PILE INTEGRITY BY LOW AND HIGH STRAIN IMPACTS

By Frank Rausche[1], Garland E. Likins[2] and Mohamad Hussein[3]

INTRODUCTION

Where deep foundations are required, loads must be safely carried both structurally and geotechnically. During installation, driven piles may be damaged due to high axial or bending stresses. Bored or augured piles may suffer from separation of concrete, necking, inclusions, voids along the pile shaft, poor concrete quality, or construction workmanship. After installation, any pile shaft can be damaged by large lateral movements from impacts of heavy equipment or slope or retaining wall failures.

It is impractical to statically test every pile to verify integrity. Replacing all suspect piles, while effective, is also very expensive. However, integrity testing by impact methods can evaluate the integrity of suspect piles at a reasonable cost. Impacts can be generated by small hand-held objects or heavy drop weights and impact pile driving hammers. The principles, applications, and limitations of both Low and High Strain Methods are discussed.

BACKGROUND

One-dimensional wave propagation applies to a linear elastic pile which is long compared to its diameter. When impacted, a stress wave travels through the pile at a wave speed, c, which is a function of the elastic modulus, E, and mass density p (i.e., $E = pc^2$). The applied load, F, and particle velocity, v, at a point are related ($F = Zv$). For a cross-sectional area A, the proportionality constant is, $Z = EA/c$; it is called the pile impedance since it is a measure of the pile's resistance to change in velocity.

Suppose that at some point along the pile shaft the impedance changes from Z_1 to Z_2. When the downward traveling stress wave, Fi, arrives at this point, part of the wave is reflected up (Fu) and part transmitted down (Fd) such that both continuity and equilibrium are satisfied. Solving the simultaneous equations yields (Rausche and Goble, 1979)

$$Fd = Fi\,[2\,Z_2/(Z_2 + Z_1)] \quad (1a)$$

$$Fu = Fi\,[(Z_2 - Z_1)/(Z_2 + Z_1)] \quad (1b)$$

For a uniform pile, ($Z_2 = Z_1$), neither the upward reflection Fu nor the downward wave Fd are generated and the input wave Fi travels unchanged. An example of extreme "nonuniformity" is a free pile end where Z_2 is zero; the oncoming downward wave will be completely reflected upward and the resulting Fu will be of opposite sign. A decrease in either area, A, or modulus, E, produces a tensile reflection (an increase produces a compressive reflection). Fig. 1 shows that for a compressive downward traveling wave which encounters a cross-sectional reduction, an upward traveling tensile wave will be observed at the pile head at a time equal to twice the distance of

---

[1] President, Goble Rausche Likins & Associates, Inc., Cleveland, OH, USA
[2] President, Pile Dynamics, Inc., Cleveland, OH, USA
[3] Manager, Goble Rausche Likins & Associates, Inc., Orlando, FL, USA

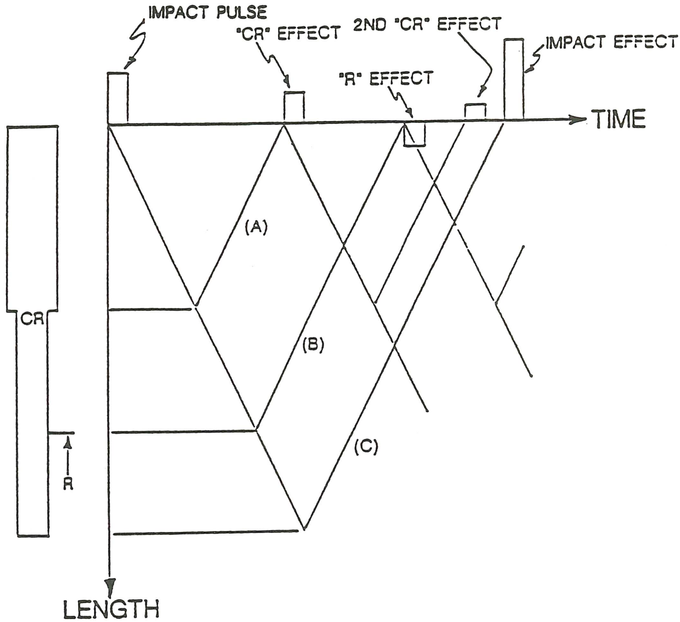

FIGURE 1: IMPACT PULSE AND REFLECTIONS FROM (A) CROSS-SECTIONAL REDUCTION, CR, (B) PASSIVE RESISTANCE, R (MODELED VELOCITY PROPORTIONAL) AND (C) PILE TOE.

disturbance divided by the wave speed, c. The figure also shows that a compressive upward traveling wave may be generated by a soil resistance force (R). At the pile head, R will create an effect opposite to that of a cross-sectional reduction.

