DETERMINATION OF PILE LENGTHS UNDER EXISTING STRUCTURES

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1. ABSTRACT

Low strain dynamic tests are performed to evaluate the structural integrity of driven or cast-in-place concrete piles. This type of testing requires minimal pile preparation, and is simply performed by attaching an accelerometer to the pile head and striking the pile head with a hand held hammer. The measured data is processed by a dedicated system, inspected for wave reflections, and interpreted based on one dimensional wave propagation theory. Piles are normally tested shortly after installation so that problems can be identified early and corrective measures taken before construction of the superstructure. However, evaluation of existing foundations is occasionally required. Often, pile installation records are not available rendering impossible any rational foundation reanalysis. This paper discusses three case histories where low strain dynamic measurements allowed determination of pile lengths and structural integrity under existing structures where pile heads were not accessible.

2. INTRODUCTION

Concrete piles may be precast and installed with a pile driving hammer or cast-in-place in a preformed hole. Both types are subject to damage during and after installation. During driving, precast piles are subjected to a complex combination of compressive, tensile, torsional, and bending forces. Factors

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causing overstressing and thus pile damage include inappropriate hammers, insufficient cushions, misalignment between pile and driving system, difficult soil conditions, inadequate splices, and pile material quality and initial defective structural condition before driving. Dynamic pile testing by the high strain Case Method is often used during installation to assess pile driving stresses and structural integrity (Hussein and Rausche, 1991).

Cast-in-place concrete piles are produced by drilling holes in the ground which are then filled with concrete. There are a number of procedures for such pile construction (Fleming et al., 1985). The constructed shape and structural integrity of this pile type is dependent on concrete quality, soil conditions, workmanship, and construction procedures. Examples of possible pile structural deficiencies include separation of concrete, necking, soil inclusions, or voids in the pile shaft. In addition, the constructed pile length in-place sometimes is questioned. Both driven and cast-in-place concrete piles may also be damaged after installation during excavation, from impacts of heavy equipment, or slope or retaining wall failures.

Evaluations of existing foundations are often required when adding to the superstructure, upgrading structural loads, investigating settlement, scour, or superstructure replacement. Often, original pile installation records are no longer available rendering impossible any rational evaluation of existing foundations. Knowing pile length and subsurface conditions are essential information to estimate the bearing capacity of the foundation system.

Low strain dynamic tests can be used to evaluate the structural integrity and pile length of driven or cast-in-place piles. Testing is ideally performed shortly after pile installation so that problems can be identified early and corrective measures taken before construction of the superstructure. This testing requires minimal pile preparation. An accelerometer is attached to the pile head which is impacted by a hand held hammer. The data is processed by a dedicated computer and interpreted according to elastic one dimensional wave propagation and reflection theories. For piles supporting existing structures, testing is complicated since the piles are an integral part of the structure. In the following three case histories, low strain integrity tests were instrumental in determining lengths of piles under existing structures.

3. LOW STRAIN INTEGRITY TESTING

3.1 Background

With the advent of electronic instrumentation and data processing, there exist today a number of computer based techniques for pile structural integrity evaluation (Fleming et al., 1985). Some methods require the pile to be prepared and/or instrumented before installation, making extensive application prohibitively expensive and impossible on existing piles. Other, procedures such as excavation around the pile or coring through its shaft are not practical for piles under existing structures. The simplest and most readily applicable economic procedure is the low strain impact NDT technique or sonic pulse echo method which is based on the one dimensional wave propagation.

3.2 Wave Mechanics

Low strain integrity testing is based on the premise that changes in pile impedance and soil resistance produce predictable wave reflections at the pile head. Impacting the pile head generates a stress wave which travels down the pile shaft at a constant speed, c, which is a function the material elastic modulus, E, and mass density, ρ, (*i.e.*, $c^2 = E/\rho$). Stress wave speeds in concrete range between 10,000 and 15,000 (3050 and 4575 in/s) ft/s. Pile impedance Z (=EA/c) is directly related to pile area, A, and elastic modulus and is, therefore, a measure of pile cross section size and concrete quality. When the impact stress wave (F_i) encounters an impedance change from Z_1 to Z_2, one part of the wave reflects up (F_u) and another part transmits down (F_d) such that both continuity and equilibrium are satisfied.

