EVALUATION OF CAST-IN-PLACE CONCRETE PILES FROM STRESS WAVE MEASUREMENTS

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EVALUATION OF CAST-IN-PLACE CONCRETE PILES FROM STRESS WAVE MEASUREMENTS

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ABSTRACT. Cast-in-place concrete piles are commonly used as deep foundations for structures of many sizes. The performance of a cast-in-place pile under working conditions is a function of its structural strength and integrity, properties of the supporting soils, method of installation and pile-soil interaction characteristics. Evaluation of pile structural integrity using low-strain dynamic testing has become routine procedure in many parts of the world. Testing is simply performed by attaching an accelerometer to the pile top and impacting the pile head with a small hand-held hammer. The measured acceleration-time record is integrated and the resulting pile top velocity data is analyzed in either time or frequency domains for conclusions regarding pile profile, length and general strength. Measurements of pile strain and acceleration histories under impacts of relatively large weights may be used to evaluate soil resistance, pile static capacity and structural integrity. This method is known as a high-strain test since the impacts generate significant forces in the pile. This paper presents discussions on the theoretical background, state-of-the-art testing equipment and analytical data analysis methods, and limitations of both low and high strain testing methods.

1. INTRODUCTION

Subsurface conditions, geotechnical considerations, structural requirements, site and project peculiarities and economy generally dictate the type of foundations to be employed. Deep foundations are considered when: structural loads need to be transmitted to competent deep soils when shallow foundations are inadequate, 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. Piles are of two major types: preformed and installed with a pile driving hammer, or cast-in-place. Driven piles may be made of wood, steel, concrete, or a combination of these materials; cast-in-place piles are of concrete. The performance of a pile is dependent on its structural strength and integrity, method of installation, strength and deformation properties of the supporting soils, pile-soil interaction characteristics and nature and magnitude of applied loads.

Cast-in-place piles are produced by forming holes in the ground and filling them with concrete. A steel reinforcing cage and outer casing may or may not be used. This type of piling is used to carry loads ranging from a few to thousands of tons. They are constructed in sizes up to 3 m in diameter and over 75 m in length, but are commonly used in the range of 0.5 to 1.5 m in diameter and 5 to 30 m length. There are numerous techniques for constructing cast-in-place concrete piles, two common methods are: (a) the continuous-flight-auger (CFA) pile where concrete grout is placed under pressure through the toe of the hollow auger stem at the bottom of the hole during auger withdrawal, and (b) the bored pile where a hole is excavated by drilling before placement of concrete.

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Advantages of cast-in-place concrete piles include: relatively low cost, fast execution, ease of adaptation to different lengths, soil sampling during construction, possibility of penetrating undesirable hard layers, high load carrying capacity of large size piles, low vibration and noise levels during installation, and the fact that piles can be formed in-place without having to wait for curing time before installation. Since pile foundations are normally employed when conditions are generally difficult, it is the very nature of these conditions that sometimes evokes questions regarding the structural integrity and bearing capacity of cast-in-place piles. The constructed shape and structural integrity of this type pile is dependent on: concrete quality and method of placement, subsurface conditions, workmanship and design and construction practices. Common modes of pile structural deficiencies are: degraded or debonded concrete, necking, inclusions and/or voids. After installation, piles may be damaged by large lateral movements from impacts of heavy equipment or slope or retaining wall failures.

Unlike pile driving where the installation process itself constitutes a crude qualitative pile test and measurements during driving are possible to quantify hammer-pile-soil behavior, methods for evaluating cast-in-place piles during construction are generally not available. There are a number of methods for assessing pile structural integrity (Fleming et al. 1985) some of which are not non-destructive and those that are may require extensive pile preparation and preplanning during design and construction which makes random checking of piles on a site impractical. The expense and time required to perform a static loading test for pile static capacity determination often limit the applicability of the method to a very small number of piles on large projects and perhaps to none on small ones. Dynamic testing methods based on stress wave measurements and one dimensional elastic stress wave propagation theories provide fast, inexpensive and accurate means for evaluating the integrity and bearing capacity of cast-in-place concrete piles.