LOW STRAIN TESTING

General Description

The Low Strain Method is a simple, quick and inexpensive test which is the primary reason for its current acceptance. After attaching a sensitive accelerometer to the pile head the hand-held hammer generates a short impact wave of appreciable acceleration but low strain (Fig. 2). The impact acceleration and subsequent reflections from either the pile toe and/or discontinuities, are captured by either a portable computer or Pile Driving Analyzer, integrated to velocity and graphically displayed, plotted, or stored on disk.

With the Low Strain Method, a large number of piles may be quickly tested at a construction site. The velocity curve is investigated for wave reflections indicating a change in pile properties (Rausche and Seitz, 1983; Reiding et al., 1984; Schaap and de Vos, 1984). However, reflections can also be caused by soil resistance. Furthermore, if the hammer causes multiple inputs, then separation of impact and reflection effects is difficult. To assist in separating effects of impact from other relevant reflections (i.e., the pile toe

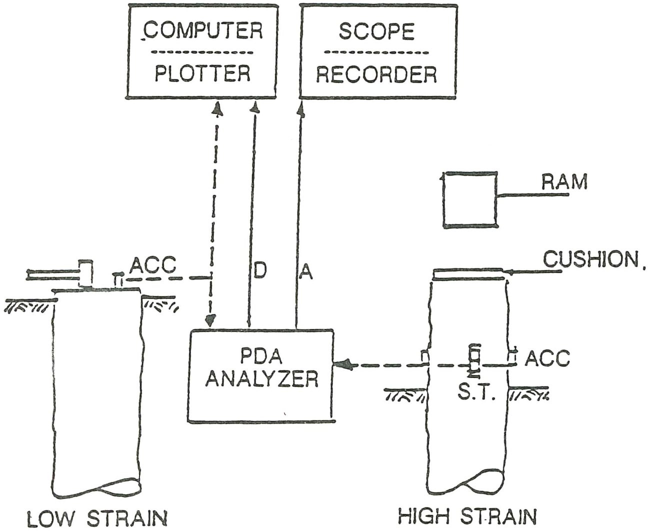

FIGURE 2: ACCELEROMETERS (ACC) AND STRAIN TRANSDUCERS (S.T.) FOR BOTH LOW STRAIN TESTING (VIA EITHER PDA OR COMPUTER) OR HIGH STRAIN TESTING (WITH PDA OUTPUT EITHER ANALOG (A) TO SCOPE/RECORDER OR DIGITAL (D) TO COMPUTER/PLOTTER).

or other discontinuities), signals from several impacts are averaged to reduce random signal effects from any particular blow. For long piles with high shaft resistance, reflections from the pile toe may be very small. By amplifying the records exponentially with time, it may then be possible to identify relevant reflections even in records of low energy.

CAPWAPC Signal Matching

To reduce the uncertainties in data interpretation, a signal matching technique such as CAPWAPC may be employed (Goble et al., 1980). CAPWAPC divides the pile into a series of continuous segments; at segment boundaries, the wave reflections and transmissions are computed. However, for certain signals, sufficient explanations could be found in shorter time and at a lower cost from a simple catalogue. Such a catalogue was prepared using CAPWAPC and a few examples demonstrate the strengths and weaknesses of the Low Strain Method.

Velocities were computed with a pile head force pulse having a 0.6 ms duration, although in reality pulse widths may vary depending on the size and hardness of the impacting device. For general applicability, any time or length effect can be referenced to this pulse width. For this study, the pile has a length of about 6 pulse widths and a CAPWAPC segment length of one eighth the pulse width.

Various soil resistances, pile impedance changes, and the resulting pile head velocities were plotted as in Fig. 3; resistances increase from bottom of figure to top of figure and impedance changes increase from left to right. The soil resistance was chosen such that the computed toe reflected signals were greater than, one half of, and a small portion of the impact wave. The impedance changes were always 70, 49, and 24% for reductions and 120, 144, and 207% for enlargements and the study contained impedance change lengths of 1/6, 1/3, 2/3, 4/3, and 3 pulse widths. Combinations of increase/decrease (or decrease/increase) with varying widths, gradual impedance changes, and very small gaps were also analyzed. Furthermore, concentrated or zero resistance layers were considered. The locations along the shaft of all changes were varied.

