Knowledge is Bliss - A Case for Supplemental Pile Testing to Ascertain Fidelity

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ABSTRACT Full-scale static loading is a widely accepted test method for authoritative assessment of deep foundations. Testing is typically performed once and the result is considered the definitive answer regarding the pile's load bearing capacity. However, there are technical and operational reasons that may cause misleading results. This paper presents a case where a large concrete pile was subjected to two full-scale static, and several dynamic loading tests. The pile was initially driven to a predetermined depth based on conventional geotechnical analyses, and its capacity was confirmed by dynamic testing. However, the static loading test indicated a pile capacity well below the anticipated value. Dynamic testing performed during restrike one day following the static test indicated a capacity close to that of the static load test. The pile was subsequently driven 4.4 m deeper until dynamic testing indicated it had achieved the required capacity. A second static loading test was performed that confirmed the required capacity. A review of the construction records revealed that in preparation for the static load test, the reaction steel H-piles were vibrated to below the test pile toe following the installation of the test pile. Analysis of the dynamic and static testing results confirmed that the installation of the reaction piles adversely affected the bearing layer resulting in reduction of pile capacity and the failed original static test. Utilization of dynamic pile testing and geotechnical analysis made it possible to uncover the flaw in the static loading test setup procedure and, thus, the unreliability of the original static load test result. This case study demonstrates that static load tests can sometimes be misleading, and supplemental dynamic pile testing is a valuable tool to establish reliability and ascertain fidelity of results.

1. INTRODUCTION

The widespread destruction caused by Hurricane Ivan in September 2004 included devastation of large sections of the Interstate 10 (I-10) twin bridges across Escambia

Bay in northwest Florida severing this vital transportation link. The Florida Department of Transportation (FDOT) quickly awarded emergency contracts for temporary repairs to provide at least limited service to the 42,000 vehicles that used the bridge daily. The FDOT then awarded a $243-million design-build contract for two replacement bridges, each approximately 4,200 m long consisting of three travel lanes and two shoulders with minimum clearance above water of 7.6 m, twice that of the original bridges. The fast-track nature of the contract required that the design-build team had only 20 months to fully construct one of the bridges to carry four lanes of traffic. The foundation design work consisted of subsurface investigations including soil borings, geotechnical studies, and an extensive test pile driving program that included static and dynamic loading tests. Large prestressed concrete piles, 914-mm square size with 589-mm circular void, with lengths up to 43 m were used. Pile ultimate load capacities ranged from 3,300 to 7,100 kN.

Full-scale static loading is a widely accepted test for assessment of pile load bearing capacity and pile load-movement relationship. The procedures for conducting this conventional method of pile testing and interpretation of results are well documented in the literature (ASTM-1143, Davisson 1972, Fellenius 1980, Kyfor et al. 1992). Testing may be done during the early stages of a project as part of the foundation design process to confirm or refine design parameters and assumptions, and/or as a proof-test procedure during construction. Testing is normally performed once on a pile and the result is typically considered with confidence as the definitive answer regarding pile load bearing capacity. There are, however, technical and operational reasons that could adversely affect the accuracy and reliability of the results. The various components involved in the test setup and performance mechanisms contain sources of errors and causes of potentially misleading results. This paper presents a case where the result of the static loading test was adversely affected by the manner in which the test setup was done; specifically, by the way the reaction piles were installed in relation to the test pile.

Dynamic pile testing is based on the measurement of pile force and velocity under driving hammer impacts during initial installation, or restrike. Field testing for this project was performed with a Pile Driving Analyzer® (PDA) system and data analyses were done with the CAPWAP™ computer program (Hussein and Likins 1995, Rausche et al. 2010). Testing results provided information regarding the hammer driving system performance, pile driving stresses and structural integrity, soil resistance and an estimate of pile static load bearing capacity. The procedure to perform dynamic pile testing, interpretation and reliability of results are well documented in the literature (ASTM-4945, Hannigan et al. 2006, Likins and Rausche 2004). The availability of dynamic testing results in the case presented here made it possible to suspect the static load test result and to discover the flaw in its procedure.

2. SUBSURFACE CONDITIONS AND GEOTECHNICAL ANALYSES

The site is underlain by the Citronelle Formation consisting of poorly sorted clean to clayey sands with the clay, silt, sand and gravel in lenses that may vary considerably over short distances. The Citronelle Formation is of Pleistocene age and extends to more than 60 m below the site surface. Specifically, the site soil profile consists of up to 4 m of water depth, up to 16 m of soft silt and clay sediments underlain by layers of medium dense to very dense silty sand, and sand with gravel that extend to in excess of 30 m below the mudline as shown in Figure 1.

Geotechnical analyses of the soils data were performed to estimate the skin friction and end bearing resistances versus depth. Figure 1 includes the results of analyses for the 914 mm square concrete test pile using procedures based on FDOT correlations between soil classification and Standard Penetration Test resistance, N, in blows per 300 mm (ASTM D-1586; Schmertmann 1978; FB Deep-2.02, 2005). The required ultimate capacity for the concrete test pile was 5,760 kN.