2. LOW-STRAIN DYNAMIC TESTING

Background. The extensive use of cast-in-place concrete piles in Europe in the 1960s prompted researchers there to explore the possibility of adopting stress wave based methods to evaluate pile structural integrity, low-strain based stress wave techniques has developed to a mature state and is now widely practiced worldwide (Davis and Hertlein 1991). During the last decade, field equipment and analytical methods needed to reliably perform the test and evaluate data has been greatly improved due to advancements made in electronics, computer technology and better understanding of wave mechanics application to pile analysis in the United States and elsewhere. Although this type of testing is primarily performed for pile structural integrity and general strength evaluation, attempts have been made (Bassiouni et al. 1991) to evaluate static pile capacity from low strain data in an empirical approach by employing statistical methods at specific sites. Application of the method was recently expanded to test piles under existing structures for determination of unknown pile lengths (Hussein et al. 1992).

Wave Mechanics. One dimensional wave mechanics applies to a linear elastic object that has a length an order of magnitude greater than its width. when an impact is applied at the pile head, a compressive stress wave travels down the pile shaft at a constant speed, c, which is a function of material elastic modulus, E, and mass density, ρ (i.e., $c = (E/\rho)^{1/2}$). Pile impedance, Z, is the product of pile area, A, and elastic modulus divided by stress wave speed and is, therefore, a measure of pile cross sectional size and quality. When the incident wave W_i encounters an impedance change from Z_1 to Z_2, part of the wave is reflected up W_u and part continues to travel down W_d such that continuity and equilibrium conditions are satisfied:

$$W_u = W_i[(Z_2 - Z_1)/(Z_1 + Z_2)] \quad (1)$$
$$W_d = W_i[2Z_2/(Z_1 + Z_2)] \quad (2)$$

For a uniform pile ($Z_1 = Z_2$), the wave travels unchanged and at the pile toe ($Z_2 = 0$) it reflects but with an opposite sign. Figure 1 shows impact and wave reflections at pile top from soil resistance and pile impedance changes.

Instrumentation. Impacts are applied with a small (1 kg) hand-held hammer and pile top motion is commonly monitored with an accelerometer. The testing system also includes dedicated computer software in a special field acquisition system capable of digitizing analog signals and data processing and storage. Figure 2 shows a modern testing system called the Pile Integrity Tester (P.I.T.) produced in the United States. The P.I.T. system is also capable of obtaining and processing force measurements with an instrumented hammer.

Testing and Data Analysis. Pile preparation is minimal requiring leveling and smoothing a small area at the pile top. Testing is simply performed by affixing an accelerometer to the pile top using jell type material and impacting the pile head with a small hammer. This testing method is based on one dimensional wave mechanics and the premise that changes in pile impedance and soil resistance produce predictable wave reflections at the pile top. The nature, magnitude and time of arrival of reflected waves at the pile top are functions of the nature, magnitude and location of pile impedance changes and/or soil resistance. The acceleration-time record created by a hammer blow is integrated and the resulting velocity record is analyzed because of ease of interpretation. The data is enhanced by averaging records from several blows to minimize random noise and emphasize repetitive features. Analysis of the averaged velocity record may be done in the time or frequency domain. For ease of interpretation in the time domain, the velocity data is plotted on a length scale. Time to length conversion is done using the stress wave speed. To amplify wave reflections which are very weak due to pile and soil damping, the velocity record can be multiplied with an amplification function whose magnitude is unity at impact increasing exponentially with time until it reaches maximum intensity at 2L/c where L is pile length. Velocity data is converted to frequency domain by a Fast Fourier Transform (FFT). In either case, the velocity data is inspected for wave reflections or frequencies that are interpreted for pile integrity

