STRUCTURAL INTEGRITY EVALUATION OF CONCRETE PILES FROM STRESS WAVE MEASUREMENTS

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ABSTRACT

Piles are deep foundation elements used to carry heavy structural loads. The load carrying capacity of a pile is a function of its structural strength and integrity, properties of the supporting soils, and pile-soil interaction characteristics. Concrete piles are either precast and installed with a pile driving hammer, or cast-in-place in a preformed hole. The structural integrity of either type may be compromised during installation, or later in service. Measurements of stress waves in driven precast piles under hammer impacts are routinely obtained for evaluating pile bearing capacity, driving stresses and structural integrity. After installation, both driven and cast-in-place piles may be evaluated for structural integrity by measuring pile top stress waves generated by small hand-held hammer impacts and wave reflections. This paper presents discussions on the principles, application, and limitations of these "high" and "low" strain testing methods. Six illustrative case histories are also included.

BACKGROUND

Pile foundations are considered when: structural loads need to be transmitted through soils exhibiting low bearing capacity to deeper more competent strata, to resist uplift or lateral forces, to support structures over water and carry loads below scour depths, and/or building in areas where future adjacent excavations are expected. The load carrying capacity of a pile is a function of its structural strength and integrity, the strength and deformation properties of the foundation soils, and the pile-soil interaction characteristics. Piles may be made of wood, steel, concrete, or a combination of these materials.

Concrete piles are of two major types: cast-in-place and precast. Cast-in-place piles are constructed by forming holes in the ground and filling them with concrete; they range in size between 250 and 2500 mm in diameter and can be more than 45 m in length, but are most commonly used in sizes less than 500 mm in diameter and up to 20 m length. Advantages of this type of piling include their relatively low cost, ease of length variation to adapt to changes in soil conditions, and absence of ground vibrations during installation. A major disadvantage, however, is the uncertainty regarding the shape and structural condition of the constructed pile. The profile and structural integrity of this type pile is a function of: concrete quality and method of placement, subsurface conditions, and workmanship. Common modes of structural deficiencies include separation of concrete, necking, voids, or contamination of concrete with soil. Precast concrete piles are mostly square in cross section with sizes between 250 and 750 mm and lengths commonly up to 30 m, longer lengths are obtained by field splicing. They are prestressed for added strength and durability and installed with impact pile driving hammers. The hammer impact and soil resistance generate a complex combination of compressive, tensile, bending, and sometimes torsional stresses in the pile. Dynamic driving stresses are at times sufficiently high to cause pile damage. Causes of pile overstressing and structural damage include: inappropriate hammer, insufficient cushions, deficient pile, soil behavior, and general dynamic incompatibility. Common modes of driving induced pile structural damage include: crushing at the pile head, toe or shaft, horizontal and vertical cracking, and failure of splices. Additionally, both pile types may be damaged after installation and under service conditions.

INTRODUCTION

One dimensional wave mechanics applies to a linear elastic pile that has a length an order of magnitude greater than its width. When a pile is impacted at its head, a compressive stress wave travels down the pile shaft at a speed, c, which is a function of the material elastic modulus, E, and unit mass, ρ.

$$c = \sqrt{(E/\rho)} \qquad (1)$$

Common stress wave speeds in concrete piles range between 3000 to 4500 m/s. For a uniform pile with no soil resistance, the wave travels unimpeded (except for minor concrete internal damping) and reaches the pile toe at a time L/c after impact (where L is the pile length) and reflects as an upwards traveling tension wave which is registered at the pile head a time 2L/c after impact. Soil resistance, distributed along the pile shaft and under its toe, generate upwards traveling compressive waves. For a soil resistance force located at a distance (x) below the pile top, its effects will reach the pile top at a time 2x/c after impact. Another cause of wave reflections is change in pile impedance Z(=EA/c, Where A is pile cross sectional area). An increase in impedance causes an upwards traveling compressive wave and a decrease causes an upwards traveling tension wave. The time at which these reflected waves reach the pile top is directly proportional to the location of impedance change along pile shaft and their nature and magnitude a function of the impedance change and its severity. Interpretation of pile top stress wave measurements for pile integrity assessment is based on the premise that changes in pile impedance generate wave reflections of predictable nature, magnitude and time at the pile top.

Early stress wave measurements on piles were made in 1938 to study stress distribution in precast concrete piles under hammer impacts [1]. The Michigan Highway Commission performed dynamic measurements in 1960 of force and acceleration near the pile head for evaluating driving system performance [2]. In 1964, a research program, funded by the United States Federal Highway Administration (FHWA) and several State Highway Departments of Transportation, was initiated at Case Institute of Technology (now Case Western Reserve University) for the purpose of developing an economical, practical, and easily portable field system which could calculate static pile bearing capacity from electronic dynamic measurements of pile force and motion during pile driving or restriking. The necessary equipment and analytical methods were developed [3], and later expanded, to evaluate other aspects of the pile driving process. These procedures are collectively called the Case Method (named after the university) and are conveniently applied in the field by a specialty signal conditioning and computing device called the Pile Driving Analyzer (PDA). A photograph of a Model GCPC Pile Driving Analyzer is presented in Figure 1. Since measurements are obtained under the impacts of a large hammer, this type of monitoring is often referred to as "High strain" testing. Today, high strain dynamic testing is routinely performed on thousands of projects annually around the world for the purposes of improving pile design, installation and construction control procedures. The following are the main objectives of this type of testing: calculation of pile static capacity, investigation of driving system performance, determination of dynamic pile driving stresses, and assessment of pile structural integrity. During the last decade, dynamic pile top measurements of stress waves under impacts from a small hand held hammer for the purpose of evaluating pile structural integrity has been developed and now enjoy widespread acceptance. Since the impact generates only very small strains in the pile, this type of testing is often referred to as "Low strain" testing and is commonly performed by monitoring pile top motion with an accelerometer. The application of low strain dynamic testing has been recently expanded to test piles under existing structures for determination of pile integrity and unknown lengths [4].

This paper presents discussions on high and low strain dynamic pile testing and data analysis for pile structural integrity assessment. The principles, application, accuracy, and limitations of both methods are presented along with illustrative case histories from various projects.

HIGH STRAIN DYNAMIC PILE INTEGRITY TESTING

The basis of high strain dynamic pile testing is the measurement of pile top force and velocity caused by the impact of a hammer blow. Reusable strain transducers are employed to measure pile force, velocity is obtained by measuring pile acceleration with piezoelectric or piezoresistive accelerometers. Figure 2 presents a photograph of a strain transducer and a piezoelectric accelerometer bolted to the side of a 356 mm square precast prestressed concrete pile. The PDA conditions and calibrates measured signals and checks the records for data quality. Required PDA inputs include pile length, area, elastic modulus, wave speed, and unit weight in addition to specific gage calibrations and a soil damping factor (dependent on soil type and dynamic behavior). Using wave propagation theory, the PDA applies specific inputs and Case Method equations to the measured records to compute some 40 variables in real time

