_p + C_q/EL$ is a function of the following factors:

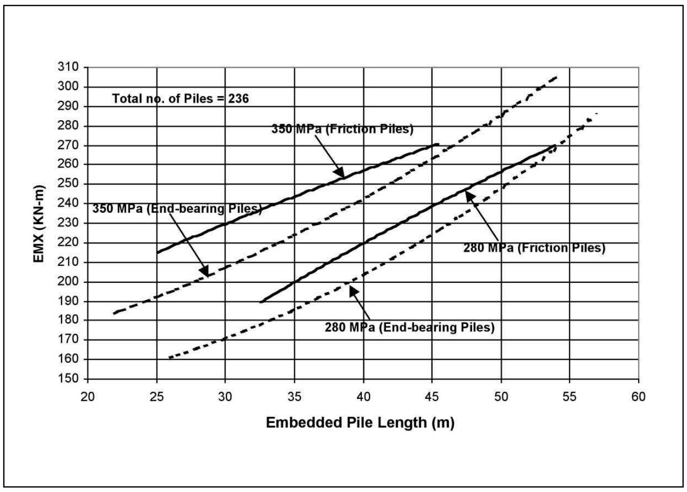


Figure 7 – Relationship between Embedded Pile Length and Energy Delivered to the Pile (End-bearing and Friction Piles)

(i) The maximum driving stress of the pile (the higher the driving stress, the larger the ratio $C_p + C_q$/EL).

(ii) The force distribution along the pile shaft and the toe ($C_p + C_q$/EL is high for end bearing piles and low for friction piles).

Fig 8 shows the relationship of $C_p + C_q$/EL and maximum driving stress. The data are obtained from strain measurements on 276 no of piles (305 x 305 x 180 kg/m) at final set. The nature of resistance (end-bearing vs friction) to driving accounts for the scatter of the ratios $C_p + C_q$/EL for a given driving stress. In choosing a suitable hammer weight for a particular project, an appropriate estimate of the $C_p + C_q$ value should be used and Fig 8 can provide some guidance.

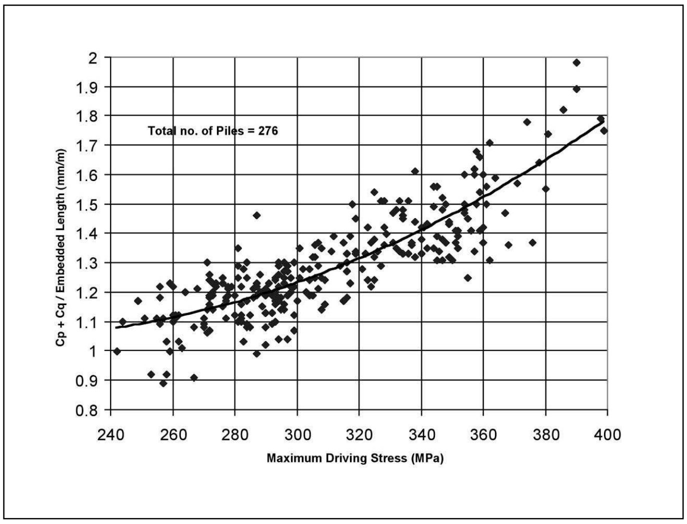


Figure 8 – Relationship between the Ratio $C_p + C_q$/Embedded Pile Length and the Maximum Driving Stress

Conclusions

(i) Based on the static load test results, it is noted that CAPWAP analysis is a fairly accurate method for pile capacity prediction.

(ii) CAPWAP analysis can give good indications of the expected load settlement behaviour of piles.

(iii) PDA tests are useful for the assessment of pile driving stresses, pile integrity and hammer performance.

(iv) PDA tests require good quality measurements. CAPWAP analyses should be performed by properly trained and experienced people.

(v) It has been shown that, provided appropriate e and E_h are used, the Hiley Formula can be applied in the assessment of pile bearing capacity with good accuracy when hydraulic hammers are used.

(vi) The efficiency of the hammer drop E_h and the coefficient of restitution of the hammer cushion e can be verified by using CAPWAP analysis of trial piles. The combination of E_h and e shall be chosen such that when these values are substituted into the Hiley Formula, the average predicted bearing capacity of the trial piles is not higher than 85% of the average CAPWAP capacity.

(vii) In most cases, the correlated coefficients of restitution e and drop efficiency E_h are high values indicating an efficient hammer. In some cases, the correlated values are low because the EMX/WH of the driving systems are low reflecting the poor performance of the driving system.

