Simulated Pile Load-Movement Incorporating Anticipated Soil Set-up

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Abstract

Dynamic pile testing and related data analysis methods are routinely used to measure soil resistance effects, estimate static pile load bearing capacity, and predict pile load-movement relationship. Analysis results represent conditions at the time of testing. For piles driven into soils with beneficial time-dependent characteristics, the capacity increases with time following initial driving due to favorable geotechnical effects. In practice, construction scheduling constraints often restrict the evaluation of "long-term" pile capacity and limit the verification testing to a short period following initial driving. This paper presents a method for predicting future pile load-movement relationship based on end of driving and short-term restrike dynamic testing results. A case study is presented where field dynamic tests were performed with a Pile Driving Analyzer® (PDA) and CAPWAP® computer analysis during initial driving and restrike eleven days later. The CAPWAP method was also used to predict the pile load-movement graph expected at seventeen days after end of initial driving for comparison with results from a full-scale conventional static loading test to be independently performed at that time. Good correlation was obtained between the dynamically predicted and full-scale static load test results based on the proposed method.

Introduction

Driven piles are commonly used as deep foundations in various subsurface conditions to support all types of structures. Effective design and economic utilization, however, must consider the temporary and permanent alterations made to the natural geotechnical conditions caused by the pile installation process. The nature and extent of the changes in the ground are mainly dependent on soil (and rock) geotechnical properties, pile physical characteristics, and installation mechanism. Displacement-

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type driven piles produce more pronounced ground modification effects than low-displacement piles. The extent of spatial soil disturbance is proportional to the magnitude of the impact hammer energy. Impact pile driving generally has desirable densification effects on cohesionless soils resulting in enhanced pile capacity. Pile driving effects on clays are mainly soil remolding and development of excess pore water pressures resulting in temporary change in the state of stress around the pile. Time-dependent changes in clay and pile/soil interaction characteristics have pronounced beneficial effects on the load carrying pile capacity. This phenomenon is commonly called soil "setup" or pile "freeze". The literature contains many references to the effects of pile driving on ground conditions and long-term pile behavior (Soderberg, 1961; Fleming et al., 1985; and Coduto, 2001).

Modern dynamic pile testing methods are based on electronic stress-wave measurements and computer data analysis (Rausche et al., 1985). Field testing is typically performed with a Pile Driving Analyzer® (PDA) during initial driving and/or restrike some time after installation. Dynamic pile test records are analyzed according to the CAPWAP® Method (a computerized systems identification process employing signal matching techniques and wave equation numerical analysis) for determining soil resistance forces (magnitude and stiffness) acting along the pile length in skin friction and under its toe in end bearing (Rausche, 1970). The analysis results also include a pile load-movement graph simulating a static loading test (Rausche et al., 1994). Naturally, the analysis results represent the pile/soil conditions at the time of testing.

In practice, construction scheduling constraints often limit the possibility of pile testing to a short period following end of initial driving, which limit the verification assessment of "long-term" pile capacity and behavior under applied load. This paper presents a method for predicting future pile load-movement relationship based on end of driving and short-term restrike dynamic testing results, by an innovative utilization of existing PDA testing practices and CAPWAP analytical methods. A case study is presented where dynamic tests were performed during initial driving and restrike eleven days later. The proposed method was used to predict the pile load-movement graph expected at seventeen days after end of initial driving for comparison with results from a full-scale conventional static loading test to be performed at that time.

Case Study

Project Description. The project involves the construction of a new bridge in Central Florida. The job had a design/build contractual arrangement. Construction scheduling and sequence dictated the need to quickly finish the deep foundations work. The eighteen bridge piers are supported by 457 mm outside diameter with 9.5 mm wall thickness, closed-ended steel pipe driven piles, with up to sixteen piles in each group. As part of the initial phase of the foundation work, a testing program was done which included driving and dynamically testing indicator piles at representative production locations along the bridge length, and statically load testing one of these piles. Dynamic pile testing was done in general accordance with ASTM D-4945 and static testing generally followed ASTM D-1143 standards. Separate consultants independently performed each type of pile testing. This case study will focus on data obtained from the pile that was dynamically and statically tested.

