Development of automatic signal matching procedure - iCAP®

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ABSTRACT: Dynamic pile testing has become the standard tool for evaluation of driven pile foundations. The "state-of-practice" is to use a Pile Driving Analyzer® (PDA) to acquire data during impact of a pile driving hammer, either during pile installation or after a wait period during restrike, and the data is then analyzed by the "signal matching" software CAPWAP®. Until recently the PDA gave estimated results during testing only according to the Case Method which are a series of closed form solutions for capacity, installation stresses, energy transfer, and pile integrity. In recent years as computational computing power has increased, faster reporting of CAPWAP results became possible using data transferred either directly to laptop computers on site or remotely to receiving computers in the office. However, the traditional CAPWAP does not allow for quick data transfer from the PDA on site for each pile during data acquisition. Thus a new program, iCAP, has been developed to do an immediate signal matching analysis during the pile testing, either during PDA data collection or review. Either on-site or remotely, the PDA data is sent to the iCAP signal matching program without any user intervention for immediate analysis. iCAP then performs an automatic signal matching, and results are then displayed numerically and graphically during data collection (or reprocessing). The applicability and background of iCAP are discussed in this paper. Case studies of different pile types have been performed to correlate the results between iCAP and CAPWAP. Examples of Real cases are presented to demonstrate how and when iCAP can be used to improve the evaluation procedure for driven piles.

1 INTRODUCTION

Research completed in early 1970's at Case Western Reserve University introduced the application of high strain dynamic testing to determine soil resistance to pile driving and evaluate long term capacity by restrike, as well as to calculate the stresses and assess pile integrity, Rausche et al. (1972; Goble et al. (1975). Since then, the Case Method (named after the university), practice procedure, and equipment for high strain dynamic pile testing have evolved considerably, Likins et al. (2009) and the method has now become the standard of practice for evaluation of driven pile foundations. Dynamic testing is required by various specifications and codes, Beim (2008) worldwide. Although initially developed for driven piles, dynamic testing has been subsequently applied to drilled and augercast piles with good success, Likins et al. (2004). This paper will however restrict its focus to only driven piles, and specifically to the vast majority of driven piles which have a uniform cross section along the pile length.

The following procedure is routine and now "state-of-practice":

1. Acquire axial force and velocity data, usually using strain and acceleration transducers attached to piles subjected to hammer impact, either during pile installation or after a wait period during restrike. For a uniform pile, stress wave propagation theory and the Case Method are used to calculate stresses along the pile, assess the shaft integrity, evaluate the hammer performance, and estimate the ultimate capacity using an assumed damping constant.
2. The data is then further analysed by the "signal matching" software CAPWAP to compute the total capacity and its resistance distribution along the length of the pile and at the pile toe more accurately. Compression and tension stresses at all points along the shaft are also determined more accurately by this more extensive numerical analysis.

Until the last few years, the PDA during step 1 displayed the estimated results during testing only according to the Case Method which are closed form solutions for capacity, installation stresses, energy transfer, and pile integrity. But the capacity estimate depends on the assumed soil damping constant. Without correlation to a static load test or signal matching CAPWAP result, the soil damping constant is only assumed based on experience. Thus, the best codes (e.g. AASHTO 2010, SAA 2009, et al) also require "signal matching". This causes some uncertainty, since soil properties vary across the project site or when a pile penetrates through different soil layers. Due to high cost and large time consumption, static load testing is usually limited to one or at most a few tests per site, but is not usually practical to test several piles penetrating to different depths due to economic constraints. Thus dynamic testing with signal matching, Likins and Rausche (2004) and Rausche et al. (2000) is performed as step 2 to refine the capacity and stress analyses using an elaborate pile-soil model in a computationally intensive process.

As the realization for the need for good quality control increases, and since the new LRFD codes such as AASHTO give economic advantages for more testing and better quality control, the demand on dynamic pile testing is high both in quality, Likins (2011) and speed. The speed of construction is increased by minimizing all delays.

