Defect Analysis for CSL Testing

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ABSTRACT: Cross-hole Sonic Logging (CSL) has become a common method to evaluate the integrity of drilled shafts. However, the interpretation of test measurements by this method requires some judgment and experience. Many previous proposals rely solely on the arrival time, or wave speed. A proposed method which takes into account both arrival time and signal strength is presented. If defects are detected, then in some cases a tomography analysis may be helpful to further quantify the result. The situations where tomography is useful will be discussed. Recommendations are given for the type and amount of data required for a tomography analysis. This discussion is illustrated with a case history of a test shaft with purpose built defects to demonstrate the advantages of these evaluation methods.

INTRODUCTION

Drilled shafts are an option for deep foundations. Since they often have larger diameters, they usually carry large loads and are relatively few in number compared to a driven pile foundation to support the same total load. Therefore, the integrity of each shaft is critical to the overall performance of the structure, and good construction procedures and supervision improve quality assurance (O'Neill and Reese, 1999). Unfortunately, such "inspection only" has proven to be inadequate to assure quality.

Cross-hole Sonic Logging (CSL) is widely used to evaluate the concrete and shaft construction quality of drilled shafts, and its use has been rapidly expanding (O'Neill and Reese, 1999). State Departments of Transportation are increasingly relying on, in addition to available information on installation, the CSL testing for acceptance or rejection of drilled shafts for their projects. The CSL test results search for changes in concrete wave speed, which is attributed to changes in concrete quality or strength due to the presence of a defect. The defects identified by CSL include but are not limited to lower quality concrete due to mixing with drilling slurry, honeycombing, necking and soil intrusions, and soft toe conditions.

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O'Neill and Sarhan (2004) in a survey of over 10,000 shafts reported detection of "flaws" in about 20% to 25% of all shafts using various Non-Destructive Evaluation (NDE) methods such as Cross-hole Sonic Logging (CSL) or Gamma Gamma Logging (GGL), and assert that "since these flaws are identifiable by NDE, they are, by definition, not 'minor.'" They further noted that 20% of the shafts tested by CALTRANS were *rejected*. From this survey, they found the most probable location for a flaw is in the upper 5 shaft diameters, which is critical structurally but fortunately the easiest to repair by excavation or other means. Obviously, their study demonstrates the necessity for good construction inspection, but also for post construction NDE inspection of the shaft to assure its integrity.

CSL TESTING METHOD

The CSL test is performed on drilled shafts with access tubes installed during construction, or cored after construction. The recommended number of tubes for a shaft is at least one tube for each 0.3 meter of shaft diameter, with ideally a minimum of 4 tubes. The tubes may be either steel or PVC, but must be filled with water during curing to insure proper bonding of the tube to the concrete, and during testing to facilitate transmitting the signal. During the CSL testing, a transmitter probe is lowered into one of the access tubes while a receiver probe is lowered simultaneously into a second access tube. Both probes are centered in the tubes by flexible "centralizers", which have the added benefit of providing a cleaner signal by eliminating the receiver rubbing the tube. The transmitter probe generates ultrasonic vibration pulses which travel from the transmitter through the concrete to the receiver which converts this vibration back to an electrical signal. The probes are typically placed at the bottom of the access tubes and then simultaneously pulled to the top. The signals are transmitted and recorded typically every 50 mm and the locations of the individual probes are separately recorded by digital encoders. The test is repeated for each tube pair combination, or "profile", to look for defects in different quadrants of the shaft. The test is well described in ASTM D6760 (2002).

The cost of access tubes and even the cost of CSL testing are modest compared to the cost of the shaft itself, particularly for larger shafts. Installing access tubes in every shaft allows testing any shaft should doubts arise during its installation, and the mere fact that a shaft could be tested often will lead the contractor to more careful and better construction practices since a failed test might result in a rejected shaft.

CSL EVALUATION

While the testing procedure for CSL is relatively well defined, the appropriate method for interpretation of the results is not as well defined and improves over time due to advances in theory and software. The most common criterion for shaft quality assesses the first arrival time (FAT). First arrival time (FAT) may be determined by when the signal first exceeds simple amplitude thresholds, or preferably by using special advanced image processing tools. The wave speed of the concrete, which is related to concrete strength, can be calculated from the tube spacing divided by this first arrival time. Another indicator of concrete quality is the signal strength.

Integrating the absolute value of the signal for a defined time results in the signal "energy." Low energy is usually the result of a defect or poor concrete quality. As seen in Figure 1a, the signal strength is large and the well defined first arrival time occurs relatively early compared to the signal in Figure 1b, from a location of a known defect. The data presented here is from a special test shaft constructed with known defects for the purpose of furthering CSL development. The first arrival time for this defect is not as well defined, and engineering judgment is then helpful.

