The Assessment of Chin Method Based on Pile Static and Dynamic Load Test Results

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Abstract

Driven-pile foundations are frequently used in industrial projects in southwest lowlands of Iran. Static pile load test to failure is the ultimate procedure available to examine the capacity of piles. Being expensive and time-consuming, the procedure is often submitted for the application of a load to a certain factor (most often two) times the contemplated design load. In fact only a proof test is carried out while the ultimate capacity remains unknown. This paper examines the performance of chin's recommendations on the interpretation of pile static load test results. Also the ability of this method in predicting the proportion of shaft capacity is discussed by using static and dynamic load test results. The sites at which this study was conducted are located on the southwest of Iran in Khuzestan and Lorestan province. Case history analyses of 22 load-tested driven piles at four sites are presented. Chin method gives a very good prediction of ultimate capacity except the cases by plunging failure. The reliability of the Chin prediction improves when the last measured gross movement approaches 10% of the pile diameter. If head movement exceeds 5% of pile diameter Ultimate capacity predicted by Chin is in the range of 90% to 112% of measured capacity. The Chin method over predicts significantly the shaft resistance when the load is mainly resisted by the toe; When the shaft capacity is greater than 60%, predicted shaft capacity is in the range of 85% to 120% of the measured value.

Keywords: Clayey Deposits, Pile Bearing Capacity, Chin Method, Dynamic Load Test, Static Load Test

1. INTRODUCTION

Proper estimation of pile bearing capacity has always been of great concern for geotechnical engineers. When designing pile foundations, static design equations, methods based on in situ tests, static load tests (SLT) and dynamic load tests (DLT) may be employed to estimate the axial bearing capacity of single piles. The study of driven-pile foundation and their behavior under static loads dates back to the late 19th century. Static load tests were the first attempt at verifying the design and determining the ultimate capacity of a driven pile. Pile dynamic testing using PDA equipment has become quite common in conjunction with wave equation analysis of piles, in particular on driven piles. For the engineer the load test is considered satisfactory when it has been possible to determine the ultimate capacity Q_u, the pile movement under working load Q_w, the shaft Q_s and toe Q_p capacity under Q_u [1]. It is usually very expensive and often impractical to extend a load test on pile until collapse. A proof test, a limited form of the static load test, is used to determine the pile performance in supporting a service load and usually carried out to twice the design load.

Different methods exist for the interpretation of the ultimate pile capacity based on a pile load test to failure. This methods relate to different principles, such as limiting maximum movement and ratio of movement to load. Terzaghi (1942) that the ultimate load of a pile be defined as that load which it will carry with the movement equal to 10% of its diameter or side [3]. Authors such as Van der Veen (1953), Brinch Hansen (1963), Chin (1970), Davisson (1972), Mazurkiewicz (1972), Fuller & Hoy (1977) and others, have proposed methods based on mathematical or graphical approaches [1]. A comprehensive comparative study of the nine methods most commonly used in practice has been carried out by Fellenius (1980) [4]. Among these methods two relate to the shape of the load-movement curve and hence can be conceptually used for determining the ultimate capacity of piles from proof test information. This method include Chin's method [5, 6 and 7] and the brinch-Hansen method [8].

In Iran, Driven piles have been introduced and used as a feasible foundation system in the construction industry since the 1990's however; the research studies carried out on their suitability for Sudanese soil conditions are still limited. Field test programs comprised mainly of static and dynamic load tests were undertaken at different sites in Iran. The present work aims to study the performance of Chin's recommendations on load tests with limited movement and the ability of his method in predicting the proportion of shaft load. The soil deposits at the study sites are dominantly fine grained cohesive.

2. SITE CONDITIONS AND PILE LOAD TESTING

The sites at which this study was conducted are located on the southwest of Iran in Khuzestan and Lorestan province. The site investigation included drilling boreholes, carrying out in-situ SPT and CPT and performing laboratory testing of representative soil samples. Field test programs comprised mainly of static and dynamic load tests were undertaken at this sites. Four selected projects are described below:

- Arvand Jahan Ara Steel (AJS) Making Plant area, near Khoramshahr city in Khuzestan province: Soil layers in the study area generally consist of clayey layers with alternates of silt and sand. A detailed field testing program was planned for the 400 × 400 mm square driven piles including dynamic load testing (PDA), CAPWAP analysis, and static load testing. A total of 13 piles were driven for the dynamic and static load testing program. All piles were tested both at "End Of Initial Drive" (EOID) and "Beginning of Restrike" (BOR) condition by PDA equipment. Static load test performed on all piles [9].
- BIDBOLAND II Gas Refinery project, near Mahshahr city in Khuzestan province: Soil layers in the study area generally consist of clayey layers. A detailed field testing program was planned for the Pre-stressed close-end spun concrete piles with the circular outer diameter of 450 and 600 mm including dynamic load testing (PDA), CAPWAP analysis, and static load testing. A total of 3 piles were driven for the dynamic and static load testing program [10].
- Mechanized Terminal of Cereals at Bandar-e-Imam, near Sarbandar city in Khuzestan province: Soil layers in the study area generally consist of stiff to hard clayey layers with alternates of silt and sand. A detailed field testing program was planned for the 400 × 400 mm square driven piles including dynamic load testing (PDA), CAPWAP analysis, and static load testing. A total of 2 piles were driven for the dynamic and static load testing program [11].
- Water Treatmen of Aleshtar city, near Khoramabad city in Lorestan province: Soil layers in the study area generally consist of medium to hard clayey layers. A detailed field testing program was planned for the 400 × 400 mm square driven piles including dynamic load testing (PDA), CAPWAP analysis, and static load testing. A total of 4 piles were driven for the dynamic and static load testing program [12].

A total of 22 loading tests carried out by the authors since 2015, have been examined. All tests were run under a QLT procedure up to a head movement greater than 10% of the pile diameter and without intermediary unloading and reloading cycle. The load was always checked with a load cell and the movements were measured with the help of dial displacement indicators linked to fixed reference beams. A dynamic testing program was planned and conducted on 22 piles. Dynamic testing is a high strain test performed by PDA (Pile Driving Analyzer) at the same time of driving the piles at "End Of Initial Drive" (EOID) condition and "Beginning of Restrike" (BOR) condition.

3. CHIN METHOD

In Chin's method [5, 6 and 7] it is assumed that the load-movement (Q vs. s) relationship is hyperbolic. It has been expressed by chin in the form:

$$s/Q = C + ms \tag{1}$$

Using different notation, equation [1] becomes:

$$s/Q = \left(\frac{ds}{dQ}\right)_{Q=0} + \frac{s}{Q_{asympt}} \tag{2}$$

Where for both equation:

Q: the applied load on the pile head

s: the pile head gross movement

m: the slop of the plot corresponding to the inverse of the asymptotic value of ultimate capacity Q_{asympt}.

C: a constant corresponding to the initial slop of the load-movement curve plotted in linear coordinates.

Plot of s/Q (vertical axis) vs. Q obtained from a routine pile test (Figure 1) becomes generally:

- Two straight lines plot with an A and B part as illustrated on Figure 1a & b. This relationship is supposed to correspond to piles supported by combined shaft friction and end bearing. Because toe resistance needs higher settlement to be mobilized than shaft resistance [5], it has been suggested that the first part (A) would represent shaft resistance while the second part (B) would represent total load. The validity of these assumptions will be shown later. This model was established in 19 piles behavior.
- Single straight line as shown on Figure 1c. This relationship is supposed to model the behavior of a pile supporting the load mainly through shaft friction or purely in end bearing [6]. Because the linearity is not always explicit for the first points of the relationship, Chin (1972) recommended that these are rejected when determining C and m [5]. This model was established in 1 pile behavior.
- S shape curve as shown on Figure 1d. This model was established in 2 piles behavior.