Delays in reporting results include return travel time to the office. As speed and coverage of wireless networks have increased, remote testing has increased, Likins et al. (2009), and eliminates all delays associated with travel time. A computer based PDA on site is connected to the internet by on-site personnel and transfers collected data to a computer in the office. An engineer remotely monitors the test in the office and starts analysing the data immediately after collecting the data. With all these developments, faster reporting of final results became possible.

Final pile capacity confirmation is often required immediately after the test to assist determining a driving criterion for all remaining production piles. However, most codes require signal matching, AASHTO (2010) to confirm the capacity results, and this process traditionally required office analysis time by an experienced engineer. Time required for the signal matching process heavily depends on the analyst's experience. Years ago, it was difficult to perform signal matching analysis on site due to limitations of the computers. However, computer technology has improved so that powerful notebook computers can now handle these analyses which involve heavy calculations. Thus signal matching analysis on site is possible, although a full CAPWAP analysis may take considerable time, depending on the engineer's ability and complexity of the data.

To reduce the time required for signal matching, several automatic signal matching procedures were added to CAPWAP, Rausche et al. (2000). However, the traditional CAPWAP interface was intended for experienced users to control the flow of the analysis and provide maximum flexibility for various options and unusual conditions. The process of starting a CAPWAP analysis does not allow for quick data transfer from the PDA for every impact so it was not possible to perform signal matching on site for each pile during data acquisition. Although this strategy is necessary and even cannot be avoided if the pile is not uniform or the soil conditions are complicated, for uniform driven piles under normal soil conditions an automatic signal matching procedure may be sufficient to give a more reliable result than the Case Method result.

With improved computational tools now in place, it is now possible to perform the signal matching during data acquisition or immediately after testing. For an analysis during data acquisition the following criteria were chosen:

1. Signal matching for one blow must be performed in a very short time, so it is possible to perform signal matching during data collection. Since the capacity generally changes only slowly from blow to blow, analysis of every blow is not critical.
2. The signal matching must avoid any user interaction and be totally automatic.
3. The solution must be reliable. It should correlate well with static load tests. Since CAPWAP correlates well with static tests, Likins et al. (2004), correlating well with CAPWAP should result in good correlation with static load tests. There should be an objective indicator of the quality of the signal matching so that a poor quality indicator can alert the user that the solution is less reliable.

To fulfill the above requirements, a new program, iCAP, was developed from the full CAPWAP to perform an immediate automatic signal matching analysis during the pile testing. The background of iCAP is described. A study of iCAP results compared against CAPWAP results is presented in this paper.

2 MODEL AND PROCEDURE

The basic CAPWAP pile and soil model, Pile Dynamics, Inc. (2006) was used to create the iCAP automatic signal matching procedure. iCAP allows for a completely automatic operation with certain controls for selecting qualifying data quality.

2.1 Data Input and Default Values

For this procedure to work completely automatically, the pile must first be modeled. For a uniform pile, the geometry can be defined by the cross section area, the pile length (below measuring location), the circumference, and the pile bottom area (defines if pile is open section or a closed section profile). The pile material properties must also be considered in the model. The elastic modulus, specific weight, and material wave speed are important and interrelated; only two need to be input and the remaining one can be computed. These parameters are all part of required input to the PDA before collecting data, so they are available and are transferred from the PDA.

The force and velocity for the subject impact are required and they are converted from the measured strain and acceleration. An accurate embedment depth helps guide the signal matching. However, during the pile driving, the pile embedment changes, so following two cases are considered:

If embedment depth is entered into the PDA as driving progresses by the testing engineer, the actually entered embedment is used, or

If embedment depth is not entered then the full input pile length minus 0.3 m is assumed.

