Interpretation of Low-Strain Pile Integrity Test Results

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Abstract. Non-destructive testing of piles has gained fair acceptance for various purposes e.g., quality control/quality assurance, verification of existing conditions, and quantification of dimensions. The correct use of this technique can greatly simplify and expedite investigation, and be economical in addressing concerns or question on pile conditions. Equally, its incorrect use can cause controversies, delays, and/or create adverse reputation for the technology.

Integrity issues for cast-in-situ piles have resulted in a serious need for non-destructive test inspection methods to detect the extent and location of serious flaws and prevent failures under service conditions. Integrity inspection performed after installation is often the most reasonable alternative available to assess the pile quality. A most commonly used post construction integrity test is the low-strain pile integrity test commonly referred as PIT. In this type of integrity testing, a low strain dynamic impulse is given to the pile top by a hand held hammer and the velocity of the pile top is monitored using an accelerometer. The low strain impulse will generate a low stress wave that propagates through the pile and reflected at places where there are changes in the properties of concrete, cross-sectional area of the pile or stiffness of the soil surrounding the pile. Such reflections are detected by the accelerometer at the pile top and the Time vs. Velocity plot recorded by the accelerometer is used to identify any defects in the pile shaft. There are two main methods of data analysis associated with the PIT viz. the Pulse Echo Method (PEM) and the Transient Dynamic Response (TDR) method.

This paper presents the analysis and interpretation of pile integrity test data by Pulse Echo Method from various project sites relating the different construction methods in Indian soil conditions.

Keywords: Low-strain integrity testing • Stress wave • Pulse-echo

1 Introduction

Deep foundation construction is an inherently ‘blind’ process, i.e. the final product is not readily available for visual inspection. The quality control / quality assurance process for such foundations is almost always through indirect measurement of other parameters, such as performance of the installation equipment, resistance to driving or drilling, examination of drilled cuttings, etc. Therefore, the quality of the final product is often a function of the installer’s know-how and the inspector’s experience. Even the most experienced foundation contractors acknowledge that there is an initial ‘learning period’ for each project, essentially impacted by ground conditions, equipment utilized, and installation processes. A process whereby confidence in the quality of the installed pile is expeditiously attained is essential to the contractor to confirm the adequacy of the deployed construction methods and vital to the engineer to verify the competence of the foundation installed. The PIT method can be a valuable tool in rapidly making these evaluations as piles are installed.

2 PIT Method

Pile Integrity Testing (PIT) is a non-destructive testing technique, sometimes referred to as the sonic pulse echo method. It involves applying low strains to a foundation element (especially pile) using light weight hammer and evaluating the collected force (optional) and velocity records to deduce qualitative information for the foundation system. Standards covering PIT performance include IS: 14893 & ASTM D5882.

2.1 Basic Theory

Details of the theoretical background and the development of PIT are discussed in various literatures (Rausche and Goble 1979 and Rausche et. al. 1992). The basics of the concept are highlighted below.

Pile Integrity Testing (PIT) is based on the theory of wave propagation in a linear direction. For a linear elastic pile having a length an order of magnitude greater than its width, stress waves travel in the pile at a wave speed (c), such that

$$c = \sqrt{E/\rho} \tag{1}$$

where E is the pile material elastic modulus and ρ is its mass density. The applied force F, imparted by hammer impact and the particle velocity v, at any point are related such that

$$F = Zv \tag{2}$$

where Z is proportionality constant, also known as impedance; it is a measure of pile resisting change in velocity. Pile impedance can be defined as

$$Z = \frac{EA}{c} \tag{3}$$

Change in impedance is related to change in pile cross-sectional area A, as well as pile material quality. Increase in pile impedance or soil resistance forces results in a decrease in measured pile top velocity. Conversely, decrease in pile impedance, results in increased velocity. By observing changes in impedance, pile quality can be assessed and dimensions estimated.

2.2 Testing Equipment – Pile Integrity Tester (PIT)

The equipment that is in common use for pile foundation evaluation is manufactured by Pile Dynamics, Inc. (PDI) USA. The PIT equipment is very compact and readily portable, consisting of a hammer, a motion sensor (accelerometer), and a processing cum display unit. The hammer size varies from about 500g to 4kg. The processor stores and analyzes the recorded signals. Components of the PIT are shown in Fig. 1.

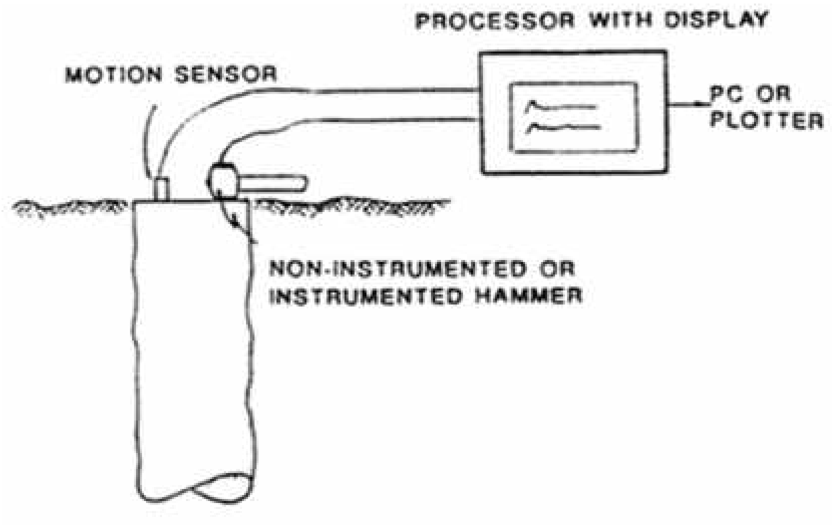

Fig. 1 Components of PIT (Source: Rausche et. al 1992)

