# Pile Driveability and Bearing Capacity in High-Rebound Soils

Mohamad H. Hussein[1] M.ASCE, Wayne A.Woerner II[2],
Michael Sharp[3], and Changsoo Hwang[1]

[1]GRL Engineers, Inc., Orlando, Florida - www.pile.com
[2]FDOT District 5 M&R, Deland, Florida - Bert.Woerner@dot.state.fl.us
[3]URS Corporation, Tampa, Florida – Michael_Sharp@urscorp.com

**Abstract**
During pile driving, static and dynamic soil forces resist pile penetration. Certain soils exhibit significant elastic behavior, causing unfavorable high-rebound which adversely affects pile driveability and complicates its bearing capacity assessment. This paper discusses the types of piles and soil conditions where the negative effects of high-rebound on the performance of the hammer system, pile, and soil have been observed, and a case history where field instrumentation and testing were performed. The case history involved the driving and testing of a 762 mm square, 35 m long, prestressed concrete pile driven into saturated fine silty to clayey sands and sandy clays that exhibited high pile rebound. Dynamic pile measurements were obtained during initial pile installation and restrikes to assess pile driveability and bearing capacity. Full-scale static load testing was performed to measure static pile bearing capacity and pile load-movement. A correlation between the static load test and dynamic test results is presented.

## Introduction

Modern pile design is an interactive process involving structural, geotechnical, and constructability considerations. Pile driveability refers to the ability of a pile to be safely (i.e., without damage) and economically (i.e., with reasonably sized construction equipment, and without excessive blow counts) driven to support the required bearing capacity and possibly to a minimum required penetration depth. Factors that affect pile driveability include the hammer driving system characteristics, pile type/size/length, and soil resistance behavior.

The static soil resistance is related to its strength and stiffness, while the dynamic resistance reflects its damping characteristics. Certain soils exhibit large elastic behavior, particularly at the pile toe in end bearing, causing unfavorable high-rebound during pile driving. High rebound results when a pile/soil system that is highly compressed during a hammer blow (due to large elastic temporary deformations of the pile and soil) springs back to near its original condition. This situation adversely affects pile driveability and complicates assessment of its load bearing capacity (Hussein et al., 2003). High-rebound typically occurs when driving displacement-type piles (e.g., solid concrete, closed-ended steel or concrete pipes, plugged pipes and H-piles) into saturated soils (e.g., dense silty sand, hard silty clay, glacial till, etc.). The pile rebound in these soils generally tends to increase as driving progresses due to increased pore water pressure. The incompressible water in the soil forces the pile rebound to increase. Conversely, as the excess pore water pressure dissipates with time, after driving stops, the pile elastic rebound tends to decrease. The technical literature contains several documented cases of high pile rebound during driving (Authier et al., 1981, Hannigan, 1985, and Likins, 1983).

Large temporary compression requires large energy input. Permanent pile penetration requires energy in excess of this temporary compression energy. If the hammer energy is consumed in temporary compression of the pile and soil, little extra energy is then available to do permanent work on the soil and refusal pile driving conditions may be reached prematurely, before the pile reaches the design penetration depth or required bearing capacity.

In cases where high rebound occurs during pile driving, some diesel hammers do not develop their maximum stroke height due to the slow elastic pile-soil response. For all hammers, the hammer energy may have to be limited in order to control pile driving stresses. During pile driving, when the toe response (end bearing) has a "large quake" or low stiffness, dynamic pile tension stresses in concrete piles may reach high levels that may result in damaging pile cracks, even at very high blow counts (Likins, 1983). Plywood cushions for concrete piles, and hammer cushions used when driving all types of piles, are replaced more frequently than normal in cases of high-rebound.

## Dynamic Pile Testing and Analysis

Pile driveability is commonly assessed by computer using wave equation analysis (Smith, 1960). The method simulates the dynamics of pile driving by utilizing numerical modeling techniques and one-dimensional elastic wave propagation principles. Each component of the pile driving system is modeled with one or more of three devices: block (representing weight), spring (representing stiffness), and dashpot (representing damping effects). The soil resistance is modeled with both dynamic and static components. The static resistance is displacement dependent, and is defined by an ultimate strength and a "quake" value. The quake represents elastic or temporary soil compression, and is inversely related to soil stiffness. Typical quake values are in the 2 to 5 mm range; soils with high rebound have considerably higher end bearing quake values, sometimes in excess of 25 mm.