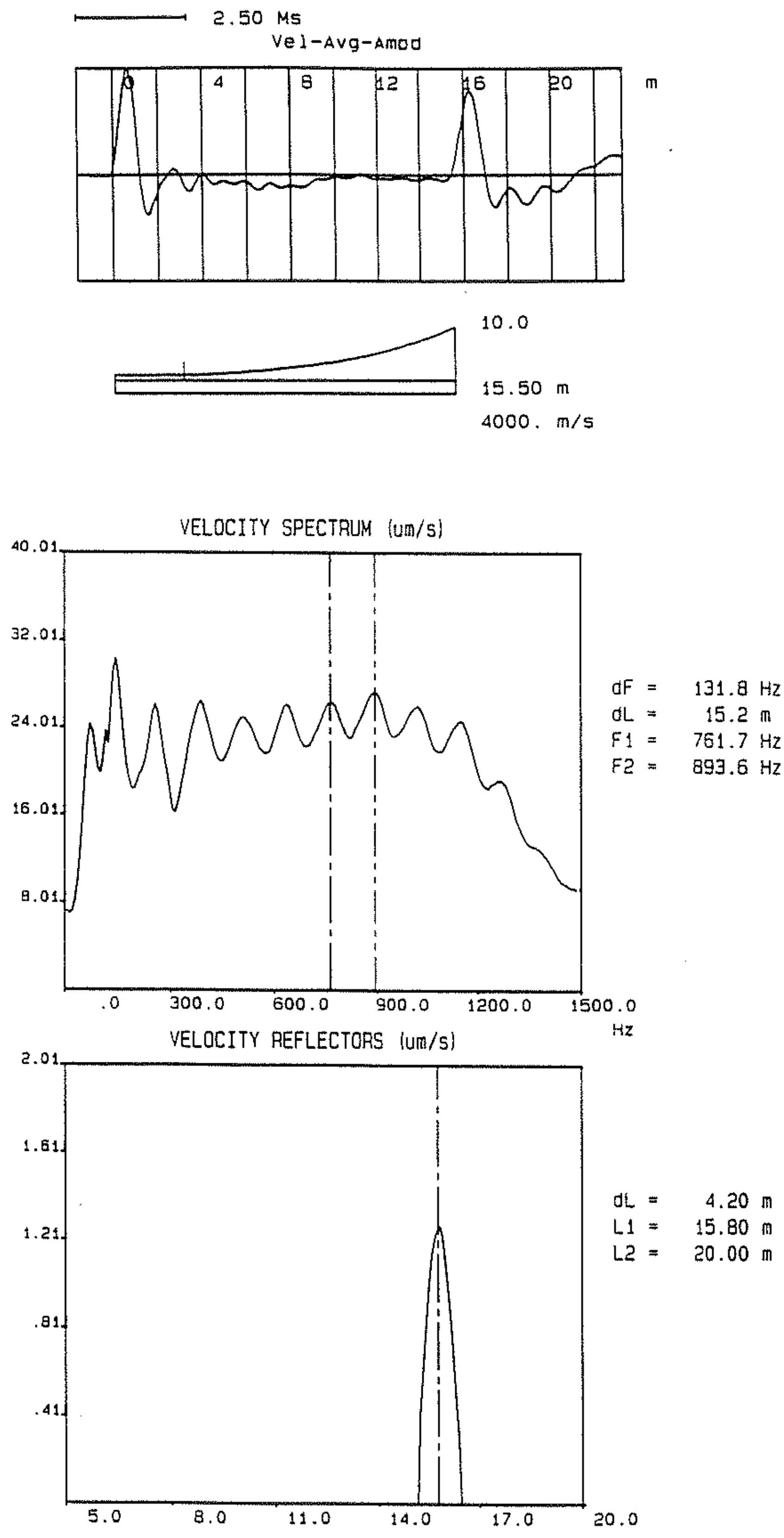
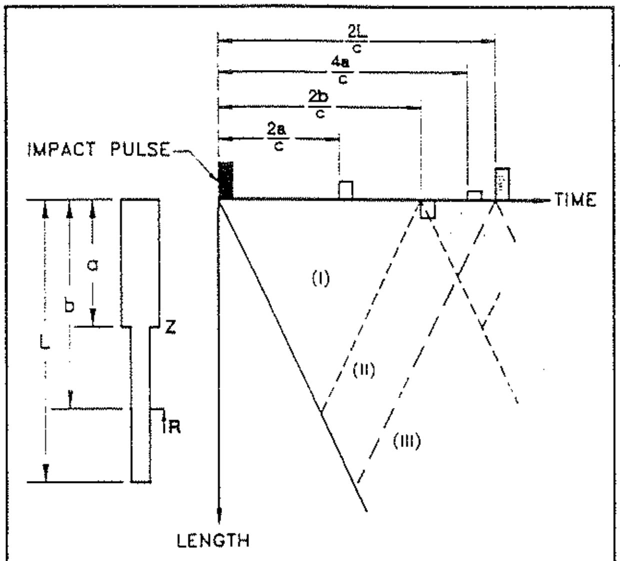


