A Review Low Strain Integrity Testing Practices in India and Complexities involved in Evaluation of Test Results

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ABSTRACT

Low Strain Pile Integrity Testing has been used in India since 1990's and several have tried to demonstrate the utility and benefits of this method. However, use of this technology was limited till 1998 as not enough data maybe was not available to justify its use and application on major infrastructure and real estate projects. The first author has done significant work in this method resulting in its use in practically all sectors of the industry that use concrete bored pile foundations as a supporting element. The paper explains various signal enhancers or modifiers involved in processing of low strain test data and its implication on the final output. It also describes how the method can lead to abuse or can provide poor interpretation if incorrectly used. The current effort is to demonstrate that data collection and evaluation becomes complex with changes in soil stratum and pile profile. The paper highlights the present testing practices and provides a guideline for classification of pile integrity into few simple categories in Indian context rather than writing complex interpretations.

Keywords: Low Strain Integrity Testing, PIT, Pile Foundation, Deep Foundation

1.0 Introduction

Cast in situ place concrete bored piles, also known as drilled concrete shafts are produced by drilling holes of various diameters in the ground and filling with concrete. Compared to driven piles, they may have advantages such as lower vibration and noise. However since direct inspection of the final product is impossible, some doubt always persist regarding the structural integrity of bored concrete piles. Integrity tests, excavated foundations, failed static tests, extracted cores have revealed defects in bored piles on numerous occasions. For this reason, concerned engineers and/or owners require that as part of a standard quality assurance program, low strain pile integrity testing be conducted on all or a certain percentage of the piles at a project site. In some cases, more emphasis is laid on testing of piles with unusual casting records[3].

Various non destructive test methods are available to evaluate the structural integrity of the piles[1]. This includes the Pulse Echo Method, the Frequency response method, Gamma Approach etc. The most commonly used method today in India is the Pulse Echo Method as it is simple and reliable if properly conducted and interpreted.

The Low Strain IntegrityTest (LSIT) method using Pulse Echo technique which is standardized by various versions of ASTM D5882 has seen increased use since early 1990's. The method has found more acceptance in India after 1998 when the first author successfully demonstrated its application on several projects.The recently available IS: 14893-2021[2] also provides significant information on the method, its application, interpretation and limitations.

The Pulse Echo technique which is described in the paper primarily involves impact of a light weight hammer ranging from 0.4kg to 5kg to generate a stress wave that travels from point of impact to the pile bottom and returns back to the top. The travel of this waveform is recorded by an accelerometer. Changes to this wave are observed when there are changes in cross-section, soil resistances, cracks or noise due to rebars. Since there are several parameters that affect the final output, the results are generally interpreted by an Engineer who has good knowledge of wave mechanics coupled with some knowledge of soil and concrete. If for example, there is a decrease in impedance at a certain distance below the pile top, then this is displayed by the stress wave as a velocity change in the same direction as the direction of the impact pulse. The impedance is defined by EA/C where E is the elastic modulus, A is the pile cross section area and C is the wave speed inside concrete. Thus even if an impedance reduction is observed, an ambiguity still remains whether such a reduction is a weaker zone of concrete defined by a reduction in E or a reduction in cross-section defined by A. For simplistic purposes, both constitute a defect as it is a requirement that the pile is homogenous and uniform along the entire cross-section. A bulge is normally not a defect although it is not preferred for initial pile load tests. For pile diameters of 1m and above, it is likely that the defect maybe in one quadrant and thus may not get detected with limited data collection if such data is collected from other quadrant. The paper describes basics of testing equipment, data collection and the features inside the software that may have a bearing on the final output. The paper also provides a classification that can be used for pile acceptance/rejection.

2.0 Testing Equipment

There are various manufacturers of equipments used worldwide for Low Strain Pile Integrity Testing. Three devices are needed for performing of low strain integrity test, Accelerometer, Hammer (with or without force Sensor) and Processor (PIT Equipment) as shown in Figure 1. Various sizes and weights of hammers varying between 0.4kg to 5.0kg are used based on the depth and the diameter of the pile. Smaller hammers have less energy and higher frequencies whereas larger hammers apply greater energies and lower frequency to the pile top[3]. Note that a smaller hammer may detect defects near the top and a heavier hammer may miss defects near the top but will more clearly identify defects near the bottom of the pile. However, due to uncertainty in the actual length and wave speed, irrespective of the hammer weight, the low strain method in general will not detect defects in the bottom 5-10% of the pile especially for long length predominantly friction piles. The method may however in some cases identify weaker pile bottom condition for rock socketed piles even though the length evaluation remains uncertain.