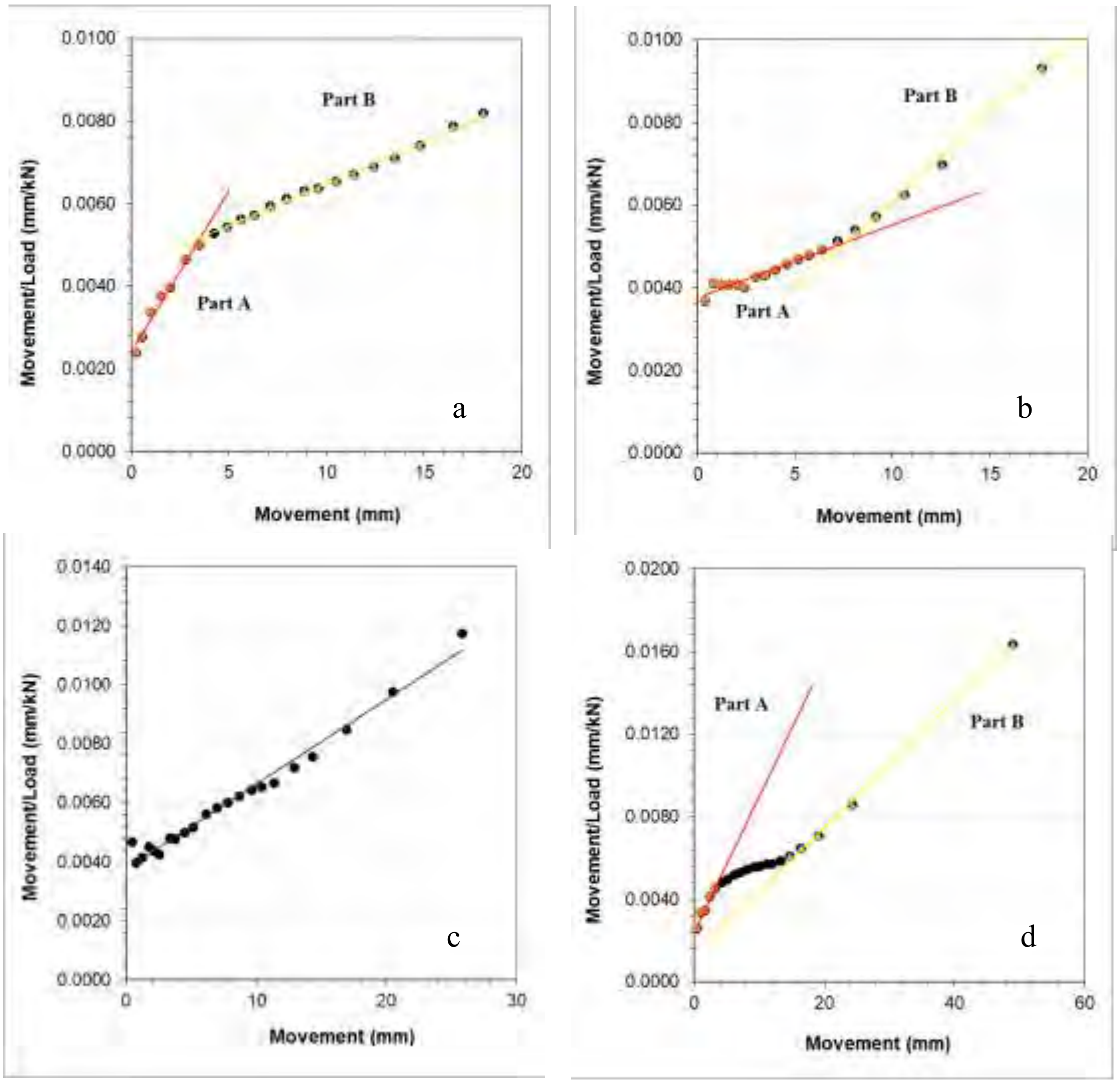

Figure 1. Various relationship s vs. s/Q diagram (a) Bilinear relationship (b) Inverse A part bilinear relationship (c) single straight line relationship (d) S shape relationship

4. Comparison of Static and Dynamic Load Test of Pile

Signal matching analysis such as CAPWAP is considered a standard procedure for the capacity evaluation from high strain dynamic pile testing data. Reliable correlations for long term capacity from dynamic tests with static load tests require simple guidelines. For driven piles in clay, dynamic tests should be performed during a restrike after a sufficient wait period to allow soil strength changes to stabilize [9]. Ideally, the time after installation for the dynamic test should be similar to that of the static test, and preferably as soon as possible after the static test completion. However, time pressures in the construction schedule often require dynamic testing after a limited wait time, and the full "setup" increase is then not achieved.

In this study, the static load tests were carried out 14 to 124 days after the initial drive, hence the setup effects were already included in the measured pile capacities. The DLT tests, however, were carried out at EOID and different time after pile driving vary from 1 to 105 days. The results derived from the BOR tests is comparable with the SLT tests, compared to that obtained from the EOID test also the time for the BOR tests is not similar to that of SLT. Figure 2a shows the comparison of interpreted pile capacity of test piles from DLT (with CAPWAP analyses) and SLT (using Davisson Offset Limit to calculate bearing capacity) results. For better comparison, we should conduct DLT and SLT at the same time as soon as possible. Due to construction problems, this is not possible most of the time and DLT conduct earlier than SLT. Hence ultimate capacity measured by SLT is greater than DLT one due to soil setup phenomena as shown in figure 2a.

Different relations have been proposed to estimate setup effect. In most of the proposed relations, a constant coefficient has been established to correlate the total capacity or skin friction to the logarithm of time [10]. Skov and Denver (1988) relation has been applied in most studies in literature. By performing EOID and BOR tests at various time after pile driving and using Skov and Denver (1988) relation, we be able to predict ultimate capacity at any time after driving. Figure 2b shows comparison of SLT results and extrapolated capacity from Skov and Denver relation for the same time as SLT.

