Non-Destructive Testing to Determine Unknown Pile Lengths Under Existing Bridges

By

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ABSTRACT

The Pulse Echo Method is commonly used to evaluate the quality of concrete pile foundations. Also called Low Strain Testing Method, this Non-Destructive test utilizes the impact of a hand-held hammer to produce a low intensity stress wave in the pile material. The major component of the impact induced motion is a compressive wave, which propagates axially along the pile and reflects at points where changes occur in the properties of the pile material or soil resistance. An accelerometer affixed to the pile near its top, registers the impact motion and wave reflection effects.

This non-destructive testing method is typically used for evaluation of the structural integrity of drilled shafts, cast-in-place, and driven concrete or timber piles. The method has also been successfully employed for an assessment of unknown pile lengths under existing structures and particularly for bridges susceptible to scour. However, occasional complications such as interaction of the pile with the structure, deterioration of the piles, and other effects require that the standard interpretation method is expanded. The analysis tools available to improve the accuracy of the results include the frequency domain analysis, two-point measurements, and wave-up calculation. This paper presents discussions on the testing method with emphasis on the special aspects associated with evaluation of unknown pile lengths under existing structures. Data from three case histories are presented and discussed.

INTRODUCTION

Deep foundations of bridges over moving water must have enough bearing capacity even after scouring has occurred. When reviewing the adequacy of such a foundation it is therefore necessary to estimate the depth of maximum scour and then assess the remaining pile shaft resistance and end bearing. For existing bridge structures on pile foundations, it is often difficult to obtain accurate information of in-place pile lengths.

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Even if pile driving records exist, the structural integrity of the piles may be in question. Concrete piles particularly are subject to damage during and after installation. Dynamic low-strain integrity testing has been used for many years, on concrete cast-in-place shafts and driven piles, for both structural integrity evaluation and unknown pile length determination (Hussein et al., 1992). The technology is not always without challenge. The method is limited by the length that can be detected depending on the size of pile and the strength of the substrata.

LOW-STRAIN INTEGRITY TESTING

Based on one-dimensional wave propagation, low-strain integrity testing is probably the simplest, quickest and most economical way to non-destructively test for unknown pile length. The principle is that a compressive stress wave will travel through a long slender rod of uniform material at a constant speed, c, which is a function of the material elastic modulus, E, and mass density, ρ, (i.e., $c^2 = E/\rho$). For concrete, this stress wave speed is between 3,000 and 4,500 m/s. To satisfy equilibrium and continuity requirements, the stress wave is reflected at points of soil resistance and changes in pile impedance (impedance is EA/c where A is the pile cross-sectional area). The magnitude of the stress wave dampens out with time.

The stress wave is produced by a small hand-held hammer impact. A heavier hammer, e.g., of 2.5 kg weight, produces lower frequency pulses than a 1 kg hammer. The lower frequency signals travel further, however, their reflections are less clearly defined and therefore more difficult to read than higher frequency signals. The stress (and corresponding strain) is very small and the wave is observed by measuring the induced particle accelerations using a relatively sensitive accelerometer (Note: The term "low-strain" is used to differentiate this testing from the also common "high-strain" testing of piles, which requires that an impact is applied with a heavy ram such that the pile experiences at least a small permanent set. Obviously, the "high strain" method is not applicable to piles under an existing structure). The acceleration signal, recorded as a function of time, can be integrated to display velocity versus time or, after multiplication with the wave speed, velocity on a distance scale.