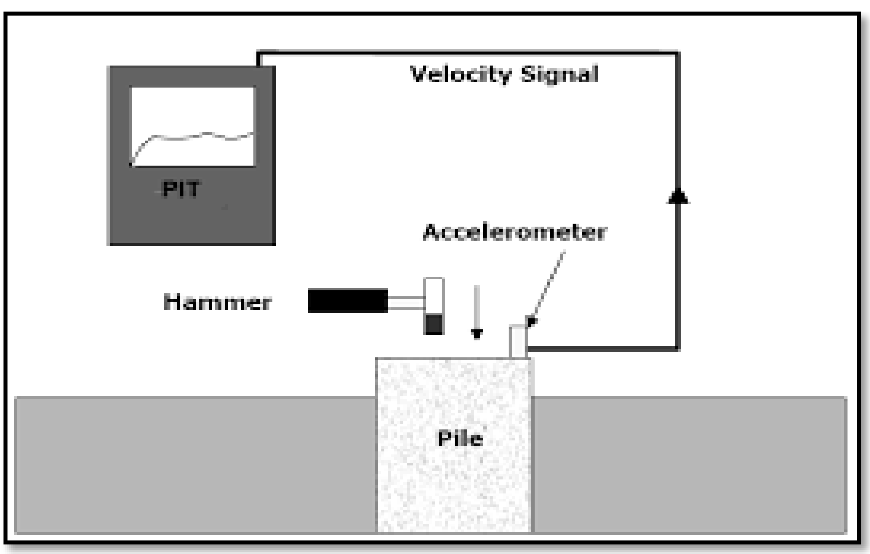


Figure 1 Schematic Diagram of Low Strain Integrity Testing

3.0 Data Acquisition and Evaluation

One of the foremost requirements for good evaluation is proper data collection. The first basic requirement is that the pile top should have sound concrete free from any weak material, laitance, soil or mud etc. There should not be any micro cracks on the pile top that may affect the results. The pile top should be easily accessible, reasonably flat and the reinforcement either bent outside or in such a position as to allow the tester to fix the accelerometer and provide impacts without any hindrance. Grinding in several cases creates micro cracks and hence a reasonably uniform surface without grinding is acceptable. A compromise in any of these requirements may result in improper data collection and subsequently poor interpretation.

The testing can be done once concrete achieves 75% strength (ASTM D5882). Early testing may result in lower wave speed and create doubts on concrete quality. It is important that the tester is aware of the pile type, diameter, length, soil stratum etc. before proceeding for testing. This will ensure that there are no unknowns during data collection or interpretation. The testing can be started by attaching an accelerometer or motion sensor with the Petro Wax or any bonding material on the top of pile and collect data with several blows to the top of the pile[6]. The position of the accelerometer should be such that it is away from the rebars and it is also preferably near the centre of the pile. For larger diameter piles, additional locations for every 500mm diameter of pile should be attempted. Since this is a qualitative process, it is important that several blows are collected and averaged so as to remove uncertainties or human error during the process. In general, it is expected that the tester is aware that improper blows with nonlinear impacts should be rejected during such process. An average of 3 to 6 blows which constitutes one data set and multiple such datasets are generally recommended for a single pile. It is important that the tester continue to collect the data until proper interpretative records are collected. Having adequate data sets will ensure sufficient data for the expert to review and make a correct recommendation.

Figure 2 LSIT Data Collection in Progress

Figure 2 shows data collection of Low Strain Integrity Testing on reinforced concrete bored cast in situ pile. The hammer should preferably be close to the accelerometer sensor although the ASTM D5882 allows a distance upto 300mm between the sensor and the hammer. Thus proper position of the hammer, accelerometer, nos. of data sets, and surface preparation all plays a very important role in the data collection process.