Dynamic pile testing measures pile force and motion under hammer impacts with a system consisting of reusable strain transducers, accelerometers, and a Pile Driving Analyzer® (PDA) unit. Real-time data processing produces testing results that allow for evaluations of hammer system performance, pile driving compression and tension stresses, pile structural integrity, soil resistance distribution and pile static load bearing capacity. In high rebound soils, the dynamic pile test records exhibit special characteristic shapes (Hussein and Goble, 1986). To quantify the soil resistance effects, the measured data are analyzed with the CAPWAP® program which employs sophisticated signal matching techniques. CAPWAP results include static resistance forces along the pile shaft (i.e., skin friction) and at the pile toe (i.e., end bearing), soil quake and damping values in friction and end bearing, and a simulated pile static test load-movement graph (Rausche et al., 1994). Dynamic pile testing, and related data analysis, is an effective tool to assess effects of high rebound on hammer, pile, and soil performance during pile installation. Dynamic pile testing during restrike some time following initial driving provides long-term static pile load bearing capacity and load-movement characteristics incorporating time-dependent geotechnical effects.

## Case History

### *Project Description*

The Florida Department of Transportation is replacing the westbound State Road 528 over Indian River Bridge on Central Florida's east coast. The two-lane, high-level structure consists of twenty-five, 47 m long spans, for a total length of 1175 m. Each end bent contains six piles, while the piers consist of groups ranging between 9 to 20 piles each. All piles are prestressed concrete, 762 mm (30 inch) square with a 457 mm (18 inch) circular hollow core extending throughout most the piles lengths (i.e., 1.2 m length at each pile end is solid). Required pile ultimate bearing capacities ranged from 3532 kN to 4760 kN. The foundation design also included scour, ship impact, and other geotechnical and structural considerations. At the beginning of construction, a pile testing program that included 26 dynamically tested piles at representative production locations was undertaken to assess pile driveability and bearing capacity across the site. In addition, two piles were installed (one on land and the other in the river) and dynamically tested in non-production locations and were subsequently statically load tested. Following the static load tests, the piles were subjected to dynamic testing during restrike to obtain long-term data for comparison with the static load test results. This illustrative case history will focus on the test pile driven in the river.

### *Subsurface Conditions*

Water depth was approximately 2 m. The subsurface conditions can be generally described as saturated very loose to medium dense slightly silty sand (SP-SM) to silty sand (SM) with shell and coquina fragments to elevation -27 m, underlain by a layer of firm to hard clayey sand (SC) to sandy clay (CL) extending to elevation -38 m where limestone was encountered to the termination of the boring at elevation -44 m.

### *Test Pile Installation*

The 35 m long, 762 mm (30 inch) square with a 457 mm (18 inch) circular hollow core, concrete test pile was installed using a Raymond 8/0 single-acting air hammer. This hammer model has a ram weight of 111 kN with a maximum rated energy of 110 kJ. To control the hammer energy, two different strokes were utilized: 460 mm and 990 mm. The hammer cushion consisted of layers of aluminum and Conbest (600 mm thick), and the pile top cushion consisted of sheets of plywood (starting thickness of 230 mm). The soil inside an 8 m long, 1220 mm diameter steel casing (used as a template) was removed with a 914 mm diameter auger to aid in setting the pile.

Pile driving started with the hammer stroke set at 460 mm. Initial driving was relatively easy to elevation -18.5 m with blow counts ranging from 3 to 17 blows per 300 mm. Blow counts gradually increased over the next meter to

43 blows per 300 mm and the hammer stroke was then increased to 990 mm. The blow counts decreased to 12 blows per 300 mm over the next 1.2 m and at this point the dynamic tension stress in the pile exceeded the maximum tension stress allowed by the specifications (8.3 MPa). No damage to the pile was observed or suggested by the test data; however, to reduce tension stresses, at elevation -20.5 m, the stroke was reduced to 460 mm and driving continued to elevation -29.5 m with blow counts ranging from 18 to 61 blows per 300 mm at which point the stroke was again increased to 990 mm and, the pile was driven two more 300 mm increments until the pile tension stresses again exceeded the allowable limit and the pile was experiencing noticeably high elastic rebound. Driving was stopped and 57 mm of plywood cushion was added to the 230 mm of original cushion thickness to attempt to control the tension stresses in the pile. The pile was then driven 1.5 m and the blow counts ranged from 103 to 170 blows per 300 mm. Driving was stopped at a pile tip elevation of -31 m at a final blow count of 147 blows per 300 mm. A short-term 15 minutes wait restrike "set check" was performed, consisting of 10 hammer blows with a corresponding 54 mm pile penetration (equivalent blow count of only 56 blows/300 mm). The observed rebound during the set check was noticeably less than that at the end of initial drive.