The Pulse Echo Method is the term given to low-strain testing with the evaluation of the velocity with time (or distance) records. A simple example of wave propagation and pile top reflections is shown in Figure 1 for a pile of length L and with a cross sectional reduction at distance x. The hammer impact produces a downward (positive) velocity at the pile top and thus a positive input "pulse" at the beginning of the velocity record. The impact wave travels down the length of the pile at a speed c. When the compressive wave reaches the pile bottom, it is reflected as a tension wave, which travels back to the pile top. Arriving at the top, the upward traveling wave arrives at a time 2L/c (twice the pile length divided by the wave speed) and causes a sudden pile top velocity increase, often referred to as the “toe reflection” or “echo”. Normally, the reflection wave causes a pile top velocity similar in shape to the impact signal. The magnitude of the reflection could theoretically be twice that of the impact pulse for a uniform pile. For a pile with non-uniformities or soil resistance, the toe signal is significantly smaller. To make the toe reflection more clearly apparent without unduly increasing the magnitude of reflections from locations closer to the pile top, an exponential amplification is normally applied to the record and it is identified in the velocity plot as an increasing curve under the time/length scale

A reduction in pile impedance, $EA/c = A(E\rho)^{1/2}$, (i.e., cross sectional area times the square root of elastic modulus and mass density of the concrete; this quantity reflects the shaft quality and size) will also cause a tensile reflection. The time of arrival of the reflection from the impedance reduction at depth x, relative to the time of impact, is 2x/c.

It is also useful to consider the velocities that would be observed at some depth z along the pile length. (Figure 1) Measuring at that location, we would first see the effect of the downward traveling wave produce a velocity equal to the impact pulse at the top (at time z/c). Next we observe the upward reflected traveling wave from the impedance reduction and then later its reflection from the pile top. Eventually, we would see the toe-reflected impact pulse and somewhat later its reflection as a downward wave. The velocity magnitudes of the waves observed somewhere along the pile are generally only one half of the velocities measured at the pile top. This is because the reflection at a free pile end causes a doubling in the velocity magnitude.

A few more observations are important:

- An increase in impedance or a sudden increase in soil resistance will cause a compressive wave reflection and therefore a negative or upward directed velocity
- The time at which an upward traveling wave arrives at the pile top is a direct measure of the distance of the cause of the reflection from the sensor location.
- The magnitude of a motion is directly related to the severity of the disturbance that causes the upward traveling wave. However, in complex situations with several impedance variations multiple reflections occur which make the interpretation very complex.
- If the pile top is restrained by a structure then it is not truly free and reflections at the pile top may be either positive or negative.
- Applying the hammer impact on a pile cap above the pile head may cause immediate reflections at the cap bottom and therefore an impact wave that is not necessarily a simple sine half wave.
- At the free pile top, motions occurring after impact are a direct indication of “the upward traveling waves” which in turn allow for a simple interpretation of the origin and cause of the upward traveling wave. However,

measuring somewhere along the pile, it is not a simple matter to decide if the measured motion is due to an upward or a downward traveling wave.

APPLICATION TO EXISTING BRIDGE FOUNDATIONS

The pile top surface is normally not accessible for accelerometer measurements. It is therefore necessary to measure the pile motion by attaching the accelerometer with bolt and anchor to the side of the pile. Alternatively, the sensor may be attached on top of the pile cap. The impact may be applied to the bridge deck or to the pile cap. Figure 2 shows one possible scenario. Where the piles extend to a bent directly under the deck, the free pile length is often long enough to allow for two accelerometer attachments. This has the advantage that it is then possible to identify the upward traveling wave (Johnson and Rausche, 1996).

The following examples demonstrate what can be done and what must be expected.

EXAMPLE 1

The tests were performed on the foundation of a 65 year old, five-span bridge, which had suffered excessive differential and total settlements. At the four pier locations, the bridge deck was directly supported by a pile cap and 6 pile–columns. The piles were 406 mm octagonal concrete sections. Only little information was known about the subsurface conditions except that the original records suggested that the piles should be a total of 13.7 m long and extend into sand with silt and clay.

All 24 piles of the four piers were tested by striking the bridge deck with a 2.5 kg hammer and attaching the accelerometer to the side of the piles. The six records for one of the center piers are shown in Figure 3. The velocity records were exponentially amplified as indicated in the graph under each velocity trace with maximum amplification values of 10 for the longer piles and 4 for the shorter piles. The strongest and clearest reflection was then interpreted as the pile toe reflection. One of the six records of Figure 3 was unclear, possibly due to some cracks in the pile. The other piles indicated pile lengths between 5.8 and 9.1 m. Adding the 2.1 m between accelerometer and pile cap would yield total lengths between 7.9 and 11.2 m. The records clearly showed that the piles on the side of the bridge with greater settlements were shorter than the other piles. Piles of the other three piers yielded similar results. Of course, the low strain method does not provide information about pile bearing capacity.