For data processing and interpretation several signal enhancers or modifiers are provided in the software. The paper describes the data processing using PIT-W software although other software and allied equipment providers also have similar features as these are generally a standard requirement of ASTMD5882. The modifiers most commonly used are wavespeed(WS), Magnification(MA), Magnification Delay(MD), Low Pass Filter(LO), High Pass Filter(HI), Pivot(PV) & Wavelet(WL). Each parameter has different use and different purpose however their basic purpose is to generate a final output that best represents the quality of pile. Figure 3 shows the example of good pile that has a first peak indicating start of the pile and second peak at 10.65m indicating termination of the pile (i.e. change in medium or material property). A clear toe response is evident at 10.65m and the computed wave speed is 3600m/sec for this length of the pile which is an input inside the software. Apparently the pile has no major anomalies and can be classified as good pile. Generally in the Indian scenario a wave speed of 3500m/sec and 4200m/sec can be expected although this will also depend on density, percentage reinforcement, quality control at site, grade of concrete etc. This variation in wave speed can be in much closer range based on site specific quality control.

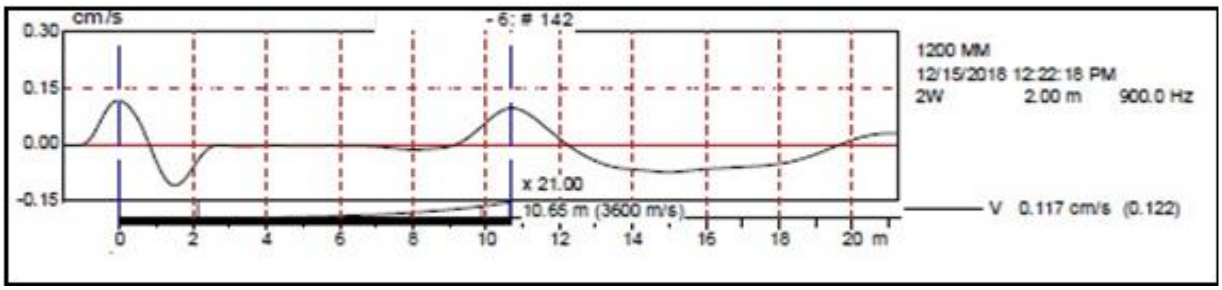


Figure 3 Typical LSIT record after Interpretation

4.0 Low Strain Testing Software Features and Interpretation

4.1 Use of Magnification (MA) & Magnification Delay(MD)

The impact of the hammer should always be such that the wave has sufficient energy to reach the bottom of the pile and reflect back to the top. However, absorption of energy due to soil resistance, pile non-uniformities and/or pile material damping reduce clear reflections as the wave propagates along the pile length. This reduction is more rapid towards the end of the pile where the soil is more stiff. As a compensation for this signal reduction, a Magnification factor(MA), exponentially increasing with time is applied to the record which helps identify and measure reflections from the lower pile portion and near the pile bottom. To prevent record distortions and misuse, the magnification shall start from approximately 20% of the pile length and exponentially increase with time. The starting time of MA is known as magnification delay (MD). The MD should generally always be a default value of 20% and under no circumstances MD should exceed 50% of pile length. An exception maybe allowed only when the pile has a large free standing length more than 50% of its total length The MA should be chosen such that its value is atleast equal to the length of the pile or a multiple of the pile length. Magnification greater than 100 is not recommended. Also for piles of different lengths at the same site, the MA should be chosen such that they produce the same multipliers at the same depths. In certain cases for more understanding of an individual pile the MA can be a value such thatthe magnitude of reflections from the pile bottom is approximately equal to the input pulse [5].

Figure 4 shows integrity record for a pile which shows a faint toe response when MD is 20% of the pile length but the MA is only 10 which is less than 50% of the pile length of 23m. Although the pile does not show any defect, a toe response identified by +/- cycle along x-axis is not clearly visible. However, refer to Figure 5, the same pile is now amplified with MA equal to 46 which is twice the pile length. The record now shows a clear response from the pile bottom. In this case too, the MD is 20% of the pile length which is a standard practice. Hence MA and MD applied should be such that clear interpretation is possible.