Dynamic pile testing using the PDA was performed during the entire initial pile driving and restrike. End of initial driving dynamic test measurements indicated pile elastic rebound of 20 mm, while restrike data indicated only 12 mm of pile elastic rebound. Towards the end of initial driving and during the short-term restrike dynamic tests, PDA computed pile static capacities were 2200 and 3100 kN, respectively. The decrease in elastic pile rebound during the restrike (as compared to the end of driving) was likely due to dissipating excess pore water pressures resulting in lower blow count even though the static pile capacity had increased by 40% due to soil setup. Based on the results of other test piles at this site with longer wait times, it was anticipated that this static test pile would continue to gain capacity to obtain the required ultimate bearing capacity of 4760 kN.

***Pile Static Load Testing***

Nineteen days after its installation, the pile was subjected to a full-scale conventional compression static load test. The static load test was performed in general accordance with the requirements of the Florida Department of Transportation Standard Specifications Quick Test procedure. Load was applied to the pile top with four 1335 kN hydraulic jacks (with calibrated load-cell) reacting against a double reaction beam (supported by a total of twenty-eight, 22 m long, reaction steel H-Piles in four groups). The loads were applied in 5% increments of the maximum load, and each increment was held for approximately 10 minutes. Pile movement dial gauges were used on two sides of the pile. A wire/mirror/scale system provided backup pile movement measurement. In addition, scales were attached to the test pile and one reaction pile in each group to be observed with a surveyor's level to measure movement of the test pile and reaction piles. Figure 1 presents the static test pile-top load-movement data points.

***Long-term Restrike Testing***

Nineteen days after the static load test, the pile was dynamically tested during restrike. The pile was subjected to 41 hammer blows that resulted in 75 mm of total pile penetration, with blow counts of 12, 12, and 17 blows/25 mm. Dynamic test records showed pile elastic rebound of approximately 9 mm per blow at the beginning of restrike (which was less than previous short-term restrike) and also showed that the rebound increased to 13 mm per blow by the end of restrike. Static pile capacity values decreased from approximately 5400 kN to 3900 kN from the beginning to end of restrike, respectively. The increase in elastic pile rebound with successive hammer blows caused the increase in blow count during the restrike process (from 12 to 17 blows/25 mm) even though the static pile capacity actually decreased (due to reduced soil setup effects). Apparently the pore water pressures increased, as they would during continuous pile driving, and the incompressible water then forced the pile rebound to increase.

***Correlation of Static and Dynamic Testing Results***

Dynamic PDA test records obtained under the initial twelve blows (which caused the first 25 mm of pile penetration) during the long-term restrike performed following the static load test were numerically averaged. The resulting pile dynamic record was analyzed using CAPWAP for assessment of static pile load-bearing capacity, soil resistance distribution, and simulation of pile-top static load-movement graph. This novel approach of numerically averaging the restrike test records produced data that incorporates pile-soil relative movement and time-related geotechnical effects. Figure 1 includes a plot of the CAPWAP analysis result pile-top static load-movement graph, which is shown to correlate well with the actual full-scale conventional static load test result.

**Summary**

Certain soils exhibit significant elastic behavior causing high-rebound during pile driving. This unfavorable condition adversely affects pile driveability (e.g., limiting hammer performance, causing high pile dynamic tension stresses, and potentially resulting in premature refusal blow counts), and complicates assessment of pile load bearing capacity. Dynamic pile testing during initial driving, and subsequent restrikes to assess time effects, provide information for qualitative assessment of hammer, pile, and soil behavior that is necessary for rational analysis. A case history is presented where dynamic testing results showed excellent correlation with full-scale static load test results.

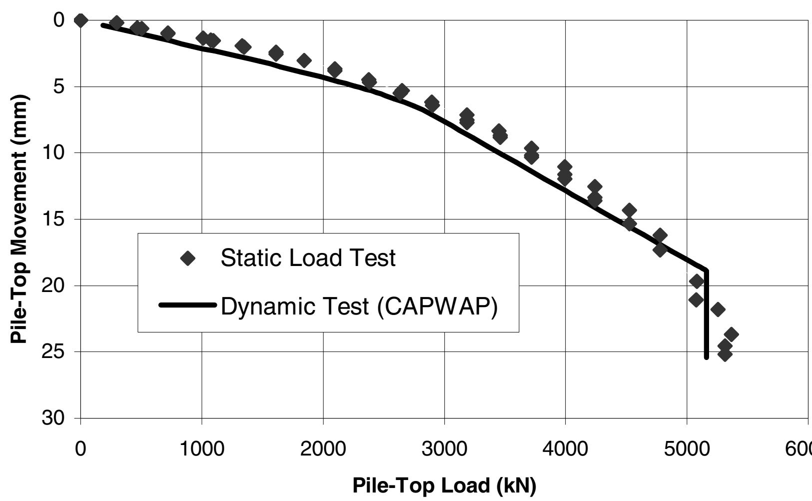


Figure 1. Comparison between actual (Static Load Test) and simulated (PDA/CAPWAP Dynamic Test) results.

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