Discussion

Cross-sectional or pile impedance variations produce predictable effects at the pile head. For example, an impedance decrease in the pile causes a tensile (positive) wave; an increase causes a compressive wave. Thus, necking or inclusions appear as a positive-negative cycle. Strong concentrated soil resistance causes wave effects similar to those from impedance increases. Gaps have effects appearing like a free pile end and spliced piles therefore can only be tested to their full depth if the splice provides for a continuous wave transmission.

A few cases are of particular interest. Consider Figs. 3f, 3j, and 4a. The reflection from a reduced impedance appears larger for a lower resistance (3j) or a greater length of reduction (4a).

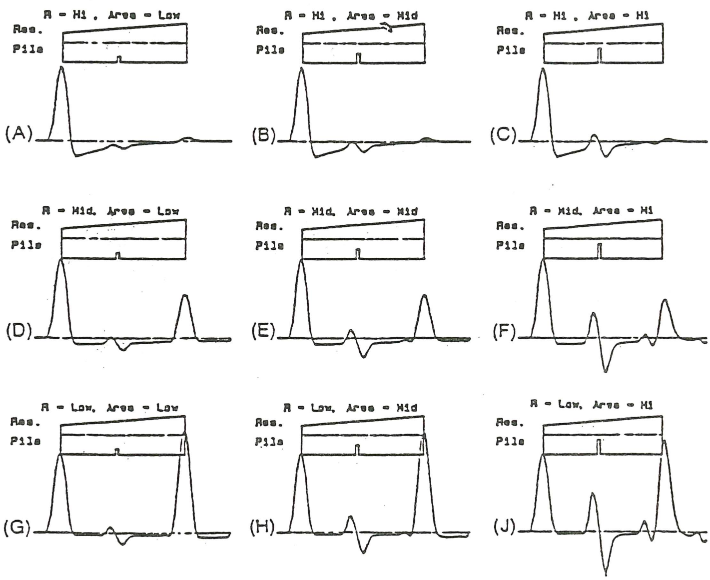

FIGURE 3: LOW STRAIN CATALOG EXAMPLE FROM CAPWAPC FOR PILE WITH DEFECT OF VARYING INTENSITY AND VARYING SHAFT RESISTANCE.

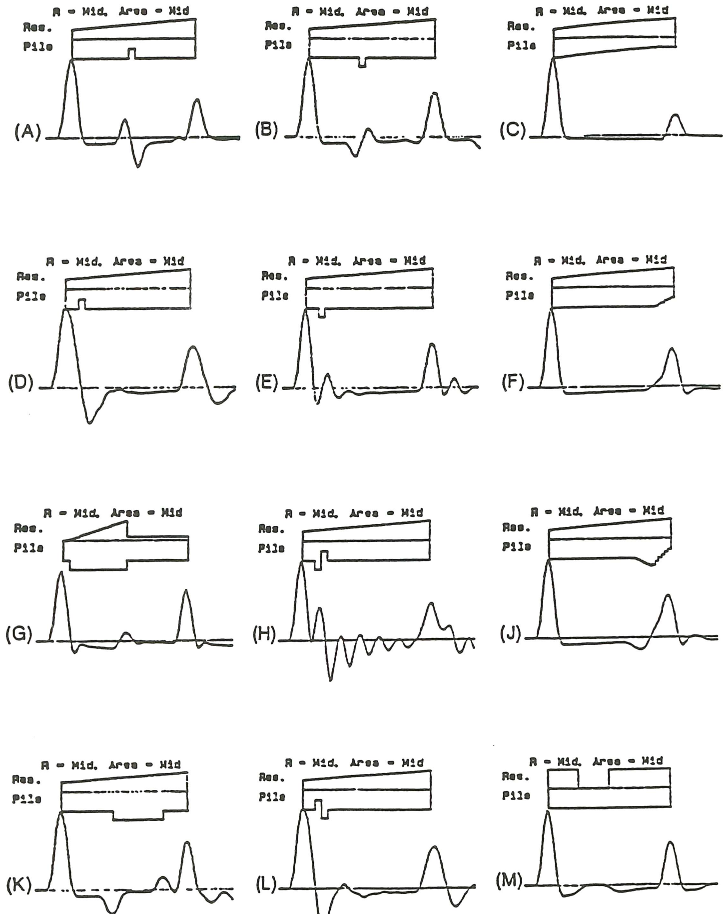

FIGURE 4: LOW STRAIN SIMULATION USING CAPWAPC FOR PILES WITH VARIOUS IMPEDANCE PROFILES.