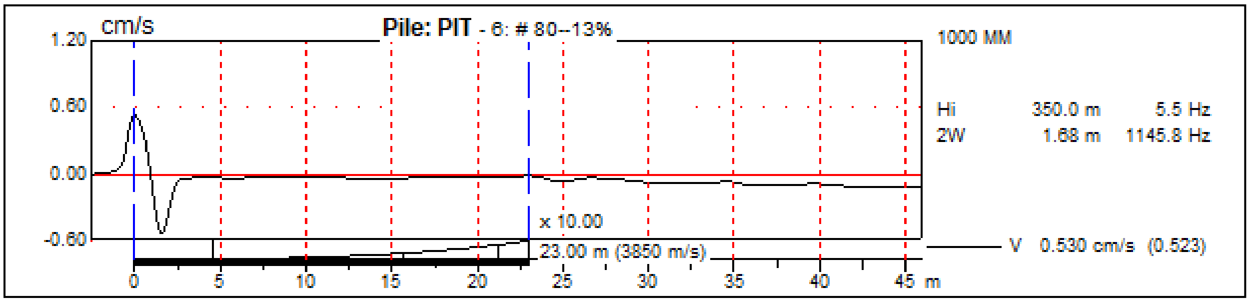


Figure 4 LSIT data shows MA< L

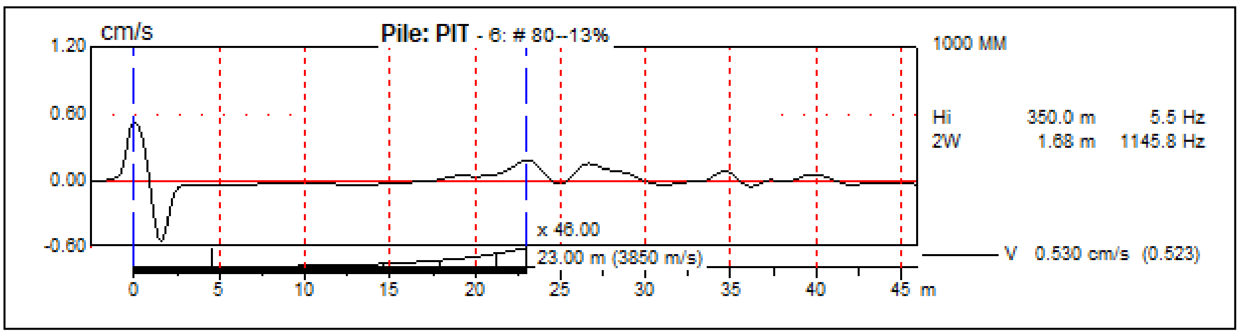


Figure 5 LSIT data shows MA= 2*Length of Pile.

Just as a proper MA only can clearly identify toe response as explained above, an improper use or abuse of magnification delay (MD) may result in making a defect within the pile. Figure 6 shows a data which looks uniform pile with a clear toe response. However a look at the scale below the graph shows that the MA is applied only from 15m, implying MD is about 90% instead of a default value of 20%. Refer to Figure 7 which now corrects this improper use of MD. The data with the proper MD now shows a clear defect at 7.5m. Thus using correct signal modifier is an important requirement before proper interpretation.