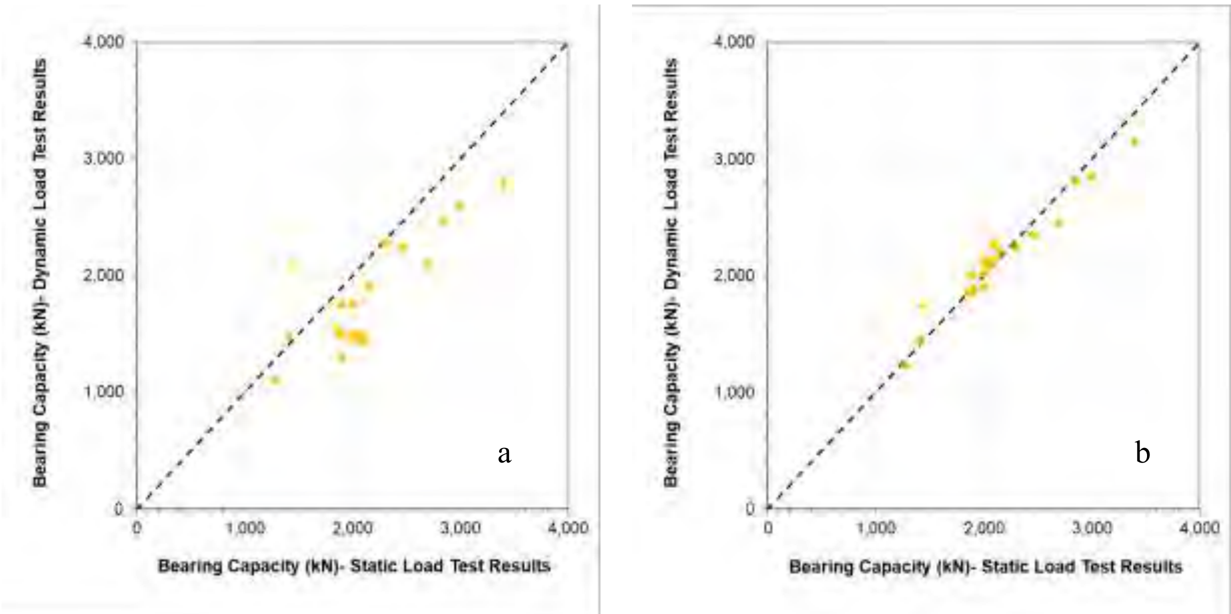

Figure 2. Comparison of SLT and DLT results (a) BOR and SLT tests conducted in different time after driving (b) Predicted simultaneous BOR capacity with SLT

5. Interpretation of SLT by Chin Method

To examine the performance of the Chin method in determining the ultimate resistance, two different approaches have been followed: (1) taking into account the complete load-movement curve and (2) considering a partial load-movement curve obtained by removing gradually the last points.

Determining the ultimate resistance from the complete curves

To each test, s vs. s/Q has been plotted. After identifying the second part of the load-movement curve (part B), Chin parameters (C and m) have been calculated. The Chin ultimate capacity defined as calculated load by s/D=10% in Equ.1 ($Q_{u,\ Chin\ 10\%}$). This ultimate capacity has been compared to measured ultimate capacity according to Terzaghi (1942) (the load which it will carry with the movement equal to 10% of pile diameter, $Q_{u,conv}$). Compression of $Q_{u,\ Chin\ 10\%}$ and $Q_{u,conv}$ is shown on Figure 3. As shown in this figure the Chin method gives a very good prediction of ultimate capacity, except 3 cases which chin capacity error exceeds than 10%. In these 3 cases plunging failure has been occurred.

One of the more acceptable method in SLT results interpretation is Davisson Offset Limit (DOL). This method in more conservative rather than conventional 10% method. After determining Chin parameters, for different ratio of s/D, the Chin load according to Equ.1 has been calculated. This load was compared whit Q_u according to DOL in Figure 4. According to this Figure in s/D ratio about 6% Q_u calculated by Chin method and DOL are similar.