$$F_d = F_i[2Z_2/(Z_2 + Z_1)]$$
$$F_u = F_i[(Z_2 - Z_1)/(Z_2 + Z_1)]$$

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

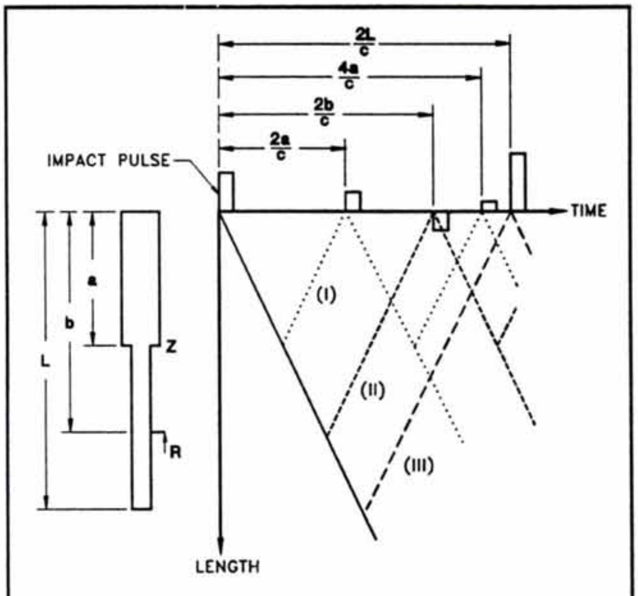
Figure 1 shows that when a compressive downward travelling wave encounters an impedance reduction at a distance "a" below the pile head, an upward travelling tension wave is generated that arrives at the pile head a time 2a/c after impact. The figure also shows that an upward travelling compression wave generated by soil resistance R at location "b" is observed at the pile head at time 2b/c after impact. Other reflections observed at the pile head are those from the pile toe at 2L/c and the secondary impedance reflection at 4a/c.

3.3 Instrumentation

The pile integrity testing system (P.I.T.) consists of an accelerometer, a hand held hammer, and a field data acquisition system capable of both converting analog signals to digital form and processing the digital data. The system is also capable of measuring force exerted by an instrumented hammer, an aspect not discussed here since it was not used in the case histories presented.

3.4 Testing and Data Interpretation

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 this smoothed area using a jell type material and the pile head is lightly tapped by the hammer. The acceleration record created by the impact is integrated and the resulting velocity record is displayed on the P.I.T. screen and then plotted on paper. The record versus time is converted to a length scale for ease of interpretation using the stress wave speed. Other arrangements are necessary for piles with inaccessible tops as described below.



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 HEAD

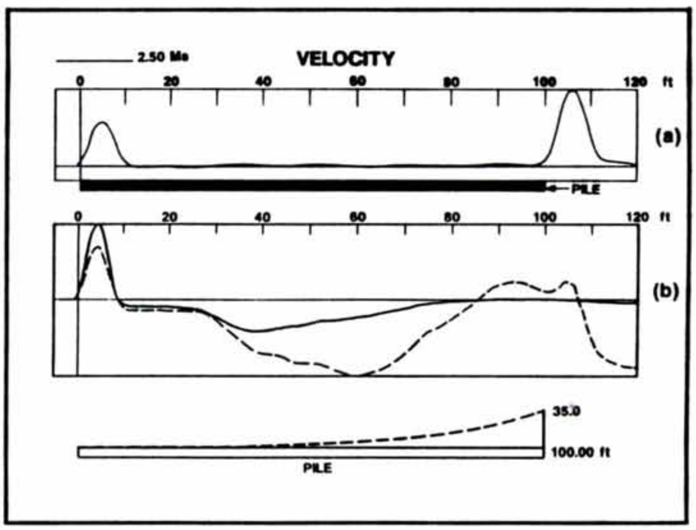


FIGURE 2: PILE HEAD VELOCITY RECORDS FOR A PRE CAST CONCRETE PILE BEFORE (A) AND AFTER (B) DRIVING

The data is then enhanced first by averaging several blows to minimize random noise, and if necessary, an exponential (with time) amplification is applied to amplify wave reflections which are very small due to pile and soil damping. In many cases, reflections from either pile toe or nonuniformities become evident only after amplification. Figure 2 presents velocity records taken on a 100 ft long, 24-inch square precast, prestressed concrete pile both before (Figure 2a) and after installation (Figure 2b). The pile toe reflection is evident in the after installation record (Figure 2b) only after amplification. In addition to visual inspection of the velocity record for wave reflections, rigorous dynamic analysis (called PITWAP) of the measured data leads to a pile impedance profile as a function of length in an interactive signal matching process (Rausche et al., 1988). An optional program displays and analyzes the same data in the frequency domain. Discussion of these options (Rausche, Likins and Shen, 1992) is beyond the scope of this paper.