Figure 3: Typical P.I.T. testing results



IMPACT PULSE AND REFLECTIONS FROM: (I), IMPEDANCE REDUCTION, (II) PASSIVE RESISTANCE R (MODELED VELOCITY PROPORTIONAL), AND (III) PILE TOE

Figure 1: Impact and wave reflections at pile top

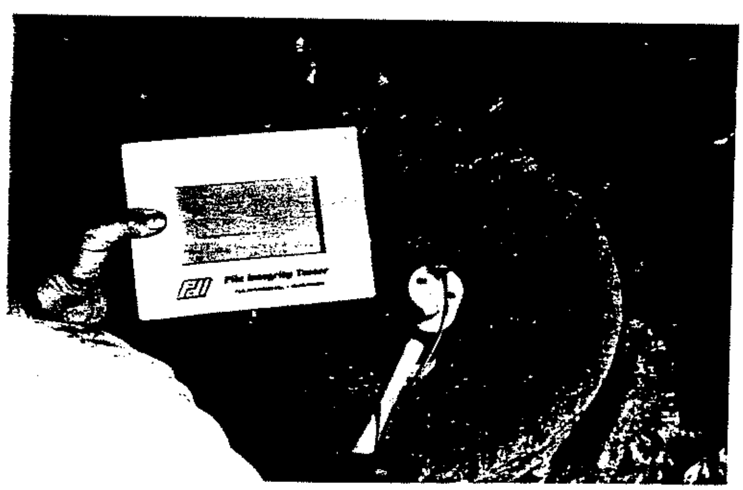


Figure 2: The Pile Integrity Tester (P.I.T.) System

assessment. Another FFT analysis of the velocity data in the frequency domain (i.e., velocity spectrum) yields a plot of velocity reflectors which may aid in pile integrity evaluation. Figure 3 presents typical test results obtained by the P.I.T. system by testing a 600 mm diameter 15.5 m long pile. For example, in the time domain, a clearly indicated toe reflection together with a relatively steady trace between impact and toe signal are signs of a structurally sound pile. When pile length is known, the wave speed computed from time of wave reflection is used for assessment of general pile strength since it is a function of material elastic modulus. In addition to visual inspection of velocity data, the record in time domain can be analyzed by a signal matching process (called the PITWAP method), or directly integrate the signal (after allowance for soil effects) to determine a pile impedance profile (Rausche et al. 1992). Typical PITWAP analysis results performed on data from a 406 mm diameter 7.6 m long pile are shown in Figure 4.

