Discussion on Observations on Using the Energy Obtained from Stress-wave Measurements in the Hiley Formula

by W K FUNG, C T WONG and M K WONG *(HKIE Transactions Vol 12 No 4 pp 19-22)*

The authors are commended for their continued efforts in promoting the use of hydraulic hammers for pile driving in Hong Kong. As indicated in this paper and a paper published earlier (Fung et al, 2004), the authors highly recommended the use of the CAPWAP method for determination of the ultimate capacity of driven piles. In this paper, the authors compared the accuracy of the pile capacity predicted by CAPWAP analysis and the Modified Hiley Formula. It should be noted that the so-called Modified Hiley Formula is the same formula recently advocated by the Hong Kong Construction Association (HKCA) in 2004 in the report entitled 'The use of hydraulic hammer for driven piles'. Although commonly used, the term 'Modified Hiley Formula' is considered to be somewhat misleading as the modified pile driving formula (Eq 1 in the paper) deviates drastically from the original concept of the Hiley formula. In this discussion, we will call this pile driving formula the HKCA 2004 formula.

Most predictive tools have limitations with varying degree of inaccuracies. While there are many publications supporting the proposition that the sophisticated CAPWAP model can produce a much better prediction of the ultimate capacity of piles, there are also many which suggest that simple pile driving formulas can give reasonably accurate predictions (eg Olson & Flaate, 1967; Tejchman & Klos, 1984; Broms & Lim, 1988; Paikowsky & Chernauskas, 1992; Zadroga & Gwizdala, 1992). It is despite the fact that conventional pile driving formulas, including the HKCA 2004 formula, are often criticised for their inaccuracy from a theoretical standpoint because they cannot account for the dynamic effect of pile driving.

A simple probabilistic model for a predictive tool of pile capacity can be formulated as (Li et al, 1993).

$$S = \beta R \tag{A}$$

R is the predicted capacity, β the bias factor and S the observed pile capacity measured by loading test. As all predictive tools are subject to model errors and uncertainties, the bias factor β and hence the predicted pile capacity R can be treated as a random variable. An unbiased predictive tool can be taken as a model with β having a mean value equal to 1.0, ie the predictive tool gives, on average, the correct pile capacity. A good predictive tool is one which has a bias factor β with a mean value close to 1.0 (ie nearly unbiased) and a small coefficient of variation (COV).

Fig 1 compares pile capacities predicted by CAPWAP and the HKCA 2004 formula with the measured capacity. It comprises data in Appendix A of the authors' paper and additional data obtained from other sites by the writers. In all cases, the pile capacity is defined as the Davisson failure load. The following observations are made from Fig 1:

a. CAPWAP analysis can significantly underestimate the pile capacity by as much as 35%. CAPWAP analysis is therefore highly biased towards the conservative side.
b. The predictions made by the HKCA formula are biased towards the unsafe side, with data ranging from about -15% to +25% of the pile capacity.

Fig 1 indicates that CAPWAP is not necessarily a better tool than the simple HKCA 2004 formula in terms of accuracy. It may be argued that the former is biased towards the conservative side while the latter towards the unsafe side, and hence CAPWAP analysis is better. The writers' views are:

a. If the bias is significant, final set tables formulated using CAPWAP will become unworkable even if the bias is on the safe side. While the data collected by the authors tends to focus on Grade 55C 305 x 305 x 180 kg/m H-piles, it may not reflect the inaccuracy of the CAPWAP analysis for piles with higher design capacities.
b. The mean bias of the HKCA 2004 formula is about 10%, which is not considered to be significant. Although the required minimum factor of safety for driven pile is 2.0, local contractors will usually aim at a higher target factor of safety in order to pass the stringent residual settlement criterion adopted in Hong Kong (Li et al 2003; Li, 2005a & b). The error arising from a mean bias of 10% can often be offset by the higher factor of safety targeted by the contractors. When further data on the HKCA 2004 formula is collected for analysis, a correction for the bias can easily be made as follows:

$$R = b\ EMX / (s + {}^{1}/_{2}\,(c_p + c_q)) \tag{B}$$

where b is the bias factor.