Subsurface Conditions. Geotechnical conditions were variable along the proposed bridge alignment. Subsurface conditions at the pier location under consideration can be described as consisting of a surficial layer of fine sand with silt (SP-SM, with N-values ranging between 16 and 45) extending to a depth of approximately 2 meters below existing ground surface, underlain by mixed layers of fat clay (CH), fine sand (SP), fine sand with silt (SP-SM), and clayey fine sand (SC) extending to a depth of 20 meters. A layer of silty fine sand (SM) with an average N-value of 25 extended to a depth of 30 meters. The natural water table was located just below the ground surface.

Pile Installation and Dynamic Testing. The 26 meters long pile was driven, and dynamically tested, using an open-ended (i.e., single-acting) diesel hammer having a ram weight of 29.4 kN and a rated energy of 95 kN-m at full fuel pump setting and maximum ram stroke height of 3.2 meters.

Initial pile installation blow counts were relatively low with values generally ranging between 5 and 15 blows per 250 mm of penetration increments, with an average hammer ram stroke height of 1.75 meters. End of driving blow count was 16 blows/250mm with a hammer stroke of 2 m at a final pile penetration of 23 meters. The pile was restruck eleven days after end of initial driving, the restrike blow count was 6 blows/25 mm with an average hammer ram stroke of 2.4 meters. The instrumented pile is shown during restrike in Figure 1. Dynamic testing was performed with a Pile Driving Analyzer (shown in Figure 2) during initial pile installation and restrike.

Dynamic pile testing data obtained by the PDA from selected hammer blows at the end of initial pile driving and beginning of restrike were analyzed with the CAPWAP computer program. Figure 4 presents PDA test data and CAPWAP analysis results for the pile end of driving and restrike conditions. Included in Figure 4 are plots of pile-top force and velocity records, shaft resistance distribution, pile forces at ultimate capacity, and simulated pile top and bottom load-movement graphs. The CAPWAP calculated shaft resistance forces as a function of pile penetration depth, and end bearing resistance are summarized in Table 1. CAPWAP analysis indicated that the end of driving ultimate static pile capacity was 1155 kN (585 kN in shaft resistance and 570 kN in end bearing). Similarly CAPWAP, indicated the 11-day restrike pile capacity to be 2115 kN (1536 kN in skin friction and 579 kN in end bearing).

Static Loading Test. Seventeen days following its initial driving, the pile was subjected to a conventional full-scale axial compression static loading test. Approximately two meters of the pile top were cut off to accommodate the load test frame and apparatus. Compression load was applied to the pile top using a hydraulic jack reacting against the dead-weight loaded frame, as shown in Figure 3. The load was quickly applied in twenty increments up to the maximum value of 2225 kN, slightly above the required pile capacity of 2000 kN and just below the capability of the loading frame (i.e., reaction dead-weight). Both a load cell and pressure gauge were used to measure the loads. Pile-top movements were monitored with dial gages and wire-mirror-scale systems. A plot of pile-top load-movement graph obtained from the static loading test is included in Figure 5.

Analysis of Dynamic Testing Results. CAPWAP analysis results performed with data obtained under representative hammer blows from the end of initial driving (EOD) and beginning of 11-day restrike (BOR) field tests were used to predict the soil resistance forces and pile capacity expected at the time of the static loading test. Linear extrapolation according to the following equation was used to compute the shaft resistance forces ($R_{17\text{-days}}$) along each two meters of pile embedment depth from the shaft resistances forces at end of driving (R_{EOD}) and restrike (R_{BOR}):

$$R_{17\text{-days}} = {}^{6}/_{11}\,(R_{BOR} - R_{EOD}) + R_{BOR}$$

The authors' own experience with the local geotechnical conditions in this project's general area suggested the use of the linear relationship, especially within the time period (approximately three weeks) under consideration. Terzaghi and Peck (1967) have also observed a linear increase of ultimate bearing capacity of a friction pile within a similar time frame. Skov and Denver (1984), however, recommend the use of a logarithmic function for pile capacity increase with time. The extrapolation method (linear, logarithmic, etc.) used does not affect the applicability of the analytical approach proposed in this paper; however, the accuracy of the results is affected by the degree of realism associated with the assumptions used by the geotechnical engineer to predict setup over time.