The measured acceleration is integrated to velocity, and velocity integrated to displacement. Both have some uncertainty due to data quality and unknown integration constants. The permanent set per impact is used to adjust the measured velocity curve so that the final computed displacement matches the observed set per blow. The nominal set per blow can be either known and input or estimated from the following formula (based on Paikowsky 1992, but modified based on correlation work by the authors).

$$S = \frac{EMX}{RX7} - DMX >= 1.0 \text{ mm} \qquad (1)$$

Where S is the set per blow, EMX is the maximum measured transferred energy (integral of product of force and velocity), DMX is the maximum computed displacement during the blow, and RX7 is the maximum Case Method capacity with a Case damping factor of 0.7. For good data quality and normal soils the total capacity determined by iCAP is not sensitive to this set per blow value.

2.2 Soil Parameters Included in the Automatic Matching

The following parameters can define a simple standard soil model, Pile Dynamics, Inc. (2006):

- Total pile capacity
- Resistance distribution, including ratio of shaft to end bearing resistance
- Smith Shaft and Toe damping constants
- Shaft and Toe quakes
- Shaft unloading ratio
- Toe resistance gap
- Shaft and Toe unloading quakes
- Soil Plug Weight attached to pile toe (toe closure plate or compacted soil beneath pile toe)
- Toe damping option, which has three choices: Viscous, Smith, Smith-Viscous

The first four parameters in this list are identical with the soil model for a standard wave equation analysis.

The data acquisition equipment to collect data for dynamic pile test data was designed for harsh field conditions, but also runs on battery power and lasts for a full day of testing. Computationally intensive operations like signal matching results in a significant extra power draw. To conserve power and shorten the computation time, a reduced search was also developed. This option, called Quick iCAP, still was required to achieve a reasonable solution. Either the full or the quick signal matching could be performed starting with a totally fresh soil model or a model based on the previous signal matching result from the previous blow. Starting with the previous solution saves computation time since the soil conditions usually only change little from blow to blow.

2.3 Basic Program Flow

If the PDA is set to request an iCAP analysis, the measured force and velocity data are sent to iCAP and a continuous pile model is created. The analysis uses the method of characteristics to perform the wave propagation computations, Pile Dynamics (2006). A soil model is generated with 2 m segments along the shaft, which matches the general resolution of the data, and an extra soil element at the pile toe. An initial total capacity is assigned, either from the previous solution or from the Case Method RX7 equation, and the resistance distribution along the shaft and at the toe is determined from the force and velocity prior to the first return of the input wave after reflecting from the pile toe.

The search procedure is shown in Figure 1. A search is made to find the optimum set of standard soil variables for the assumed capacity. A large toe quake is then investigated if the match quality is still relatively poor, and another search is made over the standard soil parameters to find the best solution. Based on previous correlation efforts, the maximum allowed capacity is limited to avoid overestimating capacity. If the iCAP capacity is larger than this limit, the capacity is reduced and another search made on the standard parameters. The balance between shaft and toe resistance is investigated. Depending on if the request is for a full or limited signal matching search, or if the analysis starts fresh or uses the previous solution, the signal matching may take more or less time to reach its conclusion.

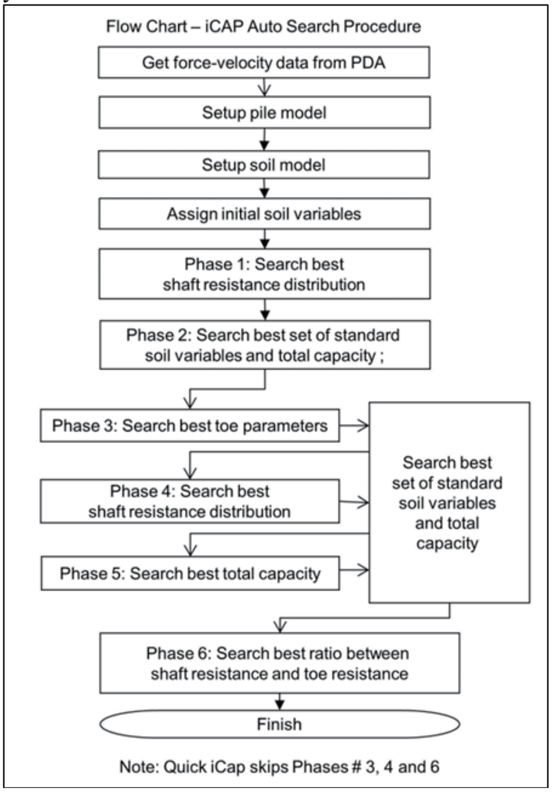

Figure 1. Flowchart of iCAP auto search.