Limitations. Wave reflections generated by changes in pile impedance at locations greater than 30 or 40 pile diameters may be too weak to detect at the pile top in cases of high soil resistance. The length (or location of pile nonuniformity) obtained is only as accurate as the stress wave speed assumed in the processing of the measured record. Major changes in pile impedance may produce secondary or even tertiary wave reflections which could make data interpretation difficult or misleading. Gradual changes in pile impedance may not be detected since they do not produce sharp wave reflections. Nonuniformities close to the pile top (within the top 1 m) may not be diagnosed correctly unless records from several piles on a site are compared or both velocity and force measurements are obtained.

3. HIGH STRAIN DYNAMIC TESTING

Background. In 1964, a research program sponsored by the United States Federal Highway Administration (FHWA) was initiated at Case Institute of Technology (now Case Western Reserve University) for the purpose of developing an economical, practical and accurate field system which could calculate static pile bearing capacity from electronic dynamic measurements in real time during pile driving. The necessary equipment and analytical methods were developed and later expanded to provide a full analysis of the hammer-pile-soil system (Goble et al. 1980). The procedures are collectively called the Case Method and are applied in the field using the Pile Driving Analyzer (PDA). After each hammer blow, data is obtained and analyzed to evaluate hammer performance, pile driving stresses, pile structural integrity, pile driving resistance and static bearing capacity. Since testing is done under impacts of a pile driving hammer which imposes significant forces in the pile, this test is often called a high strain test. An extension of the Case project was the development of the CAPWAP Method (CAse Pile Wave Analysis Program) which computes soil resistance forces using pile top dynamic records (Rausche 1970). The Case and CAPWAP Methods are routinely used on thousands of projects around the world annually and are part of many specifications (ASTM 1991). During the last decade, application of the methods was expanded to test cast-in-place piles for evaluation of structural integrity and static capacity.