The $R_{17\text{-days}}$ values, along with the end bearing calculated from the BOR data (which was essentially the same as that obtained from the end of driving test), were used as an input into the CAPWAP program to produce the simulated pile-top load-movement graph incorporating anticipated setup. This novel approach is different from conventional CAPWAP analysis in that the soil resistance forces (already computed by previous CAPWAP analyses and adjusted for time effects) are used as input, rather than being produced as an output, to the proposed CAPWAP analysis to produce the simulated pile load-movement relationship incorporating soil setup.

Correlation of Dynamic and Static Testing Results. As shown in Figure 5, the simulated pile load-movement relationship based on dynamic test data compares very well with the full-scale static loading test result. The conventional static test was performed up to a load slightly above the required value (i.e., twice the design load), but not to the level that would have fully mobilized soil resistance and showed ultimate pile capacity. The load-test simulation conducted using dynamic testing data indicated a higher pile capacity than was mobilized by the limited static loading test. Pile top and movement under applied static load was essentially the same response, whether obtained by simulation based on dynamic measurements or full-scale static testing.

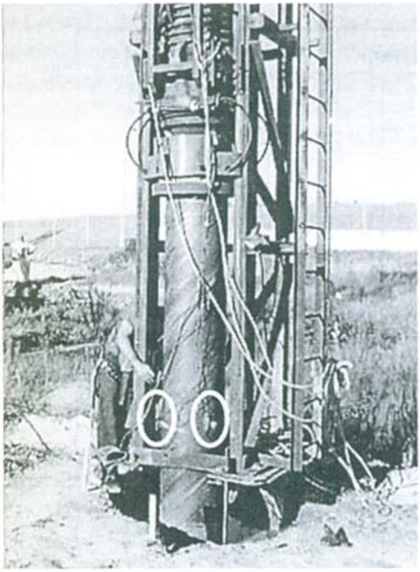

Figure 1: Pile Restrike with Dynamic Testing Instrumentation.

Figure 2: Pile Driving Analyzer.

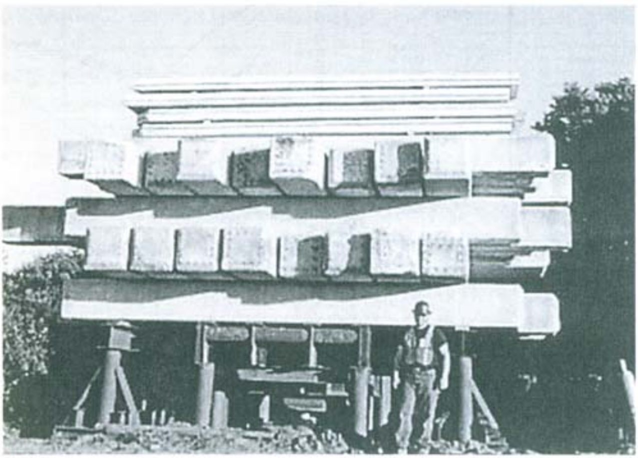

Figure 3: Static Loading Test.