EXAMPLE 2

Several 455 mm square prestressed concrete piles were driven into a sandy soil and tested with the Pulse Echo Method. The structure is a bridge with three spans. It is 20 years old and no pile driving records could be obtained. Both the 2.5 and 5.5 kg hammers were used in anticipation of possibly very long piles. An often cited general rule of thumb states that 30 pile diameters are a practical limit of depth determination for this method; however, because this limitation depends on soil properties and other factors, it doesn't always hold true. In the present case (Figure 4(a)), a clear toe reflection was apparent for an L/D ratio of 24.

It is sometimes advantageous to transform the records into the frequency domain, particularly if spurious vibrations from a variety of sources tend to mask the pile toe reflection. As a demonstration, a Fourier transform was done on the records in the present example as shown in Figure 4(b). The peaks of the transformed velocity occur at frequencies which are characteristic for the measured record. In this case, it is obvious that the time record is much clearer than the frequency transform. The latter indicates not only the frequency corresponding to the pile length, but also those of other reflections caused by structure and/or soil.

It should also be mentioned that the so-called transient response method, which additionally requires the measurement of the hammer force and which also requires the data interpretation in the frequency domain, is usually of no help when pile length of bridge foundations must be determined. The main reason is frequency components in the records, which originate from the superstructure and are therefore nearly impossible to separate from the frequency response of the pile. However, in the time domain, which identifies the phase shift between these record components, it is a much simpler task to identify the pile length. This method may be of some help in the determination of the dynamic stiffness of a pile, however, it requires that the pile top is free and not attached to a structure.

EXAMPLE 3

This example is one where it was possible to attach two accelerometers to the sides of the test pile at a distance of 2.1 m apart. The piles were 455 mm square prestressed concrete piles with design length of 15.2 m. This 40 year old bridge was experiencing differential settlements near the river channel.

Figure 5 shows the velocities recorded at gage locations g1 and g2. Obviously the two velocities are somewhat complex, i.e. they do not only show an impact pulse and a toe reflection but also other characteristics. Helpful is the time shift between the onsets of the two velocity records, which indicates a wave speed of approximately 4,100 m/s. In order to more confidently interpret the record, the wave up curve for the gage location g1 was calculated, using the algorithm developed by Johnson and Rausche, 1996.

This wave-up record shows very clearly a damage (or crack) reflection at a distance of 4.6 m below the gage 1 location and possibly a pile length below gage 1 of roughly 13.7 m (if the largest wave-up reflection is interpreted as the toe reflection). The calculated wave up record also shows several additional reflections between damage and toe reflection, which may have been caused by additional cracks or some other dynamic effects. Of course, it is also possible that the wave-up calculation method introduces errors because it requires that differences of the two records are taken, which introduces roughness and uncertainty in the resulting curve.

SUMMARY AND CONCLUSIONS

Low-strain dynamic testing can be effectively used to assess the length of piles under existing bridge structures. The method is generally applicable if the pile penetration is not much greater than 30 pile diameters. Although, successful tests may also be possible for deeper pile embedment depending on the strength of the soil and the quality and the uniformity of the pile. Several data interpretation tools exist, among them frequency analysis and wave up determination from two acceleration records. The most powerful tool is, however, the exponential amplification of the time record.

The low-strain method is also frequently used for the quality and length assessments of deep foundations, buildings, telecommunication tower foundations, masts, antennas and other structures. These applications are often simpler than bridge foundations since they allow for an attachment of the sensor at the top of the shaft or pile.