These three effects cannot be clearly distinguished. Thus, the reflection from a very serious but short length defect with high damping may be similar to that from a less serious defect with less damping and/or greater defect length. Fig. 4d shows that a serious defect near the pile head has an effect similar to an impedance increase or high shaft resistance due to superposition of impact and reflection waves. Fig. 4e shows that an impedance increase near the pile head may erroneously be interpreted as a defect. From Fig. 4f, a defect near the pile toe may be difficult to discover. Under certain circumstances, the pile diameter may increase in a soil with high shear strength while the nominal diameter is maintained in a deeper cohesive but low resistance material. Although the pile is satisfactory, the observed reflection in Fig. 4g suggests a serious defect. The presence of a clear pile toe reflection does not necessarily confirm that the pile is of sound quality.

Clearly, the Low Strain Method has serious limitations which must be understood by those performing the tests and interpreting the results. The method is limited when a high soil resistance masks the lower pile portion and when a wide pulse width hides deficiencies near the pile head. The method cannot determine gradual impedance changes. Mechanical splices may appear as gaps and may screen deficiencies in the lower pile segments. Auger piles with greatly varying cross-sections are difficult to analyze with confidence. The length and severity of a defect both affect the reflection in a similar manner making a precise conclusion about the defect impossible. Small hairline cracking over a partial section will probably not be properly interpreted. The method cannot determine the bearing capacity of the pile. The condition of or below the pile toe cannot be easily assessed.

Reality does not always produce clearly defined and repeatable impact signals. On the other hand, if a large number of piles are tested on a single site, then, a standard response may be observed which includes site dependent soil resistance effects. Unusual test results on any pile should be cause for concern and further investigations. Fortunately, the Low Strain test requires little to no assistance from the contractor and large numbers of piles can be checked each day for very little cost.

Examples

Fig. 5 contains records including a pile length indicator of four different concrete piles on the same site. Fig. 5a shows the record of a structurally sound single section pile with a reflection occurring only at the pile toe. The records in Figs. 5b and 5c show a reflection at the epoxy/dowel splice caused by the epoxy having slightly different characteristics than the concrete. These piles were classified as structurally sound since splice reflections were small and pile toe reflections were apparent. The records in Fig. 5d show a much larger reflection than the splice reflection from most other piles; this reflection occurs repetitively since the wave is reflected between the pile head and at the damage location. This pile was classified as broken and the conclusion was confirmed by extraction. The pile was actually broken a short distance below the splice.

Fig. 6 contains records of four concrete piles from a second site where a slope failure produced large lateral displacements. The soil profile showed silty clay with very high shear strength below 13 m (40 ft). The reflection

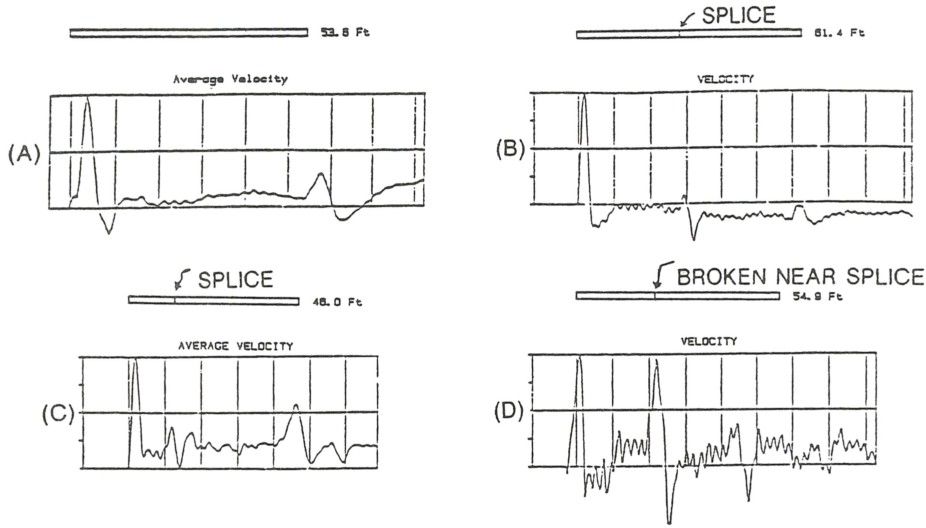

FIGURE 5: LOW STRAIN TESTS OF 4 PILES ON SITE A.