(viii) It has been shown that a suitable selected hammer should produce a maximum driving stress approximately between 280 MPa (0.65 f_y) and 350 MPa (0.8 f_y) for grade 55C steel H-piles during final set.

(ix) Sometimes, the Energy Transfer Efficiency, EMX/WH, measured seems to be high. This is because the actual drop height of the ram may be up to 5 to 10% more than that assumed.

(x) The findings of this study are from steel H-piles of size 305 x 305 x 180 kg/m. Their applicability to other sizes of steel H-piles or other types of piles needs further investigation.

References

1. Davisson, M. T., (1972), "High Capacity Piles", Proceedings, Lecture Series, *Innovations in Foundation Construction*, SM & FD, ASCE, Illinois Section, Chicago.
2. Likins, G., Rausche, F., Thendean, G., and Svinkin M., "CAPWAP Correlation Studies," Fifth International Conference on the Application of Stress-Wave Theory to Piles, Orlando, FL, 1996.
3. Pile Dynamics, Inc., (2000). "Pile Driving Analyzer Manual." *4535 Emery Industrial Parkway*, Cleveland, OH 44128.
4. Biddle, A. R., The Steel Construction Institute, (1997). "Steel Bearing Piles Guide." Publication No. P156.
5. Deep Foundations Institute, (1986). "Standard Testing Method for Deflection Characteristics of Pile Driving Cushion Material." P. O. Box 281, Sparta, New Jersey 07871.
6. Abe, S., and Thendean, G., "Hammer Performance Evaluations." Fifth International Conference on the Application of Stress-Wave Theory to Piles, Orlando, FL, 1996.

Appendix 1

Davisson's Failure Criterion

Davisson's failure load of a pile of normal dimension, approximately 300 mm wide, is defined as the load corresponding to the settlement which exceeds PL/AE + D/120 + 4 mm.

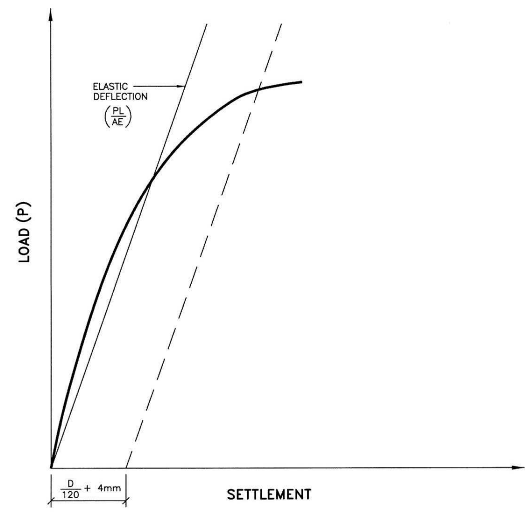
Where P = Pile load

L = Nett length of pile

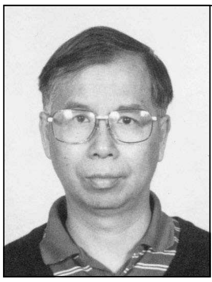
A = Cross sectional area of pile

E = Young's modulus of pile

D = Diameter of circular pile or least lateral nominal dimension of other pile in mm



INTERPRETATION OF PILE LOAD TEST



W K FUNG

Ir W K Fung graduated from the then Hong Kong Technical College in 1966. After working for Palmer and Turner for 4 years, he joined the then Public Works Department and worked as Assistant Structural Engineer in the Buildings Ordinance Office. Since his transfer to the Architectural Office in 1972, he has worked his way up to his present rank of Assistant Director (Structural Engineering) of the Architectural Services Department. Between 1997 and 2002 he served as Chairman of the Standing Committee on Concrete Technology. His main interests are foundations and material science. He is currently Chairman of the Materials Division.

C T WONG

Ir Wong Chi-tong is a senior structural engineer of the Architectural Services Department. He graduated from the Hong Kong Polytechnic in 1976. Since then, he undertook civil and structural engineering training in Palmer and Turner and became a chartered engineer in 1980. Mr Wong joined the Government in 1981 working in Arch SD responsible for the design and construction of various types of building structures. Mr Wong has completed many school buildings, markets, offices, in-door game halls, swimming pool complexes and sport grounds. He has a wide range of experience in using different construction materials, eg concrete, structural steel.

M K WONG

Ir M K Wong is a structural engineer of the Architectural Services Department. After graduating from the Hong Kong Polytechnic in 1985, he joined the Architectural Services Department and worked as Structural Engineering Graduate. He became a chartered engineer in 1989 and obtained a MSc degree in Civil Engineering from the University of Hong Kong in 1994. His main interests are dynamic pile testing and related research work.