In utilizing PIT, one must recognize the capabilities and limitations of the method. The quality of the PIT results is a direct function of the operator's familiarity with the system and experience with pile foundations, e.g. factors such as pile surface preparation for attachment of the sensors, use of certain hammer weight for certain pile size (diameter & depth), amount of effort used to impact the pile top surface, data processing while collecting the data, etc., can readily influence the results if their contributions are not recognized.

Foundations such as bored piles or cast-in-situ driven piles with multiple or large variation in cross-section can result in complex records that are difficult or impossible to analyze.

Also piles with L/D ratio not exceeding 30 are successfully tested, without excessive damping due to soil resistance or pile material properties. Although this rule can sometimes be deviated and piles with greater ratio are reasonably tested under special circumstances. Fig. 2 shows PIT graph of a pile with L/D ratio of 50.

PIT does not produce information on pile capacity or pile load transfer mechanisms. PIT is, however, capable of producing information on pile quality, e.g. the presence of defects such as voids or breaks, and pile length. Even these capabilities are impacted by assumptions that will need to be made during signal processing, e.g., assumptions on the propagation of wave speed based on judging the pile materials. In addition, even under ideal conditions, it is prudent to allow a level of uncertainty in the results although the level of uncertainty is affected by the confidence in available information. It is very common to assume PIT results on pile length to vary by as much as 10%, especially that wave speed variations of ±5% are known to be quite possible due to varying pile material quality (Massoudi N et. al. 2004)

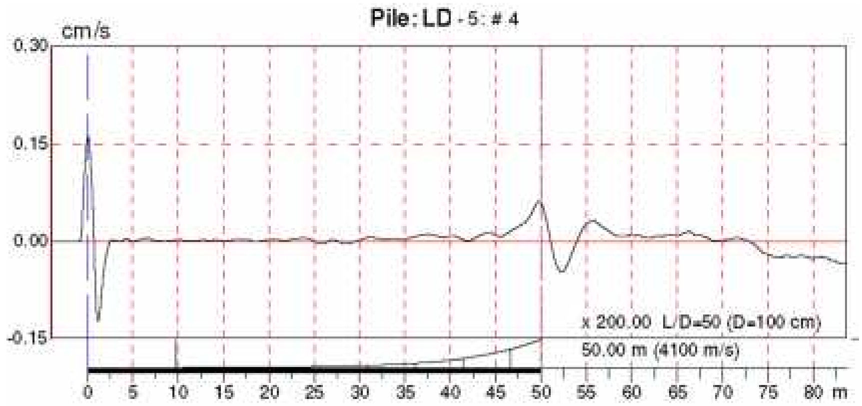

Fig. 2 PIT Graph of pile with L/D = 50

3 Data Collection, Processing and Evaluation

The data collection effort is extremely important if data evaluation is to be meaningful. The accelerometer must be firmly attached. Probably re-attach accelerometer every time between acquiring sets of records to make sure the bonding. The top concrete should always be evaluated visually for hardness and for contaminated concrete. If contaminated concrete is observed, it should first be removed prior to test.

While collecting PIT data on site, random noise is most easily minimized by averaging several records. Even small defects within a short distance of the surface may distort the sensor signal with high frequencies; sensing and impacting at several pile-top locations may eliminate such difficulty. For large diameter shafts, it is recommended practice to test at several locations around the top of the pile to inspect for local defects near the pile top. For any pile it is helpful to have more than one record to compare consistency of results. *Consistent records are the result of uniform impacts on sound concrete, transducer systems that are properly functioning, motion sensors that are firmly attached, and the apparatus for recording, reducing and displaying data properly functioning (ASTM D5882).*

Soil friction and poor concrete quality are often the greatest obstacles for successful integrity testing (latter the most) since they dissipate the stress wave energy. Exponential amplification with time may help overcome these problems, but only if the records contain discernible details reflected by the lower pile portion (in case of high skin friction). Late-occurring vibrations imposed at the pile top are also amplified and distorted so interpretation after amplification should be performed carefully. The Magnification Factor (MA) is best kept constant on similar pile lengths on the same jobsite and is often chosen to make the toe reflection visible. Importance of MA is shown in Fig. 3. Toe response becomes visible only after exponentially magnifying the velocity curve. Exceptions would be piles of different size and/or in different soil conditions.