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Johnson. M. and Rausche. F., "Low Strain Testing of Piles Utilizing Two Acceleration Signals", 1996, Fifth International Conference on the Application of Stress Wave Theory to Piles, Orlando, Florida.

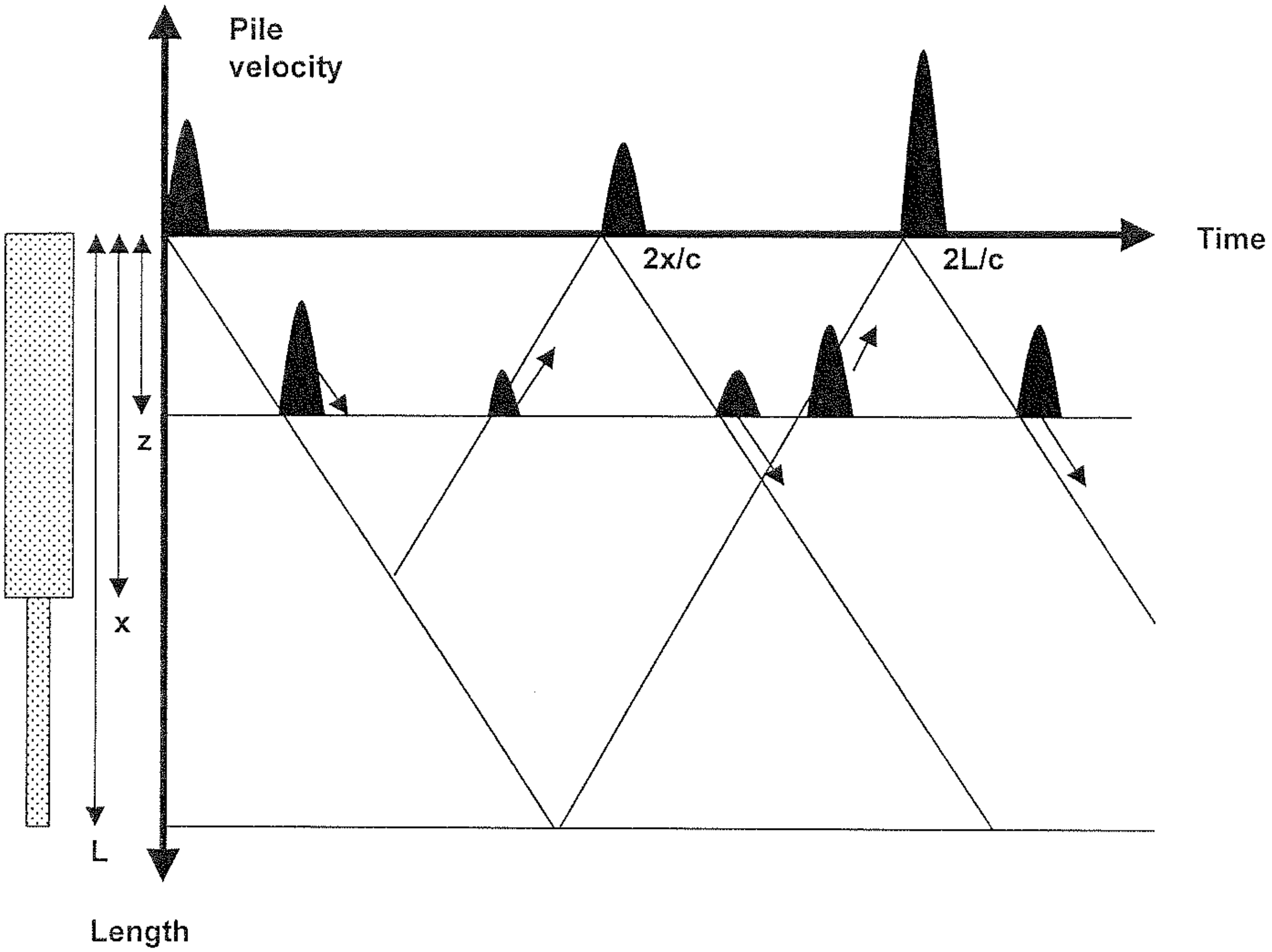

Fig. 1 – Length-Time Plot of Wave Travel Paths and Velocities at Pile Top and in Pile.