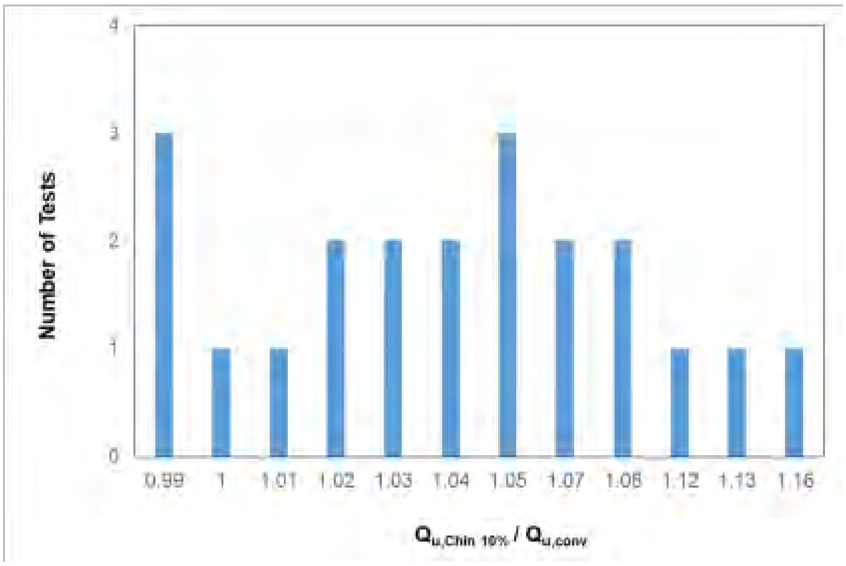

Figure 3. Comparison of $Q_{u,\ Chin\ 10\%}$ and $Q_{u,conv}$

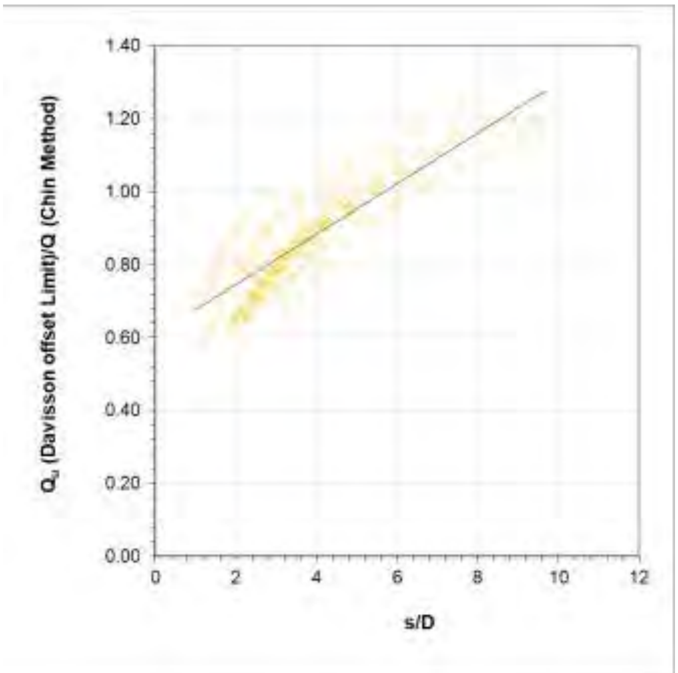

Figure 4. Comparison of Q_u (DOL method) and load calculated by Chin method in various ratio of s/D

Determining the ultimate resistance from partial load-movement curves

As illustrated before it is usually very expensive and often impractical to extend a load test on pile until collapse. However, in order to determine the working load, there is need to know what the ultimate load would be if the load test had been extended to failure. To examine the Chin method in prediction load-movement behavior of non-failed load tests, the load-movement curves have been progressively altered by removing, one after another. Figure 5a to c shows this process on a square concrete pile (D=0.4m and L=20.5m). By removing two last points, calculated ultimate capacity is 2343 kN while by considering all data this capacity is equal to 2412 kN.

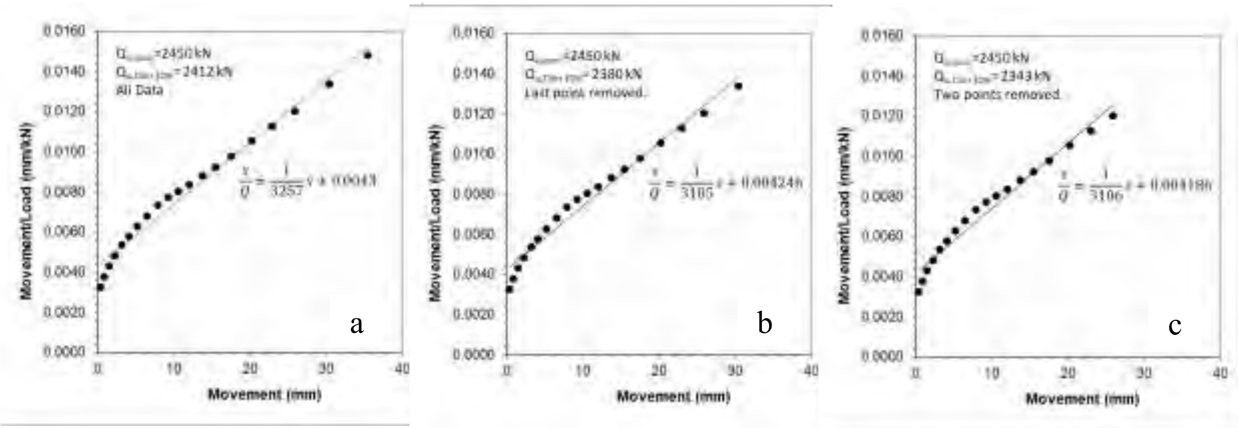

Figure 5. s vs. s/Q plot for driven square concrete pile (D=0.4m, L=20.5m) (a) All data (b) By removing last point (c) By removing two points