3.5 Limitations

Wave reflections generated at locations deeper than the rule of thumb 30 to 40 pile diameters may be too weak to be detected at the pile head, especially when soil resistance is high. Since they do not produce sharp wave reflections, gradual changes in pile impedance may not be detected. Cast-in-place piles with greatly varying cross sections, especially in layered soils, are difficult to analyze and lead to a lower confidence in the results. Severe pile damage, full section cracks, or mechanical splices impede the stress wave propagation and therefore hide deficiencies in the lower part of the pile. Testing piles under existing structures adds difficulty 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 structure.

4. CASE HISTORIES

4.1 Case 1

As part of a feasibility study for the replacement of a 35 year old, 1700 ft bridge, structural re-evaluation required determination of foundation pile lengths since initial construction records were not available. The bridge consists of 46 bents, each supported by five 18-inch prestress concrete piles. The majority of the bridge length is located over water with strong currents and is therefore susceptible to scour. Pile heads were capped with a 2.7 ft deep beam supporting girders which carry the concrete slab. The pile cap was above the ground or water surface. Subsurface conditions can generally be described as 20 ft of shells and sand with organic material evident in the top 10 ft over a 5 ft clay layer. Below the clay, the soil consisted of sandy material.

Using P.I.T., three piles were tested to determine their length. The accelerometer was attached to the top of the cap beam at a location axially in line with the pile shaft axis. Hammer blows were also applied directly to the top of the beam near the accelerometer.

Low strain testing results of one pile are shown in Figure 3. The figure shows superimposed velocity records of five blows (top), their average (middle), and the final amplified record result (bottom) with predicted length, wave speed and amplification function. As mentioned before, the time to pile length transportation was accomplished by multiplication with one half of the stress wave speed.

This record indicates significant skin friction starting approximately 13 ft below ground level (22 ft below top of cap beam where data was obtained), and a distinct reflection, interpreted as the pile toe, at 37 ft below the top of the cap beam (corresponds to a pile toe penetration of approximately 28 ft).

