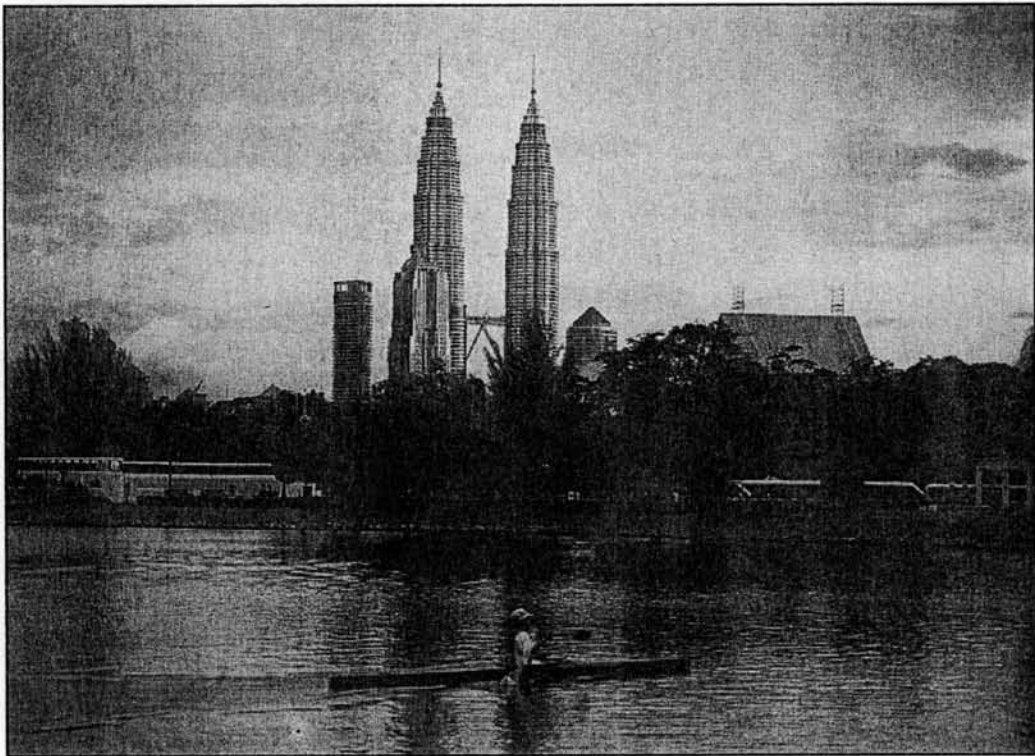PROCEEDINGS OF

# THE SEVENTH INTERNATIONAL CONFERENCE ON THE APPLICATION OF STRESSWAVE THEORY TO PILES 2004

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## *The Millennium Challenge*

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# DYNAMIC PILE TEST RECORDS
# WITH UNUSUAL CHARACTERISITCS

## Mohamad Hussein[1], Marty Bixler[2], and Brian Mondello[2]

## ABSTRACT

Measurements of pile strain and motion under hammer impacts are the basis of dynamic pile testing. Data is obtained electronically with reusable strain transducers and accelerometers affixed to the pile top. Testing results are typically presented as plots of pile force, velocity, wave-down and wave-up time records. The data is visually inspected, and numerically analyzed with computer methods. Generally, dynamic test records have standard features that are common to most cases. Under certain circumstances and special conditions, however, the test records exhibit unusual characteristics. This paper presents six cases where dynamic pile test records contain uncommon features. Peculiar aspects in the testing records are delineated, likely explanations for their occurrence and potential implications on the test results are presented, with suggestions for procedures to account for their presence in data analysis and evaluation of test results.

Keywords: dynamic testing, test records, high-strain, force, velocity, strain transducer, accelerometer.

