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Recent advances and proper use of PDI low strain pile integrity testing

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ABSTRACT: Low strain Pile Integrity Testing (PIT) is a valuable tool to locate major defects in drilled shafts or concrete piles. It has demonstrated its worth in detecting defective piles when other methods are not practical. It requires no advance planning or access tubes so can be applied to any concrete pile after installation. Since the testing is quick and simple, the cost per test is quite reasonable. However, proper application and interpretation are essential to obtain reliable results. The advent of digital processing has opened up a wide variety of possibilities for enhancing the information contained in the data. Many of these procedures will be discussed and examples shown depicting their application. Certain rules of processing are presented and should be followed to assure good interpretation.

INTRODUCTION

Structural engineers are often faced with the question of pile integrity. Difficulties during installation, excavation procedures, slope failures or lateral movements due to accidental impact can create doubt about the integrity of any pile. In some cases, doubt also arises due to lack of information about existing piles when a new use or increased design loads are required. In some cases lack of inspection on current installations leads the structural or geotechnical engineer to question the foundation adequacy.

If access tubes have not been installed in the questioned piles (required preplanning and extra cost) to allow for Cross Hole Sonic (CSL) testing, then the costs for evaluation can quickly become large. Static loading for every pile is obviously prohibitively expensive. Coring every pile is likewise not feasible, and even if it were it would only provide a small sample that could easily miss a local defect at some depth. Therefore, the only practical alternative is often PIT. Since PIT is simple and low cost, it is conceivable to inspect every pile on a site if required. Often a statistical sample is made and if no problems are found, then testing may end. If defective piles are located, then additional tests of neighboring piles are then justified. The selection of which piles to test can be based on various observations, or made considering redundancy of the pile, or at random

TESTING PRACTICE

The pulse echo method (Rausche et al 1992) uses a hand held hammer to impact the pile top and generate a compressive stress wave in the pile. Figure 1 shows a Pile Integrity Tester (PIT) for pulse echo testing. The small battery powered main unit is highly portable from pile to pile and extremely rugged. It uses a touch screen for input rather than a computer keyboard. Experience has proven this to be a highly reliable method and extremely user friendly. The screen displays intuitive menus to guide the user and shows the graphical signals for field interpretation. Stress wave inputs and reflections (from non-uniformities or the pile toe) are measured as a function of time by an accelerometer attached to the pile top. The acceleration is integrated to velocity by PIT, and then interpreted by the test engineer.

The pile top surface is prepared by removing the upper concrete if it has been contaminated with soil, bentonite slurry or other foreign materials during construction, and finding or making a smooth location when a driven pile top may have been rough cut. An accelerometer is then attached to the smooth pile top surface as shown in Figure 1 with a thin layer of a soft paste like vaseline, petro wax, etc. Accelerations from several hammer blows are normalized, integrated, averaged and displayed as velocities. Further data processing includes

Figure 1. Pile Integrity Tester (PIT) with hammer and accelerometer for the application of the pulse echo method.

application of an exponentially increasing magnification function. The magnification restores reflection details which are diminished by soil resistance, pile material damping or pile non-uniformities.

To demonstrate the usefulness of PIT in distinguishing a good pile from a defective one, Figure 2 shows an example output with an exponential magnification increasing from zero at the left or pile top to a maximum multiplier (40 times in this example) at the expected time of reflection from the pile bottom on the right; the pile length is 25 meters (82 ft), and the stress wave velocity is 4150 m/s (13,610 ft/s) in this example. The bottom plot shows a clear signal from the pile bottom together with a steady velocity signal between the time of impact and pile bottom reflection, indicating a good pile shaft. The upper plot for another pile on the same site shows a pronounced velocity increase at about 16 m (52.5 ft) which indicates a reduction in pile cross section or concrete quality. In general, relatively sharply defined reflections are attributed to impedance changes, while slowly changing reflections are usually caused by soil resistance. If the effect of soil resistance is known from reference piles, then unusual shafts can be identified. This method can be applied to almost any shaft.