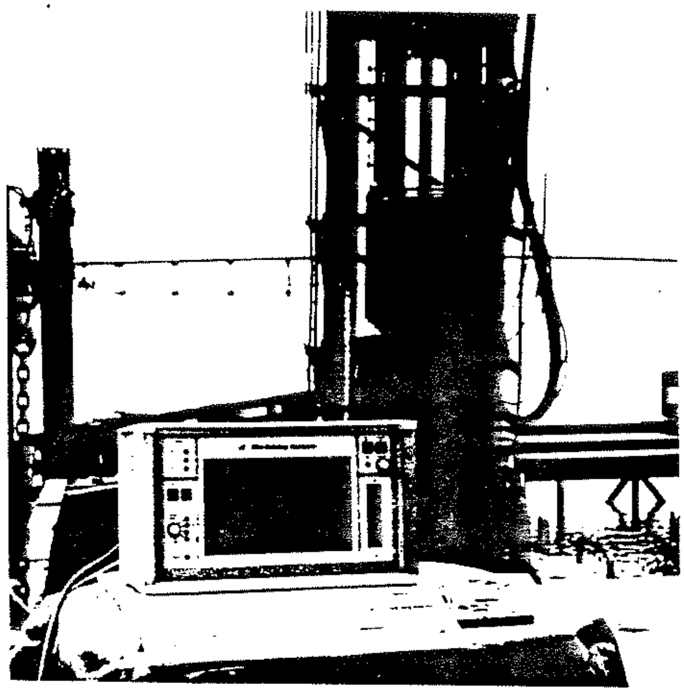


Figure 1: The Pile Driving Analyzer

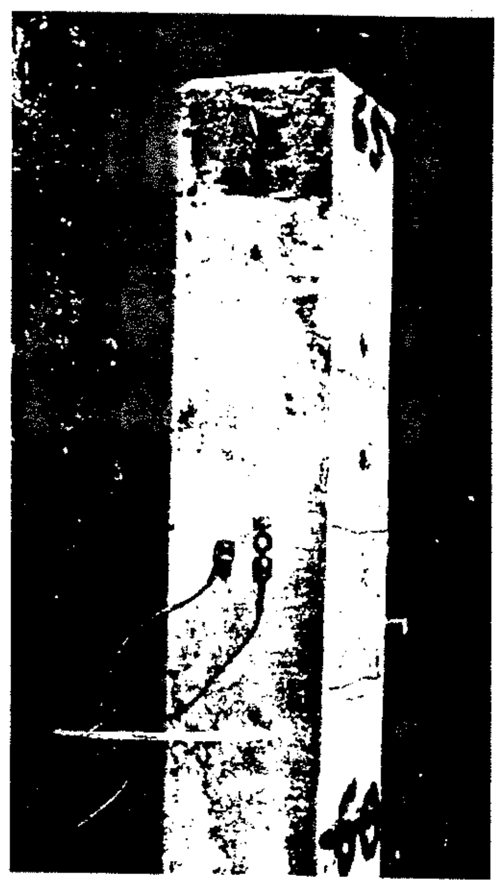


Figure 2: Accelerometer (left) and strain transducer (right) attached to a precast concrete pile

between hammer blows. The most interesting of these values are: Case Method axial pile static capacity [5], maximum energy delivered to the pile, ram impact velocity and cushion stiffness [6], maximum pile compressive and tensile stresses [7], and pile structural integrity factor and location of damage [8].

An applied hammer impact causes at the pile top a force (F) and particle velocity (v). As long as the wave travels in one direction and no reflections are introduced, it can be shown that the force, F, and velocity, v, are proportional by the pile impedance (Z), i.e.,

$$F = Zv \qquad (2)$$

A decrease in pile impedance causes a relative decrease in force and a relative increase in velocity. An increase in pile impedance will produce an opposite effect. Since both force and velocity are measured, the forces in the downward, W_d, and upward, W_u, traveling waves can be computed from:

$$W_d = (F + Zv)/2 \qquad (3)$$
$$W_u = (F - Zv)/2 \qquad (4)$$

Pile top compressive stress can be obtained directly from the measured data as the maximum magnitude of the force record divided by the pile cross sectional area. For concentrated end bearing soil resistance, the compressive stress at the pile toe can be calculated from pile top measurements and one dimensional wave propagation considerations. Maximum dynamic tension stresses occur at some location along the shaft below pile top. Maximum tension stress can be computed from the pile top measurements by considering the magnitude of both upward and downward traveling waves. If any one of these waves is negative, a tension wave exists. It is also checked whether the wave traveling in the opposite direction is sufficiently compressive to reduce the net tension force.

It has been pointed out that stress waves are reflected whenever the pile impedance changes and that reflected waves arrive at the pile top at a time proportional to the distance to the impedance change. The reflected waves cause changes in both pile top force and velocity measured records. The magnitude relative change of the pile top variables allows for determination of the magnitude of impedance change. Thus, with "β" being a relative integrity factor which is unity for no impedance change and zero for the pile end, the following can be calculated:

$$\beta = (1 - \alpha)/(1 + \alpha) \qquad (5)$$

with

$$\alpha = [(W_{ur} - W_{ud})/(W_{di} - W_{ur})]/2 \qquad (6)$$

where "W_{ur}" is the upward traveling wave at the onset of the reflected wave (it is caused by soil resistance), "W_{ud}" is the upwards traveling wave due to the damage reflection, and "W_{di}" is the maximum downward traveling wave due to impact.

Empirical correlations has been established between computed integrity factors and degree of pile damage. The following are classifications of pile structural integrity based on computed "β" factors:

"β"	Pile Condition
100	uniform Pile
80-100	slight damage
60-80	damage
below 60	broken.

By the time "β" becomes 60 or less, it is unlikely that the concrete will withstand further impacts and additional deterioration is therefore likely; distinct pile toe reflections are rarely observed at this level. Reasons why "β" does not show zero values in reality for a completely broken pile include pile damping, static and dynamic soil resistance under the new pile end (damage location), potentially still attached prestress strands, etc.

Limitation to this method of pile structural integrity assessment include high soil resistance at and above damage location which tend to mask relatively minor pile impedance reduction, large compressive force in the pile that causes cracks to close during wave transmission, relatively long impact wave length limit the method's resolution, and gradual changes in pile impedance can not be detected since they do not cause sharp wave reflections.

The following three case histories illustrate the applicability of high strain dynamic measurements in determining pile structural damage. Since these are all case histories with the original work done in the English units, soft conversion factors were used to present the results in SI units.

Case History - 1

A pre-construction pile driving and testing program was undertaken at a highway bridge site for evaluating pile drivability and determination of relevant foundation design parameters. Two 457 mm square, 36.6 m long precast prestressed concrete piles were installed. Structural analysis of pile elements indicated allowable dynamic compressive and tensile driving stresses of 22.4 and 8.6 MPa, respectively. This case study will consider one of the piles that was damaged during installation.

Pile driving was accomplished with an open ended diesel hammer having a ram weight of 45 kN and a rated energy of 99 kJ at the fuel setting used. Sheets of plywood, with a total thickness of 230 mm, were used as pile top cushion. Soil conditions at the site can generally be described as layers of sand and silty sand over a dense sand layer. One each strain transducer and accelerometer were bolted on opposite sides of the pile four feet below its top. Dynamic testing was performed during the entire driving process. Pile driving resistance was less than 25 blows per 0.3 m to a depth of 9.14 m at which point the pile plunged 4.6 m under its own weight and that of the hammer due to lack of soil resistance; final pile penetration was 28.7 m and a blow count of 24 for the last 0.3 m of penetration.

During the installation process, maximum pile top compressive stresses reached 28.2 MPa and tensile stresses 12.4 MPa. High pile stress values were attributed to the hammer's inability to run with low soil resistance and are the result of having to continuously re-start the hammer with relatively high strokes each time. After the hammer continually fired, computed tensile stresses reached 5.5 MPa, but were usually less than 4.1 MPa. High tension stresses caused pile cracking that developed into pile breakage with repeated blows. Plots of pile top force and proportional velocity, along with wave down and wave up records, taken form the beginning of driving and later after pile damage are presented in Figure 3. Data from early driving contain a clear reflection from the pile toe indicating pile continuity (i.e., $\beta=100$). The second record indicate total pile breakage ($\beta = 23$) at a location 61 ft below gages (19.8 m below pile top).

Case History - 2

A pile driving and testing program was performed to evaluate installation procedures and assess pile static bearing capacity at a proposed bridge construction site. A total of seven 457 mm square prestressed concrete piles were driven. Pile lengths varied between 30.5 and 42.7 m. The overburden soils at this site consisted of interbeded layers of loose to medium dense silty fine sands overlaying weathered limestone. Pile driving was accomplished with an open ended diesel hammer having a ram weight of 45 kN and a rated energy of 116 kJ at the fuel setting used. Typically, 12 sheets (19 mm thick each) were used as a pile top cushion. This case history discusses the driving and determination of damage of one of the test piles.