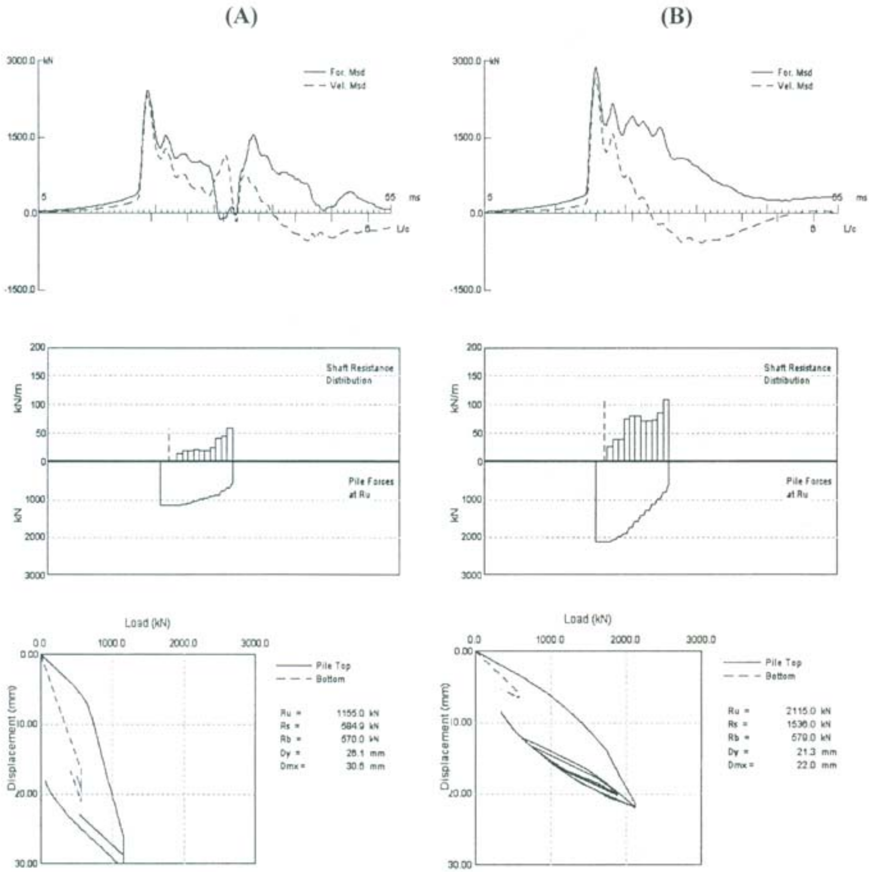

Figure 4: Pile Driving Analyzer Test records and CAPWAP Analyses Results, (A) End of Driving, and (B) Beginning of Restrike Data.

Table 1:Sumary of CAPWAP Analyses Results

Pile Depth, m	Soil Resistance, kN		
	End of Driving	Restrike 11 Days	Anticipated 17 days
3	0	56	86
5	30	80	107
7	42	81	102
9	42	152	212
11	44	165	231
13	40	165	233
15	40	146	203
17	50	146	198
19	83	149	185
21	93	176	221
23	121	223	278
End Bearing	570	579	579
Total	**1155**	**2115**	**2634**

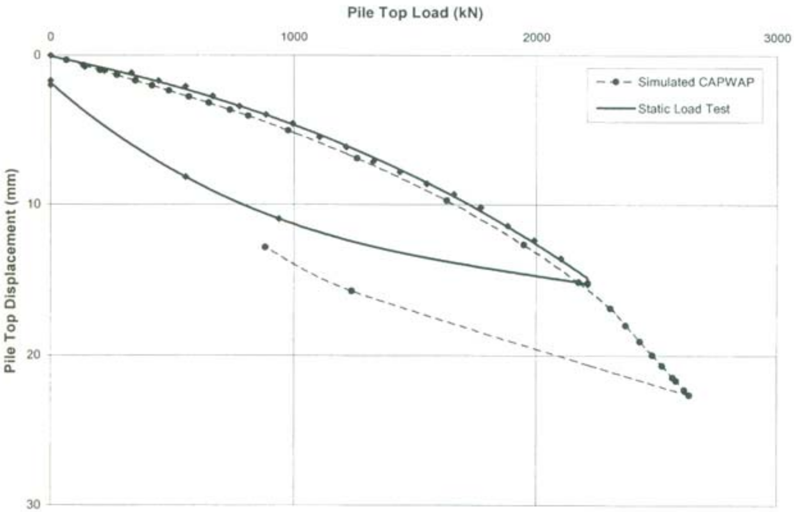

Figure 5: Actual and Simulated Pile Top Load- Movement Relationships.

Summary

In most subsurface conditions, the pile load carrying capacity increases with time due to favorable geotechnical effects. Recognition and incorporation of this beneficial phenomenon in design procedures and construction practices are essential for effective and economical use of pile foundations. Dynamic testing, just as conventional full-scale static loading tests, measure pile/soil interaction effects and represent pile load carrying capacity at the time of testing. Construction scheduling constraints, and other factors, often limit the possibility of pile testing to a short period following initial driving. This paper presented an innovative approach utilizing routinely used dynamic pile testing and analysis methods to predict the pile behavior some time following its initial installation and short-term restrike. A novel use of the CAPWAP computer analysis program produced a simulated pile load-movement graph incorporating anticipated soil setup. A case study was presented that illustrated the applicability, and demonstrated the accuracy of the proposed method.

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