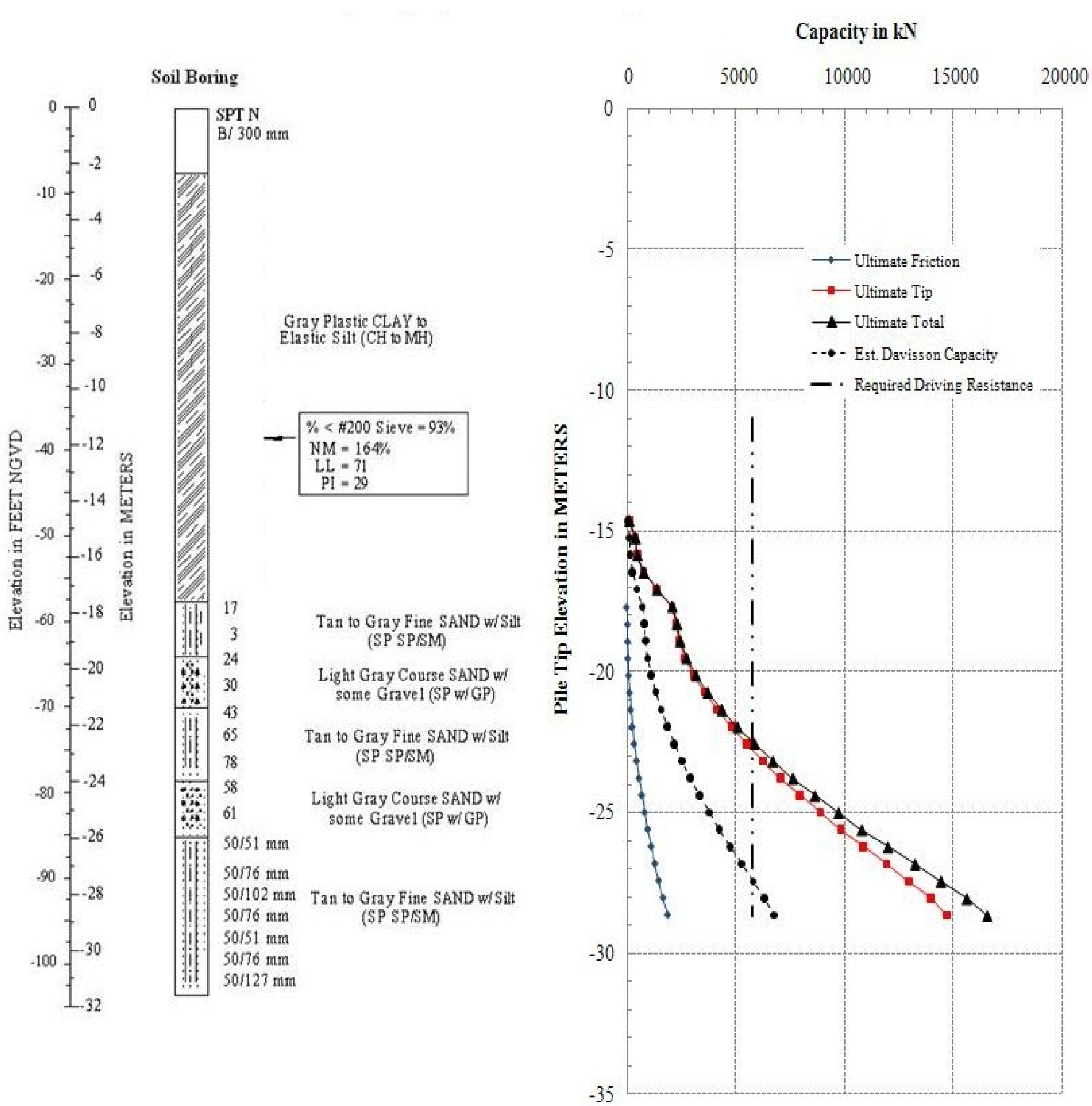

Fig. 1 Soil boring and geotechnically calculated pile capacities.

3. INITIAL PILE DRIVING AND DYNAMIC TESTING RESULTS

The test pile was a 29.3 m long, 914 mm square with a 589 mm diameter void extending throughout the pile length except the bottom 1.2 m where the pile section was solid. The pile had a residual prestress of 8.3 MPa. Pile driving, and dynamic testing, was performed with a Raymond 60X single-acting air hammer (ram weight of 267 kN and rated energy of 203 kNm at maximum stroke) utilizing a pile top plywood cushion with a thickness of 130 mm.