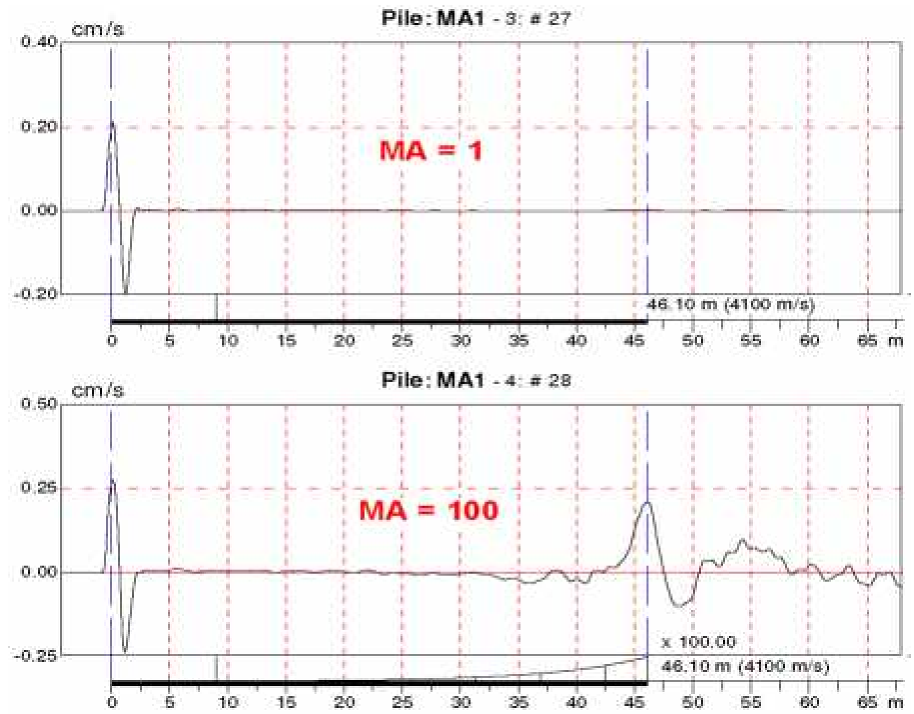

Fig. 3 PIT Graphs with different magnification factors

Magnification Delay (MD) identifies the beginning of the magnification function. It should start early enough so that effects of soil and internal pile damping are properly compensated. Making the MD value so large that amplification only starts shortly before 2L/c produces a false impression of a smooth pile with a clear toe signal and is totally improper. Fig. 4 clearly shows that using MD of 40 improperly hides the impedance reduction at 30m which otherwise is clearly visible with MD of 10. It is best to use the 20% default or a fixed value slightly larger than the pulse width.

High Pass Filter (HI) helps remove slowly changing record portions usually caused by soil resistance. If HI is too low (corresponding to a high cut-off frequency), then the record may lose features that are important for damage or length identification. The lowest suggested value is about ten times the signal pulse width or 50m whichever is higher.

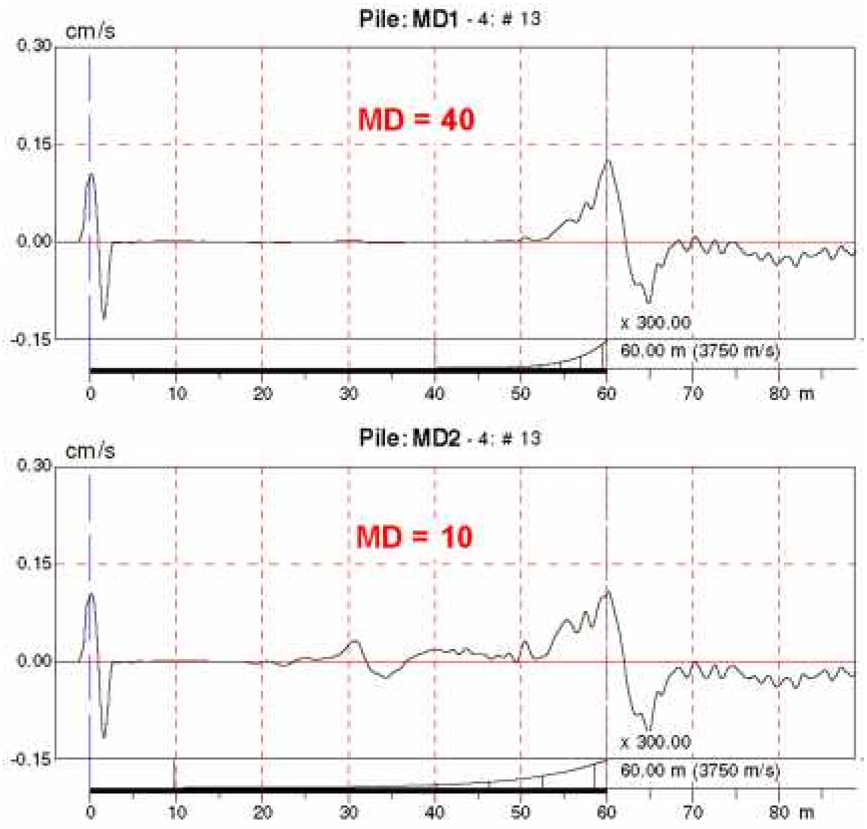

Fig. 4 PIT Graphs with different Magnification Delay factors

'Wavelet' (WL) and 'Low Pass' (LO) are filters generally used to smooth the velocity trace. Hence both filters should not be used for the same record. The Wavelet filter is preferred over LO. If Wavelet is used, LO pass filter should be set to zero. If chosen with high value (corresponding to a low frequency limit), these filters can remove significant high frequency components of the record and cause an improper interpretation. A WL value of about equal to the impact pulse width is preferred (typically 1m). Fig. 5 shows processed PIT graph with above discussed parameters necessary for analyzing the data.