The pile was spliced from an original length of 30.5 m to a total length of 42.7 m. The first section was driven to a depth of 29.6 m and a driving resistance that did not exceed 12 blows per 0.3 m. The 12.2 m section was added, using epoxy-dowel splice, and redriving resumed five weeks after end of initial driving. The pile was driven an additional 4 m during which the blow count dropped from 30 blows per 0.3 m at beginning of redrive to 12 blows per 0.3 m at end of installation. During the redriving process, the maximum pile top compressive stress averaged 22 MPa and maximum pile tension stress reached 7.6 MPa. Approximately midway through the redrive, dynamic pile top data indicated tensile wave reflections originating from the splice location. The structural integrity of the pile was monitored after each hammer blow (by evaluating the β factor) until driving was finally stopped when β reached a value of 74. It is likely that further hammer impacts would have broken the pile totally. Plots of force, proportional velocity, and wave down and wave up histories from the beginning and end of redrive are presented in Figure 4. The data from beginning of redrive show a clear toe reflection and a $\beta = 100$, while data from end of redrive indicates pile damage ($\beta=74$) at a location near the splice (12.5 m below pile top).

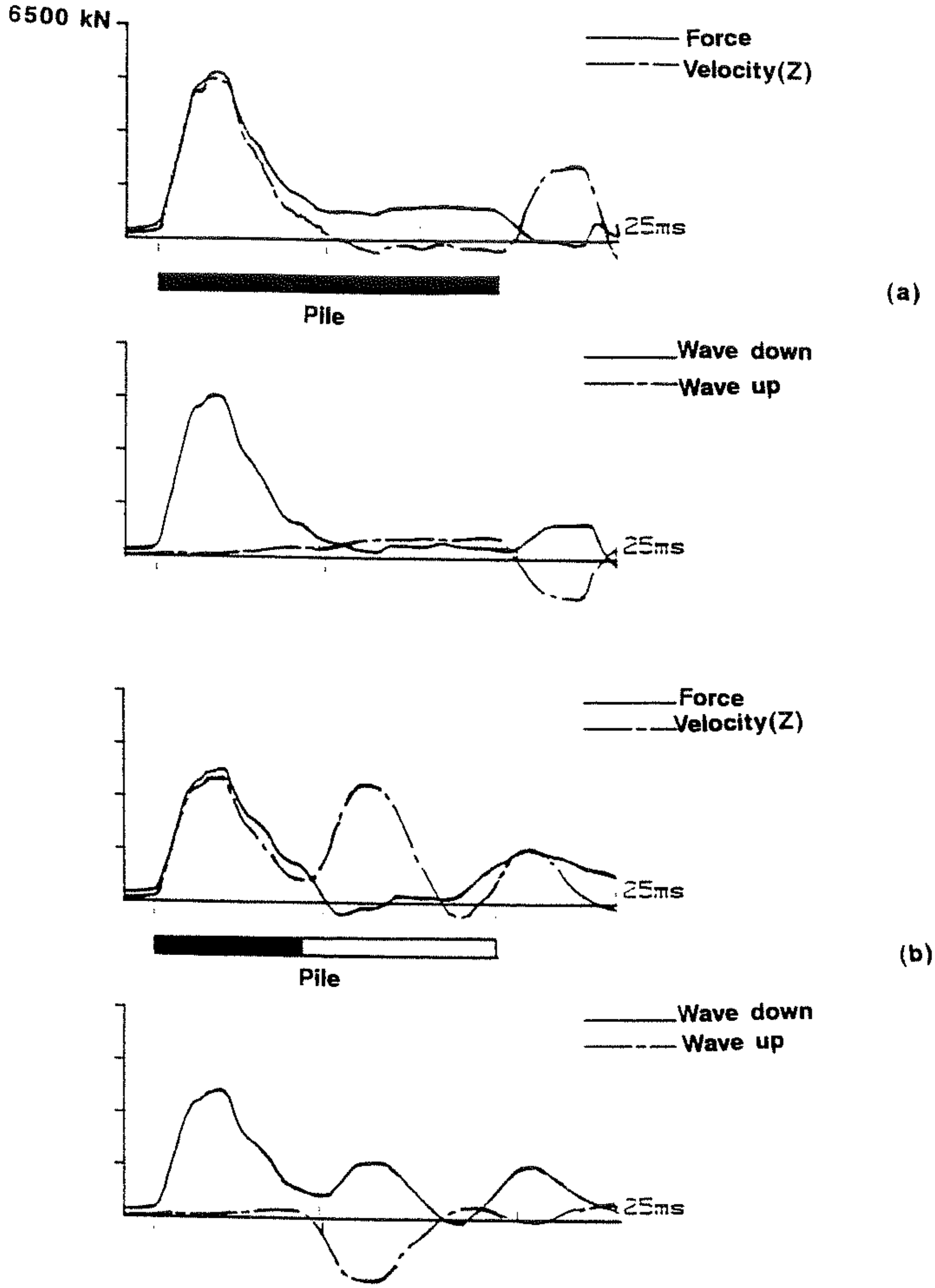


Figure 3: Plots of pile top dynamic records, (a) beginning of driving and (b) end of driving - Case History 1.