A total of 982 hammer blows drove the pile to a depth corresponding to a toe elevation of –25.3 m. Beginning of driving was relatively easy with blow counts in the 15 to 30 blows/300 mm range, which increased to about 70 blows/300 mm during the final 3 m of pile penetration. Maximum pile dynamic compression and tension stresses reached 18 and 4 MPa, respectively. The end of driving static pile capacity indicated by the dynamic pile testing data and analyses results was 5,630 kN (1,446 kN in skin friction and 4,184 kN in end bearing). Figure 2 presents the PDA dynamic pile monitoring results showing pile dynamic compression and tension stresses, static pile capacity and blow counts versus pile penetration depth. CAPWAP analysis results including plots of measured pile head data obtained under a hammer blow from the end of driving and associated simulated pile head and toe static load-movement relationships are presented in Figure 3.

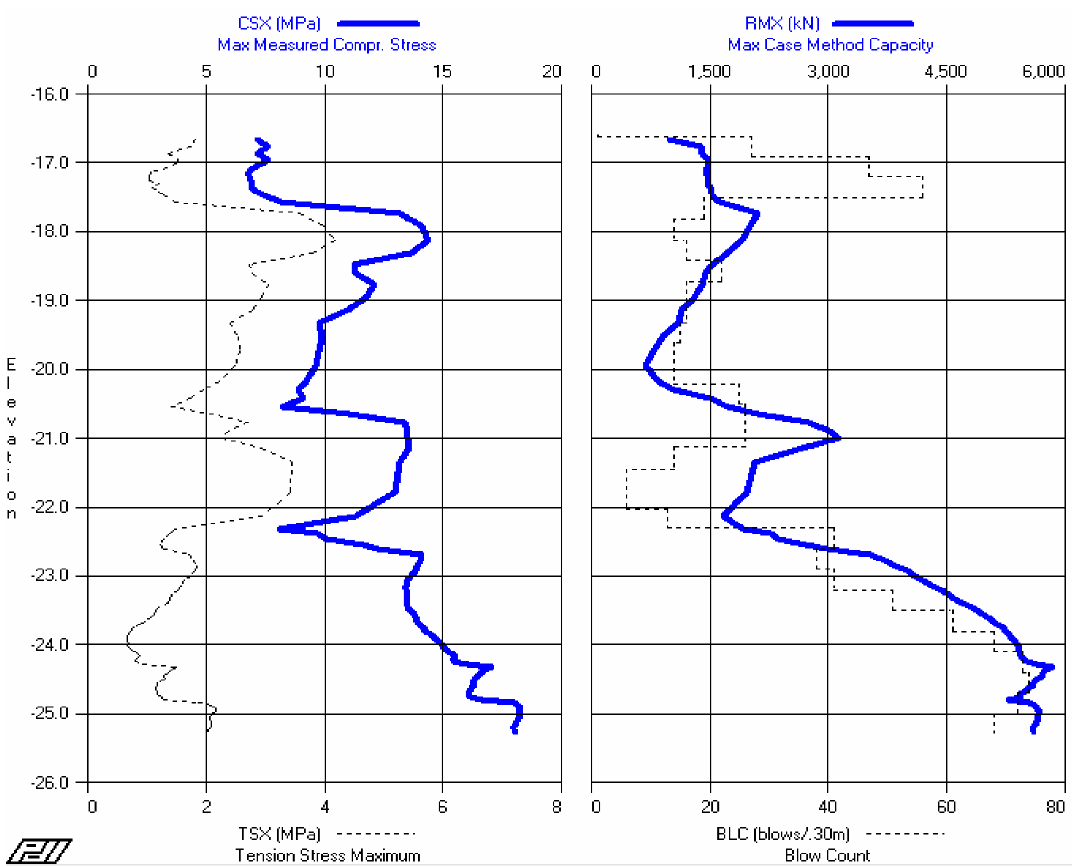

Fig. 2 Pile initial driving dynamic testing results.