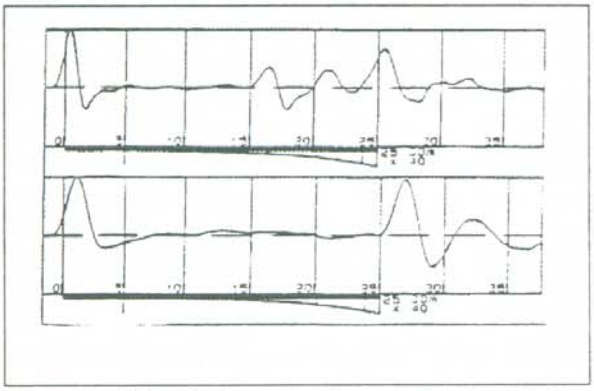

Figure 2: PIT velocity vs depth records of a deficient pile (top) and normal pile (bottom).

DATA ENHANCEMENT AND ANALYSIS

How do we obtain a clear graph such as the one in Figure 2? The actual raw data for the defective pile is shown in Figure 3.

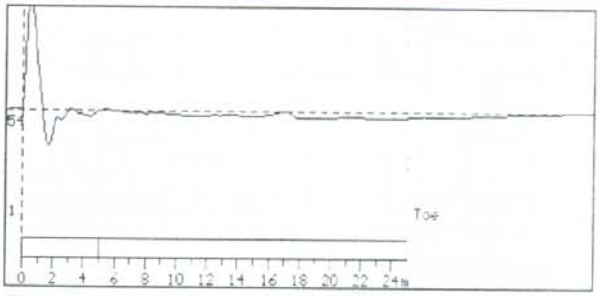

Figure 3: "Raw data" from a PIT test

Interpretation would be difficult at best since the soil resistance has greatly dampened the reflecting signals. The standard method to compensate for the soil damping is to apply a magnification function that begins shortly after the input pulse with a value of unity and increases exponentially to some factor (40 in this example) at the pile bottom. The amplification function should be shown graphically. The result of the application of this exponential magnification function is shown in Figure 4. In this case the curve also gradually wanders from the zero axis and in part resembles the magnification function.

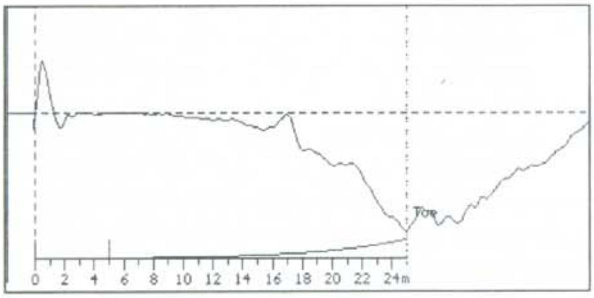

Figure 4: With only magnification

Slow changes are difficult to interpret. Generally they are the result of soil resistance effects. However, the real goal for integrity testing is to evaluate structural pile integrity so soil resistance is not important. Therefore, a high pass filter (HPF) is applied which removes low frequency events usually caused by soil resistance. In the case of the extreme example in Figure 4 (most data is generally near zero even after magnification), the data is subjected to high pass filtering which removes components with less than a defined filter frequency. In general, care must be taken to not apply HPF with too high a filter frequency which could eliminate the frequencies of interest. The most important frequency components are those that make up the input pulse and the reflections from changes of pile properties. Reflections from defects or the pile bottom should have frequencies which are similar to that of the forcing input function.

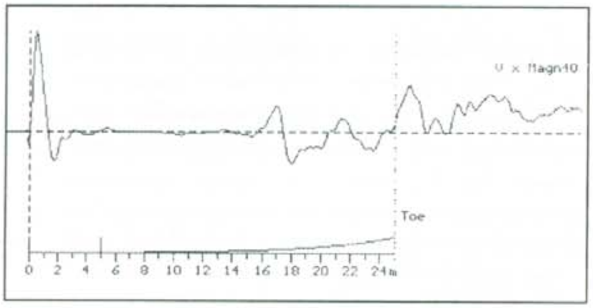

Figure 5: With 40 magnification and 25 high pass filter

The results shown in Figure 5 were further improved to the top curve in Figure 2 by use of the wavelet analysis, although in this case the improvement is slight. The wavelet analysis (Rioul 1991, Seidel 2000) is a specialized filter that effectively strengthens the signal frequency components that match the input pulse and removes undesirable frequency components resulting from noise

To more clearly demonstrate the effectiveness of wavelet analysis, consider the record in Figure 6 which includes significant high frequency "noise" components in the data caused by perhaps by the vibration of reinforcement bars protruding from the pile top cracked pile top concrete or other surface effects. Since the "noise" frequency is much higher than the input frequency, if we select a wavelet mother function with similar frequency content to the input pulse, unwanted frequency content will be suppressed as shown by the wavelet filtered Figure 7 which is much more easily interpreted.