## 1. INTRODUCTION

For a uniform pile, the intensity and length of the incident stress-wave caused by the suddenly applied hammer impact are mainly functions of: ram weight and drop height, cushion(s) stiffness, and pile weight and stiffness. Soil resistance effects generate upwards-traveling compressive waves that superimpose on the impact induced compression pile forces and reduce the pile velocity. Pile non-uniformities and the pile end also cause wave reflections. Modern dynamic pile testing is based on the measurement and analysis of the stress waves in the pile under hammer impacts. Data is obtained electronically with reusable strain transducers and accelerometers affixed to the pile just below its top. Testing results are typically presented as plots of pile-top force, proportional-velocity, propagating wave-down and wave-up time records. Analysis methods range from simple visual inspection of the test records to sophisticated computerized numerical techniques (Rausche, et al. (1985); Hussein and Goble (1987); Hannigan (1990); Hussein and Likins (1995)).

Since most pile driving systems have standard components and normal performance, in general, dynamic pile testing records have similarly common features. Typically, a test record can be divided into five phases: **pre-impact** (usually a flat zero line, except in cases such as a pre-igniting diesel hammer, etc.), **impact event** (a pulse-like feature present in the force, velocity, and wave-down records) usually designated as "0" time, **2L/c period** (covering the time of wave travel from pile top-to-toe and back, contains information regarding soil skin friction and pile structural integrity), **toe reflection** (occurs at time 2L/c following impact, indicates end bearing resistance effects including stiffness), and finally the **end** portion which follows the toe reflection after time 2L/c to the end of the record (typically indicates total soil resistance). This paper presents six cases where peculiar features and unusual characteristics in the dynamic pile test records are delineated; likely explanations for their occurrence and potential implications on the testing results are presented, with suggestions for procedures to account for their presence in data analysis and evaluation of test results.

[1]Partner, Pile Dynamics, Inc., Cleveland, Ohio, USA, www.pile.com
[2]Project Engineers, GRL Engineers, Inc., Orlando, Florida, USA, Marty@pile.com; Brian@pile.com

## 2. TEST RECORDS WITH UNUSUAL FEATURES

**2.1 Case 1.** The natural dynamic interaction between the hammer components (ram, impact block, etc.), cushions (hammer and pile), helmet, and pile may in some cases produce a "double impact" effect in the measured test records. This may be due to characteristics in the development of the hammer system impacting event and/or frequencies in the multi-degrees of freedom driving system. Figure 1 presents plots of force and velocity (A) along with wave-down and wave-up (B) records obtained under a hammer blow on a 45 m long, 610 mm square concrete pile driven with a diesel hammer. The fact that the second "hump" of the double impact evident in the force and velocity records is only present in the wave-down and not in the wave-up records assures that it is indeed a part of the impact and not a wave reflection. This feature has no effect on the quality of the data and does not require special attention in data analysis.
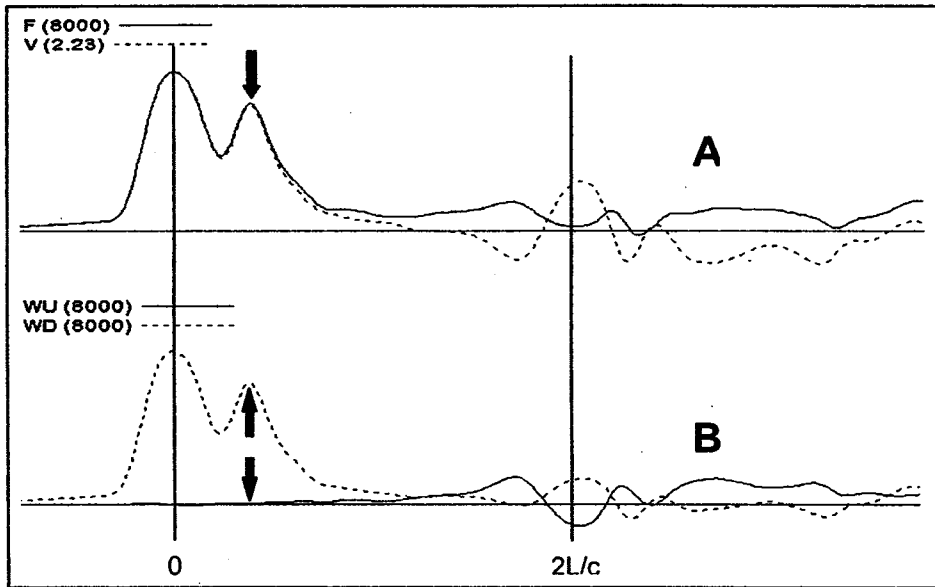


Figure 1: Double-impact effects in force and velocity (A), and wave-down and wave-up (B) records.