As explain before s vs. s/Q plot has three type including two straight lines plot with an A and B part (4 piles with inverse A Part relationship and 15 piles with typical relationship), single straight line (1 pile) and S shape relationship (2 piles). By doing mentioned process above on 4 piles with inverse A part relationship and 2 piles with S shape relationship, Figure 6 was obtained. Also Figure 7 shown analyzing data from 15 piles with typical relationship. The reliability of the Chin prediction improves when the last measured gross movement approaches 10% of the pile diameter. In static load tests, if head movement exceeds 3% of pile diameter Ultimate capacity predicted by Chin is in the range of 79% to 103% of measured capacity. As soon as head movement exceeds 5% of pile diameter Ultimate capacity predicted by Chin is in the range of 90% to 112% of measured capacity.

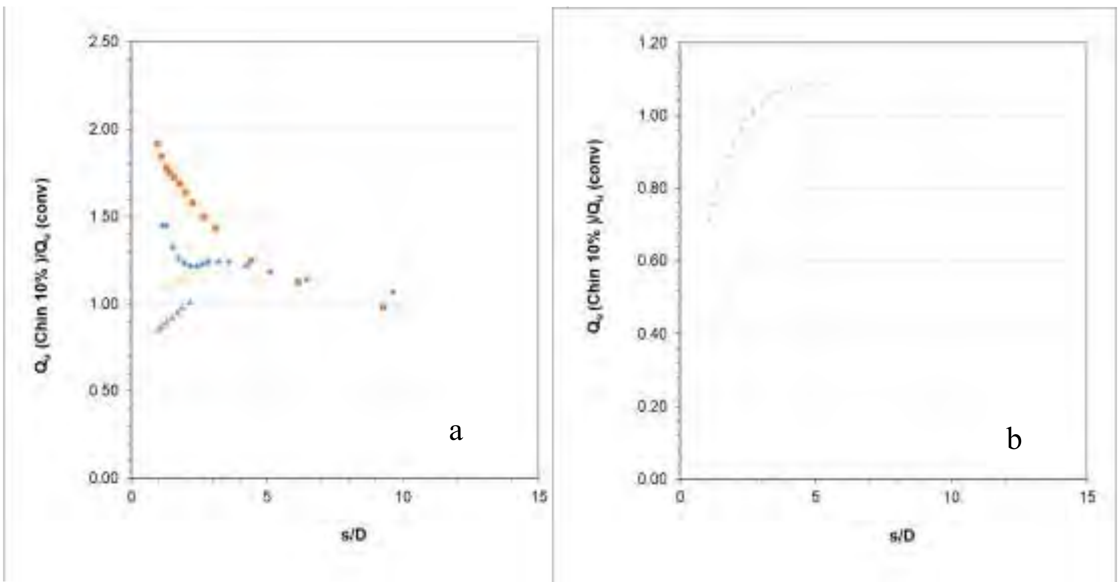

Figure 6. Performance of Chin method in prediction of non-failed SLT (a) Piles with invers A part (b) Piles with S shape behavior

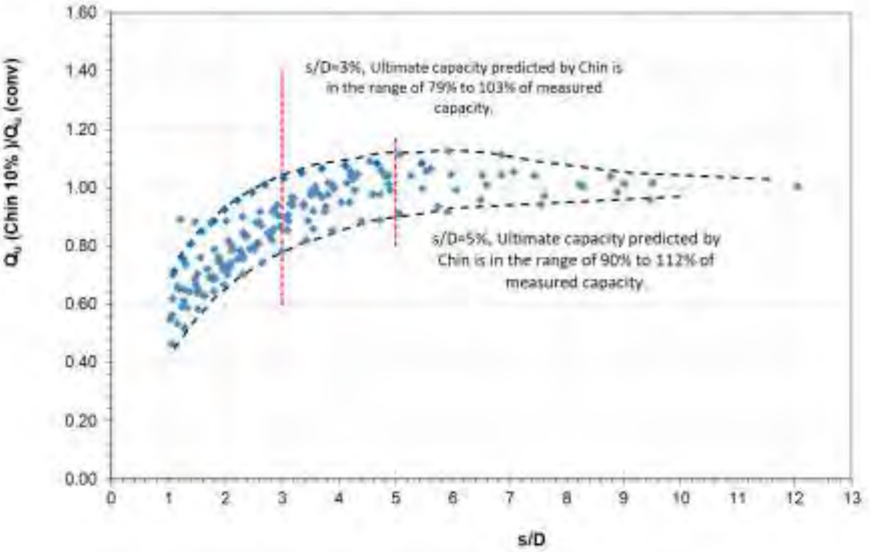

Figure 7. Performance of Chin method in prediction of non-failed SLT in piles with typical two straight line behavior