Although the acceleration curve could be interpreted, integration to velocity generally enhances the record by bringing out details otherwise overlooked. Both force and velocity have a positive value at the beginning of the record (PIT assigns a positive value to the compressive and downward inputs). The force returns to zero as the hammer rebounds from the pile top.

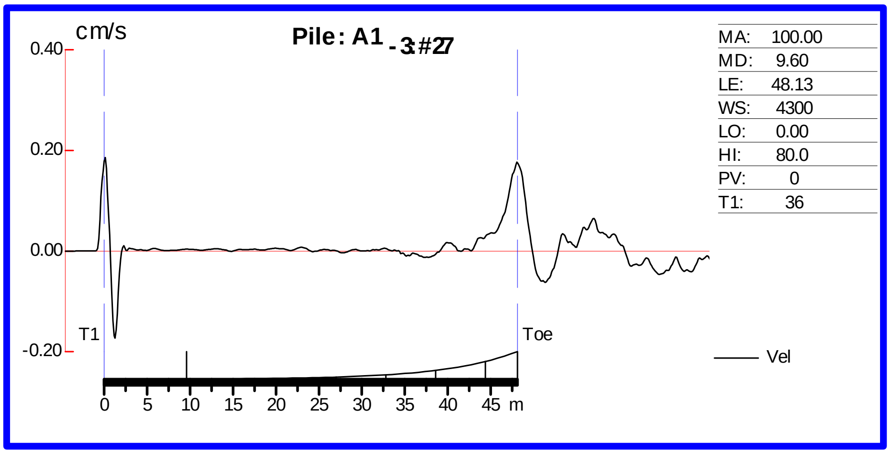

Fig. 5 Typical Processed PIT Graph

A record from a perfect shaft would have the initial impact (positive sign) followed by a flat (zero) response until a reflection (usually positive sign) from the bottom is observed. In practice there is usually shaft friction which, by absorbing energy, shifts the velocity record negative after the initial impact. For a stiff concrete pile in relatively weak soil (strength compared to the concrete), the toe reflection will have the same sign (positive) as the velocity input. Fig. 6 shows velocity plot of a sound pile in soil. For a pile with a fixed end (such as a rock socket), the toe reflection may be of the opposite sign (negative) as the velocity input. Fig. 7 shows velocity plot of a pile well socketed in hard rock.

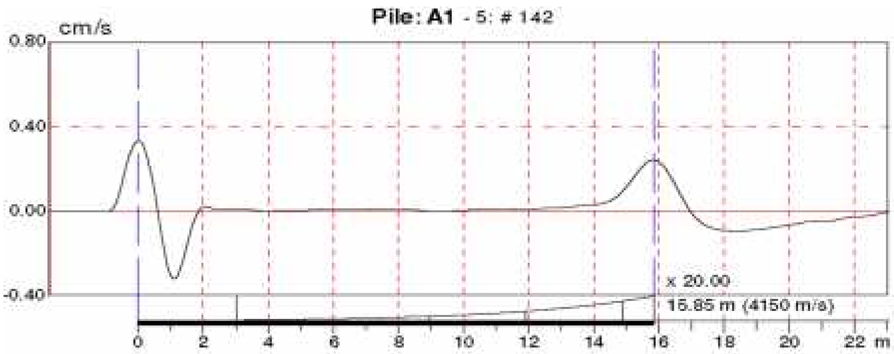

Fig. 6 Typical PIT graph for a uniform pile shaft in soil

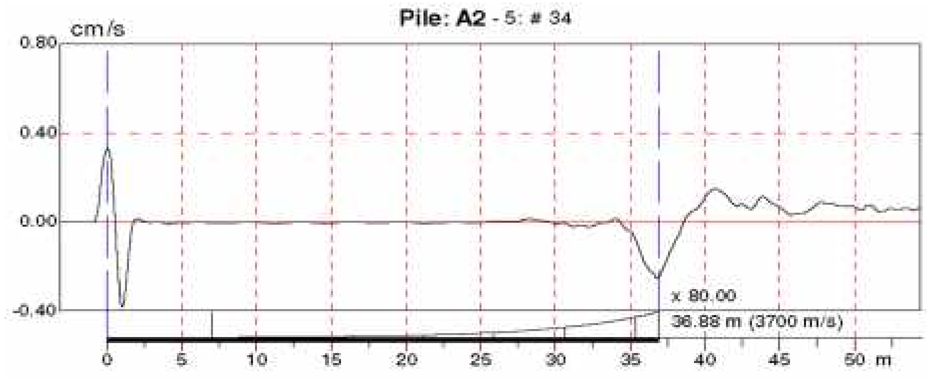

Fig. 7 Typical PIT graph for a pile founded in hard rock

Other reflections, observed only in the velocity record, are caused by changes in the pile impedance (Z=ρ.A.c). Such reflections can be due to changes in either the cross-section or the pile material (density). A region of impedance reduction exhibits a positive reflection (same sign as initial input, which for this discussion is assumed as a positive signal); an impedance increase causes a negative reflection (opposite sign of initial input). A local decrease (necking) would have a positive reflection followed by a negative reflection (positive – negative cycle). Example is shown in Fig. 8. A local increase (bulb/bulging) would have a negative reflection followed by a positive reflection (negative – positive cycle). Sample PIT graph is shown in Fig. 9. The reflections must be interpreted to determine whether the associated changes are acceptable or of serious concern to the integrity of the pile. The magnitude of the reflection is related to the size of the impedance change. The resistance level R (low, mid or high) affects the magnitude of the response; the size of the change also influences the reflection.