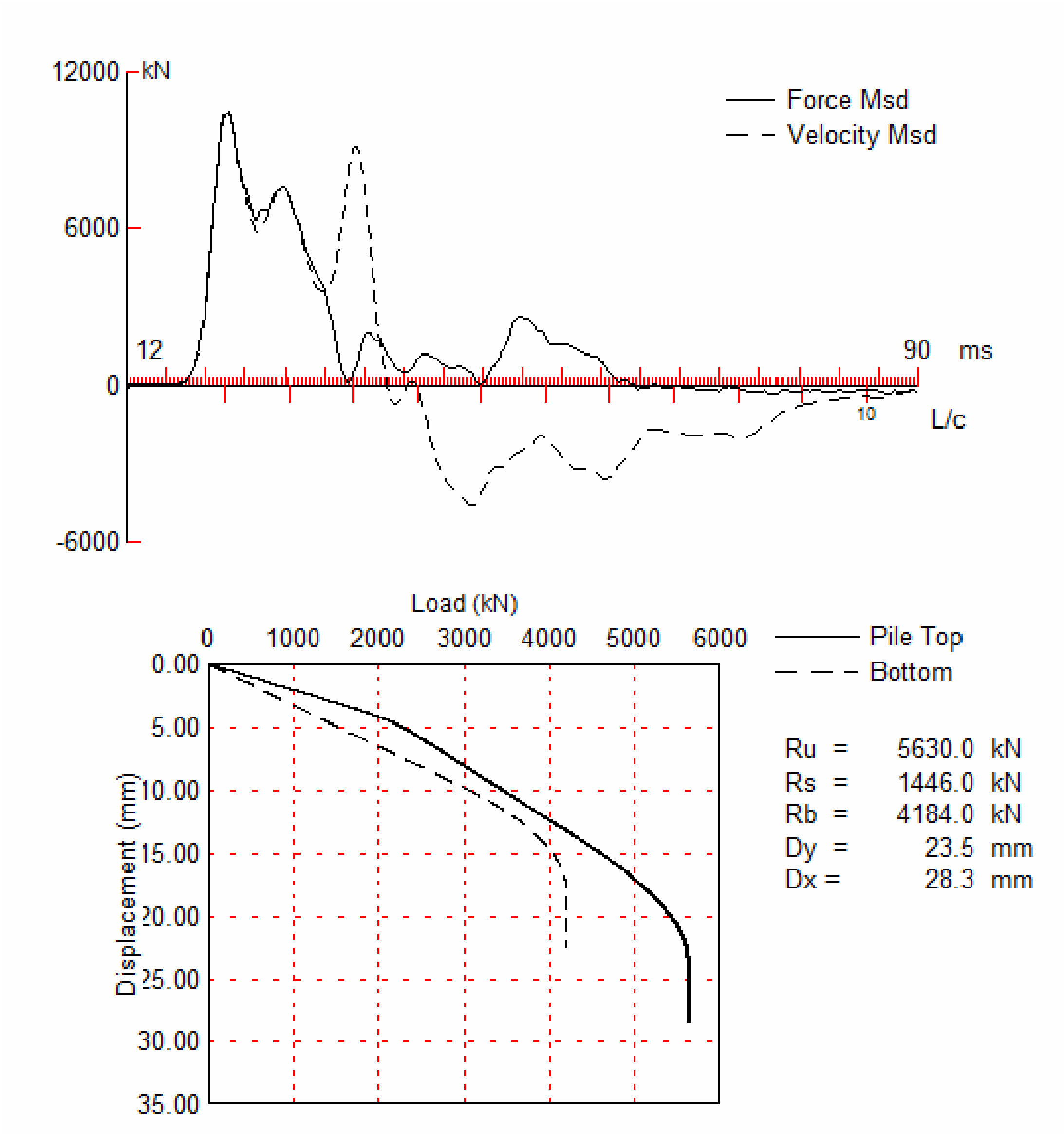

Figure 3 CAPWAP analysis results for end of initial driving.

4. STATIC LOADING TEST

Forty-three days following the end of initial driving, the pile was subjected to a conventional full-scale static loading test. Based on the dynamic pile testing results from the end of pile driving with consideration of favorable soil setup effects over time, as well as geotechnical analyses results, it was anticipated that the static loading test will show a pile capacity in excess of the required value of 5,760 kN.

Following the installation of the test pile, a test frame was setup using 16 steel HP 360 x 132 piles laid out as shown in Figure 4. Each of the 41 m long HP reaction piles was driven to a tip elevation of -29 m with a vibratory hammer, approximately 4 m below the tip of the completed test pile.

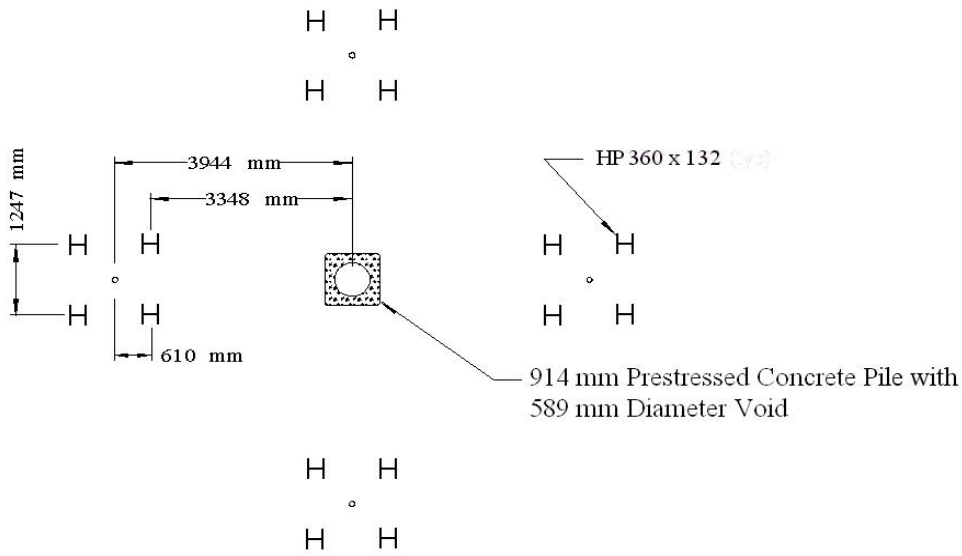

Fig. 4 Layout of test pile and reactions piles.