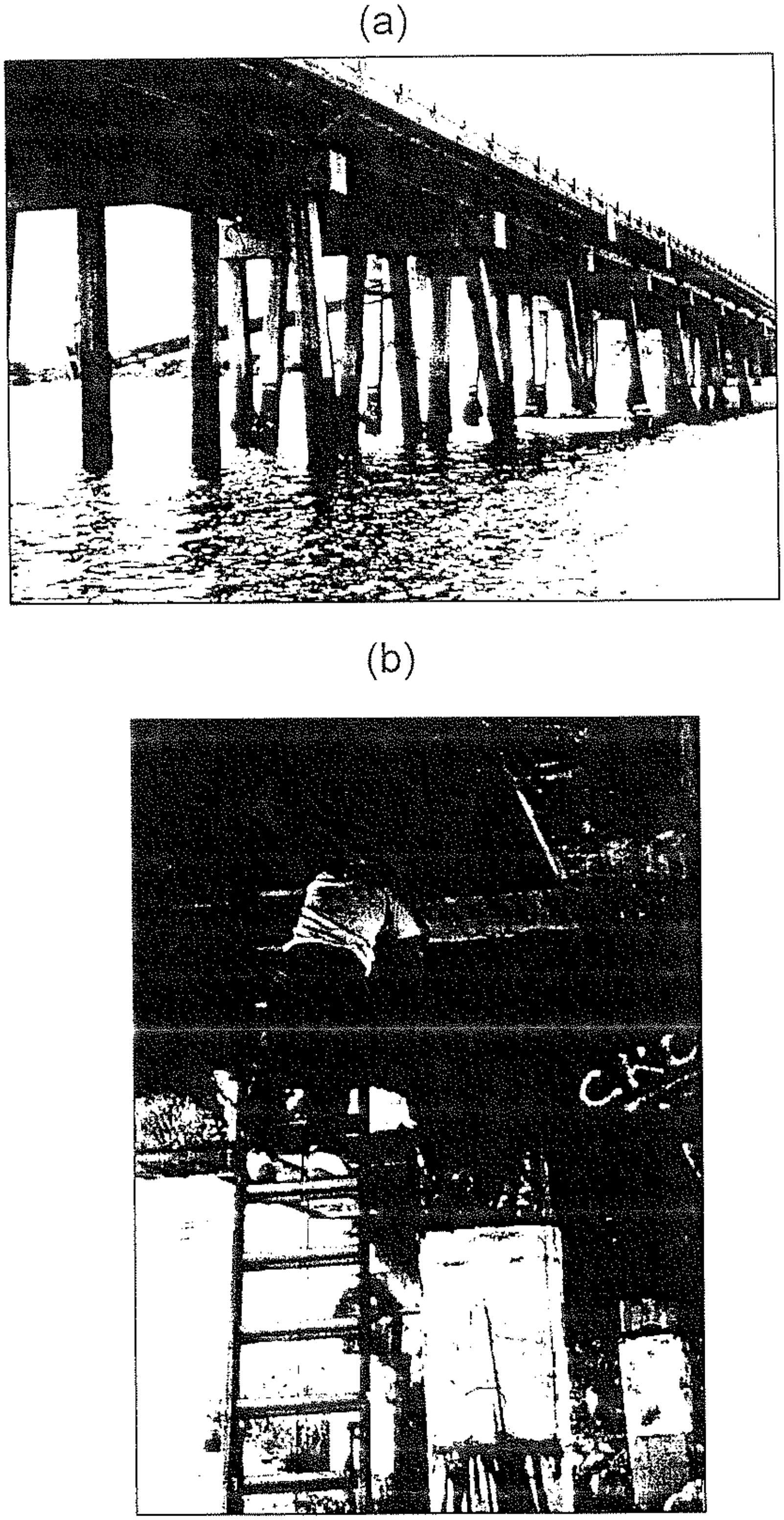

Fig. 2 – Photographs of (a) Bridge Foundation Tested and (b) Application of Impact