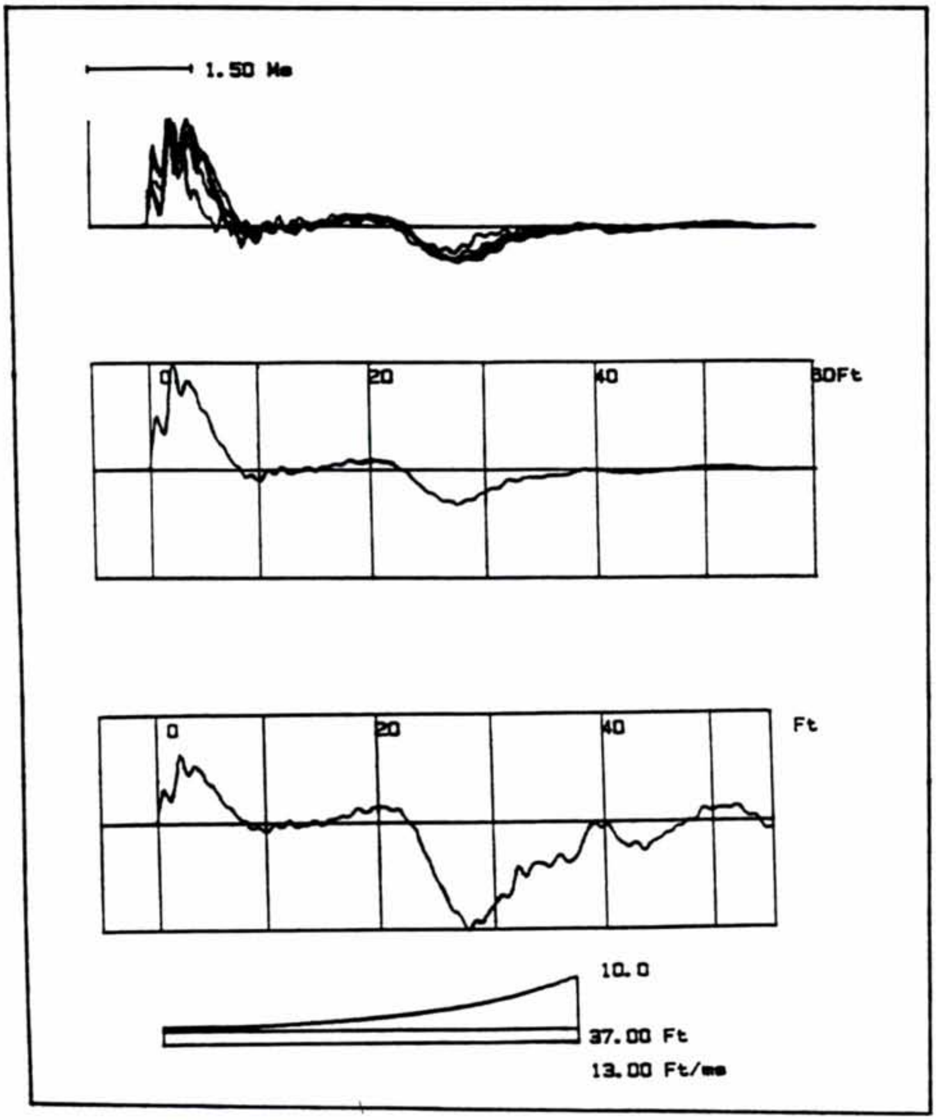


FIGURE 3: CASE 1 - PILE HEAD VELOCITY HISTORY OF FIVE HAMMER IMPACTS (TOP), THEIR AVERAGE (MIDDLE), AND THE AMPLIFIED AVERAGED RECORD (BOTTOM) WITH PREDICTED LENGTH, WAVE SPEED AND AMPLIFICATION FUNCTION.

4.2 Case 2

Two existing pile caps (carrying two 12-inch water pipes over a small creek) were evaluated to determine if a third pipe could be supported by the same foundation. Each cap (5.5 ft wide, 2.7 ft high, and 2.2 ft long) was supported by two 12-inch square driven prestressed concrete piles. Pile installation records were not available. The bottom sides of the pile caps were 2 ft above ground level.

Subsurface conditions can be described as sand (with SPT N-values increasing from 5 to 17) to a depth of 12 ft, over silty sand (N-values of 20) to a depth of 28 ft, over silty clayey sand (N-values of 6). P.I.T. testing was performed on all four piles. Each pile was tested twice, once with the accelerometer attached to the top of the cap axially in line with the pile shaft, and later again with the accelerometer attached to the side of the pile below the bottom of the cap. In all cases, hammer impacts were applied to the top of the caps directly above each pile. Figure 4 presents velocity records for the two tests conducted on the same pile. Both records indicate wave reflections from the pile toe. The reflection location (29 and 26 ft) are consistent considering the difference in locations of the accelerometer. Tests on all four piles showed similar results indicating pile penetrations of approximately 24 ft below grade and noticeable soil resistance over the lower 10 ft, which is consistent with the soil conditions.

4.3 Case 3

After excessive settlement of pile supported footings carrying sections of two 6-ft diameter concrete pipes occurred a study of the foundation system was initiated. Two 14-inch square driven prestressed concrete piles supported each cap. The piles were driven 25 years ago and installation records were still available. These pile driving logs indicated furnished pile lengths of 80 ft and driven penetrations between 70 and 80 ft. Subsurface conditions included a 5 ft layer of fill over 40 ft of organic silt over sand and gravel.