6. VALUATION OF SHAFT CAPACITY

As state before, two straight lines relationship for s vs. s/Q plot will appear when a pile acting combined friction and end-bearing. It has been suggested that the first part (A) would represent shaft resistance while the second part (B) would represent total load. This model was established in 19 piles behavior in this study. 15 piles have typical two straight line behavior according to Figure 1a and 4 piles have inverse A part behavior according to Figure 1b. An example of shaft capacity prediction by Chin method is illustrated in Figure 8a. Shaft capacity determined according to Chin's criterion on the first part of the curve Q_s, Chin=1217 kN. PDA test and CAPWAP analyses on the pile makes it possible to measure the shaft capacity of pile. The measured value of shaft capacity by CAPWAP analyses is 1400 kN. For the considered case the agreement can be considered as quite good in geotechnical terms, as the difference between the calculated and measured values is only 13%.

Figure 8b shows predicted (by Chin method) and measured (by PDA tests and CAPWAP analyses) shaft capacity for 17 case histories. Except two piles with inverse A part behavior, good agreement between predicted and measured shaft capacity is shown. Figure 9a shows the ratio of the predicted/measured shaft capacity versus the percentage of the load carried by shaft to allow better identification of the cases for which the Chin method gives poor results. Due to shortage of data, the initial points is taken from paper by Borel et al. 2004. The Chin method significantly over predicts the shaft capacity where load is mainly carried by the toe (less than 40% of load carried by the shaft). If 40 to 60% of load carried by the shaft then Chin method over predicts the shaft capacity up to 50%. When the shaft capacity is greater than 60%, predicted shaft capacity is in the range of 85% to 120% of the measured value. Figure 9b shows the error made in the predicted shaft resistance based on ultimate resistance (two point by inverse A behavior have been ignored).

7. CONCLUSIONS

Chin's method has been applied to 22 full-scale pile tests in order to assess its performance. Total 22 driven piles including precast square concrete 400 × 400 mm and pre-stressed close-end spun concrete piles with the circular outer diameter of 450 and 600 mm have been discussed. Static and dynamic load tests were performed on all the piles. The most important findings of the study are summarized below:

- Comparison of CAPWAP results with static load tests on the same piles shows excellent agreement results. Accuracy of prediction by CAPWAP of long-term ultimate capacity is improved by perform simultaneous static and dynamic load test as soon as possible. Dynamic load test could be cost effective and also less time consuming for larger driven piles as compared to static load test. Therefore, SLT can be safely replaced with DLT at piling sites.