**2.2 Case 2.** The data in Figure 2 was obtained during the installation of a 610 mm square concrete pile, with length L = 48 m consisting of two 24 m long sections with a mechanical splice. The records in (A) are from the beginning of re-driving following the splicing of the top section onto the already driven bottom piece. The data contains all the expected standard characteristics. The records in (B) are from a blow after the pile has been driven a few more meters. It shows a peculiar reflection (indicated by the arrows) in the end portion of the records, located at time 3L/c after initial impact. Apparently, the "closed" splice did not at first produce a reflection upon the passing of the incident compression wave, but did so when the upward-traveling wave "opened" it causing the downward-traveling compression wave to reflect in tension following its reflection from the pile top (i.e., 2L/c + 2(½L/c)). This phenomenon would be difficult to simulate and analyze with standard numerical methods, but the test records can be monitored to evaluate the integrity of the pile despite the "opening" effect at the splice.

**2.3 Case 3.** Dynamic pile driving stresses, especially in tension, produce micro-cracks (and other degradation effects) in concrete piles. The data in Figure 3 was obtained during the driving of a 500 mm square, 22 m long concrete pile with a diesel hammer (30 kN ram weight and up to 3 m stroke). Figure 3 (A) shows test records with normal characteristics, while the plots in Figure 3 (B) contain features indicating the
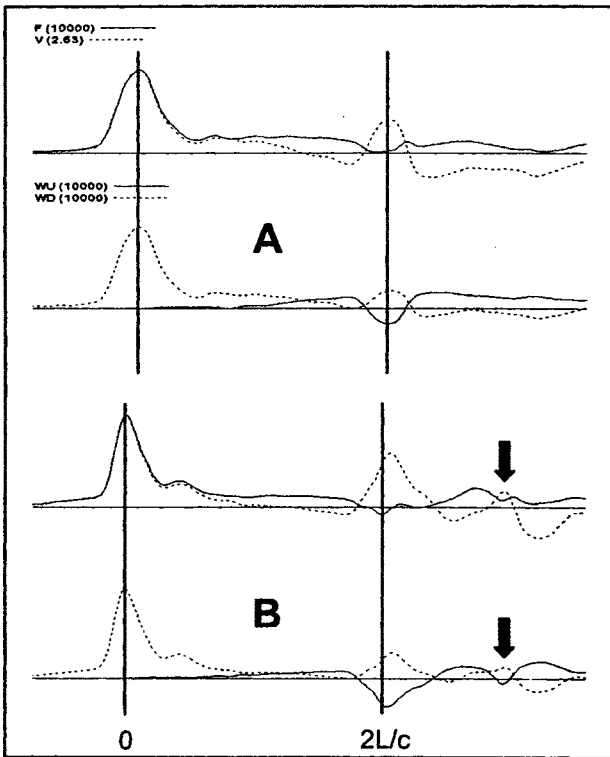
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Figure 2: Data from a concrete pile with a mechanical
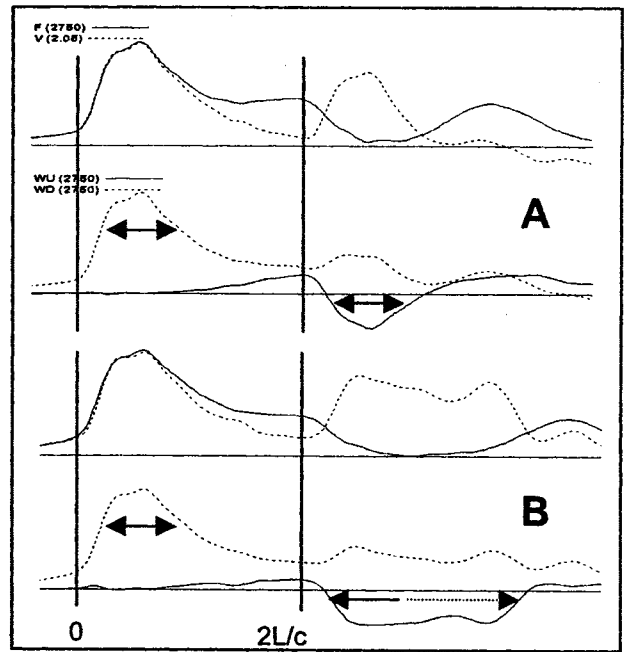splice, two hammer blows A and B.