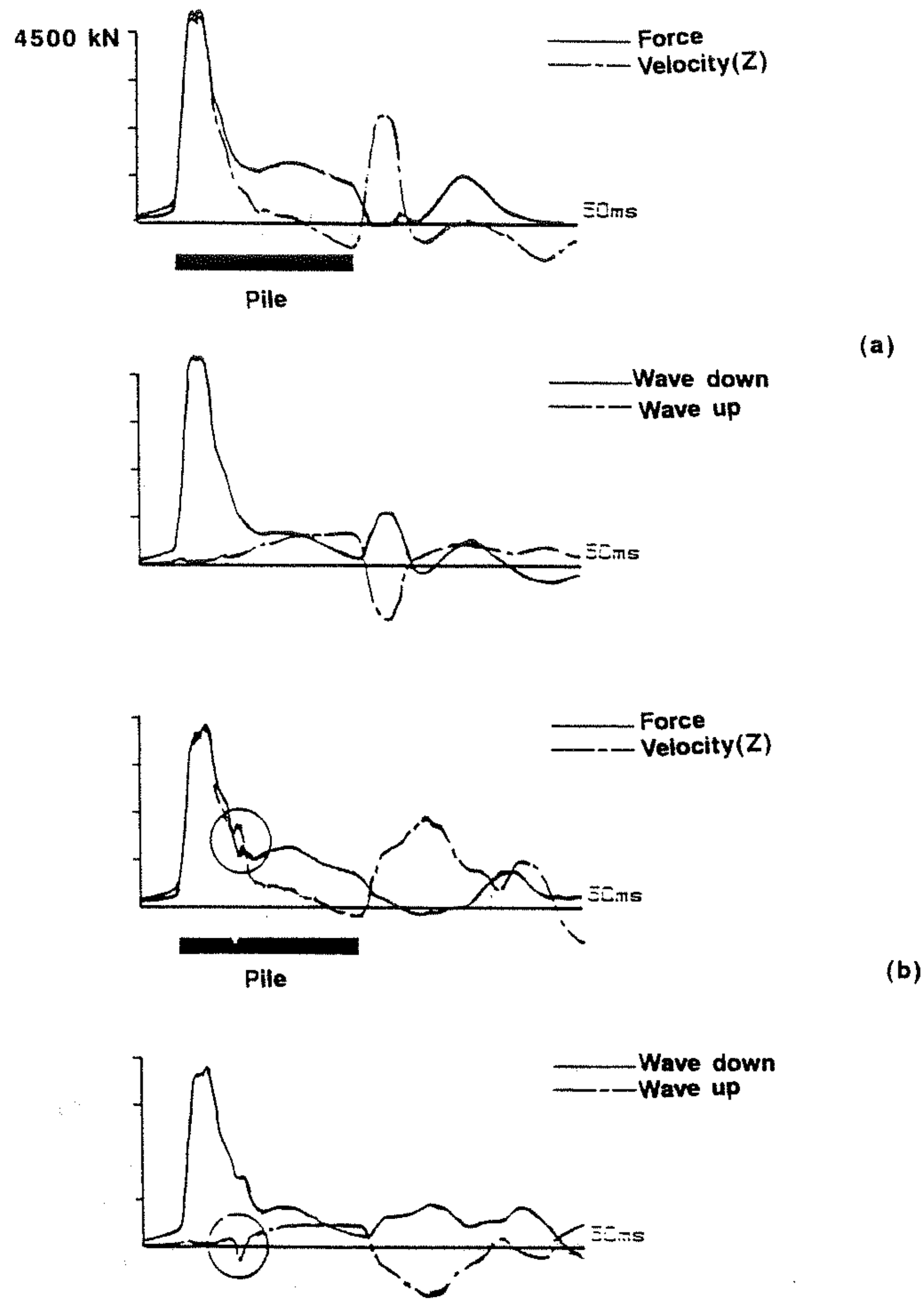


Figure 4: Plots of pile top dynamic records from the beginning of driving (a) and end of driving (b), respectively - Case History 2.

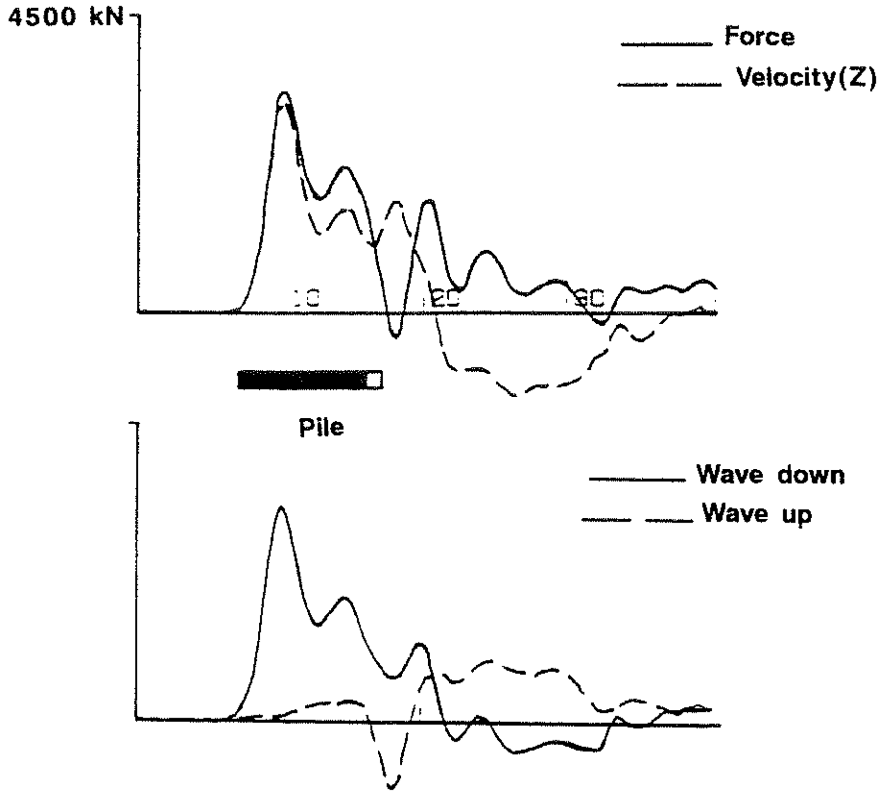
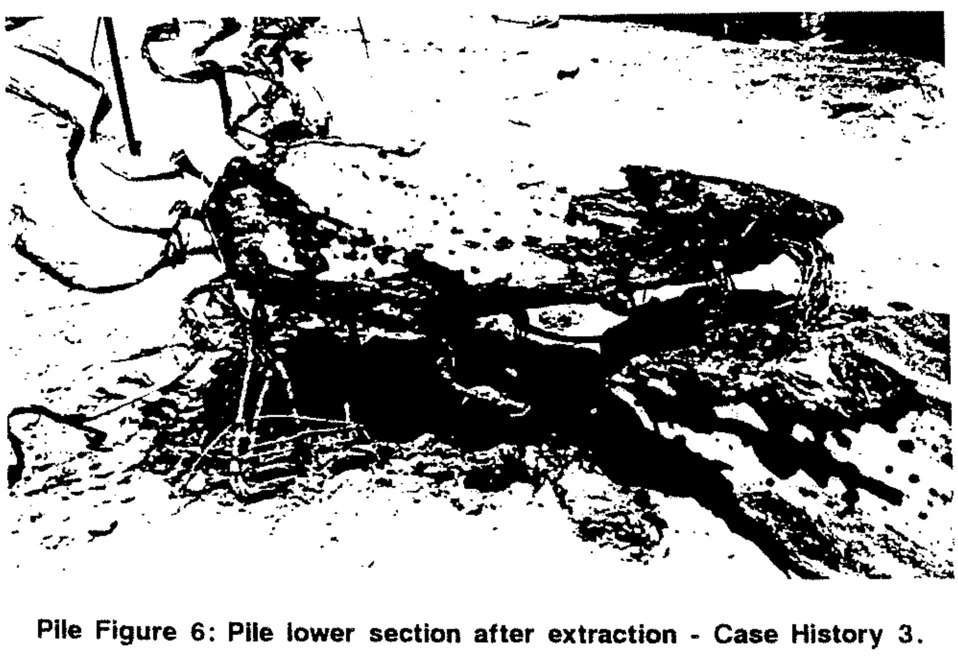


Figure 5: Plots of pile dynamic records - Case History 3.



Pile Figure 6: Pile lower section after extraction - Case History 3.

Case History - 3

Structural requirements and subsurface conditions dictated that a new large structure be founded on deep foundations. Square prestressed concrete piles of different sizes were driven. Subsurface conditions at the project site were generally described as a layer of soft soil over a thin hard layer under which existed a layer of loose sand and finally a deep hard layer was found. A spud was used to form a hole down to within 1.5 m of each pile's estimated final tip elevation. The piles were then lowered into the spudded cavity. Because the sands on the sides of the hole tended to cave in, each pile had to be further advanced with the help of a high pressure water jet before actual pile driving started. Pile driving was accomplished with a single acting air hammer with a ram weight of 62 kN and a rated energy of 57 kJ. Some of the piles were dynamically tested during restrike a few days after initial installation for evaluating their static bearing capacity and structural integrity. This case history discusses testing results of one of the piles that was found damaged.

Under consideration is a 22.8 m long, 457 mm square prestressed concrete pile that was initially driven to a final penetration of 14.6 m and a driving resistance of 40 blows for the last 25 mm of penetration. The restrike consisted of a few hammer blows that resulted in a very small pile set. During the restrike, maximum pile top compressive stresses averaged 16.5 MPa and the "β" factor was 45 or less. Plots of pile top force, proportional velocity, and wave down and wave up records representing one of the restrike blows are shown in Figure 5. The early wave return with its distinctive characteristics along with the computed low β value indicated that the pile is broken at a location approximately 16.4 m below the gages location (i.e., 20.7 m below the pile top). A large crane, with assistance of water jets along two pile sides, was used to extract the pile for verification of pile damage. Figure 6 presents a photograph of the lower section of the pile after extraction.