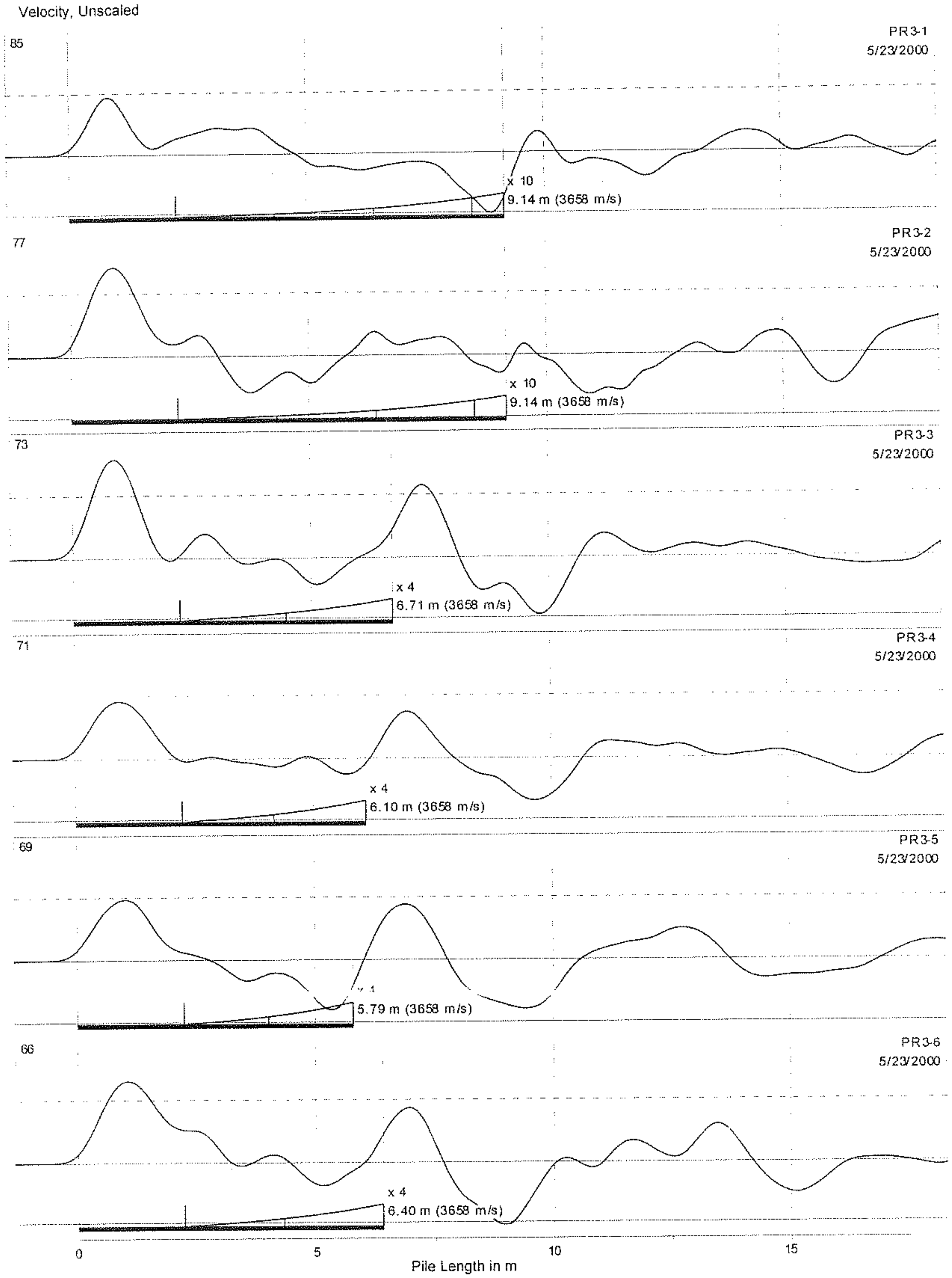

Fig. 3 – Example 1, Pile Velocity Records from 6 Piles Located in the same Bent

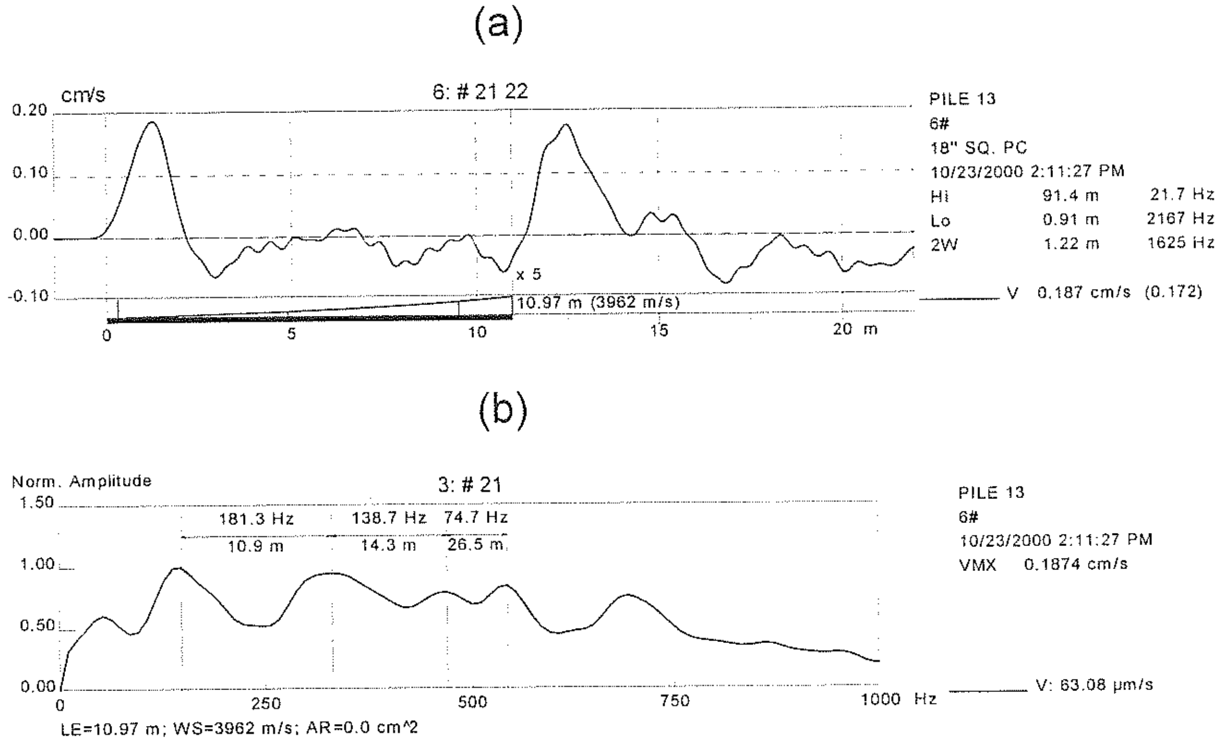

Fig. – 4: Example 2 (a) Pile Integrity Tester (PIT) Velocity Record of a 455 mm Square Concrete Pile and (b) the Associated Frequency Plot