The static loading test was conducted in general accordance with Procedure A of ASTM D1143. Two hydraulic jacks were used in tandem to apply the loads. Pile head movement was measured using dial gages and a tight wire with mirror mounted rulers referenced to unloaded piles supporting the access platform around the test pile. Pile loads were applied in increments that were approximately 5 % of the anticipated maximum test load. Figure 5 presents a graph showing the test results as pile head load versus its vertical displacement.

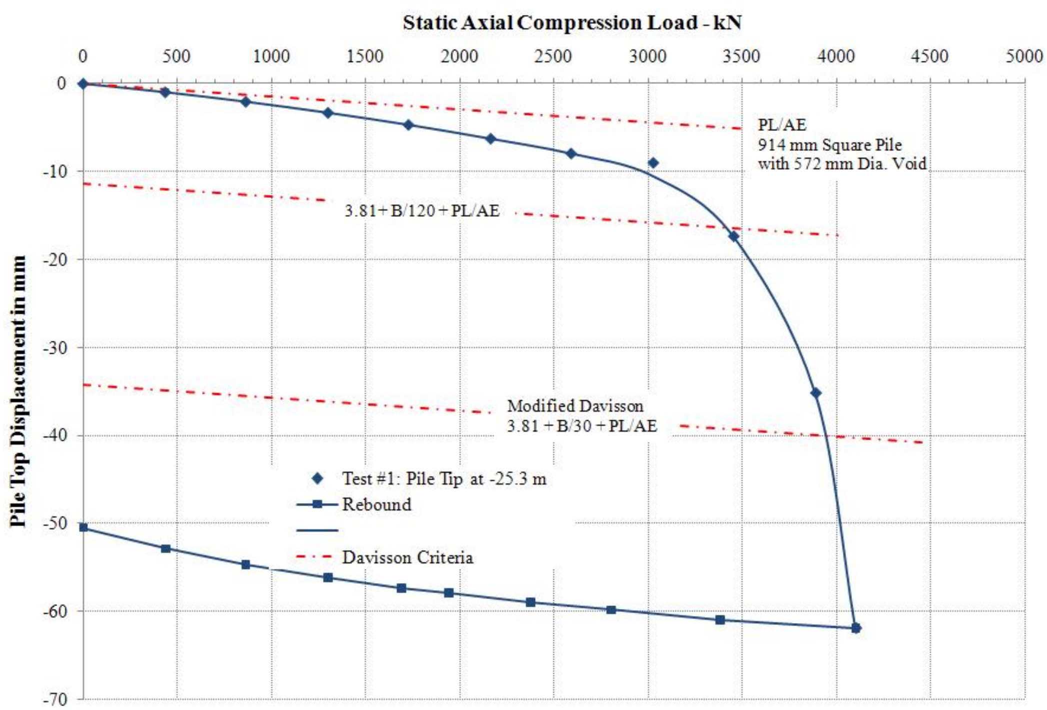

Fig. 5 Results of static loading test.

The load test data were interpreted to determine the pile capacity using the criteria in the FDOT Standard Specifications, 2004, Section 455-2.2.1 (b). That is, the "failure load" (i.e., pile capacity) is the load that causes a pile head movement equal to the calculated elastic compression plus 4 mm plus an additional 1/30 of the pile width. This modification of the commonly used procedure proposed by Davisson (1972) is applied because the piles exceed 610 mm in size. The static loading test indicated an ultimate capacity of only 3,950 kN; much less than the required value, and less than the anticipated value from both the geotechnical analyses and the end of driving dynamic testing results.

5. PILE RESTRIKE AND DYNAMIC TESTING RESULTS

One day after the static loading test, the pile was subjected to a restrike dynamic loading test. Plots of PDA data obtained under a restrike hammer blow along with corresponding CAPWAP simulated pile head and toe load-movement relationships are presented in Figure 6. The dynamic loading test results showed close correlation with the static loading test results, with an indicated ultimate capacity of 3,790 kN compared with the 3,950 kN value from the static load test. CAPWAP computed pile head movement of 10 mm at 3,000 kN load level is consistent with the measurements from the static loading test, with progressively increased pile movement under additional load.