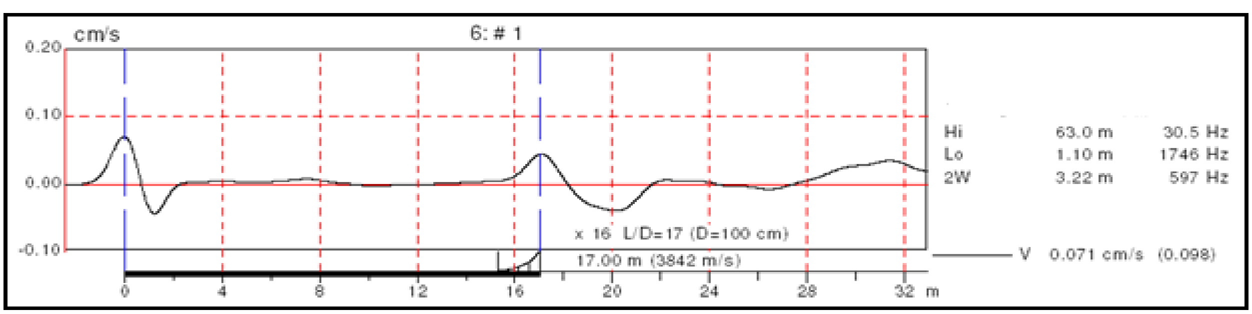


Figure 6 LSIT data showing MD = 90% of L and MA < L

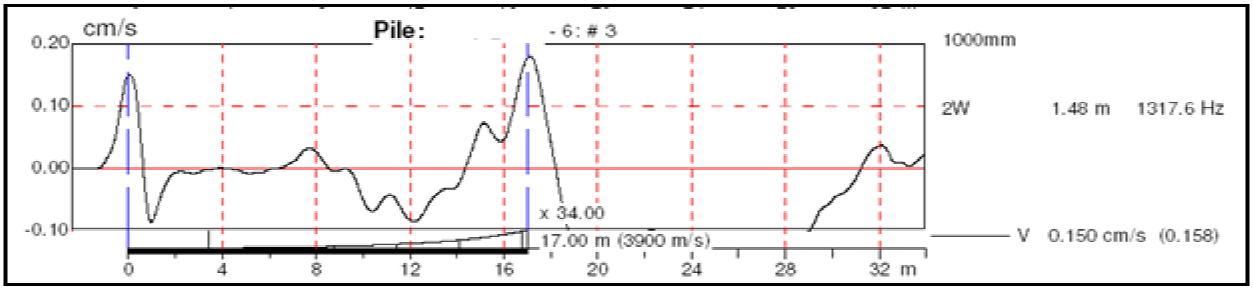


Figure 7 LSIT data shows MA= 2*L and MD =20% of L

4.2 Use of Hi Pass Filter (HI)

HI helps remove slowly changing record portions usually caused by soil resistance or removes the low frequency component from the record. Typical values of Hi Pass filter should be zero where it is not required to be used or can be 15-20 times the input pulse width for longer piles and maybe even more for shorter length of piles. The value should be such that the velocity curve co-insides with the x-axis as much possible. A very low value between 0 and 30.5m will distort the graphical record.

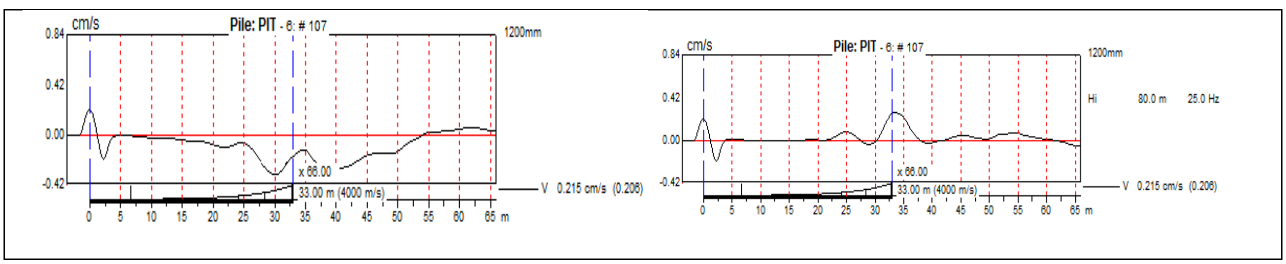


Figure 8 LSIT Graphs without and with HI Pass Filter (HI = 80)

Figure 8 represents such a case study with zero value of HI Pass filter and a corrected response with a value of HI = 80 which is more than 20 times the pulse width. Once a proper value is input, the pile shows clear defect which otherwise was not evident with an incorrect or "zero" value. The HI can be any value of zero or 30.5 or more and no specific basis can be assigned to it as along as the basic curve is corrected to co-inside with the x-axis. Thus the experience of the tester will play a very vital role in selecting the correct value based on the soil resistance offered to the travel of the waveform along the pile length.