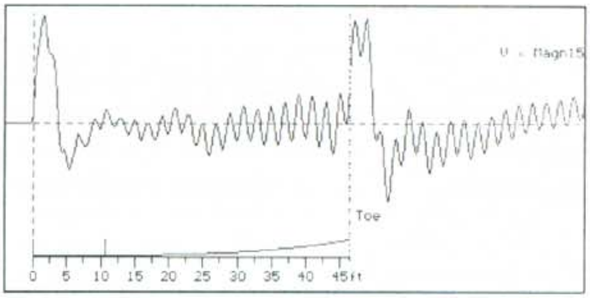

Figure 6: PIT record with significant "noise"

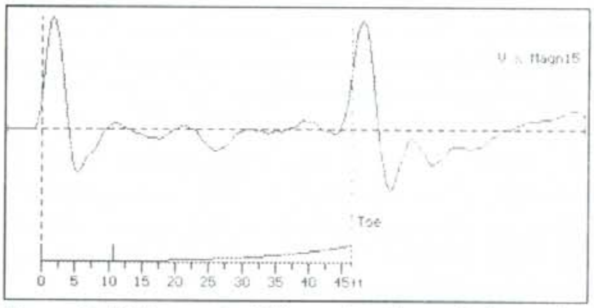

Figure 7: PIT record of Figure 6 with applied wavelet filter

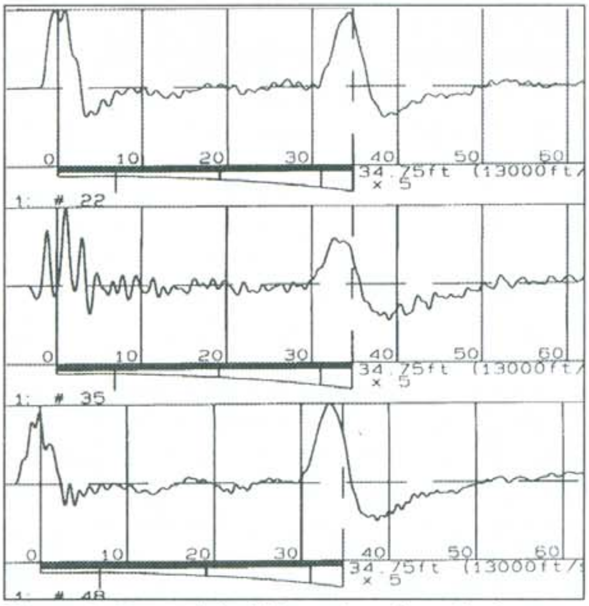

Figure 8: Data with different locations for hammer impact and accelerometer.

Another consideration in PIT is the location of the accelerometer and the applied hammer impact. The three records shown in Figure 8 have different characteristics.

The top curve has the hammer input applied at the pile center while the accelerometer is attached at the edge. The middle curve has the same accelerometer location but the force is applied at the extreme opposite pile edge; obviously this configuration is less desirable. In the bottom graph, the hammer

