DAMAGE DETECTION FOR CONCRETE PILES USING A SIMPLE NONDESTRUCTIVE METHOD

MOHAMAD HUSSEIN
Partner, Goble Rausche Likins and Associates, Inc., Orlando, Florida 32809
JOHN GARLANGER
Principal, Ardaman and Associates, Inc., Orlando, Florida 32809

ABSTRACT

Piles are often used as deep foundations to support structural loads. Concrete piles may be either precast and installed with a pile driving hammer, or cast-in-place in a preformed hole. Both pile types can be damaged during installation and also during service. This paper discusses a nondestructive testing method for pile structural integrity assessment. The test is performed by affixing an accelerometer to the pile top and then impacting the pile top with a hand held hammer. The measured acceleration-time record is integrated, the resulting velocity-time record is displayed as a function of pile length, and then studied using elastic one dimensional wave propagation theories. One case history is presented in which a large percentage of the piles so tested were found to be damaged.

INTRODUCTION

Subsurface conditions and structural requirements often dictate the employment of deep foundation systems to support structural loads. Elements for deep foundations (i.e., piles) may be made of timber, steel, concrete, or a combination of these materials. Concrete piles may be precast and installed with a pile driving hammer, or cast-in-place in a preformed hole. They vary in size from 10 to over 100 inches in diameter and can be more than 150 ft in length.

Precast concrete piles may be regularly reinforced, prestressed, or post-tensioned and are mostly square in shape. They are installed with drop, air, steam, hydraulic, or diesel hammers. During driving, piles are subjected to a complex combination of compressive, tensile, torsional, and bending forces. Overstressing the pile material causes damage; fatigue may result in pile damage at lower stress levels. While the installation process itself constitutes a "test" for the soundness of the pile in-place, it can also be the cause of pile structural failure. Common modes of driving-induced pile damage include: crushing at the pile head, toe, or shaft, vertical and horizontal cracking, and failure of splices. Dynamic pile testing by the Case Method is often performed during installation to assess pile driving axial stresses and to evaluate pile structural integrity [1]. In cases where piles are not instrumented during driving, questions sometimes arise concerning their structural integrity.

Cast-in-place piles are produced by excavating holes in the ground and filling them with concrete. A steel reinforcing cage may, or may not, be used. A common method is the continuous-flight auger (CFA) where concrete grout is placed under pressure through the toe of the auger stem starting at the bottom of the hole during auger withdrawal. The constructed shape and structural integrity of this pile type is dependent on: concrete quality, soil conditions, workmanship, and construction procedures. Common modes of pile structural deficiencies are: separation of concrete in pile shaft, necking, inclusions, or voids. Both driven and cast-in-place concrete piles may also be damaged after installation by large lateral movements from impacts of heavy equipment, or slope or retaining wall failures.

This paper presents a method called the Pile Integrity Test (P.I.T.), which is based on low strain impacts and one dimensional wave propagation and reflection mechanics. A case history illustrating the applicability and validity of the method is also discussed.

Low Strain Integrity Testing

Background. With the advent of electronic instrumentation and data processing, there exists today a number of testing techniques to evaluate the structural integrity of deep foundations [2]. Other procedures are excavation around the pile, or drilling and coring through its shaft. Some tests require that the pile be prepared and/or instrumented prior to, or during installation making its random application prohibitively expensive. Stress wave tests can be either "high" or "low" strain [3]. High strain testing requires the presence of a pile driving hammer, or a large drop weight on site. The simplest and most readily applicable method is the low strain technique requiring minimal instrumentation and testing effort.

Wave Mechanics. One dimensional wave mechanics applies to a linear elastic pile that has a length an order of magnitude greater than its width. When impacted at the top, a stress wave travels down the pile shaft at a wave speed, c, which is a function of the material elastic modulus, E, and mass density, ρ (i.e., $c = \sqrt{E/\rho}$). Pile impedance, Z, is the product of cross sectional area, A, and elastic modulus divided by the stress wave speed and is, therefore, a measure of pile cross sectional size and quality.