4.3 Testing of micro piles or piles with Reinforcement closely spaced.

Micro piles are commonly installed in Mumbai for load bearing as well as shoring wall applications. These bored micro piles are typically 273mm in diameter with an outer casing and having 4-8 number of 25mm rebars or equivalent and filled with concrete. Permanent casing is provided in most cases upto starting of weathered rock or stiff soil. The lengths of these piles are typically from 8m to 15m. This implies an L/d ratio from 30 to 55 with closely spaced rebars.

Figure 9 Picture of Closely Spaced Micro Piles

Figure 9 shows a picture of a project site with closely spaced bored micro piles and rebars projecting for significant height above cutoff level. It is a challenge to evaluate integrity for such small diameter piles where the diameter is small, percentage reinforcement is high, piles are closely spaced and rebar extending for longer depths above concrete. The first difficultly is to find space to place a accelerometer and top surface for hitting the pile with the hammer. Another problem is that the wave reflecting from the pile concrete gets super-imposed with reflections from rebars creating a ringing effect or a distorted wave. The software does provide filters commonly known as Wavelet or LO PASS to remove high frequency component or ringing effect of the rebar to make it appear smooth. LO PASS is generally not recommended in current practice. Also WL can be generally a value not more than 4m in most cases l. Excessive use of WL may only distort data and not provide conclusive findings. Figure 10 shows data on such a micro bored pile. As evident, the waveform does not provide any conclusive findings on the pile integrity inspite of using WL as 3. The first author has evaluated several hundred data sets and most of them provided similar results. Thus testing of small diameter micro bored piles will in general not provide conclusive findings on pile integrity and instead high strain dynamic load tests on 5% of the piles should be considered to confirm integrity and pile capacity.

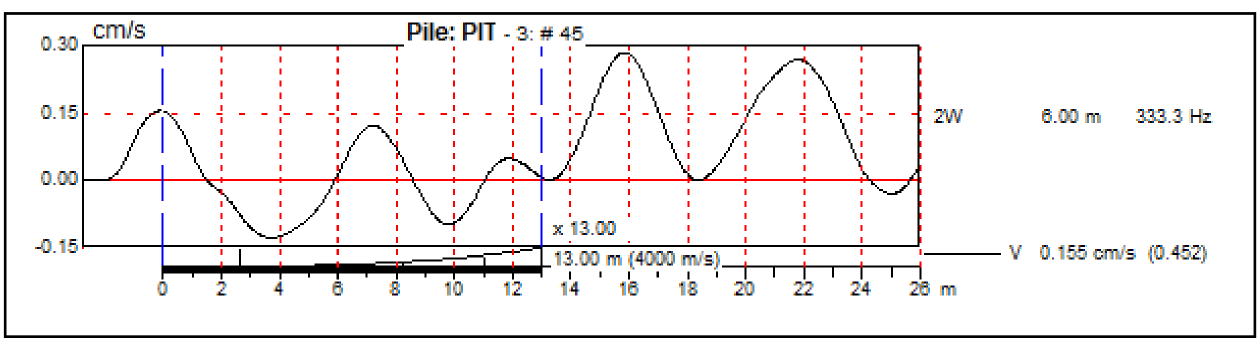


Figure 10 LSIT on Micro Piles

4.4 Incorrect Data Collection / Interpretation or Abuse of Data

Another case study shows a graph in Figure 11 which is basically a sinusoidal curve with no apparent input peak and a clear output peak but was reported as having no integrity problems. The data shows that amplification was only 4.4 for a length of 9.7m. The filter applied is not clear and apparently 42 blows seem to be averaged. The data was referred to the authors and since there was no clear graph, a re-test was recommended. The re-test done by the authors now clearly show a defect at 7m with proper data collection and processing as shown in Figure 12.

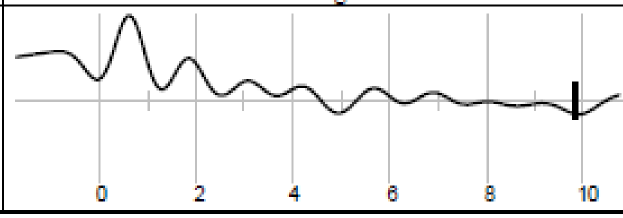
Pile	Details	Reflectogram	Remarks
P/79	11/06/2019 C:3950 Amp:4.4 F:4 9.7 Avg:42		No Integrity Problem.