LOW STRAIN DYNAMIC PILE INTEGRITY TESTING

While relatively large hammers are needed for high strain dynamic testing, impacts of small hand held hammers are sufficient to perform low strain tests. Small hammer impacts typically generate accelerations in the 10 to 100 g range, pile strains around 10^{-5}, velocities near 30 mm/s, and displacements less than .03 mm. Low strain dynamic testing is performed to evaluate the structural integrity of driven or cast-in-place concrete piles, although it has also been recently used to test wood piles [9]. This type of testing is also based on one dimensional elastic wave propagation and the premise that changes in pile impedance and soil resistance produce predictable wave reflections at the pile top. The time after impact at which the reflections reach the pile top are directly proportional to the distance of the origin of the reflected wave. Since pile impedance (Z) is directly related to pile area and elastic modulus, impedance is, therefore, a measure of pile cross section size and concrete quality. When the incident stress wave (W_i) encounters an impedance change from Z_1 to Z_2, one part of the wave reflects up (W_u) and the other part transmits down (W_d) such that both continuity and equilibrium are satisfied:

$$W_d = W_i[2Z_2/(Z_2 + Z_1)] \quad (7)$$
$$W_u = W_i[(Z_2 - Z_1)/(Z_2 + Z_1)] \quad (8)$$

At the free pile toe ($Z_2 = 0$), the impact wave is therefore completely reflected, but with an opposite sign.

Stress waves at the pile head are commonly monitored with an accelerometer. Field testing is conveniently performed using the Pile Integrity Testing (P.I.T.) system which consists of an accelerometer, a hand held hammer, and a field data acquisition system capable of converting analog signals to digital form and processing the digital data. The system is also capable of measuring force exerted by an instrumented hammer and incorporating the force data into the analysis.

For normal applications, where pile heads are exposed, pile preparation simply involves smoothing a small area at the pile head. The accelerometer is attached to the smoothed area using a jell type material and the pile head is lightly tapped with the hammer. Figure 7 shows the P.I.T. equipment and instrumentation of a cast-in-place concrete pile during testing in the field while Figure 8 shows testing of a precast driven concrete pile. Other arrangements are necessary for piles with inaccessible pile tops [4,9].

The acceleration record created by the impact is integrated and the resulting velocity record is displayed on the P.I.T. screen. The data is enhanced by averaging several blows to minimize random noise and emphasize repetitive features in the data. To simplify interpretation, the averaged velocity record is plotted on a length scale (using the stress wave

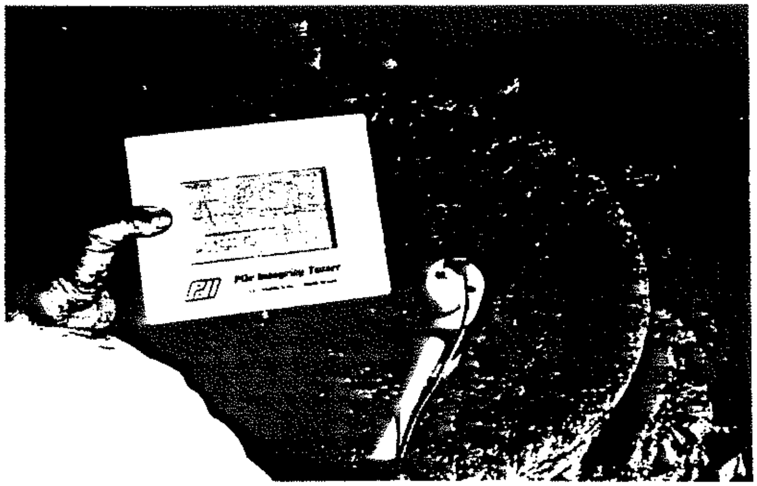


Figure 7: The Pile Integrity Tester

Figure 8: Low strain integrity testing of a precast pile

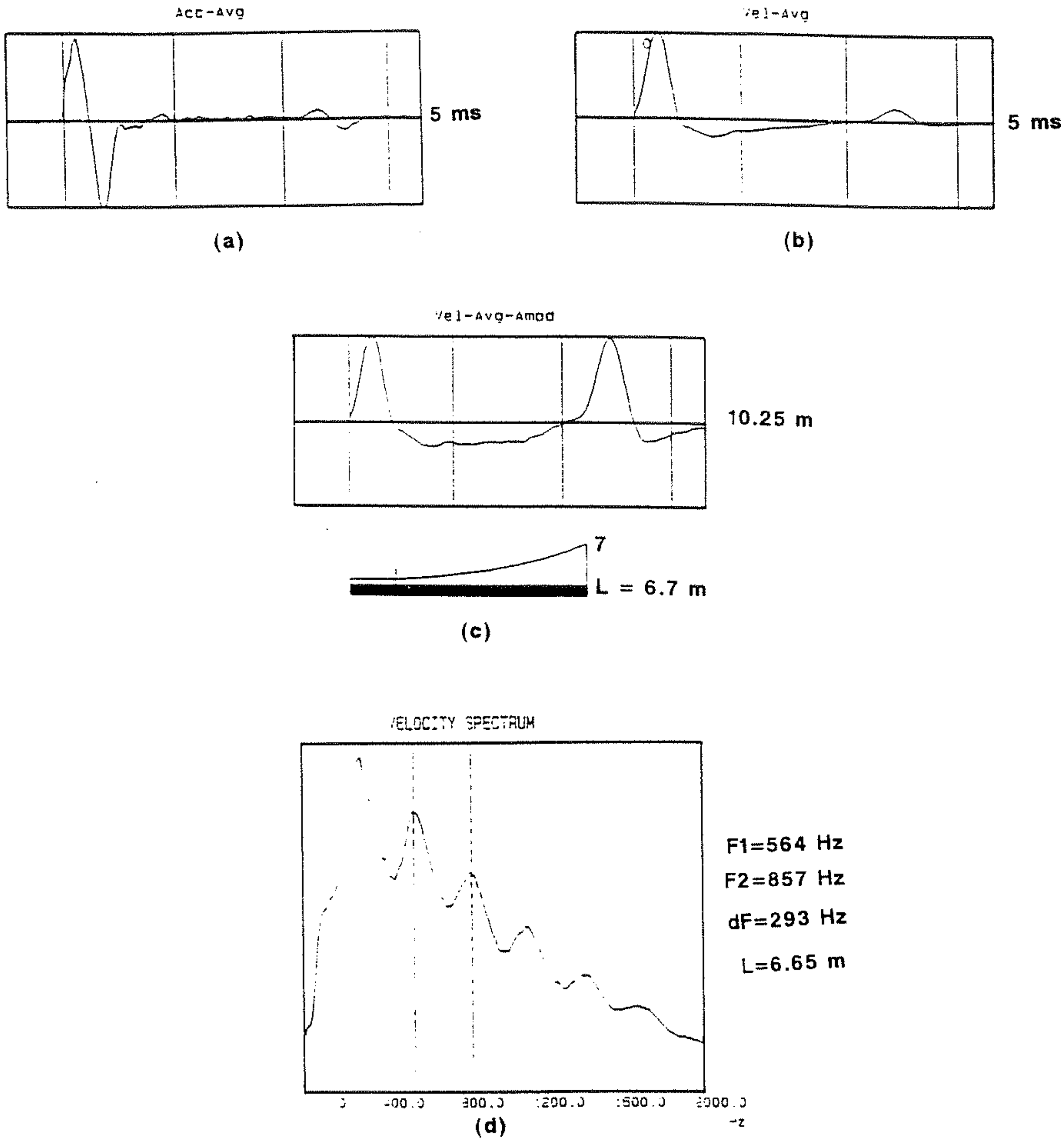


Figure 9: Plots of low strain dynamic testing data:(a) averaged measured acceleration, (b) averaged velocity (integral of acceleration). (c) averaged and amplified velocity versus length, and (d) velocity spectrum for a 355mm, 6.7m long cast-in-place pile.

speed). To amplify wave reflections which are very weak due to pile and soil damping, the averaged velocity record can be multiplied with an amplification function whose magnitude is unity at impact increasing exponentially with time until it reaches its maximum intensity at 2L/c. The following two procedures are used by the testing engineer to determine the wave speed for the time to length scale conversion: (a) assuming that the pile or shaft length is known accurately, the wave speed is back calculated from the time between impact and pile toe reflection (if that is apparent), and (b) if the shaft length is unknown then a wave speed is assumed (usually 4000 m/s for concrete) and the pile length is then calculated from the time of wave reflection (if evident). Since wave speeds of piles in the same site normally fluctuate within ± 5%, similar errors in predicted lengths must be expected. Case History 6 below presents a procedure for determining both pile length and wave speed by monitoring pile motion at two points along its shaft.