When the impact induced stress wave, Fi, arrives at a point along the pile length where the impedance changes from Z1 to Z2, part of the wave is reflected up, Fu, and part transmits down, Fd, such that both continuity and equilibrium are satisfied. The downward and upward propagating waves are related to the impact wave by:

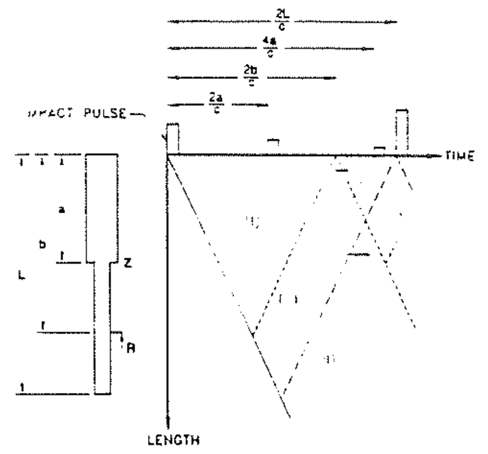
$$Fd = Fi[2Z2/(Z2 + Z1)] \qquad (1)$$

$$Fu = Fi[(Z2 - Z1)/(Z2 + Z1) \qquad (2)$$

For a uniform pile (Z2 = Z1), the impact wave travels unchanged. An example of extreme "nonuniformity" is a free pile end (Z2 = 0), the impact wave will be completely reflected upward and the resulting Fu will be of the opposite sign.

Figure 1 shows that for a compressive downward travelling wave which encounters an impedance reduction at distance, a, from pile top, an upward travelling tension wave will be observed at the pile top a time 2a/c after impact. The figure also shows that a compressive upward travelling wave is generated by soil resistance R at location, b, and is felt at time 2b/c after impact. Other reflections monitored at the pile top are those from the pile toe and the secondary reflection at 4a/c. Low strain integrity testing is based on the premise that changes in pile impedance and soil resistance produce predictable wave reflections at the pile top.

Instrumentation. The testing system consists of an accelerometer (15 g/v), a hand held hammer, dedicated software, and a field data acquisition system capable of converting analog signals to digital form and data processing. The system and method is commonly referred to as the P.I.T. tester. The impact generates accelerations in the 10 to 100 g range and pile strains around 10^{-5} micro strain.



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.

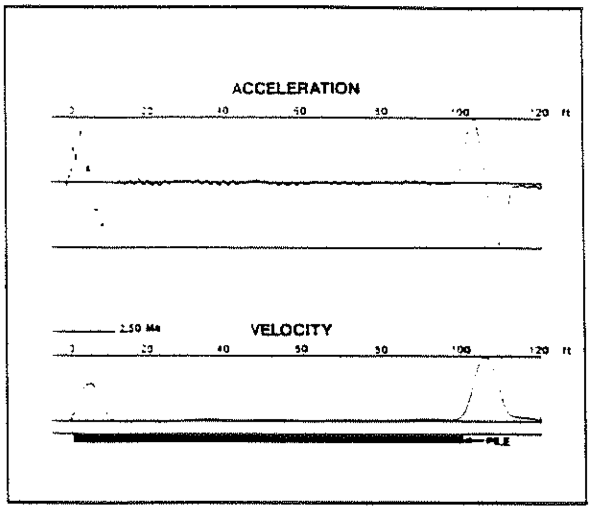


Figure 2. Pile Top Dynamic Data.

Testing and Data Interpretation. Pile preparation simply involves smoothing and leveling of a small area of the pile top. The accelerometer is affixed to the pile top using a jell type material and a hammer blow is imposed to the pile top. The acceleration record created by the impact is integrated and the resulting velocity record is displayed as a function of pile length. Time to length conversion is done using the wave speed. Figure 2 presents a measured acceleration and its integrated velocity record obtained from a test performed before installation of a 24-in square prestressed concrete pile 100 feet in length. An analysis option in the program is an exponential (with time) amplification routine. This option is used to amplify wave reflections which are very small due to pile and soil damping. Another analysis option allows the user to average a number of records. Normally, 4 to 6 test blows are taken for each pile and averaged. The technique is useful in separating effects of random mechanical and electronic noise from relevant reflections.

In addition to visual inspection of the velocity records for wave reflections, additional rigorous dynamic analysis, called PITWAP, can be performed on the measured data to obtain pile shape as a function of length in an interactive signal matching process [3].

Limitations. Wave reflections coming from locations greater than 30 to 40 pile diameters are generally too weak to be detected at the pile top, especially if high soil resistance is present. Gradual changes in pile impedance over a long distance can not be detected since they do not produce sharp wave reflections. Mechanical splices, or severe damage may screen deficiencies from the lower parts of the pile. Cast-in-place piles with greatly varying cross sections, especially in layered soils, can not be analyzed with confidence.