Figure 3: Tension cracks effects on a concrete pile
data, two hammer blows A and B.

development of tension cracks along the pile length (with a potentially more significant crack at about two-thirds the pile length below its top). This is illustrated by the "elongated" wave reflection from the pile toe at 2L/c time, due to cumulative wave travel delay/reflection effects. Analysis of such data can only be done by utilizing tension slacks in modeling the pile (CAPWAP program, 2003). The records can be evaluated in real-time during driving to monitor pile structural integrity.

**2.4 Case 4.** Open-ended pipe piles may plug with soil during driving, and like other pile types, they may be subject to damage at their toe during hard driving into rock. Presented here is the case of a 22 m long steel pipe pile (1118 mm diameter with 16 mm wall thickness) driven with a diesel hammer (100 kN ram weight and up to 3 m stroke) through clay-sand overburden into hard rock. The plots in Figure 4 present force and velocity test records obtained under four hammer blows selected from throughout the entire driving process. Of special interest in this data is the time of wave reflection from the end of the pile. Plot (A) shows data from the beginning of driving with the toe reflection occurring at the expected 2L/c time. Plot (B) shows a delayed wave reflection likely due to pile soil plugging inertia effects, which is absent from the data in (C) indicative of pile soil-plug slippage (unplugging) effect. Plot (D) shows an early toe reflection, as compared to the one observed in (A), indicating an axial impedance reduction at the pile end (i.e., damage at the pile toe). Numerical analysis with the CAPWAP program can be used to analyze the pile plugging effect by incorporating a soil plug component into the pile/soil model. The use of a protective "pile-shoe" in cases like this may be beneficial in avoiding pile tip damage.