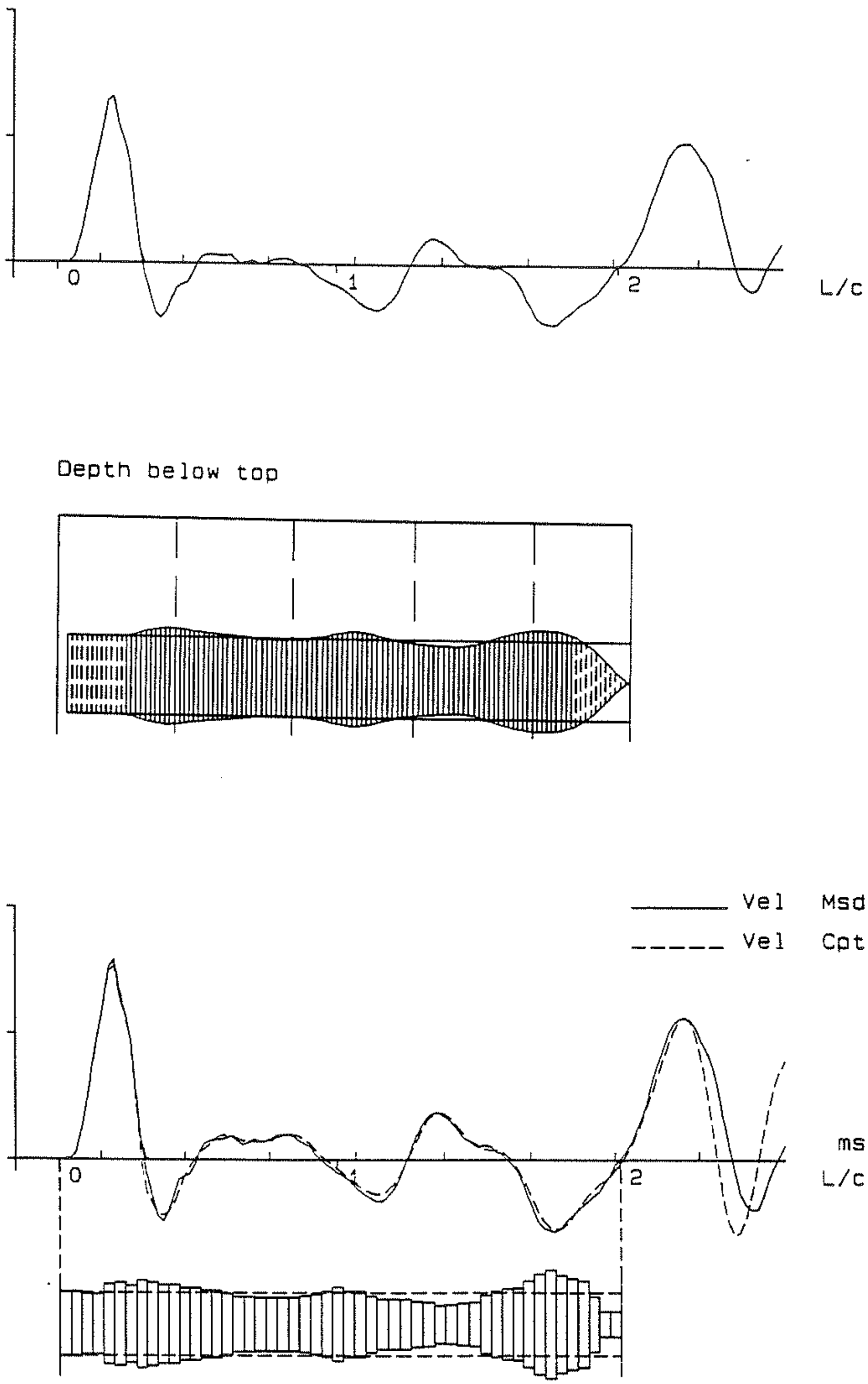


Figure 4: PITWAP analysis results: (a) amplified pile top velocity record, (b) pile profile by integrating velocity data, and (c) measured and computed pile top velocity and corresponding pile profile.

Equipment. High strain dynamic testing is based on the measurement of pile strain and motion under impacts of a relatively large weight. Testing of precast driven piles is done under the pile driving hammer. For testing cast-in-place piles, however, it is necessary to bring a drop weight to the site since a hammer is not needed for pile installation. The weight needed is approximately 1 to 2% of the pile capacity and the drop height is generally between 1 to 3 m. Sheets of plywood are commonly placed on the pile top to reduce the possibility of pile damage. Figure 3 shows a 2.8 ton hammer used to test a 600 mm diameter, 16 m long pile. Pile strains are monitored with reusable dynamic strain transducers and pile motion is measured with piezoelectric accelerometers. Strain is used to obtain pile force and acceleration gives pile velocity records. Typically, two strain transducers and two accelerometers are used, one each on opposite sides of the pile (approximately one and a half diameters below its top) in order to minimize (by averaging) the effects of non-uniform hammer impacts. Figure 4 shows a strain gage and an accelerometer bolted to a pile. Field testing and data evaluation are done with a Pile Driving Analyzer (PDA). The PDA is a user friendly field computer and data acquisition system that provides power supply and signal conditioning for the transducers and evaluates pile force and velocity records according to the Case Method. Figure 5 shows a Model PAK Pile Driving Analyzer. Data analysis according to the CAPWAP method is done using the PDA or any other type of digital computer.

Static Pile Capacity. An applied hammer impact causes a force F and particle velocity v at pile top. As long as the wave travels in one direction and no reflections are introduced, force and velocity are proportional by the pile impedance (i.e., $F = Zv$). A decrease in pile impedance causes a relative decrease in force and a relative increase in velocity; an increase in impedance produce opposite effects. Soil resistance forces cause an increase in pile force and a decrease in velocity. Since both force and velocity records are measured, the forces in the downward, W_d, and upward, W_u, travelling waves can be computed from:

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

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

Assuming a uniform elastic pile, it can be shown (Rausche et al., 1985) that static pile capacity may be computed as follows:

$$R_s = (1 - J_c)(W_{d1}) + (1 + J_c)(W_{u2}) \qquad (5)$$

Where J_c is the Case damping factor which is dependent on soil grain size and dynamic behavior under hammer impacts, W_{d1} is the value of wave down at time 1 (generally taken at impact) and W_{u2} is the value of wave up at time 2L/c after time 1.