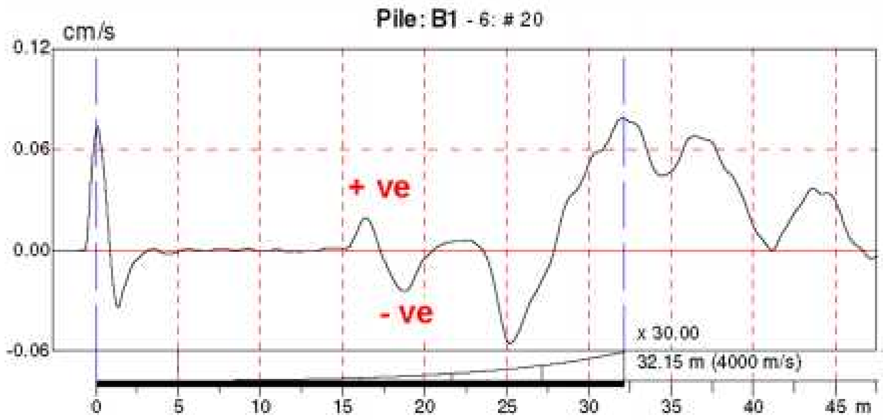

Fig. 8 Typical PIT graph showing impedance reduction

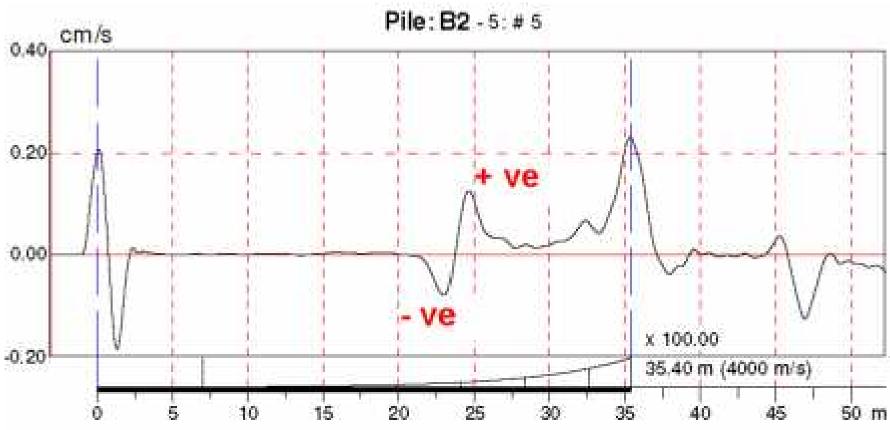

Fig. 9 Typical PIT graph showing increase in impedance

4 Interpretation of Complex PIT Data

PIT data is not always as shown in previous pages hence ASTM D 5882 states *'Engineers with specialized experience in this field are to make final integrity evaluation as interpretation of PIT data is a matter of engineering judgment and experience'*. Below are examples of few complex PIT data.

Figure 10a and 10b shows PIT graphs from two different piles (C1 and C2). Impedance increase (negative – positive cycle) can be clearly seen at 25m in both the piles. But pile C1 shows yet another reflection (positive – negative cycle) at 37m. How this should be classified? Is this a matter of size and extent of impedance change at 25m?