Figure 11 Incorrect LSIT Data and Interpretation

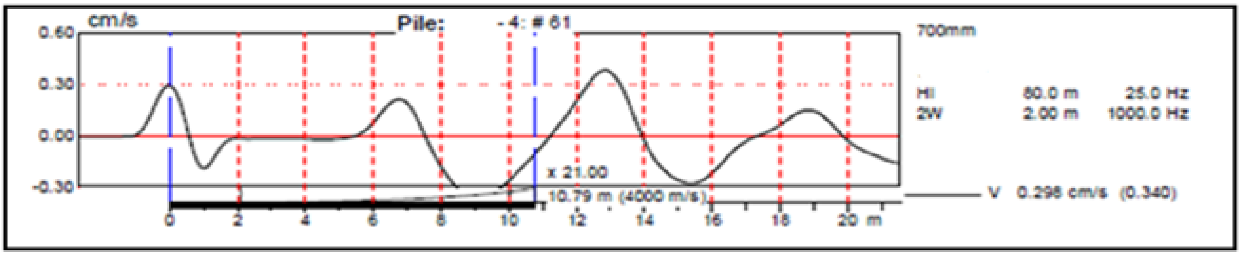


Figure 12 Proper Data Collection with a Re-test

To further verify the findings of low strain testing, a high strain dynamic testing was also conducted on the same pile. Figure 13 presents the results of such a test. As evident, the pile shows a significantly high a settlement of 26.5mm and a major impedance reduction at pile bottom to the extent of 73%. This shows the risks associated by employing testers who are not competent to conduct or interpret test data due to poor knowledge. The case study also highlights that mere acceptance of the pile in the test report has no relevance unless it is backed by proper data collection and processing.