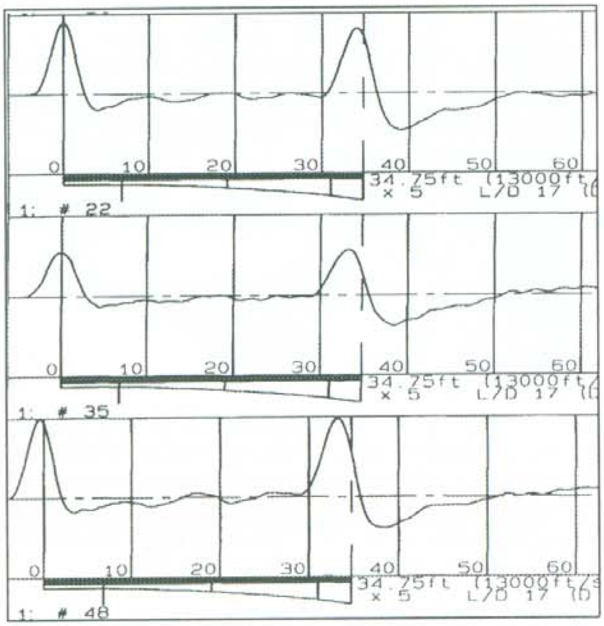

Figure 9: Same data as Figure 8 but with Wavelet processing

input and accelerometer locations are at the 1/4 and 3/4 points of a major diagonal. The only signal processing in Figure 8 is a five times magnification. The data can be further improved by wavelet filters as shown in Figure 9. Even the originally poor input data is now easily evaluated. However, caution is advised for cases where the defects near the pile top produce a record as shown in the middle of Figure 8.

Data quality is not the only consideration for location of accelerometer and hammer impact. For large shafts, the ratio of hammer to shaft diameter becomes very small. Example 10 shows four records for an 800 mm (32 inch) diameter drilled shaft. In all cases the accelerometer was attached to the pile center location. The hammer impact location was varied around the pile at the four compass directions (specifically North, South, West, and East, respectively). It is relatively clear that there is a local defect near the pile top in the NW quadrant.

Figure 10: Accelerometer at center of 800 mm pile; hammer impact applied at N, S, W and E locations

For piles installed in a soil bearing layer the toe reflection is almost always tension because the soil stiffness is less than the pile stiffness. Tension reflections are observed in PIT data as a velocity reflection at the toe with the same sign as the impact signal. In all example cases presented in this paper the pile toe produced such a tension reflections. The question often arises as to what magnification factor to apply. In general one should try to make the strongest reflection as high as the impact signal.

For similar piles in similar soils on the same site, it is logical that the signals obtained by PIT should be processed with similar parameters and result in similar curves. It is relatively simple to identify piles with unusual records and thus properties. However, what if the piles are different? For example, the results of tests on two piles installed in similar soil conditions on the same site but with different lengths are shown in Figure 11.

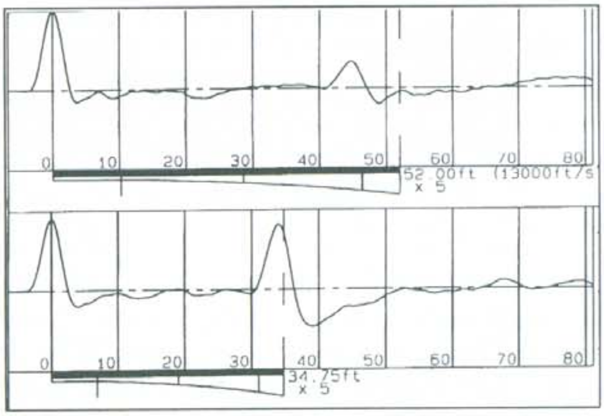

Figure11: PIT records for two piles of different lengths

The toe reflection for the shorter pile is the same amplitude as the input using a magnification factor of 5. However, the longer pile has a smaller reflection using the same magnification. This is logical due to the effect of extra soil damping on the longer pile. The binary magnification factors (2, 4, 8, 16, 32..) are shown as the vertical markers inside the graphical representation of the magnification curve. For the shorter pile in Figure 11 with magnification at the pile toe, a magnification of 4 is at about 31 ft depth. However, for the longer pile, at 31 ft the magnification factor is only about 2.5 while the factor 4 is only achieved at a depth of 47 ft. Thus the use of similar magnification factors for different length piles does not result in "consistent" magnification functions.