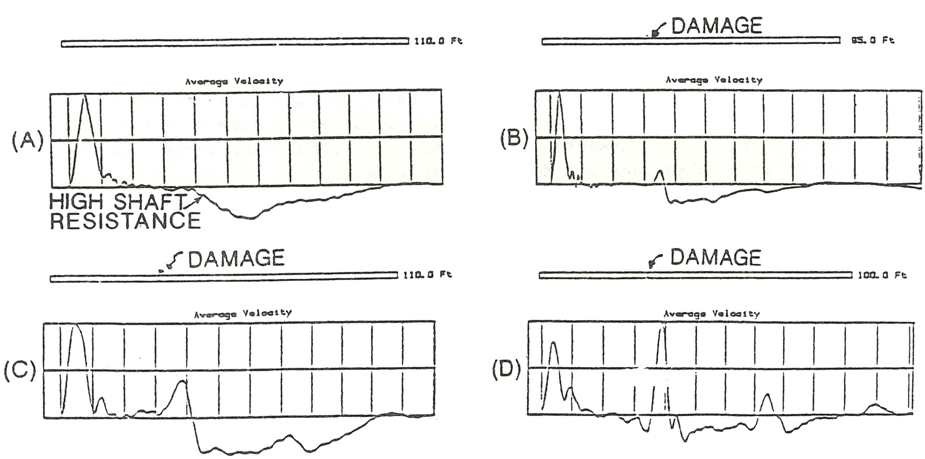

FIGURE 6: LOW STRAIN TESTS OF 4 PILES ON SITE B.

from the pile toe is not clearly apparent in Fig. 6a due to high shaft resistance which produced a relative velocity decrease at approximately 13 m (40 ft). Otherwise, this pile was classified as structurally sound. Figs. 6b, 6c, and 6d show discontinuities approximately 10 m (33 ft) below the pile head. The magnitude of the return wave at the damage location varies greatly for each pile indicating the relative severity of the damage which could be estimated if necessary by CAPWAPC signal matching or comparison with catalog figures. The piles classified as damaged were rejected in this case.

HIGH STRAIN TESTING

General Description

Beginning in 1964, research was conducted at Case Western Reserve University to develop an economical, easily portable, field use system which calculates pile bearing capacity from measurements of pile force and velocity during pile driving. Researchers developed both the transducers and equipment required for data acquisition and numerical computation. Now known as the Case Method, the system gathers information for the evaluation of pile bearing capacity, hammer and driving system performance, pile driving stresses and pile structural integrity (Goble et al., 1980; Likins, 1984).

To evaluate integrity by inducing both motion and strain in a pile, a heavy mass must strike the pile. For driven piles, the impact hammer is available on site to apply a test blow. High strain tests for drilled shafts, however, require that a large weight be dropped. In either case, the weight and drop height of the impacting object, and cushion material can be selected using of a wave equation analyses (Rausche et al., 1988). When the hammer strikes, pile strain and motion signals are converted by the PDA to force and velocity, respectively by a Pile Driving Analyzer (PDA) system. A PDA system for High Strain is also shown schematically in Fig. 2.

Because both velocity and force are measured, the forces in the upward and downward traveling waves can be easily computed from

$$Wd = (F + Zv)/2 \quad (2a)$$

$$Wu = (F - Zv)/2 \quad (2b)$$

to distinguish between hammer impact effects and reflections. The upward wave allows determination of shaft friction and distribution (compressive increases in the Wu curve) or damages (a local decrease in Wu prior to 2L/c). The magnitude of damage and its location are estimated (Rausche and Goble, 1979) by relating the integrity value B with the reduction in impedance.

$$B = Z2/Z1 = (1-a)/(1+a) \quad (3a)$$

where

$$a = [v(t^*) - F(t^*) - R]/[2(Fi - R)] \quad (3b)$$

with Fi being the impact force, R the total resistance above the damage, and t* the time of the local Wu decrease corresponding to the damage location.