When the signal matching process is complete, the results are returned to the PDA for display. The most important results are the total capacity and its distribution between shaft resistance and end bearing. Since the analysis tracks the propagating stress wave, the force at any location in the pile is determined as a function of time and the maximum compression and maximum tension forces are thus a byproduct of the process. The maximum toe force, which is useful to prevent toe damage, is also output.

With the exception of timber piles, iCAP does not currently allow for non-uniform piles to be analyzed. The model also currently will not allow splices with slacks or allowance for minor tension cracking in concrete. Radiation damping, Likins et al. (2004) is not yet considered (and thus the iCAP result stays on the conservative side). Options to allow these model extensions into the search are in progress.

3 CASE STUDIES

Sixty eight (68) cases were randomly selected for this study. Three types of uniform driven piles were included: H piles, steel pipe piles, and concrete piles. The following criteria were used to validate data to be included in this study:

- The CAPWAP analysis was already independently performed before this study,
- The original CAPWAP analysis did not use radiation damping, Likins et al. (2004) or residual stress analysis.

For each case, two iCAP analyses were performed:

- Quick iCAP uses less searching; best suitable to analysis during pile driving where time is limited and analysis speed is important.
- Full iCAP performs more searches and where analysis time is not critical; suitable for restrike tests or reviewing the quick iCAP results after driving has stopped.

The total resistances estimated using iCAP were compared with the original CAPWAP solutions for each pile type, and the pile condition of end of drive (EOD) or begin of restrike (BOR) is noted. The comparisons are plotted for H piles as shown in Figures 2 and 3, for steel pipe piles as shown in Figures 4 and 5, and for concrete piles as shown in Figures 6 and 7 for Full iCAP and Quick iCAP respectively.

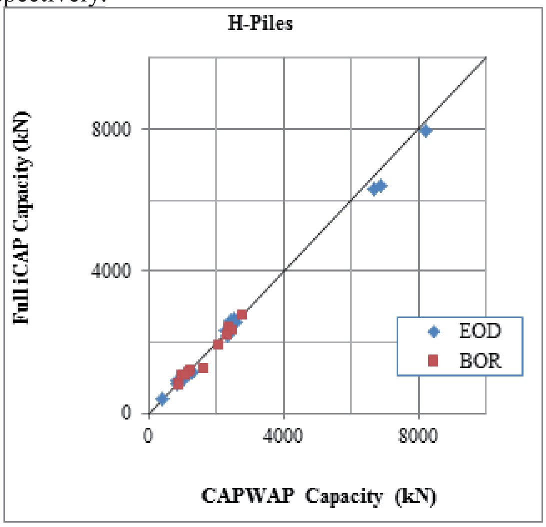

Figure 2. Capacity Estimation Comparison for H Piles: Full iCAP vs. CAPWAP.

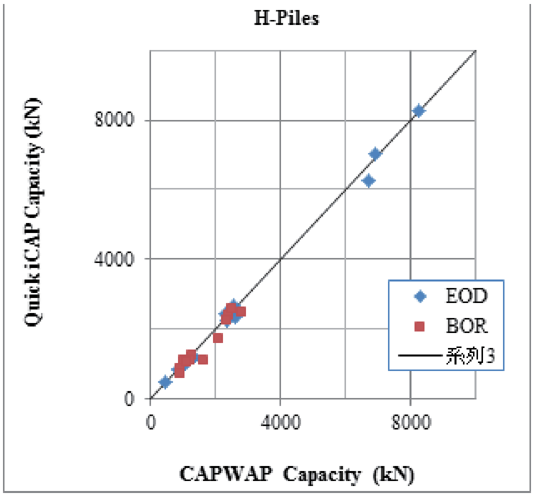

Figure 3. Capacity Estimation Comparison for H Piles: Quick iCAP vs. CAPWAP.