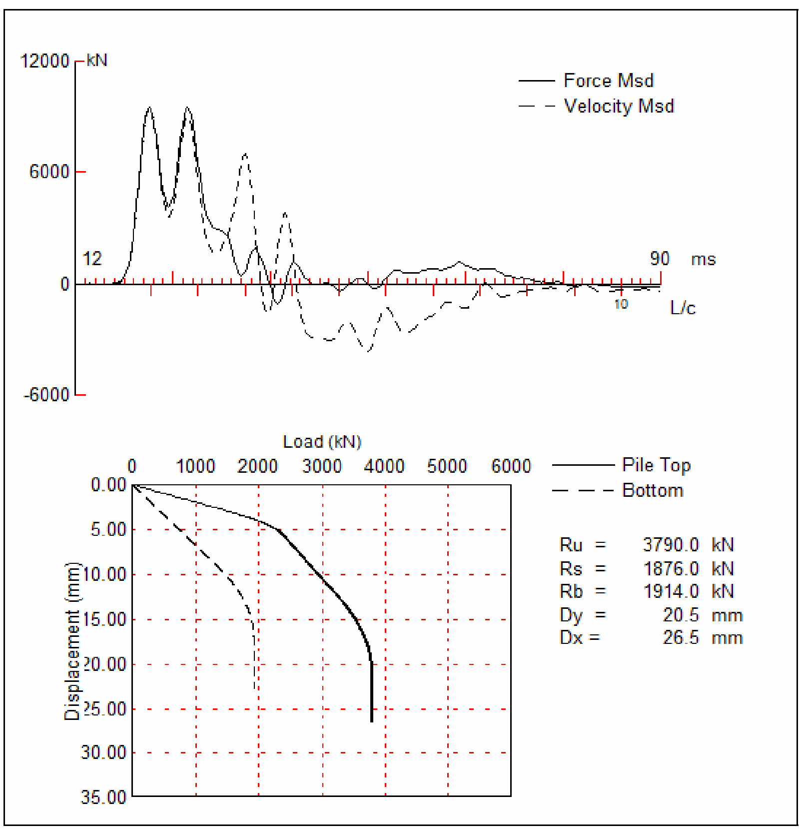

Fig. 5 Dynamic testing results of pile restrike test after static loading test.

The dynamic measurements from the restrike blows help to explain the apparent relaxation. The restrike dynamic load test data analysis indicated 1,876 kN in skin friction and 1,914 kN in end bearing. These values represent an increase of 430 kN in skin friction, but a significant decrease of 2,270 kN from the end of initial driving condition. The increase in skin friction would have been expected due to setup effects, but the reduction in end bearing was a surprise since no such relaxation effects had been observed at this site before.

The observed relaxation at the pile toe prompted a critical evaluation of the entire pile design and testing process, including review of the reaction piles installation procedures and their potential adverse effects on the in-place geotechnical condition of the test pile. As noted, the reaction piles were installed using the vibratory hammer almost 4 m deeper than the test pile toe, and the installation of these piles was suspected as the cause of the apparent relaxation at the test pile toe.

6. PILE REDRIVE AND DYNAMIC TESTING RESULTS

The test pile was driven 1.8 m deeper while instrumented with the PDA for dynamic testing. Five days later, the pile was dynamically tested again during restrike. The restrike test indicated an ultimate pile capacity of 4,723 kN, which represents an increase of 933 kN over the capacity obtained from the first dynamic restrike test. The pile was then driven another 2.6 m to a pile toe elevation of –29.7 m until dynamic pile testing indicated a pile capacity of 6,160 kN. Plots of PDA test records obtained under a hammer blow from the end of driving along with corresponding CAPWAP simulated load-movement plots are presented in Figure 7.

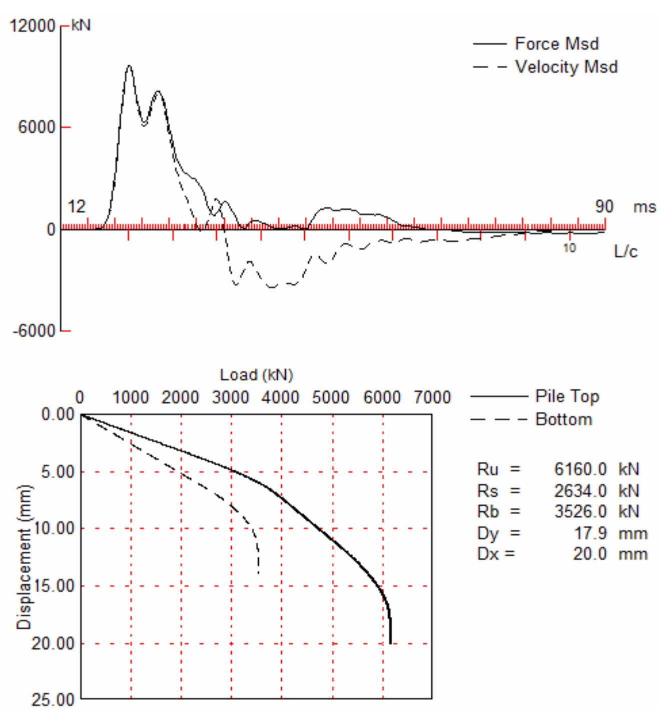

Fig. 6 PDA and CAPWAP testing and analyses results for end of driving.