A clearly indicated toe signal together with a relatively steady velocity trace between impact and toe signal are signs of a structurally sound pile. Strong variations in the velocity record may be the result of changes in pile cross section, concrete quality, or soil resistance. In general, relatively sharp reflections are attributed to impedance changes while slowly changing reflections are attributed to the soil response. The effect of soil resistance may be evaluated by testing several piles on a site and establishing a reference record.

The velocity curve can also be transformed to the frequency domain and interpreted for determination of pile length and structural integrity assessment. In this analysis, a peak occurs at a frequency indicative of the velocity changes due to a reflection from pile toe or an intermediate impedance change. Peaks occurring at regular intervals (Δf) are indicative of a dominant frequency. The corresponding depth at which the change occurs is calculated from:

$$x = c/2\Delta f \qquad (9)$$

Figure 9 presents plots of a typical low strain test performed on a 355 mm square, 6.7 m long cast-in-place concrete pile. It shows averaged measured acceleration and its velocity records along with its interpretations in both time and frequency domains.

Interpretation of records is more or less depended on the experience of the testing engineer. An invaluable aid in the interpretation effort are similar curves analytically developed. The special purpose computer program P.I.T.WAP (Pile Integrity Testing Wave Analysis Program) requires that the description of the pile and soil are input, and generates as an output pile top velocity and mobility records. A large catalogue of these calculated responses considering many pile profile and soil resistance combinations was compiled as a guide for data interpretation [10].

The P.I.T.WAP program can also be employed in the interpretation of measured velocity or force and velocity records using a signal matching technique. The measured force record is imposed as a boundary condition for an analytical model of pile and soil and a pile velocity record is computed. Comparison between computed and measured velocity records is then evaluated and a modified pile profile in input until a good match is achieved. The program also contains a second option for pile impedance calculations. The basis of the pile profile calculation is the fact that a step-wise change in impedance causes a pulse-like velocity wave effect at the pile top. In other words, the effect of an impedance change has the appearance of the derivative of the impedance change. Inversely, the profile is the integral of the wave effects at the pile top. In the absence of soil resistance effects, the pile profile, therefore, has the appearance of the pile top displacement.

Low strain pile integrity testing is powerful, quick, inexpensive but, naturally, limited. The length information obtained is only as accurate as the wave speed value assumed in the processing of the measured records. Certain defects produce secondary and even tertiary wave reflections which may make data interpretation difficult or misleading. Piles with severe damage or mechanical joints, impede the stress wave propagation and, therefore, assessment of pile integrity below damage location or splice is limited. It is not possible to determine slow changes in pile impedance since they do not produce sharp wave reflections. High soil resistance limit the applicability of this test on long piles (more than 30 to 40 diameters in length) since the wave is dissipated into the soil before reaching the lower part of the pile. Assessment of integrity of upper section of pile (i.e., top 1 m) may not be possible with velocity measurement only (measurement of force data in addition provides information that will aid in integrity assessment in the top section). Finally, testing piles under existing structures adds difficultv to performing the test since the pile head is not available for instrumentation or impact, and data interpretation is complicated due to waves travelling through and reflected by the superstructure.

The following three case histories illustrate the applicability of low strain dynamic pile testing for determination of pile integrity and length for cast-in-place and precast concrete piles.

Case History - 4

The addition of a new section to an already existing structure was founded on 42 cast-in-place concrete piles. All piles were reportedly 7.6 m long, had 406 mm nominal diameter and installed by the continuous flight auger (CFA) method. Soil conditions at the site were described as sands and silty sands. All piles were tested using the P.I.T. system for assessment of structural integrity and confirmation of pile lengths in place.

Records of most piles contained clear toe reflections. Assuming pile lengths to be 7.6 m, a consistent wave speed of 3750 m/s was computed from the data. Figure 10 presents plots of pile top velocity records for three piles. Testing one of the piles indicated a length of 6.5 m, assuming the established wave speed of 3750 m/s. Test result for this pile is presented in Figure 11. If the pile was assumed to have the full 7.6 m length, then the required stress wave speed would have to be 4385 m/s, an unlikely value given the testing results of all other piles at this site. Pile top test records of another pile indicated a non-uniform pile shaft and no clear toe reflection. Figure 12 presents plots of velocity record and P.I.T.WAP computed impedance profile for this pile. Dynamic testing results concluded that 37 piles appear to be structurally sound, one pile was shorter than design length, two piles had variations in shaft impedance (mostly bulging), and records of two piles were inconclusive due to the lack of a clear toe reflection.

Case History - 5

Subsurface conditions, structural considerations, and specific project requirements dictated that a new structure, to be built alongside an existing hospital, be founded on cast-in-place concrete piles. All 95 piles used were constructed using the CFA method with a nominal diameter of 406 mm and varied in length between 9 and 30 m. Because of the potential of pile damage resulting from heavy construction equipment moving over and around heads of constructed piles, the presence of cavities in the underlaying rock, and the unexpectedly large amount of concrete needed to form some of the piles, it was decided to test a number of the piles for structural integrity assessment.

A total of 46 piles were tested using the P.I.T. system. Figure 13 presents testing results of a 9.15 m long pile that was found to be broken at a location 2.3 m below pile top (assuming a stress wave speed of 4000 m/s). The top section of the pile was extracted (no steel reinforcement was used in the piles) for verification and is shown in Figure 14. The length of the recovered pile section confirmed the stress wave speed assumed during testing. Twelve of the tested piles were found broken at locations 0.6 to 3.0 m below pile tops.

Case History - 6

As part of a feasibility study for the replacement of a 30 year old bridge supported on driven precast concrete 457 mm square piles, structural re-evaluation required determination of foundation pile lengths since initial construction records were not available. Water depth at the site varied between 1 and 10 m along the bridge alignment. Soils at the site were described as mostly sands. The piles extended above the water surface to carry the roadway above. A total of 20 piles were tested with the low strain method for determination of pile lengths and assessment of structural integrity. The accelerometer was attached to the side of each pile and hammer impacts were applied axially to the top of the pile cap. Each pile was tested twice, each time changing the location of the accelerometer along the pile shaft. This case history considers one of the piles tested.

Figure 15 presents plots of velocity records versus time, the top plot was obtained when the accelerometer was 1 m below the bottom of the pile cap and the bottom plot when the accelerometer was placed 3.5 m below the first test location. Both records contain clear toe reflections. The 2L/c times from both tests were 8.5 and 6.75 ms, respectively. Given this information, it was possible to compute pile length and stress wave speed from the two test records (three equations with three unknowns). It was found that the pile length was 8.5 m below the location of the accelerometer during the first test (i.e., 9.5 m below the bottom of the cap). Testing of other piles indicated similar pile lengths.