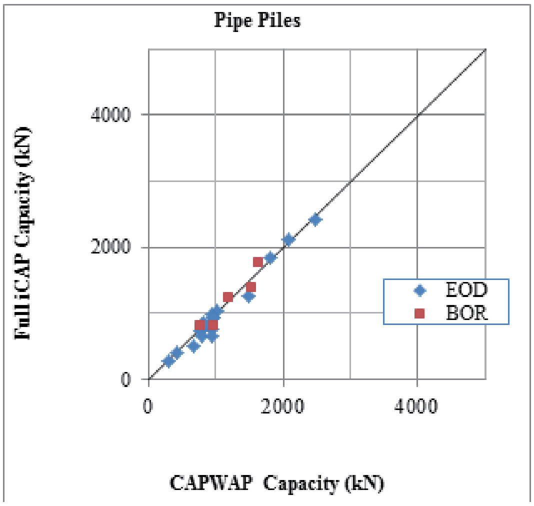

Figure 4. Capacity Estimation Comparison for Steel Pipes: Full iCAP vs. CAPWAP.

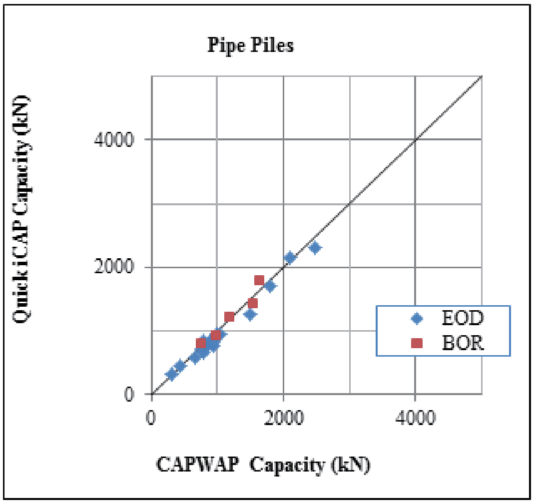

Figure 5. Capacity Estimation Comparison for Steel Pipes: Quick iCAP vs. CAPWAP.

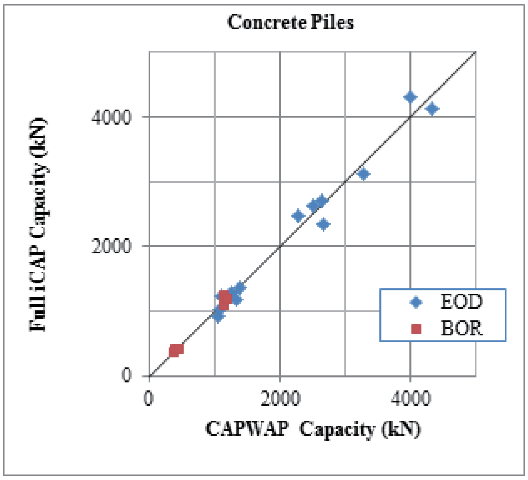

Figure 6. Capacity Estimation Comparison for Concrete Pipes: Full iCAP vs. CAPWAP.