Case History

This case history describes a project where low strain dynamic testing was performed on cast-in-place concrete piles. The job involved the construction of both 1- and 3-story building additions adjacent to an existing 6-story structure, with provisions that another 3 stories may be added to the proposed 3-story building addition in the future. The new construction area had plan dimensions of approximately 60 by 180 ft. Subsurface investigations included 9 SPT borings, 8 CPT soundings, and a ground penetrating radar survey. Geotechnical investigation results indicated a complex, irregular, and nonuniform stratigraphy. The overburden included soft clays, clayey sand, and cemented silts. The bearing layer was limestone containing solution cavities.

Considering the subsurface conditions, structural loads, and the proximity of construction to the existing structure, foundation recommendations were to use nondisplacement deep foundations.

A total of 95 cast-in-place concrete piles were used. The piles were 16 inch in diameter, varied in length between 25 and 95 ft, and were constructed using the CFA method. Because of the potential for damage resulting from heavy construction equipment moving over and around heads of the constructed piles, the presence of cavities in the underlaying rock, and the unexpectedly large amounts of concrete needed to form the piles, it was decided to test a number of the piles for structural integrity.

A total of 46 piles were tested randomly covering the range of soil conditions and pile lengths. Twelve of the tested piles were found broken at locations 2 to 10 ft below pile tops. Four piles had impedance reduction below 18 ft. Two piles indicated bulging in their shafts. Breakage was verified by soil excavation around the broken piles. Fortunately, most of the breakage was above the eventual pile top cutoff elevations. When the piles were broken below cutoff elevations, the broken section was removed, the pile retested, and the pile top was built-up to the requires elevation. Pile impedance reduction or increase could not be verified due to its location at greater depths. Figure 3 presents plots of four velocity histories from four piles, Figure 3a shows a good pile, 3b a pile with a bulge at 35 ft and toe reflection at 95 ft, 3c a pile with impedance reduction at 18 ft, and 3d a pile broken at 8 ft below pile top.

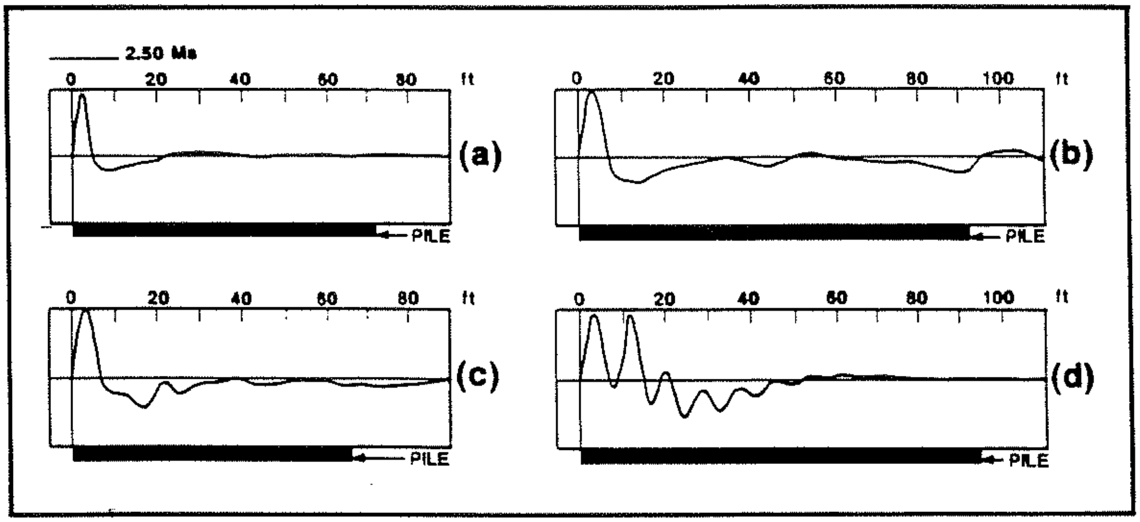


Figure 3. Pile Top Dynamic Records, Case History Piles.

REFERENCES

1. Hussein, M., and Rausche, F., Determination of Driving Induced Pile Damage. Foundations Profondes, Presses Ponts et Chaussies, Paris, 1991, pp. 455-62.

2. Fleming, W.G., Weltman, A.J., Randolph, M.F., and Elson, W.K., Piling Engineering, Surrey University Press, London, 1985, pp., 283-300.

3. Rausche, F., Likins, G., and Hussein, M., Pile Integrity by Low and High Strain Impacts, Application of Stress Wave Theory to Piles, ed. Bengt H. Fellenices, BiTech Publishers, Vancouver, 1988, pp. 44-55.