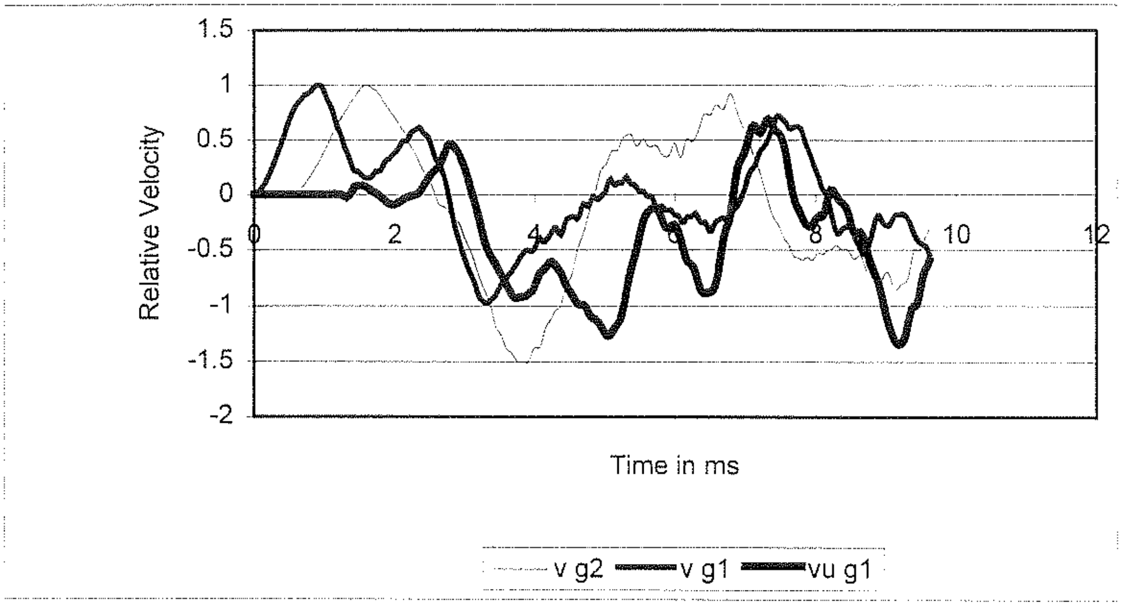

Fig. 5 – Example 3 Velocity Records Taken at Two Locations on Pile and Calculated Upward Traveling Velocity (vu g1) at Upper Location

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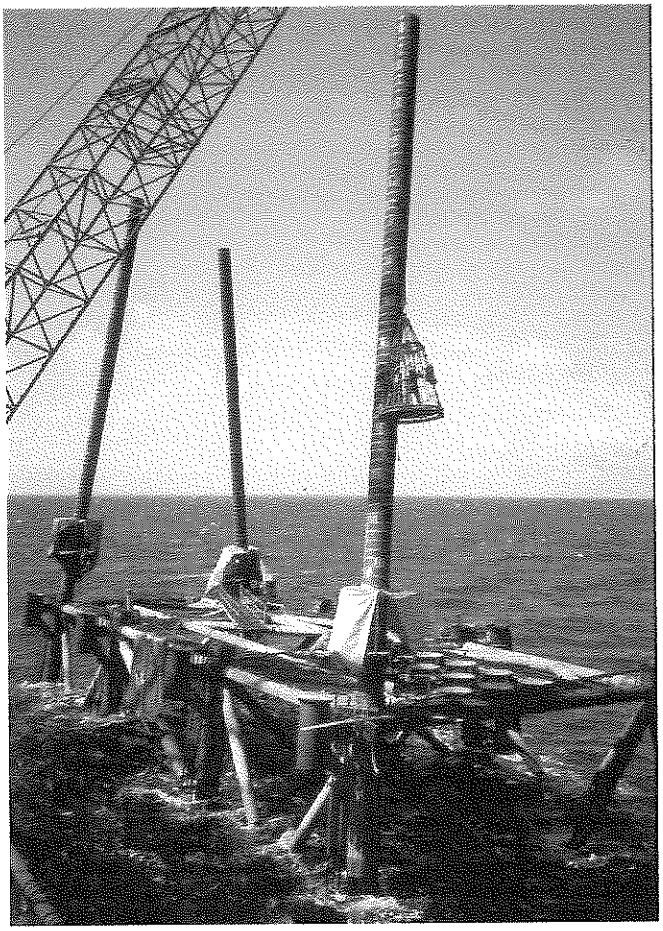

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