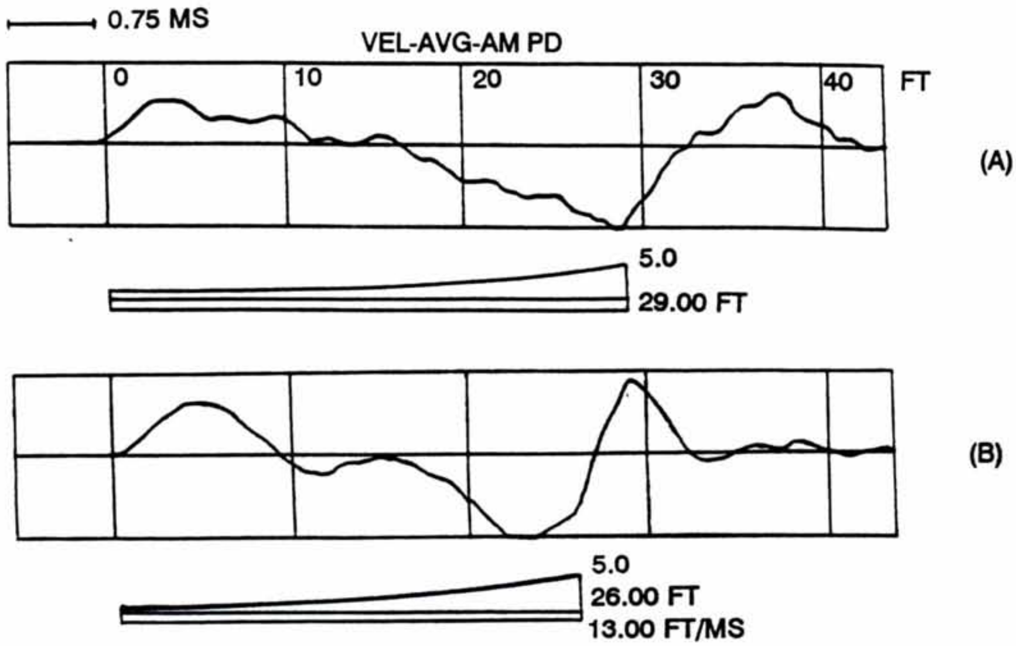


FIGURE 4: PILE HEAD VELOCITY RECORDS FOR CASE 2,, ACCELEROMETER ON TOP OF PILE CAP (A), AND ALONG PILE SHAFT (B)

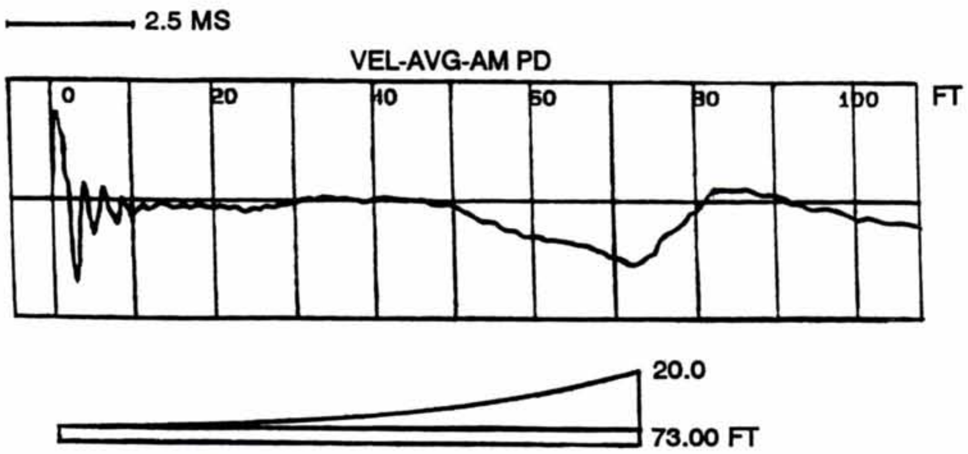


FIGURE 5: P.I.T. RESULTS, CASE 3

Along with geotechnical studies, a P.I.T. investigation was conducted in the structural integrity and the length of the piles under the structure. The accelerometer was attached to the side of the pile and the pile was tapped directly above the accelerometer location. As indicated by Figure 5, the pile toe reflection is evident at a location of 73 ft. Thus, testing verified pile lengths and satisfactory pile integrity. The observed excessive settlements had to be caused by reasons other than improper pile installation.

5. SUMMARY

Low strain dynamic testing, normally performed on precast and cast-in-place concrete piles shortly after installation, was used to test piles under existing structures. This article presented discussions on the P.I.T. method along with three case histories where P.I.T. testing was the only economical means of pile length and integrity verification. It was shown that meaningful and consistent results can be obtained even if the piles are already integrated in the structure.

6. REFERENCES

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