Pile top dynamic records of force and velocity are analyzed according to the CAPWAP Method in an interactive mode between the engineer and the program using signal matching

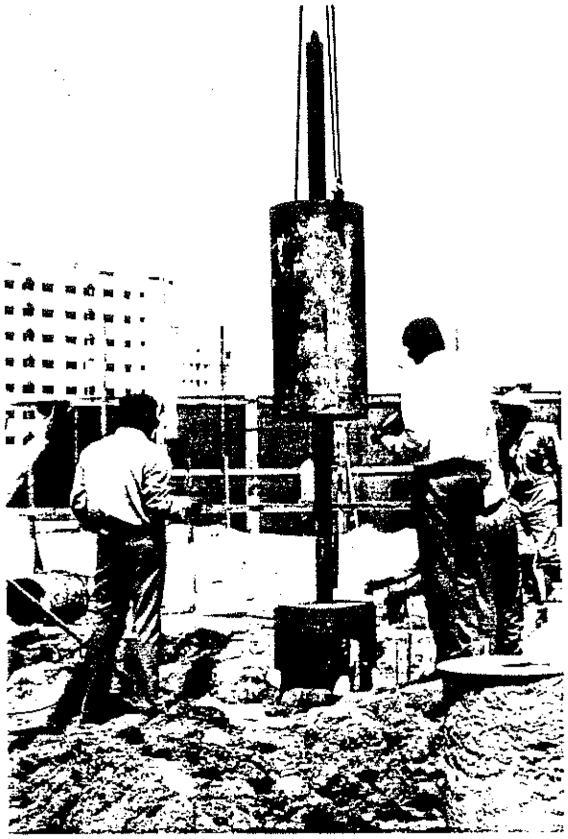


Figure 5: Typical hammer used for high strain testing

Figure 6: Strain transducer and accelerometer bolted to a pile

techniques. For an assumed pile profile, parameters in the soil model are adjusted until a best fit is obtained between computed and corresponding measured data. The soil model used is presented in Figure 6. Analysis results include pile capacity, soil resistance forces along pile shaft and under its toe, static soil stiffness and dynamic damping values, simulated pile load-movement plots and pile forces at ultimate load.

Pile Structural Integrity. It has been pointed out that changes in pile impedance cause wave reflections that reach the pile top at a time proportional to the location of the impedance change and that the reflected waves cause changes in the measured pile top force and velocity records. The magnitude of relative change allows for qualitative determination of the amount and nature of the 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 (Rausche and Goble 1978):

$$\beta = (1 - \alpha)/(1 + \alpha) \qquad (6)$$

with $$\alpha = [(W_{ur} - W_{ud})/(W_{di} - W_{ur})]/2 \qquad (7)$$

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 impedance change reflection, and W_{di} is the maximum downward travelling wave due to impact. Empirical correlations has been established between the computed integrity factor and degree of pile impedance change.

limitations. Although high strain dynamic testing is quicker, less expensive and yield more information than conventional pile testing, it has some limitations in practice. The lack of a readily available hammer to strike the pile requires that a relatively heavy weight be brought to the site to test piles. Due to relatively large pile displacements required to mobilize ultimate capacities of large diameter piles, it may only be possible to proof test the load carrying capability of a large size pile. Relatively long impact wave length limit the method's resolution in detecting minor pile nonuniformities. Engineers experienced in using the equipment and methods are needed to perform the test and data analysis.