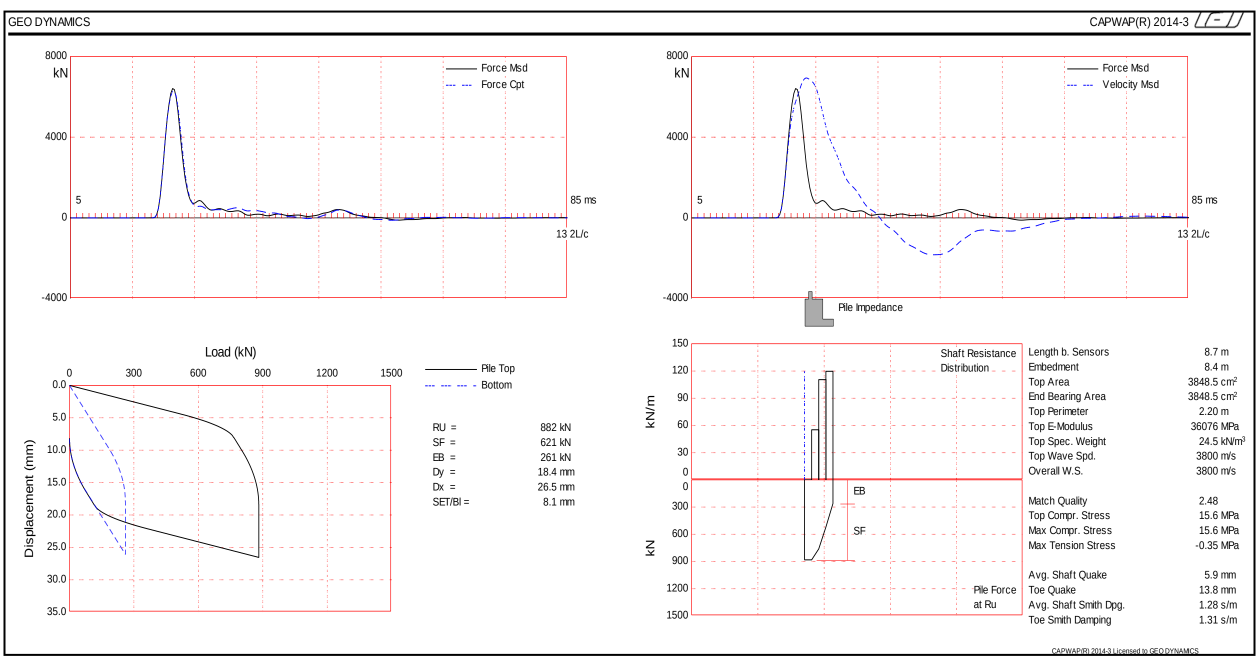


Figure 13 HSDPT confirms defect as seen in LSIT

Hence, it is important for the end user to not only merely believe the conclusions written in the table, but also understand and read the graph. A catastrophe may occur or structural safety maybe compromised, if several defective piles in a pile group or in a project are certified as acceptable by inexperienced or pliant testers

The first author has reviewed several testing reports provided by various testers in India and wide discrepancies in comments were observed. This also leads to further confusions in language, interpretations, end purpose etc. and in several cases does not serve the intended purpose of the test report. That the low strain integrity test is a basic tool is well known and trying to make a herculean effort or to read too many things from the graph only leads to more confusion. Thus in the opinion of the author, the conclusions can be provided in the following categories after mentioning the limitations of the test.

Table 1 Low Strain Integrity Testing Categories as per Toe Response[4]

Category A	Piles those are acceptable with a clear toe response (response from pile bottom).
Category B	Piles that show clear Indication of serious defect (Impedance reduction) and toe response isnot apparent. Such piles maybe subject to further investigation or maybe underrated, rejected based on site specific experience, design requirements etc.
Category C	Clear Indication of small defect but toe response is apparent. If more than 15% of the piles at a project are in this category, further investigation in the form of static/high strain dynamic load testing is recommended to identify the reason and then take suitable action based on the findings of such results.
Category D	Inconclusive piles. Very high soil resistance or bulges may absorb most of the hammer energy impact and thus a clear toe response may not be evident. Such piles are termed as inconclusive. A decision on such piles can be taken on the basis of construction records, overall findings at the project site, criticality of the structure above it, load on the pile etc. A load test may be considered in certain cases before acceptance. If more than 10% of the piles at a project site are inconclusive, then it may warrant a detailed investigation on the reasons for such a conclusion before acceptance of such piles.

5.0 Conclusion

1. The use of signal enhancers or modifiers in the examples demonstrated in the paper show that, even if data collection was reasonably good, there are several signal modifiers which need to be used to produce a LSIT record that best defines the pile health. The discretion to choose a particular signal modifier and its value has to be left to the user as the use may depend on the type of soil, projecting rebars, location of testing within the pile etc. Thus the LSIT needs expertise, experience before a judgment is made on pile integrity.

2. Several signal modifiers are required for processing implies it is a bit of state of art. There is subjectivity in the final output and thus a standardization of the output is generally not possible as even on the same pile no two blows will be exactly the same but will only be similar. Location of accelerometer on the top of the pile and variability in hammer impact, weight of hammer is also one of the reason for the signals not being exactly the same even when repeated with the same tester. However, the results will still be very similar if the test is properly done and significant variability between different testers is not expected. This implies final interpretation is still expected to remain the same or similar even considering variability in data collection and processing.

3. Abuse of the method as explained in Para 4.4 is easily possible by testers who are either inexperienced or who are forced to produce reports to merely satisfy project requirements rather than a genuine feedback on the quality of the pile. If majority of the piles at a project are bad, then mis-interpretation or poor interpretation can lead to a potential catastrophe. However, a proper test is expected to reveal significant information on pile integrity which otherwise is unknown.

4. The method is not applicable to bored concrete micro piles as noise from closely spaced rebars interferes with the reflections from concrete. Hence, if there is a genuine requirement to assess micro piles, limited piles be tested first and only if proper output with a toe response is available, then testing be continued. High Strain Dynamic testing on upto 5% of the piles should be considered instead of low strain integrity testing for micro piles.

5. It is strongly recommended that the Contractor, Engineer and the Owners all select an experienced tester with adequate knowledge. It is essential that all the stakeholders or the reviewer of the report studies the graphs and its findings in detail before the piles are finally accepted or rejected on the basis of the low strain findings.

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