The end of driving results were further analyzed utilizing a procedure that uses CAPWAP to predict pile head load-movement relationship incorporating anticipated increase in soil resistance (Hussein et al. 2004). The same 933 kN increase in pile capacity that was observed during the earlier testing sequence was applied to the end of driving value as an approximation of what can be expected over time, resulting in an anticipated pile capacity of 7,093 kN. Figure 8 presents the CAPWAP simulated pile head static load-movement graph. It shows a near-linear relationship between pile head load and corresponding movement up to a load level of approximately 6,600 kN and movement of 15 mm, after which relatively modest incremental loads result in progressively increasing pile top movement.

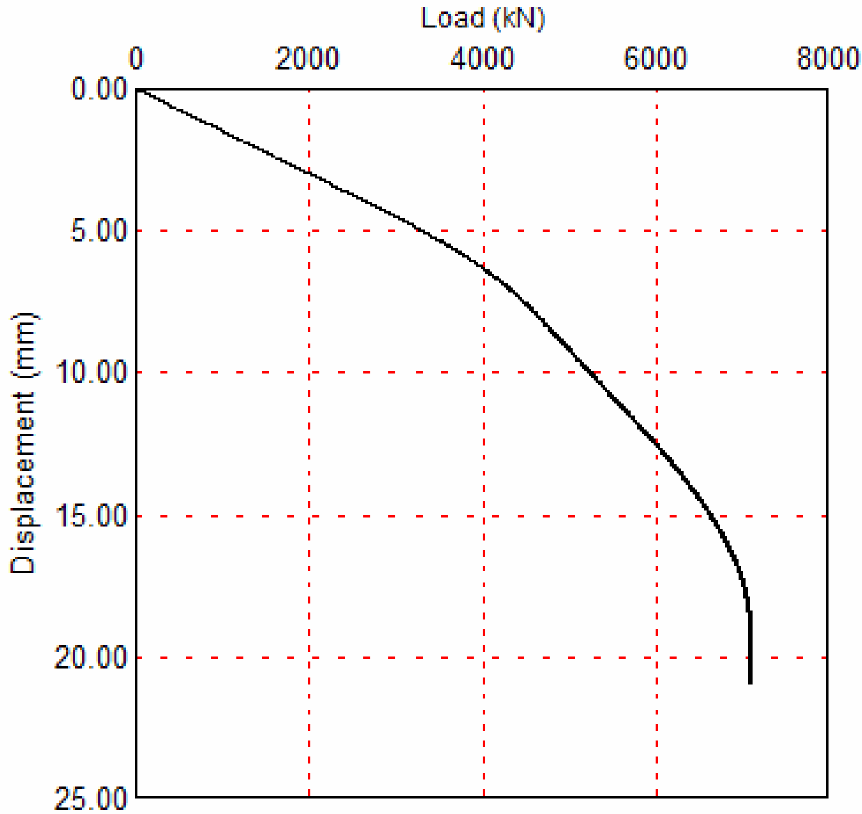

Fig. 7 CAPWAP simulated pile top load-movement relationship incorporating end of driving results and anticipated increase in pile capacity.

7. SECOND STATIC LOADING TEST

Six days after the end of final pile driving, the pile was subjected to a second static loading test. The results are presented in Figure 9 and indicate an interpreted pile capacity of 7,240 kN. The results of the second static loading test are consistent with the behavior anticipated from the dynamic load testing in terms of both the pile capacity and pile head load-movement relationship. No apparent relaxation was observed during the second load test sequence, thus adding credibility to the explanation that the relaxation observed during the first load test sequence was likely related to the installation of reaction piles.