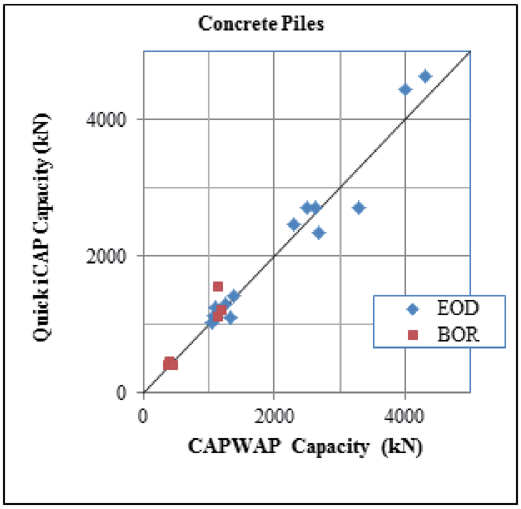

Figure 7. Capacity Estimation Comparison for Concrete Pipes: Quick iCAP vs. CAPWAP.

As shown in Figures 2 to 7, a reasonable overall agreement between total capacities estimated by iCAP and CAPWAP can be observed. The best correlation agreement was observed from H-piles.

Statistical analyses on all cases were performed to establish the frequency distributions as shown in Figure 8 and Figure 9 for the relative differences between Full iCAP and CAPWAP and between Quick iCAP and CAPWAP respectively. The calculated mean and standard deviation were also shown in the figures and two vertical lines were placed at ±10% to indicate a ±10% relative difference window.

Based on the statistical analyses summarized in Figures 8 and 9, it can be seen that in about 80% of the cases the capacity estimated using Quick iCAP are within 10% relative to the capacity estimated using CAPWAP.

About 84% of the cases have the capacity estimated using the Full iCAP within 10% relative to the capacity estimated using CAPWAP. Statistically, compared with CAPWAP, the Quick iCAP result had a mean of -1.7% and a standard deviation of 8.8%. The Full iCAP result had a mean of -3.2% and a standard deviation of 8.0%.

iCAP results are slightly conservative in general compared to CAPWAP results.

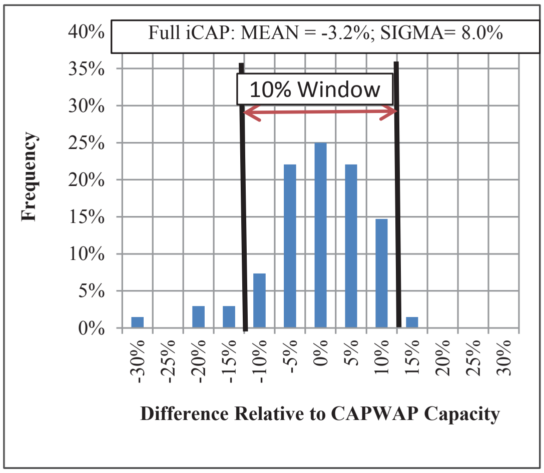

Figure 8. Frequency of Relative Capacity Difference Between Full iCAP and CAPWAP.

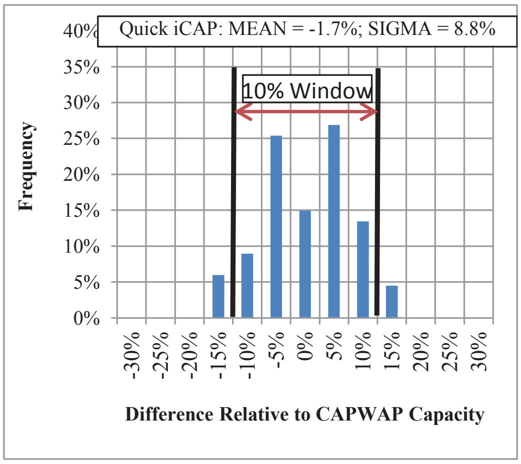

Figure 9. Frequency of Relative Capacity Difference Between Quick iCAP and CAPWAP.