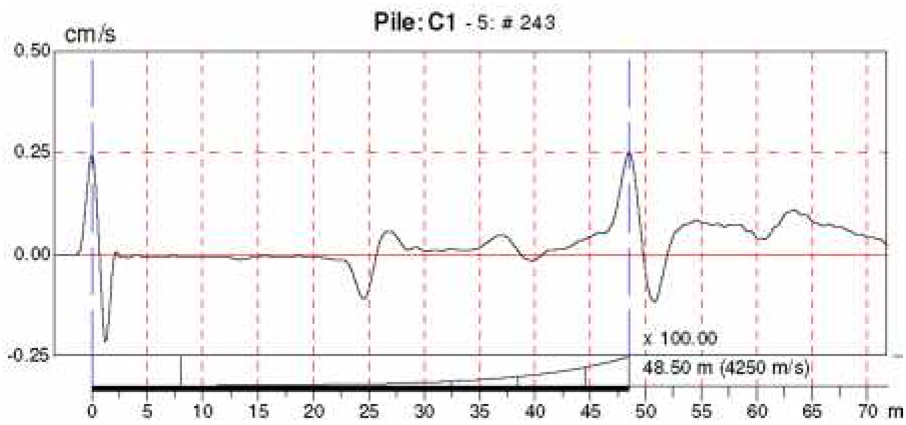

Fig. 10a Typical PIT graph showing change in impedance

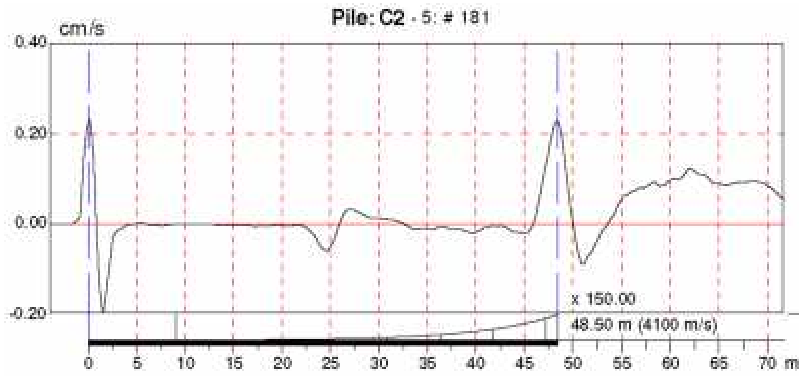

Fig. 10b Typical PIT graph showing change in impedance

Figure 11 shows integrity test graphs from two different piles D1 and D3 showing impedance decrease (positive – negative cycle). Pile D1 shows impedance decrease at 16m, 32m and 48m. Toe response is also possibly clear at 53.21m (i.e. pile length as per site records). Reflections at 32m and 48m are secondary from the impedance decrease at 16m. Pile D3 shows impedance decrease at 12m, 24m, 36m, 48.43m (pile length as per site records). Again these are secondary reflections from impedance decrease at 12m. Toe response might have got super-imposed with these reflections. Secondary reflections are also observed beyond 48m (60m, 72m and 84m) all in multiples of 12m.

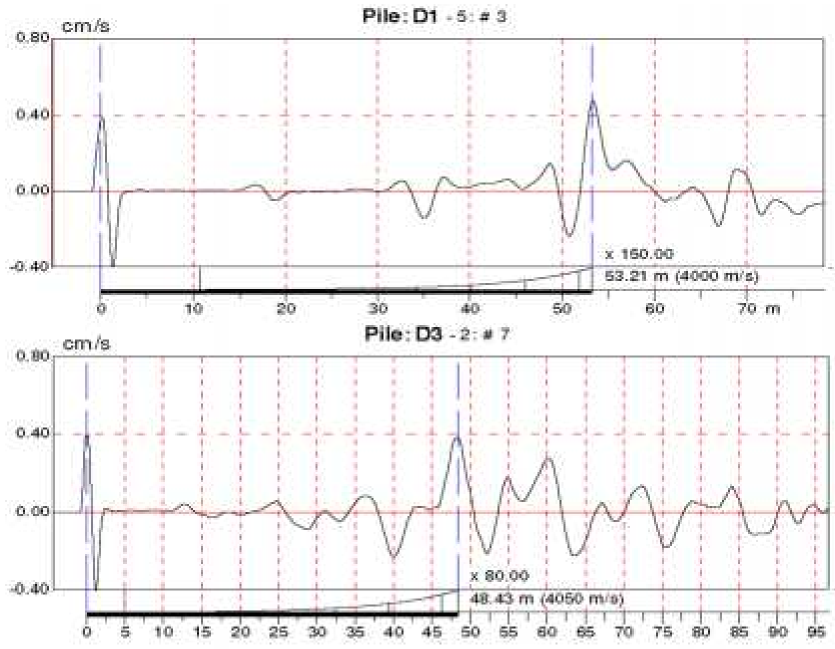

Fig. 11 Typical PIT graphs showing change in impedance

Figure 12 shows integrity test graphs from two different piles (H1 and H2) with possible impedance changes of same nature and at multiple levels within the pile shaft. Pile H1 shows impedance decrease at 11m and again at 16m. Reflections at 26m and 32m may be secondary but cannot be confirmed and so is the reflection from the pile toe. Pile H2 shows possible increase in impedance at 19m and also at 32m. Toe reflection in this case may be considered as clear at 56.36m (as per site records).