**2.5 Case 5.** The records presented in Figure 5 were obtained under a hammer blow from the end of driving of an open-ended, 19 m long, steel pipe pile (610 mm diameter with 13 mm wall thickness). They are typical of the data obtained during most of the driving of this pile. The general project area is characterized as karst
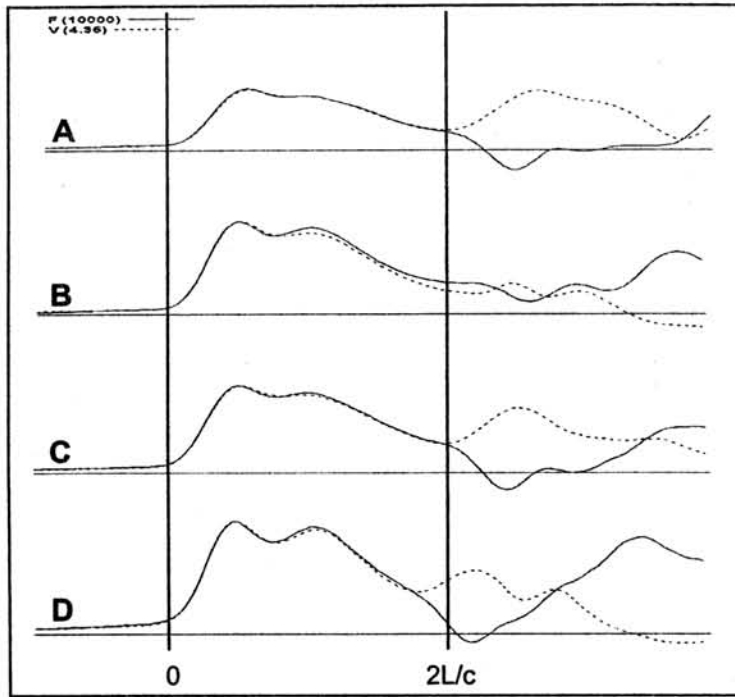
Figure 4: Data from four hammer blows from a steel pipe pile
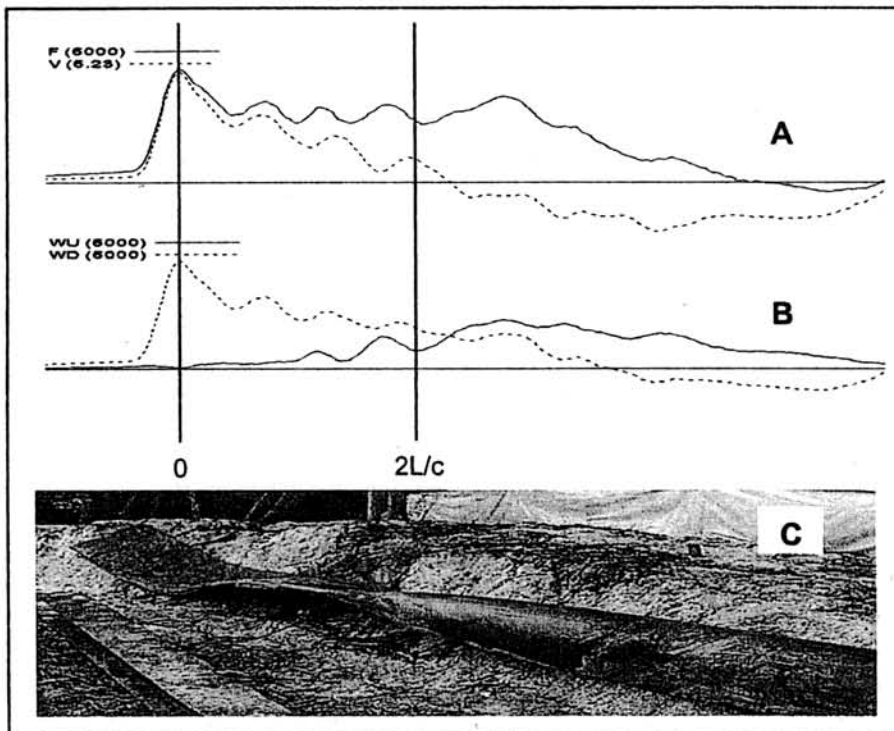showing plugging/unplugging and damage.



Figure 5: Plots of (A) force and velocity, and (B) wave-down and wave-up
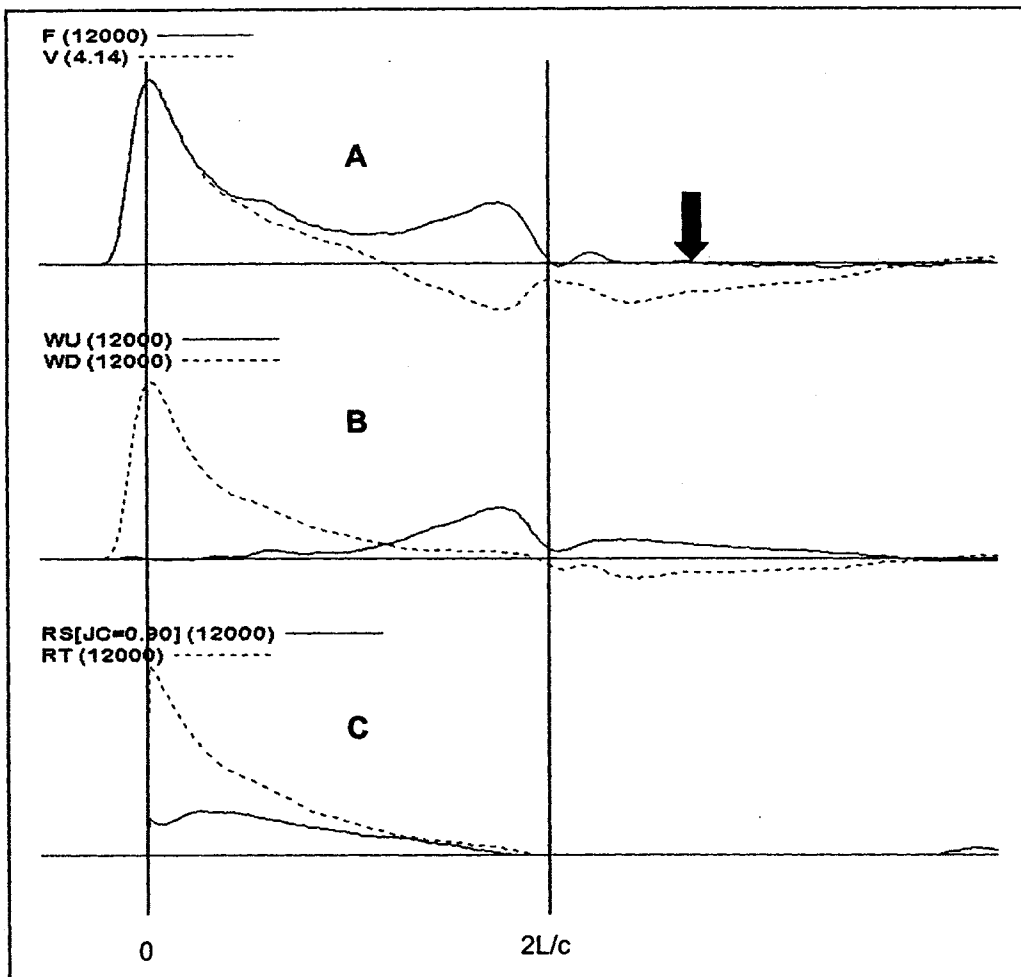along with photo of a damaged steel pipe pile -Case 5.