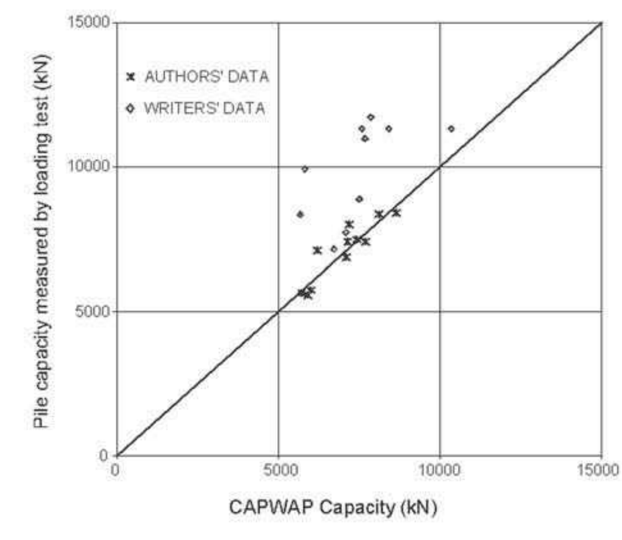

Figure 1a – Comparison of Pile Capacity Predicted by CAPWAP with Static Capacity

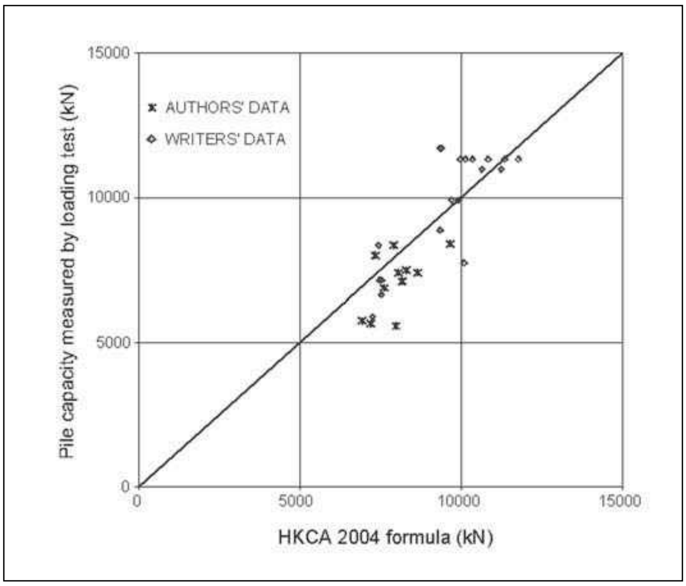

Figure 1b – Comparison of Pile Capacity Predicted by HKCA 2004 Formula with Static Capacity

Given the above, both CAPWAP and the HKCA 2004 formula require bias factors to account for their biases. Once such improvements are made, both approaches could well be adopted as practical tools for formulating the final set table.

There are four elements which characterise the current practice of installation of driven piles in Hong Kong, viz.

a. the pile driving formula used for determining the final set table

b. definition of ultimate capacity

c. the pile acceptance criteria

d. the rules for setting the applicable range of allowable maximum final set values in the final set table

Modernisation of the current practice of driven piles requires rationalization of all these four elements rather than just the choice of the most accurate pile driving formula (Li, 2005b).

Pile behaviours are highly complex. As argued by Li (2005b), all approaches for predicting the pile capacity are, to a certain extent, deficient in terms of accuracy. Apparently, there is no point in claiming that the HKCA 2004 formula is more accurate than other approaches or vice versa. CAPWAP analysis is certainly more complex than the HKCA 2004 formula, but the complexity with which CAPWAP is formulated and the numerous assumptions involved may not necessarily make it more reliable than the semi-empirical HKCA 2004 formula. The choice of the tool for predicting pile capacity is very much an individual preference.

As discussed by Li et al. (2003) an Li (2005a,b) and HKCA (2004), the impediment encountered by piling contractors in Hong Kong is the very stringent pile acceptance criteria for residual settlement and the restrictions currently imposed for formulating the final set table. To improve the situation, the focus should be shifted to reviewing whether such restrictions could be lifted or relaxed.

Finally, the Writers would like to address the variation of the ratio of predicted pile capacities. For ease of discussion, we denote the capacity predicted by CAPWAP by R_C and the capacity by the HKCA 2004 formula by R_H. In the prediction, the Authors observe a large variation of the ratio R_H/R_C, apparently assuming the predicted capacity R_C as error-free. With such a large variability, the readers may tend to think that the HKCA 2004 formula is less accurate. However, it must be pointed out that a large variation in the ratio of R_H/R_C can result from the inaccuracy of either CAPWAP or the HKCA 2004 formula, or both. If the ratio R_H/R_C varies over a large range of 0.81 to 1.65 as in Figure 5 of the Authors' paper, the reciprocal of this ratio (i.e. R_C/R_H) will also vary over a large range of 0.6 to 1.23. Therefore, one cannot simply use the variation of R_H/R_C or R_C/R_H to conclude which approach is more accurate.

We could examine this issue in greater depth from a probabilistic point of view. Let us denote the bias factors for CAPWAP analysis and the HKCA 2004 formula by β_C and β_H respectively. A more objective way to compare the variability of predicted capacity is to compare the COV of β_C and β_H, rather than the COV of the ratio of predicted capacities. For a pile which has reached the Davisson failure load, the bias factor for that pile can be computed as $\beta_H = S/R_H$ or $\beta_C = S/R_C$ as appropriate.

The followings are results obtained based on the data on Figure 1.

HKCA 2004 formula, β_H		CAPWAP, β_C	
No of piles	COV (%)	No of piles	COV (%)
29	13.1	21	19.5

The above data suggests that the variability of the bias factor for CAPWAP analysis is comparable to that of the HKCA 2004 formula, at least for the data available to the writers.

The ratio of predicted capacities is in fact the ratio of bias factors for the two different predictive models. If Z is the ratio of two random variables X and Y, ie Z = X/Y. Using the Taylor's series method as discussed, for instance, in Ang & Tang (1975), it can be proved that the COV of Z can be approximated by $\Delta_Z = [(\Delta_X)^2 + (\Delta_Y)^2]^{1/2}$, where Δ_Z is the COV of Z and so on. According to this formula, the COV of Z is always higher than that of X and Y. For instance, if the COVs of X and Y are the same, the COV of Z will be about 40% higher than that of X or Y. Presenting the data in the format of either R_H/R_C or R_C/R_H will result in a large spread of the presented data. One is easily misled to perceive that the data R_H or R_C is more variable than it actually is.

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