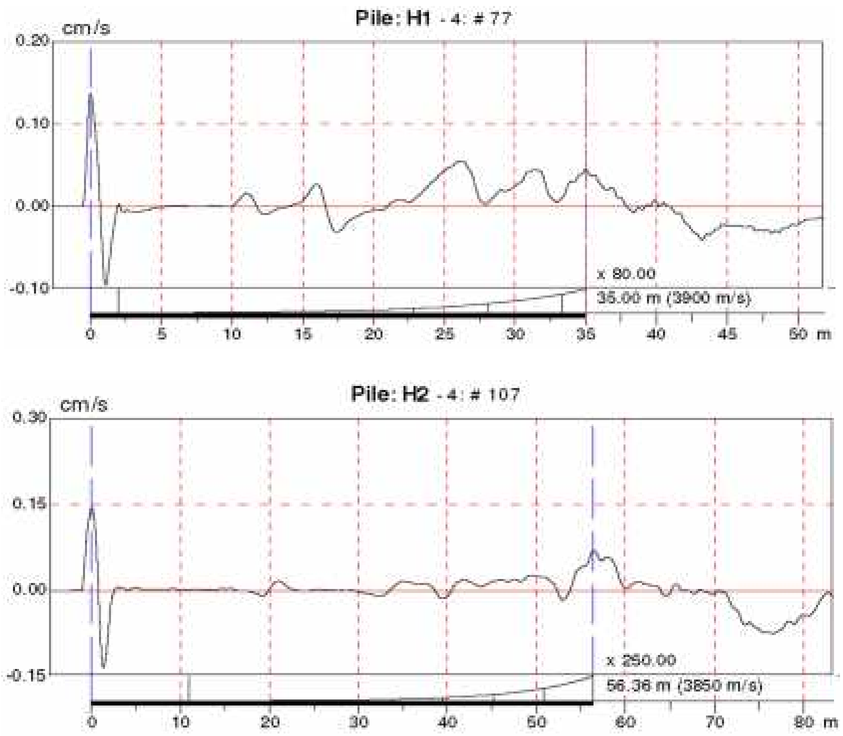

Fig. 12 Typical PIT graphs showing change in impedance at multiple levels

Figure 13 shows some interesting data which in fact is from two different job sites. Pile M1 shows increase in impedance (bulging) at 21m and its mirror (reverse) reflection can be seen at 42m. As per site information the pile had a permanent casing till 21m and the soil investigation report does not indicate any soft soil layer around 42m. Hence the reflection at 42m is a secondary reflection of the bulge. Similar observations were in case of Pile M2 with increase in impedance around 18m and its secondary reflection at 36m. This is predicted by the stress wave theory – *the wave goes down in compression and reflections off the bulge (like a fixed end or hard rock) are in compression (negative). The resulting upward travelling compression wave reflects off the free pile top and moves down the pile in tension. When it reaches the bulge a second time, the tension wave reflects in tension (positive) just as the initial compressive wave reflected in compression.*

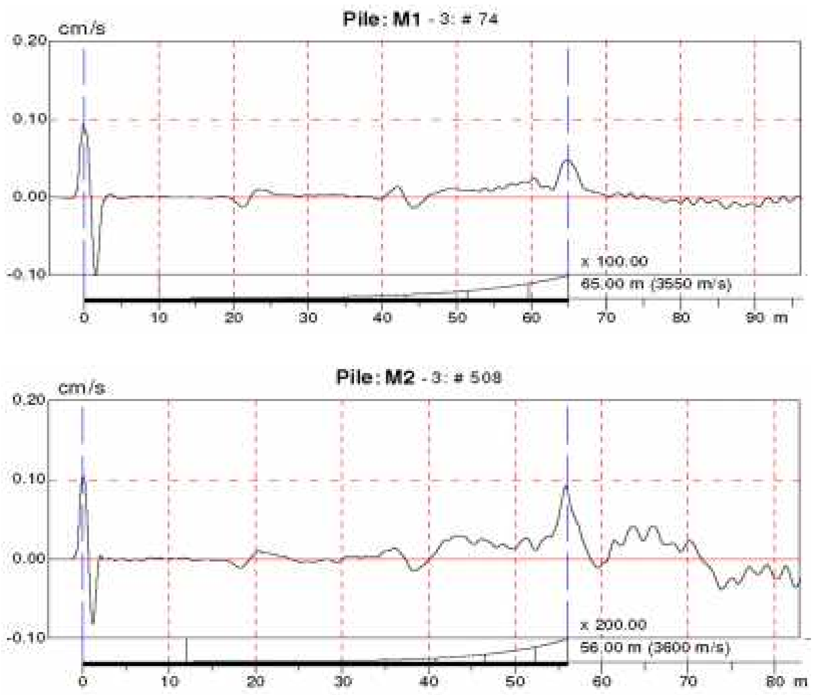

Fig. 13 Typical PIT graphs showing change in impedance with mirror reflections

Figure 14a and 14b shows integrity test graphs from two different piles with improper sensor attachment and improper pile top surface respectively. Such reflections (wavy pattern) are commonly obtained by the inexperienced operators. Also no attempt should be made to conduct the integrity test on a weak or loose concrete surface. Such integrity test data are good for nothing and contain no meaningful information which can be utilized for interpretation and for concluding the pile integrity.