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Figure 6: Plots of (A) force and velocity, (B) wave-down and wave-up, and (C) total and static resistance under one hammer blow - Case 6.

geology. The force and velocity records in (A), as well as the wave-down and wave-up records in (B) show peculiar wave reflections within the bottom half of the 2L/c time period with characteristics that are unusual for a steel pile. These features in the test records indicate pile damage in an unusual manner, as can be seen in the photo presented in (C) showing the pile after it had been extracted from the ground.

**2.6 Case 6.** The data in Figure 6 was obtained under a hammer blow from the beginning of restrike of a 53 m long, open-ended, steel pipe pile (1220 mm diameter with 19 mm wall thickness) struck with an air hammer (with a ram weight of 118 kN and stroke of 1.2 m). The restrike blow count was at a moderate level of approximately 5 blows/25 mm. The soils generally consist of fine-grained, saturated, silty clays. The test records (shown in A and B) appear to have standard features (for a long friction pile), except for the uncharacteristic near-zero force and very low velocity, wave-up and wave-down magnitudes following the 2L/c time. This may be due to the dynamic interaction between the hammer and pile weights ratio with the high-damping soils. Part (C) of the figure presents plots of Case Method calculation results for the total and static component of the soil resistance. As can be seen in the resistance plots, a damping factor of 0.9 is needed in this situation, which gives a static capacity that is less than 25% of the total resistance value. CAPWAP analysis indicated a static pile capacity of 2334 kN (out of a total resistance of 9703 kN), and a

relatively high Smith skin-damping factor of 2.13 s/m. The use of radiation damping in analysis of the data in this case would produce a static capacity value that is unconservative, as later confirmed with a static loading test performed on this pile.

## 3. CONCLUSION

Dynamic pile testing relies on the measurement and analysis of the stress waves in the pile under hammer impacts. The data is typically displayed as plots of pile-top force, proportional-velocity, propagating wave-down and wave-up time records. In most cases, dynamic pile testing data generally have standard aspects and qualitative features. However, under special conditions, the test records contain unusual characteristics. This paper presented six cases (from concrete and steel piles) where the test records include peculiar features. The reasons for the uncommon features include: double-peak impact, mechanical splice in concrete pile, micro cracks in concrete pile, plugging and toe damage of steel pipe pile, unusual damage of steel pipe pile, and high soil damping effects. Likely explanations for the occurrence of the special features and potential implications on the test results are presented, with suggestions for procedures to account for their presence in data analysis and evaluation of test results.

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