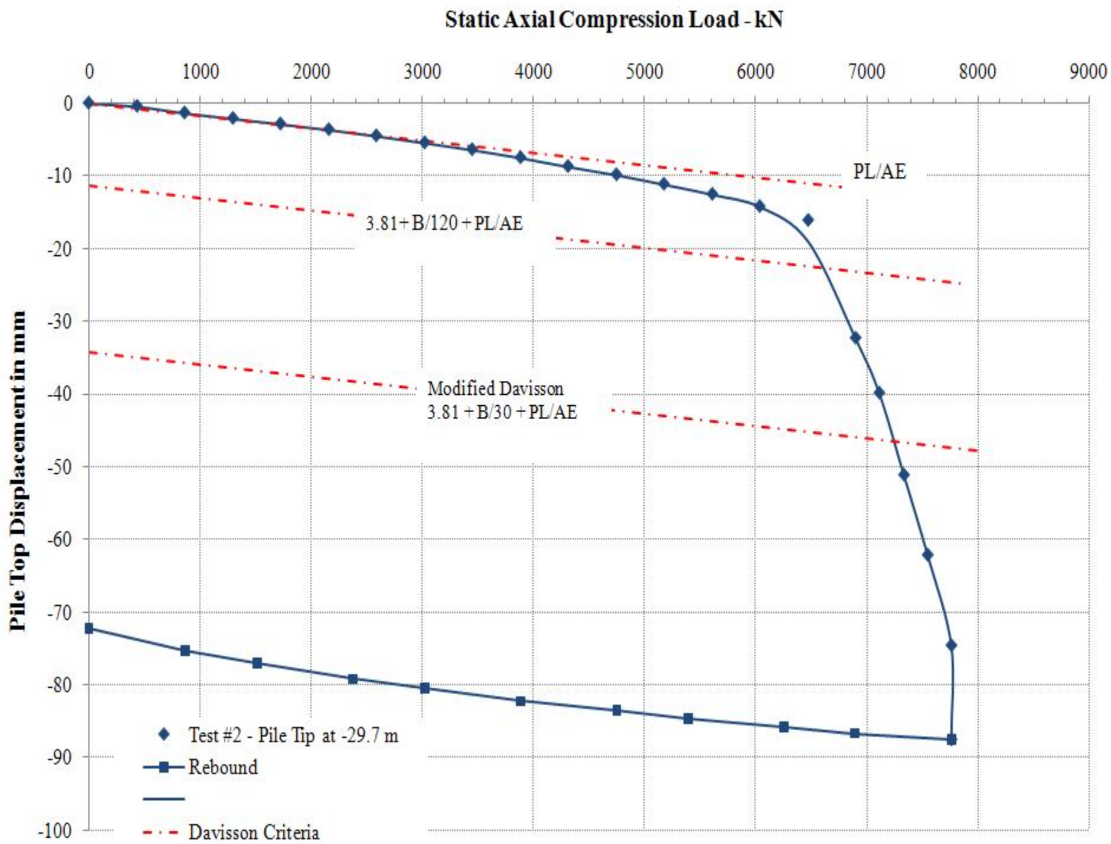

Fig. 8 Results of the second static loading test.

8. SUMMARY

Following extensive hurricane damage to the existing I-10 bridges over Escambia Bay in northwest Florida, the FDOT awarded their largest to-date design-build contract for the construction of two new bridges, 4,200 m long each. Large prestressed concrete piles were used as deep foundations. The extensive piling work included static and dynamic loading tests. This paper presented the results of one of the test sites where multiple static and dynamic loading tests were performed on the test pile. Results from the first static loading test were surprisingly lower than was anticipated based on geotechnical analyses and dynamic load test results. Subsequent dynamic testing, pile redrives, and an additional static loading test were performed on the same test pile for purposes of foundation design. In the process, it was discovered that the installation of the reaction piles needed for the static loading test altered the geotechnical condition of the test pile, and adversely affected the test results. Evidently, vibrating the steel H-piles to a depth below the toe of the test pile reduced the test pile's end bearing resistance.

Utilization of dynamic pile testing and geotechnical analysis made it possible to uncover the flaw in the static loading test procedure and thus the unreliability of the original static load test result. Should the flaw in the first static loading test had gone undetected; it would've had a costly consequence on the project budget and construction schedule. This case study demonstrates that static load tests can be misleading, and supplemental dynamic pile testing is a valuable tool to establish reliability and ascertain fidelity of results. Comparisons between static and dynamic loading tests results showed good correlations as far as pile capacity and pile head load-movement relationship are concerned.

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REFERENCES

FB-Deep V. 2.02, 2005. Bridge Software Institute, Gainesville, Florida.

Davisson, M.T., 1972. High capacity piles. Proceedings, Soil Mechanics Lecture Series on Innovations in Foundation Construction. ASCE Illinois Section; 52 p.

Fellenius, B.H., 1980. The analysis of results from routine pile load tests. Ground Engineering, London, 13(6) 19-31.

Kyfor, Z.G, Schnore, A.R., Carlo, T.A., and Baily P.F., 1992. Static Testing of Deep Foundations. Report # FHWA-SA-91-042 Federal Highway Administration, Washington, D.C.; 174 p.

Hannigan, P., Goble, G.G., Likins, G., and Rausche, F., 2006. Design and Construction of Driven Pile Foundations (two volumes), Report # FHWA NHI-05-042, National Highway Institute, Washington, D.C.

Hussein, M. and Likins, G., 1995. Dynamic testing of pile foundations during construction. Proceedings of ASCE Structures Congress XIII: Restructuring America and Beyond; pp. 1349-1364.

Hussein, M., Mondello, B., and Alvarez, C., 2004. Simulated pile load-movement incorporating anticipated soil setup. ASCE GSP 126: Geotechnical Engineering for Transportation Projects; pp. 1153-1160.

Likins, G.E. and Rausche, F., 2004. Correlation of CAPWAP with static load tests. Proceedings of the Seventh International Conference on the Application of Stress Wave Theory to Piles 2004: Petaling Jaya, Selangor, Malaysia; pp. 153-165.

Rausche, F., Likins, G., Liang, L, and Hussein, M., 2010. Static and dynamic models for CAPWAP signal matching. ASCE GSP 198: The Art of Foundation Engineering Practice; pp. 534-553.

Schmertmann, J.H., 1978, Research Bulletin RB-121, Florida Department of Transportation.