In Figure 12 a magnification of 15 has been applied to the longer pile resulting in a factor of 4 at about 31 ft so this then is a consistent magnification as a function of depth. The toe response is now of similar amplitude for both piles even though the lengths are different. It appears that the longer pile is only about 13.7 m (45 ft) long rather than the planned 15.8 m (52 ft). While there is some uncertainty (up to 10%) in the wave speed of concrete for the same concrete supplier, the same wave speed is usually used for all piles at one site to plot the records. If the toe reflection occurs at a time that indicates more than a 10% variation of wave speed, the pile length is questioned. In this case, the length of the shorter pile matches well the toe signal with the normally assumed wave speed of 3,960 m/s (13,000 ft/s). For the longer pile the wave speed would have to be 4,580 m/s (15,000 ft/s) to match the toe signal with a pile length of 15.8 m (52 ft). Since this wave speed exceeds the average one by more than 10% it would be concluded that the pile was indeed too short.

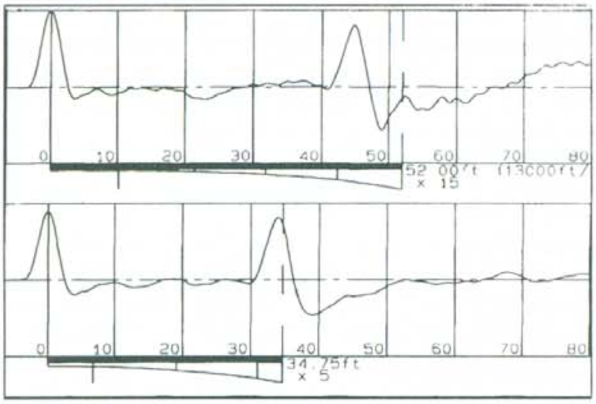

Figure 12: Pit records with consistent magnification for different length piles

There are further processing options for data. Data can be analyzed in the frequency domain for mobility and dynamic stiffness. However, determination of length or shape is better made in the time domain as presented in the examples in this paper since the magnification function can only be used in the time domain. Lack of a magnification severely limits the effective length that can be analyzed in the frequency domain. Further, if something is clear in the frequency domain, then it is even more apparent when presented in the standard time record. The major advantage for the frequency analysis in our opinion is to obtain a quantification of shaft quality by calculating the relative pile stiffness (piles with lower stiffness are more likely to be defective.)

One other tool associated with PIT is to obtain an impedance profile. This makes a shape visualization as in Figure 13. However, experience has shown that this is not often required and piles can be classified without this extra effort for most piles.

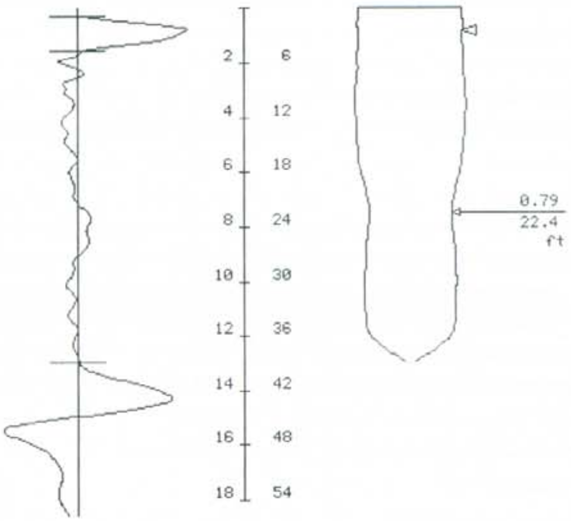

Figure 13: Processed signal and calculated profile

RECORD CLASSIFICATION

Before embarking on any type of pile integrity test, there should be a clear understanding among all parties involved as to the consequences of the test and the action to be taken if the test generates a question in the integrity of the foundation. The test results can generally be placed into the following 4 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 good piles within the accuracy limits of the method. For example, a it is generally agreed that a defect that affects less than 20% of the pile cross section cannot be detected with certainty (actually this a strength of the method since it does not create questions where only minor problems exist.) In this category pile integrity is satisfactory and unless there is some other reason to suspect the shafts, they are generally acceptable. Of course, this assumes that also the pile length indication is satisfactory.

Category B piles are somehow defective and some contingency plan must be used. Extra tests could be made. If the defect is near the ground surface, excavation to expose and repair the defective pile portion is generally possible. The shaft could also be cored and the defective are pressure grouted, a subsequent PIT could confirm the effectiveness of any repair measure. The pile could be abandoned and simply replaced. The course of action may depend on the cost of a new pile versus the cost to repair.