4 EXAMPLES OF APPLICATION

4.1 Example 1: Closed End Pipe Pile Driven to Silty Soil

For a waste water treatment plant project, a 457 x 12.7 mm spiral weld closed end pipe with a length of 30.5 m was driven to a penetration of 28.7 m. Soils consisted mostly of silt and silty sand. The blow count at end of initial drive was about 98 blows per meter and the capacity estimated by the Case Method (average numerical result over the last ten blows) was about 2000 kN or 1700 kN for RX7 and RX9 respectively. CAPWAP analysis on a previously installed dynamic test pile indicated that RX7 matched CAPWAP result better. However, considering the large variability in soil layers and conditions at this site, and the apparent sensitivity to the damping constant selection, the relatively inexperienced engineer needed further confirmation of the RX7 selection prior to leaving the project site. Since a quick decision was needed, full iCAP analyses were performed for last five blows of driving to determine if the damping factor previously used was still appropriate. As shown in Table 1, the average iCAP resistance for the last five blows was only 1585 kN, which is lower than required. Thus a restrike test was requested.

Table 1. Example 1: Capacity Estimation.

	Capacity (kN)			Match Quality (MQ)
	Total	Skin	Toe	
Full iCAP on Last 5 Blows with fresh start on each blow				
Average	1585	418	1167	2.98
CAPWAP (Blow #519)	1552	560	992	2.91
RX7	2000	Average numerical result considering the last 10 blows		
RX9	1700			

A restrike was later performed that same day and verified a higher resistance that then met the requirement. The CAPWAP analysis performed after returning to the office estimated the capacity at end of driving to be 1552 kN as shown in Table 1, confirming the decision to ask for the additional restrike.

4.2 *Example 2: Steel H pile driven to shale bedrock.*

HP 305x110 piles were installed for a highway bridge abutment. The test pile length was 10.8 m. The final embedment was 9.8 m with a blow count over 700 blows per meter.

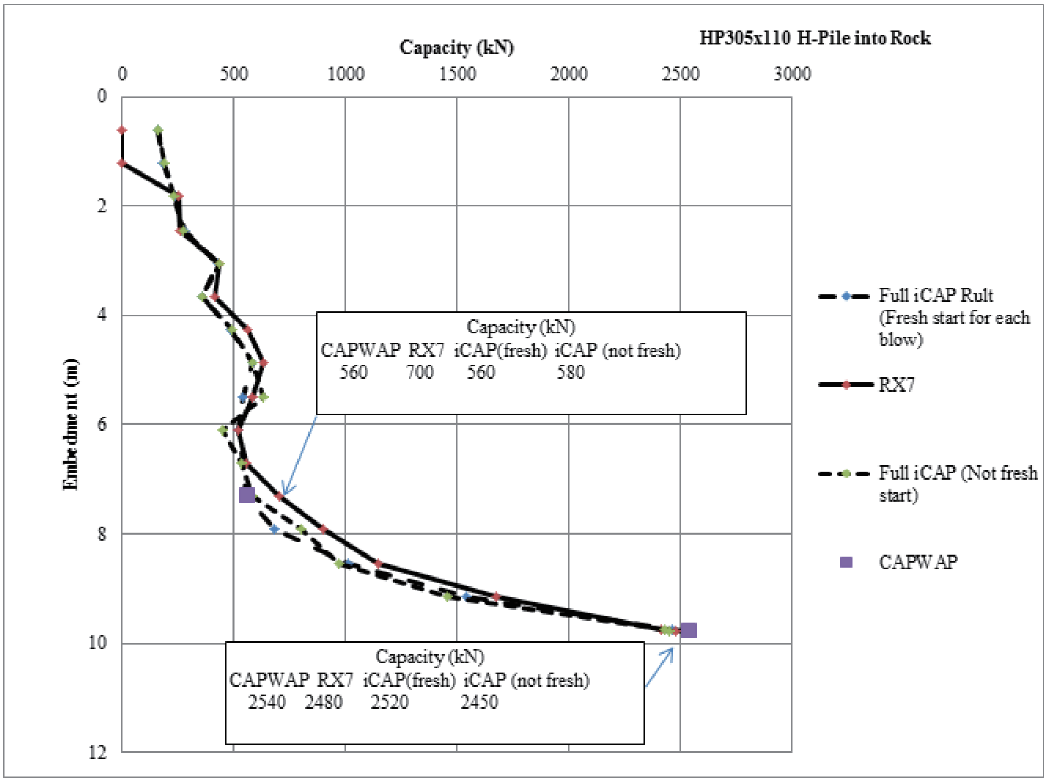

Figure 10. Example 2: Capacity Estimation vs. Penetration.