4. CONCLUSIONS

Stress wave measurements under impact of small hand-held hammers may be analyzed for evaluation of cast-in-place pile structural integrity and general strength. Analysis of measurements of stress waves under impact of a relatively large weight yield information regarding pile static bearing capacity, soil resistance distribution and structural integrity. Dedicated electronic equipment and computer software make the field application and data analysis routine procedures. Stress wave measurements based techniques are quicker and less expensive than conventional pile tests. Limitations of either method may be minimized by performance of both tests on a given pile. There are numerous case histories reported

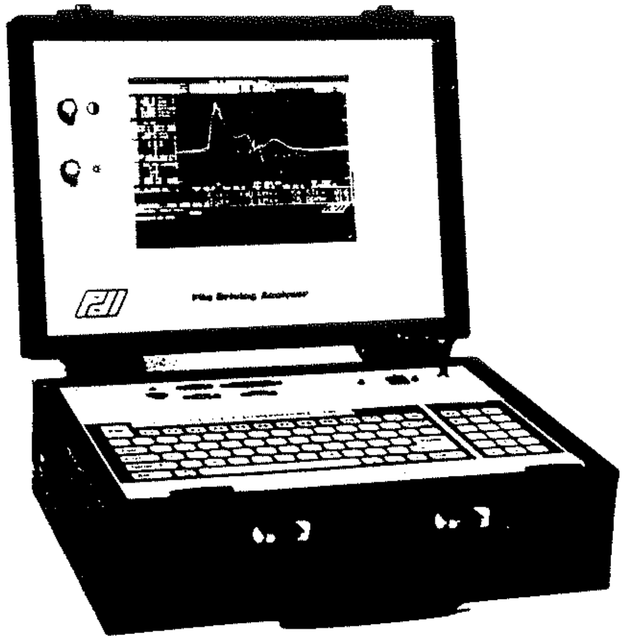


Figure 7: The Pile Driving Analyzer (PDA) - Model PAK

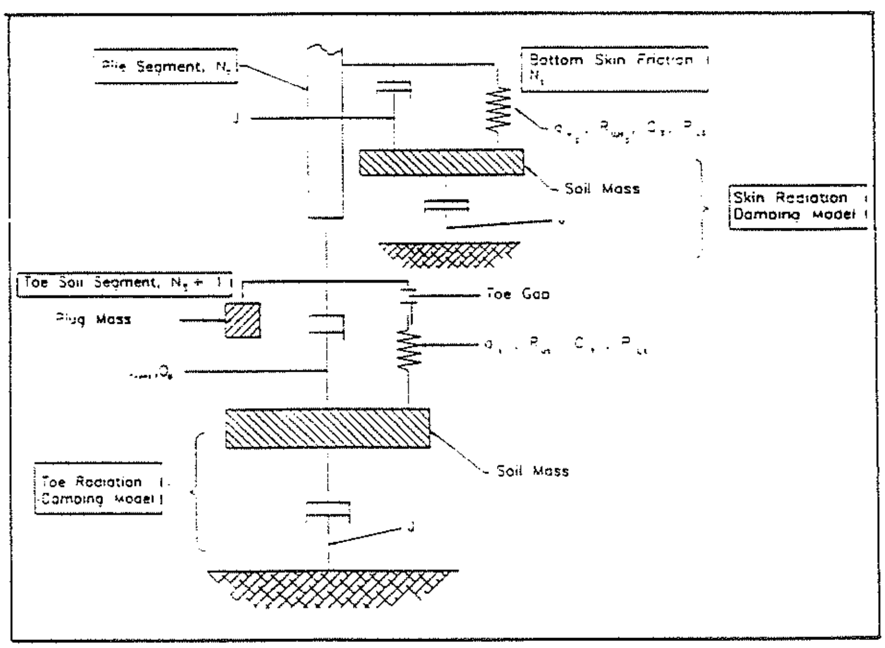


Figure 8: CAPWAP Method soil model

in the literature on the application of the methods for determination of static capacity (Rausche and Seidel 1984) and structural integrity (Hussein and Garlanger 1992) of cast-in-place concrete piles.

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