Discussion

The High Strain Method outlined above can be utilized to quantify pile deficiencies. The precise nature of a deficiency cannot be given although an effective impedance can be estimated. It is not always possible, however, to detect impedance changes which are gradual in nature or of a very short extent. The relatively slowly changing high stress wave may not produce sufficiently clear reflections.

If the length of an existing pile is unknown, it may be determined using the High Strain Method. However, a reflection from the pile toe must be evident in the measured pile head records. The calculated pile length is then as accurate as the knowledge of the stress wave speed. For situations where only pile integrity is to be evaluated, the necessary mobilization of a heavy mass and a crane raises the cost of the test substantially. Often, the cost and effort of the High Strain Method is considered a major disadvantage; on the other hand, any pile which can sustain this test is also likely to survive the applied service load. Further, the double measurements of both force and velocity provide sufficient information to separate the upward and downward waves making interpretation of damage very accurate.

Examples

Fig. 7 contains high strain force velocity records of four blows during a long redrive of a prestressed concrete pile of 28.7 m (94 ft) length below transducers. Compared to the first very early blow number 19, the second record from blow number 424 shows little change except a minor damage indication. Throughout the entire redrive, the compressive stresses were high and the tensile stresses were near the reported level of prestress for this concrete pile. The last three blows shown are from consecutive blows and show a rapid failure. The last blow shows a large tensile return substantially earlier than the theoretically correct 2L/c return shown in blow number 19.

Fig. 8 contains a High Strain record of the fourth pile tested by the Low Strain Method on the slope failure site (Fig. 6d). The High Strain test confirms a complete break at 11.6 m (38 ft) below the transducer location.

COMPARISON OF THE METHODS AND CONCLUSIONS

If a pile has major damage along the shaft, either Low Strain or High Strain testing can potentially detect the deficiency. As the pile becomes longer and the shaft resistance becomes correspondingly larger, the High Strain Method is better able to detect damage in the lower part of the pile. An impedance change near the pile head is more reliably detected by the High Strain Method (which clearly separate upward and downward traveling waves) than by the Low Strain Method. On the other hand, the short duration pulses of the Low Strain Method are sometimes more clearly resolving reflections from narrow impedance changes. The longer High Strain waves, in turn, will penetrate almost all pile splices which could limit the Low Strain Method to a check of the pile portion above the splice. If a High Strain impact is applied to a pile and is transferred along its full length, it is quite likely the pile will statically sustain corresponding loads; this cannot be