Category C piles may also be assigned a reduced capacity. Also, other pile tests may be considered, or excavation 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 results such as a long or irregular pile are discussed in the next section. It is reasonable to accept a certain percentage of piles with inconclusive records at a site where soil and pile conditions produce complex records.

LIMITATIONS

PIT is a very useful test for many situations. In some cases it is the only practical alternative to doing nothing which may not be acceptable where questions arise during construction. It is certainly a simple and relatively inexpensive test and thus is widely used. It is intended to locate major defects and to that purpose it generally is adequate. It is a strength of the method that it does not generate concern where there are localized defects of small extent.

The method works particularly well on solid pile cross sections, such as concrete or timber piles. It has only limited applicability to steel piles. Of course, concrete filled pipes can be tested.

In cases 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.

Defects which are very short compared with the input pulse width and do not cover the entire section can be misleading due to superposition of the waves generated by both initial reduction and following increase. A similar problem exists for gradual changes which create relatively slow changes in the record. Normal processing of PIT data then removes the reflections from gradual changes since they are similar in frequency content as the soil resistance effects. Therefore if a pile gradually increases and then quickly returns to the nominal cross section as it enters a new strong soil layer, the sudden reduction may produce a record that indicates a defect. It is, therefore, important to compare any PIT result with the general soil profile to assess the likelihood of these situations.

There is a general rule of thumb that the test effectiveness is limited to piles with lengths less than 30 times their diameter (L/D ratio). This is really applicable to the length embedded in soil since there is little signal degradation for shafts acting as columns in water until below the mudline. In some cases it might not be possible to "see" even this far down the pile. However, with recent improvements in electronics including lower noise and higher precision 16 bit sampling (which gives 8 times more resolution to older 12 bit samplers), PIT now regularly tests piles with L/D ratios far in excess of 30.

The pile length effectively investigated by PIT 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. In such cases the records collected under comparable circumstances can be compared. Records that differ significantly from the "normal signature" should be further investigated.

PIT gives no information about load carrying capacity. To confirm capacity a static loaad test or a dynamic pile test are required (Hussein 1996, Likins 2000a).

OTHER APPLICATIONS, SOLUTIONS

PIT is essentially an after-the-fact test. The pile must be already installed and the concrete hardened. If a major defect is present in the pile, it can be detected, but the consequences and costs of repair are relatively high and it is obviously better to avoid any defects. An installation monitor for Continuous-Flight-Auger Piles also called Auger-Cast Piles is an instrument that inspects the pile during installation when correction of the defect is both simple and relatively inexpensive (Likins 2000b). Even with such installation monitors, the need for PIT remains, for example, when problems occur after the installation such as lateral impacts, slope failures, or often merely the need to evaluate existing piles.

Piles have also been often successfully tested after they had already been put to service under a structure (Hussein et al., 1992). However, the more complex the structure-foundation system the more difficult will be the data interpretation. For example, it is possible to tests piles located below a pile cap, but the bottom of the pile cap will produce a major reflection. This is acceptable if the pile below the cap is uniform and of reasonable L/D ratio. Testing on a pile below a structure will produce waves that travel up in the structure as well as down the pile. To clearly separate reflections of pile from those of the structure it is often necessary to install two accelerometers on the side of the exposed pile at two different levels.

CONCLUSIONS

Modern digital electronics and signal processing techniques have made it possible to build equipment and develop analysis methods that extend the natural limits of the simple Pulse Echo Method. Although the PIT equipment meets all the demands that can be put on a modern equipment, successful testing still requires experience both during the test process itself and when analyzing the data.

The field engineer has to make sure that clear records are obtained by avoiding the test on contaminated pile top concrete and by assuring meaningful records where the pile top is large relative to the hammer size. In many instances it is helpful to vary hammer size and impact and measurement location at the pile top. The former to produce records that have sufficient resolution and the proper frequency content for a particular pile-soil system, the latter to find any defects near the pile top but only at one side.

The analysis and data interpretation process also has to be done carefully, particularly when choosing magnification and filter parameters. Fully automated data processing is usually not advisable: each step of the data processing procedure should be reviewed as to its effects 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 PIT.

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