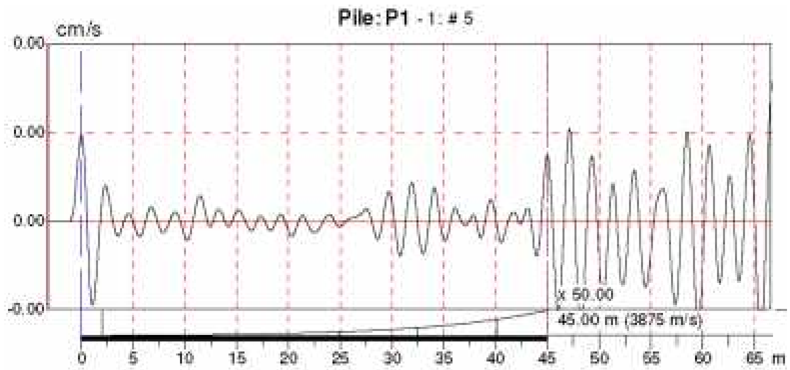

Fig. 14a PIT graph indicating improper sensor attachment

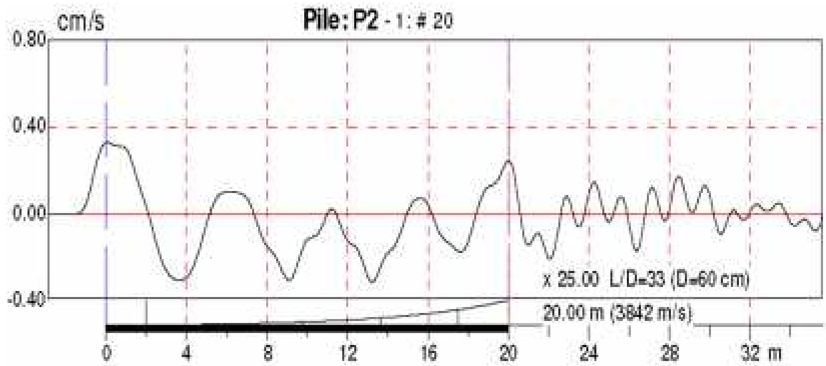

Fig. 14b PIT graph indicating improper pile top surface

5 Acceptance Criteria for Pile Integrity Testing

As per ASTM D 5882, *the low strain impact integrity test evaluation should not be used as the sole factor in establishing pile acceptance or rejection. A contingency plan should be formed that allows the engineer to possibly perform further tests or dictate pile repair or replacement prior to the low strain impact integrity testing, in case a serious defect is indicated*. Hence the test results can generally be placed into the following four categories and each one of them may require a different course of action.

A – Clear toe response. No apparent defect.
B – Clear indication of serious defect. Toe reflection is usually not apparent.
C – Indication of possible defective shaft, although toe response is apparent.
D – Inconclusive data

Category A piles are fairly uniform piles within the accuracy limits of the method. It is generally agreed that a defect that affects less than 20% of the pile cross section cannot be easily detected with certainty (actually this is strength of the method since it does not create questions where only minor problems exist) (G. Likins et al. 2000). In this category pile integrity is satisfactory and unless there is some other reasons to suspect the shafts, they are generally acceptable. Of course, this assumes that the pile length indication is also satisfactory.

Category B piles are somehow defective and doubtful piles and some contingency plan must be used. Extra tests could be made to prove the acceptability of the pile. If the defect is near the ground surface, excavation to expose and repair the defective pile portion is generally possible.

Category C piles may be assigned a reduced capacity. Also other pile tests may be considered or excavate and repair if the defect is located near the ground surface. If the pile is a friction pile and the defect is located far down the pile, the upper soil resistance above the defect may render the force in the pile at the defect as acceptable structurally and the defect may in some cases be not serious.

Category D piles may have poor data due to poor concrete quality at the pile top. Trimming the pile to a lower elevation where good quality concrete is assured and retesting the pile is an alternative. Other reasons for inconclusive data are long or irregular pile shapes (with multiple anomalies) producing complex records. Extra tests or expert advice for data interpretation may help solving the problem.

6 Limitations

The successful application of the technology, however, requires understanding its limitations as well, including operator's familiarity with the system and experience with pile foundations, applications to bored piles or driven cast-in-place piles with potentially multiple or large variation in cross-sections, L/D ratio limits, etc.

In case where there are mechanical joints or full section cracks, the wave cannot usually cross the resulting gap. Therefore only the portion above the gap is really tested.

The evaluation of pile length by integrity test depends not only on soil damping but also on the non-uniformity of the pile; because any change in pile quality or shape produces reflections. The first non-uniformity detected will be more reliably analyzed than additional sources of reflection farther down the shaft. Highly non-uniform piles produce complex records which are difficult to analyze.

Pile integrity test gives no information about load carrying capacity. To confirm pile capacity, a static load test (as per IS: 2911) or a high-strain dynamic load test (as per ASTM D4945) are required to be performed.

7 Summary & Conclusion

Pile Integrity Testing is a quick and therefore inexpensive testing method. However, it requires a good deal of care to get a reliable, high quality test result. Since the late 1990's, low strain integrity testing has gained wide acceptability in India in the foundation engineering and construction community. It has become an important tool for verifying the pile integrity. It is relatively easy and can reasonably be performed on all working piles. It can be successfully used during initial stages of a project to assist engineers and contractors with quality control / quality assurance needs.

The method offers several advantages over other testing methods, including other NDTs, for its rapid deployment, mobility, speed and cost. A large number of piles can be tested in a short time, probably 50 – 60 piles in a day. It is capable of quickly producing information on the possible presence of defects such as voids, breaks, discontinuities, or inclusions, and provides estimates on pile length.

During processing, extreme values of certain parameters (magnification and filters values) may make the trace look good but distort the trace or remove important features. Hence, the analysis and data interpretation process has to be done very carefully. Fully automated data processing is usually not advisable; each step of the data processing procedure should be reviewed as to its effect on the records.

The processed data should be plotted and the records classified. Depending on the data interpretation certain additional actions may be required on the construction site. It is important that such possible actions are clearly established prior to conducting pile integrity test.

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