As a common practice, CAPWAP analysis was performed on a record selected at the end of initial drive to estimate the resistance and find an appropriate damping factor for the Case Method estimation. The Case damping factor of 0.7 was deemed appropriate. Then the estimated Case Method capacity (RX7) for each blow was plotted versus pile embedment in Figure 10. However, since different soil layers were penetrated, the damping factor may not be the same throughout the entire pile driving process. Although the RX7 Case Method result matched the CAPWAP result at the end of drive at 9.8 m embedment, RX7 may not be appropriate at other pile embedment depths where the toe is in different soil conditions. While it is not practical to perform CAPWAP at multiple embedments, the minimal effort to perform an iCAP analysis during pile driving allows a signal matching and thus a higher confidence in the result.

A later comparison study was made. Two iCAP analyses were performed for every 0.6 m increment of embedment: one analysis was started fresh for each blow, and the other analysis was started based on the previous result. Both iCAP results are shown in Figure 10. An additional CAPWAP analysis performed for a blow at 7.3 m embedment indicates a total capacity of 560 kN. The RX7 Case Method result of 700 kN at this embedment overestimated the resistance. Since the iCAP analysis is a signal matching result, it can better estimate the capacity as a pile is driven through varying soil layers.

CONCLUSIONS

Modern construction requires timely results with high accuracy. Since dynamic pile testing requires signal matching, a fast and completely automatic signal matching procedure called iCAP was developed, based on the widely used and highly documented CAPWAP model. The analysis is fast enough to be performed and provide guidance to even inexperienced engineers during pile installation or during restrike tests. In addition to determining capacity more accurately, the analysis determines the maximum compression and tension stresses at any location in the pile as well as the compression stress at the pile toe.

A total of 68 cases were selected for comparison with the original CAPWAP signal matching results. Three common types of uniform driven piles were included in the study: steel H-Piles, steel pipe piles and concrete piles. The total capacities estimated by iCAP and by CAPWAP are in reasonable agreement. In more than 80% of the cases, the Quick iCAP estimated capacity was within 10% of the CAPWAP estimated capacity. For the Full iCAP analysis, the estimated total capacity of 84% of the cases is within 10% relative to the CAPWAP result. The statistically calculated mean indicates that iCAP estimated total capacities are slightly conservative compared with CAPWAP at -3.2% and -1.7% for Full iCAP and Quick iCAP respectively. The calculated standard deviations indicate that the Full iCAP (8.0%) is slightly more consistent with the CAPWAP result than Quick iCAP (8.8%).

The Quick iCAP which starts with the result of the previous solution is better suited for tests during driving. The Full iCAP can be used for evaluation on site when driving has ceased, such as after a brief restrike test or to confirm the capacity of the last blows at end of driving.

Although iCAP was developed based on CAPWAP models, there are advantages, limitations, and differences between iCAP and CAPWAP:

- The current iCAP is designed only for uniform driven piles. The exception is timber piles where a diameter reduction rate of 1/120 (consistent with natural tree tapers) is assumed to create a non-uniform tapered pile model. Joints, slacks, mechanical splices with “gaps”, or cracks cannot currently be considered. When applicable, the iCAP solution is more reliable than the Case Method capacity result.
- It is possible to perform iCAP on each blow of each pile during driving or restrike.
- CAPWAP analyses should be performed as soon as practical to compare with the iCAP result.
- iCAP only searches standard soil parameters automatically. iCAP cannot be applied to radiation damping or residual stress analyses.

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