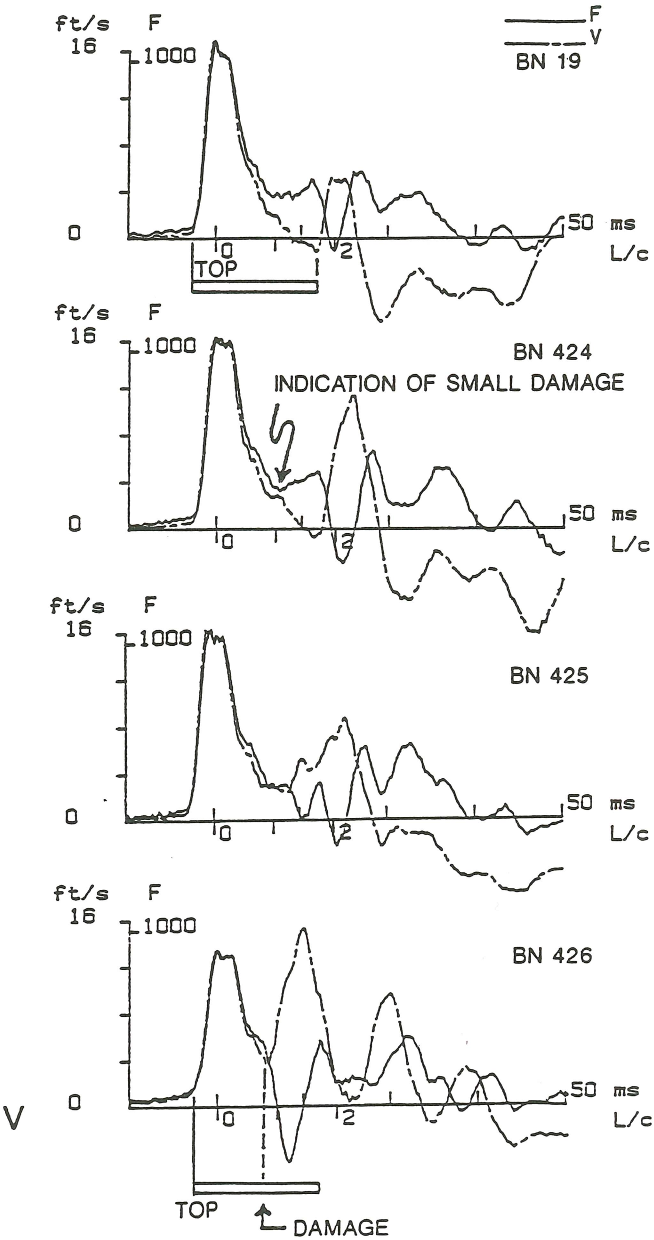

FIGURE 7: HIGH STRAIN TEST WITH ONE EARLY AND THREE LATE BLOWS SHOWING SUDDEN BREAKING OF PILE

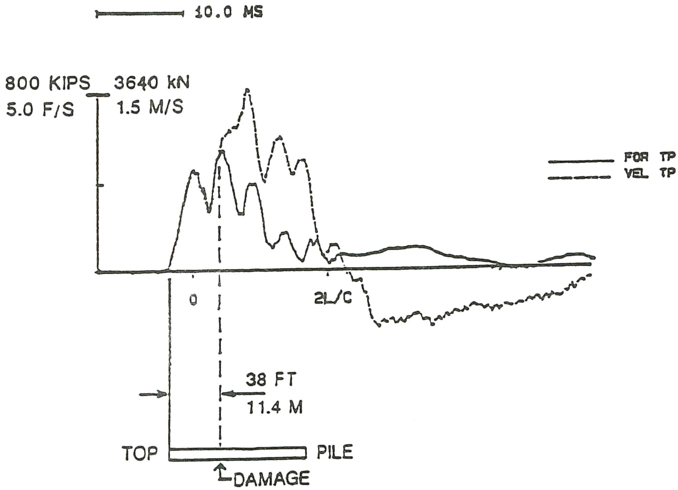

FIGURE 8: HIGH STRAIN TEST OF DAMAGED PILE.

concluded from a Low Strain impact. Only the High Strain Method can give reliable information on the pile bearing capacity, driving stresses and ammer performance.

For the above reasons, the High Strain Method is generally preferred when only a few suspect piles are to be investigated. However, the high cost of High Strain testing all piles for a larger site is generally prohibitive since the pile must be struck by a large mass, generally requiring contractor assistance. The Low Strain Method can be a cost effective solution if many or all piles of a foundation must be checked; suspect piles can then be subjected to further tests, perhaps by High Strain Methods, or simply replaced.

REFERENCES

GOBLE, G., RAUSCHE, F., LIKINS, G. 1980, The Analysis of Pile Driving, State of the Art, Proceedings of the First International Seminar on the Application of Stress Wave Theory on Piles, Stockholm, pp. 131-162.

LIKINS, G., 1984, Field Measurements and the Pile Driving Analyzer, Proceedings of the Second International Seminar on the Application of Stress Wave Theory to Piles, Stockholm, pp. 298-305.

RAUSCHE, F., and GOBLE, G. 1979, Determination of Pile Damage by Top Measurements, Behavior of Deep Foundations ASTM, STP 670, Raymond Lundgren, Editor, American Society for Testing and Materials, pp. 500-506.

RAUSCHE, F., GOBLE, G., LIKINS, G. 1988, Recent WEAP Developments, Proceedings of the Third International Seminar on the Application of Stress Wave Theory to Piles, Ottawa.

RAUSCHE, F., AND SEITZ, J. 1983, Integrity Testing of Shafts and Caissons, Presented at the Specialty Session on Shafts and Caissons, the ASCE Annual Convention, Philadelphia, 17 pages.

REIDING, F., MIDDENDORP, P. and VAN BREDERODE, P. 1984, A Digital Approach to Sonic Pile Testing, Proceedings of the Second International Seminar on the Application of Stress Wave Theory to Piles, Stockholm, pp. 85-93.

SCHAAP, L. and DE VOS, J. 1984, The Sonic Pile Test Recorder and Its Application, Proceedings of the Second International Seminar on the Application of Stress Wave Theory to Piles, Stockholm, pp. 79-84.