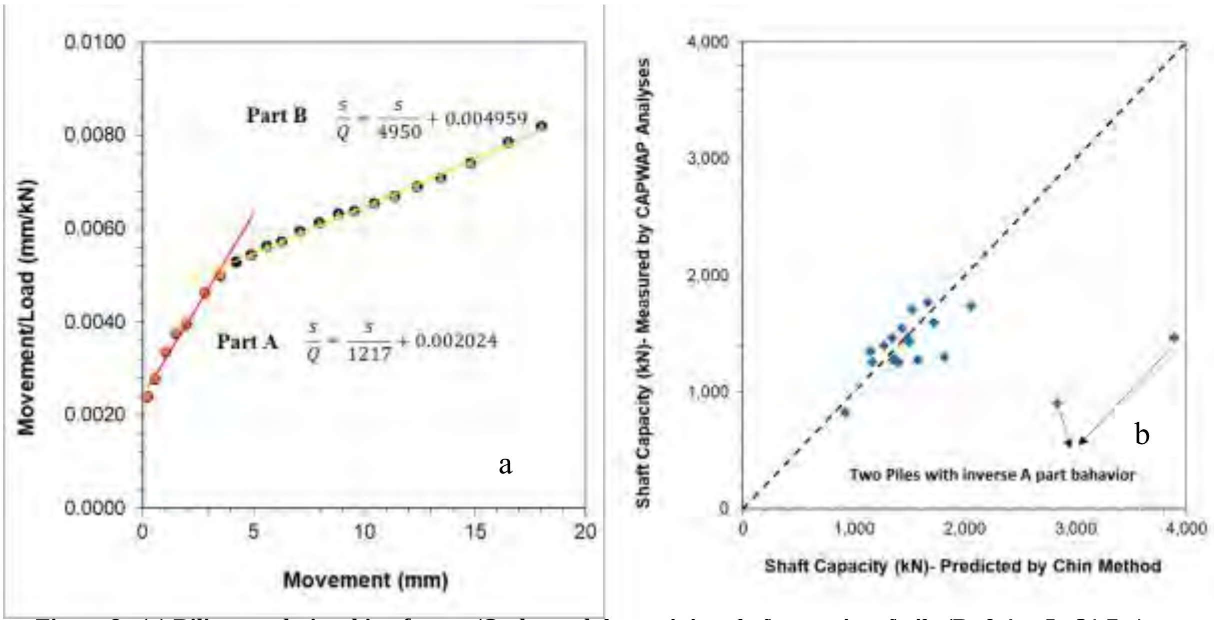

Figure 8. (a) Bilinear relationship of s vs. s/Q plot and determining shaft capacity of pile (D=0.4m, L=21.7m) (b) Comparison of predicted (Chin method) and measured (CAPWAP analyses) shaft capacity

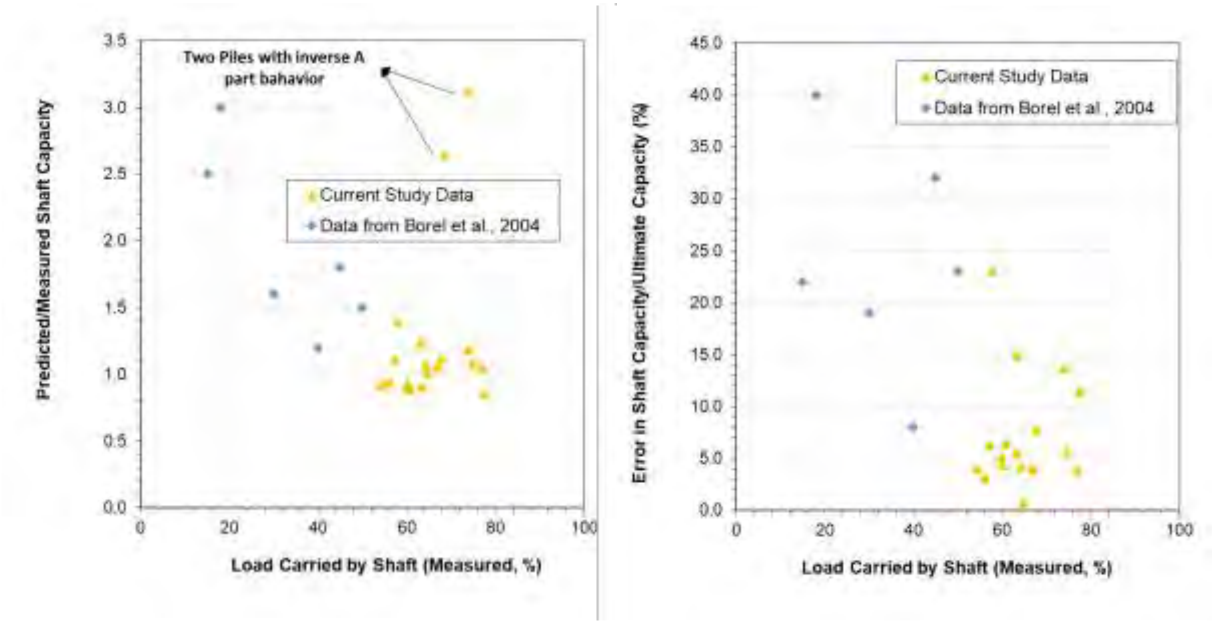

Figure 9. (a) Predicted vs. measured shaft capacity (b) Error in shaft capacity compared ultimate capacity

- Chin method gives a very good prediction of ultimate capacity except the cases by plunging failure. The reliability of the Chin prediction improves when the last measured gross movement approaches 10% of the pile diameter. In static load tests, if head movement exceeds 3% of pile diameter Ultimate capacity predicted by Chin is in the range of 79% to 103% of measured capacity. As soon as head movement exceeds 5% of pile diameter Ultimate capacity predicted by Chin is in the range of 90% to 112% of measured capacity.
- The Chin method over predicts significantly the shaft resistance when the load is mainly resisted by the toe; When the shaft capacity is greater than 60%, predicted shaft capacity is in the range of 85% to 120% of the measured value.

8. ACKNOWLEDGMENT

The authors would like to thank the technical information provided by Pars GeoEnviro Co. regarding the geotechnical investigation and pile test program data.

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