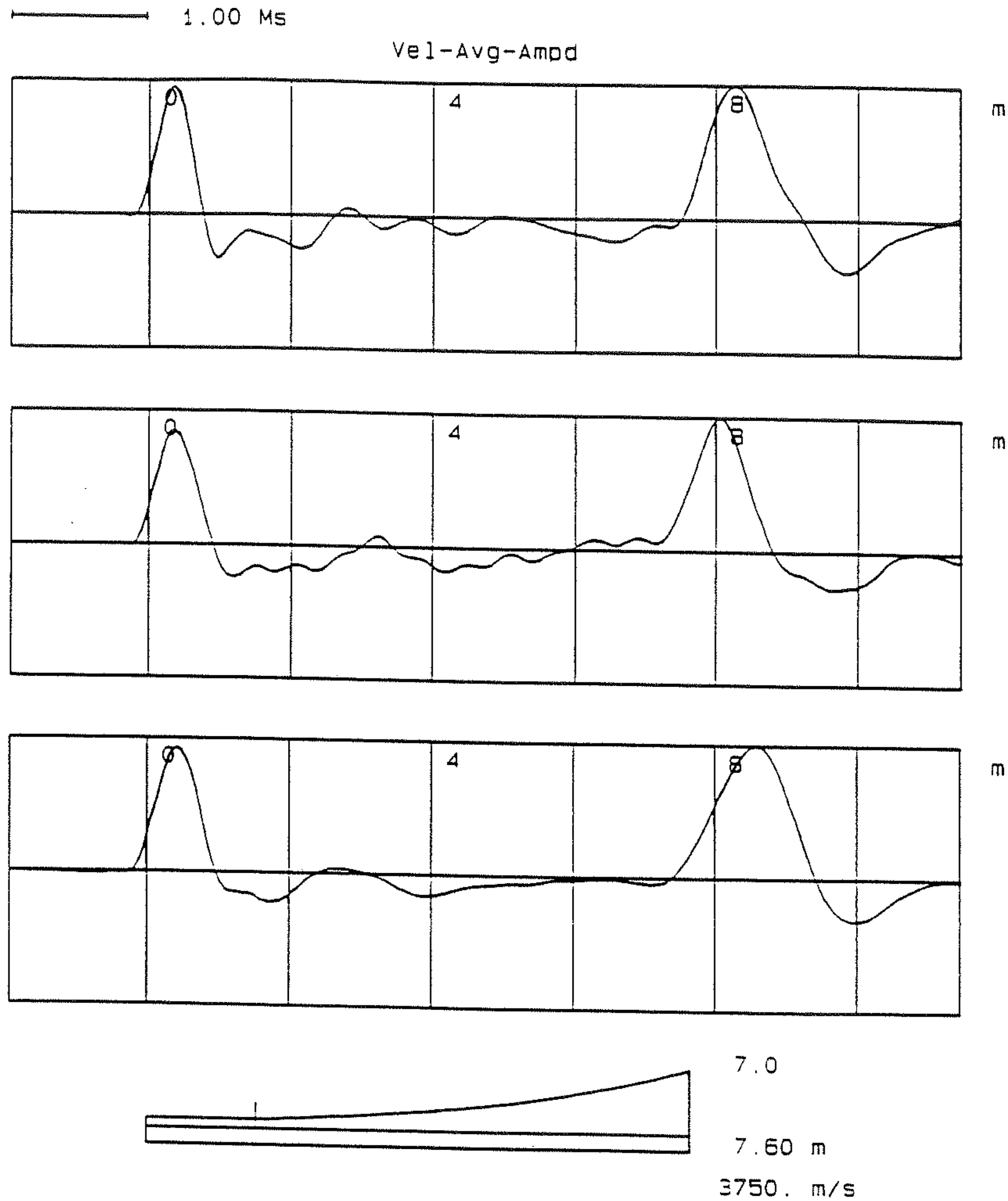


Figure 10: Pile top low strain records for three piles - Case History 4.

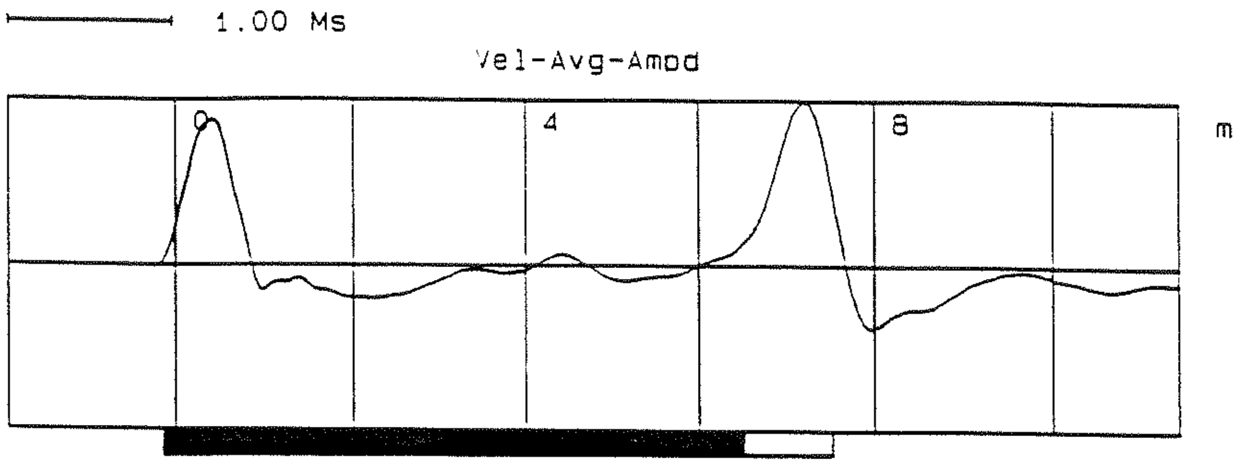


Figure 11: Pile top velocity record indicating short pile - Case History 4.

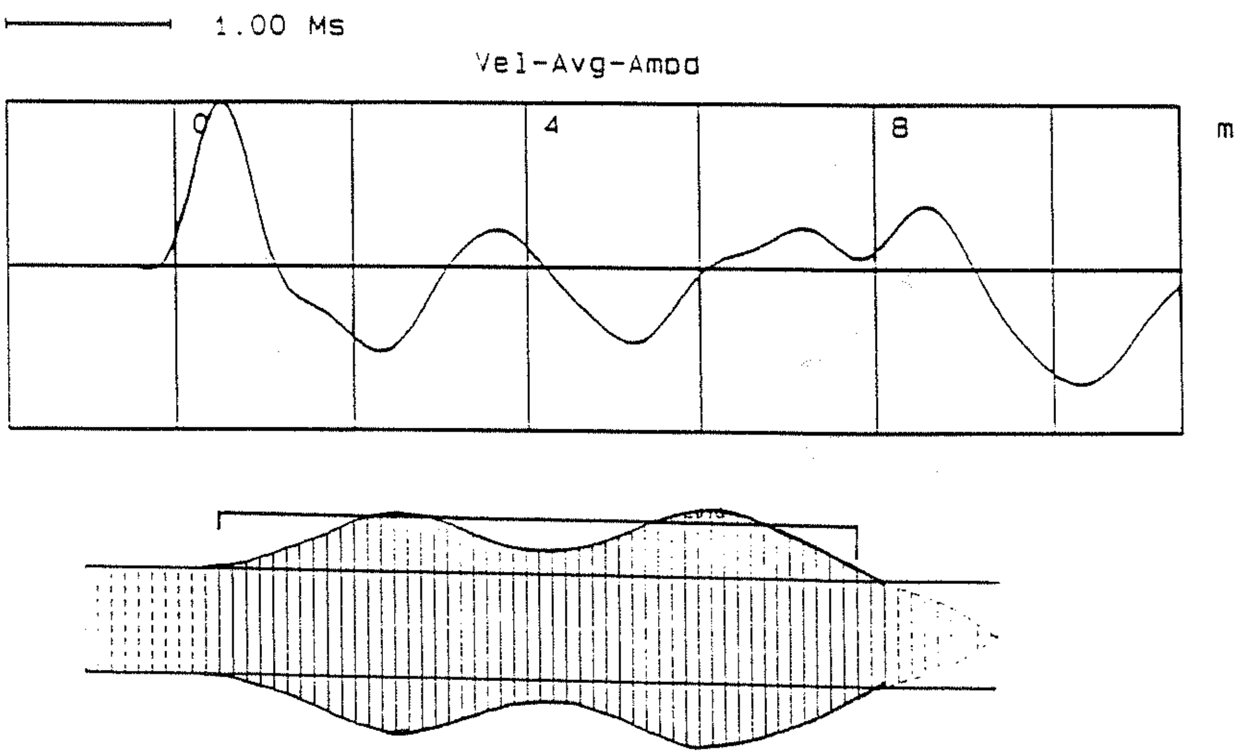


Figure 12: Pile top velocity record and P.I.T.WAP generated pile impedance profile - Case History 4.

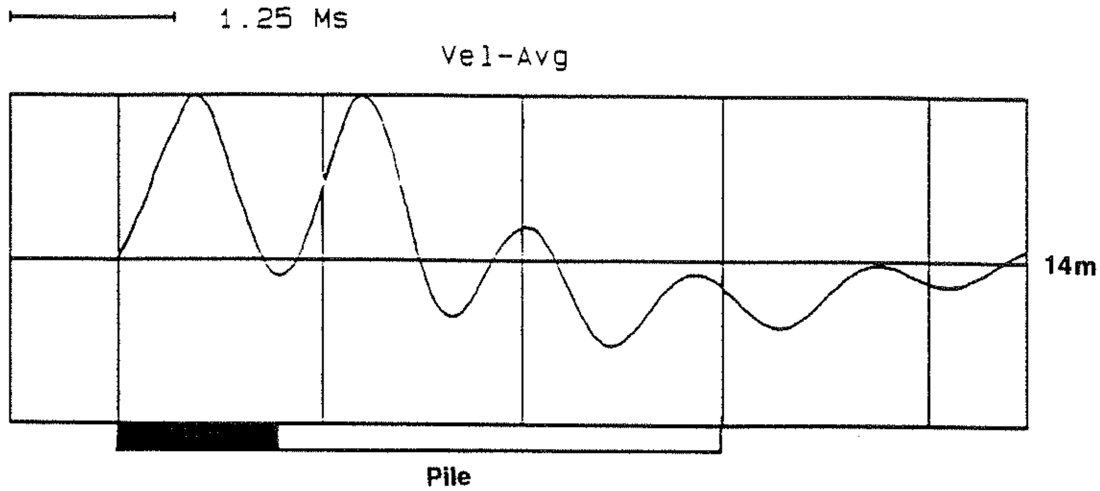


Figure 13: Pile top velocity record indicating broken pile - Case History 5.

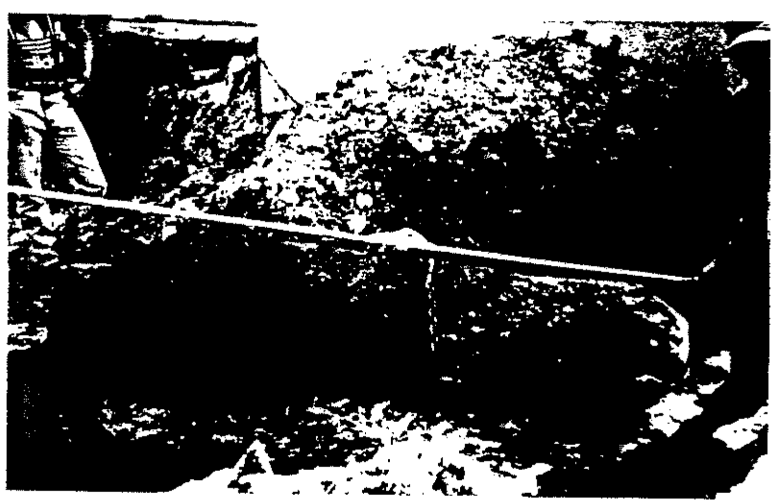
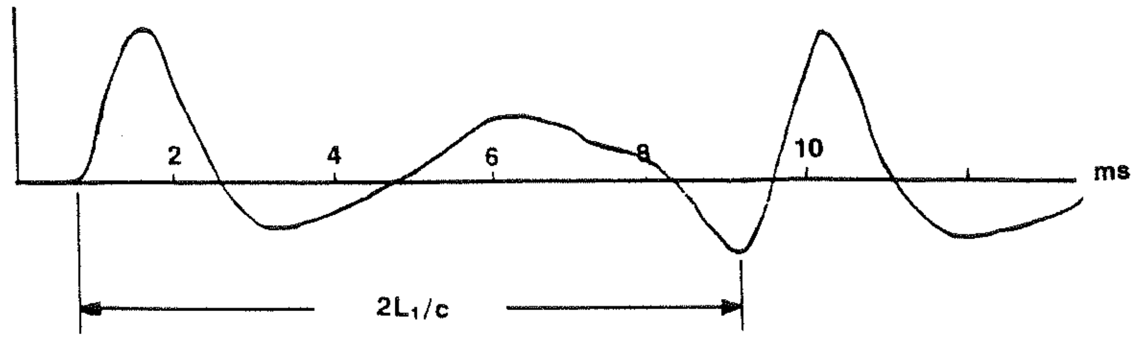
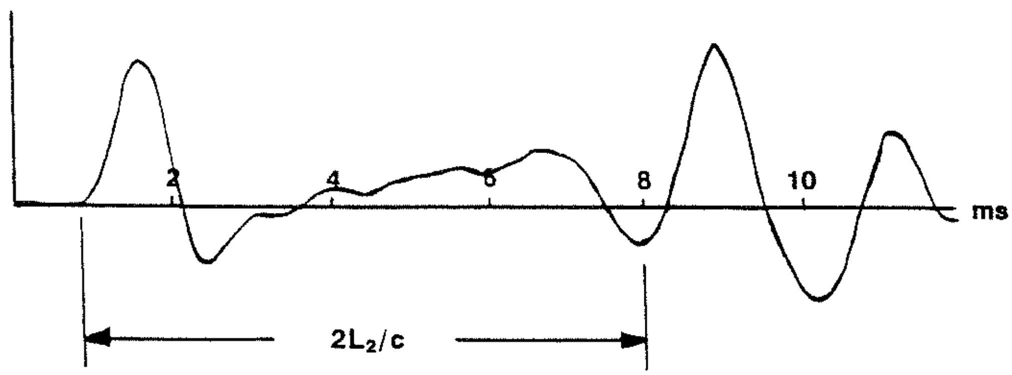


Figure 14: Top section of broken pile after extraction - Case History 5.





$$2L_1/c = 8.5\text{ms}$$

$$2L_2/c = 6.75\text{ms}$$

$$L_1 = L_2 + 3.5$$

Therefore, $L_1 = 16.9$m, $L_2 = 13.4$m, and $c = 4000$m/s

Figure 15: Low strain pile velocity records and calculations of pile length and stress wave speed - Case History 6.

CONCLUSION

Stress wave measurements can be used to evaluate the structural integrity of concrete piles. Impacts of the pile driving hammer produce large strains in the pile, while a small hand held hammer generate very small pile strains. Equipment and analytical procedures were presented for both high and low strain dynamic pile testing methods along with six case histories illustrating the applicability of each method. For long piles with high soil resistance, the high strain method is better able to detect damage in the lower part of the pile. The short duration pulses of the low strain method provide more resolution for detecting narrow impedance changes. High strain stress waves are able to penetrate almost all pile splices which could limit the low strain method to a assess the integrity below the splice. Only the high strain method can give information of pile static load bearing capacity. While a few piles on a project may be tested with the high strain method for structural integrity and load bearing capacity determination, the speed and low cost of low strain tests make it possible to evaluate all piles for structural integrity. If defective piles were found, then more extensive load testing or pile replacements may be undertaken to assure the adequacy of the foundation. As illustrated by one of the case histories discussed, stress wave measurements may also be used to determine the length of piles under existing structures.

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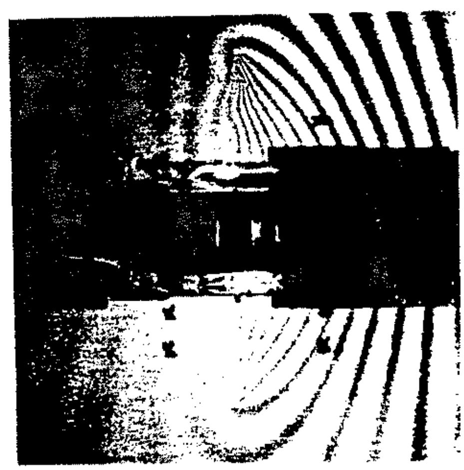

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