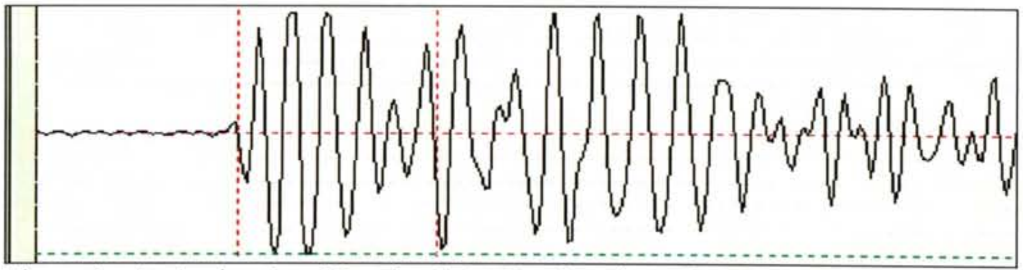

Figure 1a (top): signal at 10 m depth (top) at location of good concrete

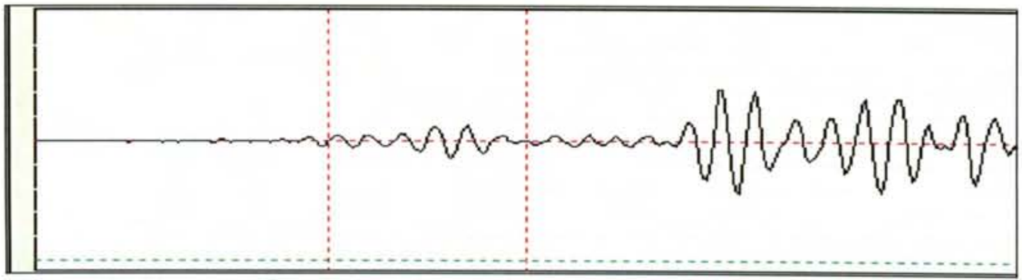

Figure 1b (bottom): signal at 7 m depth (bottom) at location of known defect
(vertical scale is normalized "signal strength")

FAT (or derived wave speed) and the received signal "energy" both indicate relative quality of the concrete between the transmitter and the receiver. Unfortunately wave speed alone cannot be used as an absolute indicator since the tubes are often not parallel, particularly for PVC tubes. Since arrival time also varies with tube spacing, FAT is usually assessed by comparing it to FAT in a nearby zone of good concrete. Therefore, looking for relative increases in FAT within relatively short distances along the shaft length is the generally accepted method of locating areas of concern, often called "anomalies".

In Figure 1b, the obvious delay and signal reduction results from the purpose built defect, created by inserting a substantial piece of Styrofoam within the reinforcing cage, thus blocking the *direct* signal path. The small signal is likely caused by signal travel outside the cage with reflections from the concrete-soil interface. The engineer can use judgment to manually override the automatically selected FAT in any CSL testing system (and is required for systems with manual only selection ability), since any FAT selection is subject to selection of the image processing control parameters. In Figure 1b, arguments can be made for either a slightly earlier selection, or a considerably later selection. The relative energy can influence the engineer's judgment when deciding how aggressive to be on the selection of FAT. An early "aggressive" or later "conservative" selection of FAT approach may be taken.

Whether an aggressive or conservative approach is taken will affect the FAT, but will have little influence on the relative energy. Therefore, relative energy can be a good tool for assisting the engineer in FAT selection. In the present example, a later conservative selection seems appropriate for the known defect. However, even the very earliest aggressive selection would clearly indicate a defect. In this case the very low relative energy is due to the reduced signal transmission in the general region; signals travel not only on the *direct* path but also *indirectly* through a bulb or cone due to particle refractions. When part of the full signal transmission path zone is blocked by a defect, as in this case, the resulting energy clearly reflects this defect condition. Low energy can alternatively be due to poor quality concrete. Repeating the CSL test after a longer waiting period may be helpful if the concrete was not sufficiently cured at the time of the first CSL test. If the second test after a much longer curing time confirms the earlier test, then the anomaly is real.

Once the FAT and signal energy/strength reduction have been determined for the entire profile length, the shaft integrity may be evaluated with the following scale:

(G) Good -	*FAT increase 0 to 10%*	*and*	*Energy Reduction < 6db*
(Q) Questionable -	*FAT increase 10 to 20%*	*and*	*Energy Reduction < 9db*
(P/F) Poor/Flaw -	*FAT increase 21 to 30%*	**or**	*Energy Reduction 9 to 12 db*
(P/D) Poor/Defect -	*FAT increase > 31%*	**or**	*Energy Reduction > 12db*

Flaws (P/F) should be addressed if they are indicated in more than 50% of the profiles. Defects (P/D) must be addressed if they are indicated in more than one profile. Addressing a flaw or defect should include, at a minimum, an evaluation by tomography if the area of concern is localized, and/or additional measures such as excavation, core drilling, or pressure grouting. Defects or flaws indicated over the entire cross section usually require repair or shaft replacement. This scale, based on the author's experience, adapts a common scale used by many State departments of transportation, separates the more marginal Flaw from the more serious Defect, while assigning actual numerical values to the Energy Reduction rather than current USA practice of vague statements about energy. Both French (2000) and Chinese (2003) national standards use numerical values of Energy Reduction when evaluating CSL.

DEFECT ANALYSIS

After data collection, the engineer must compare the processed results with the rating scale and present a report. When multiple shafts are tested, particularly for shafts with many tubes creating multiple profiles, an automatic evaluation technique is helpful to summarize the results. Since tubes are often not parallel and sometimes not even straight, a method that follows the general FAT trend improves finding the location of local defects. This process can be accomplished with "filters" that take a running average as a "baseline." Using the average of typically 75 consecutive data samples at the typical 5 cm vertical resolution represents the trend for the local 3.75 m of shaft length. If the actual FAT compared with this moving baseline is significantly increased, or the energy significantly reduced, compared with its baseline and user input limits, an anomaly is defined at that depth location.

Figure 2 shows the analysis for tube combination 3-5 for the same test shaft with purpose built defects. The "waterfall diagram" at the right presents a "nesting" of the data. Sections of low color intensity, such as at 1, 7 and 10.5 m depths, indicate relatively low signal strength. The left edge of the waterfall maps the FAT. The processed data at the left in Figure 2 displays the computed wave speed (thick line) and the relative energy (thin line) plotted on a log-energy graph, with lower values to the right. The horizontal dashed lines identify locations of peak concern based on the FAT increase limit of 10% and energy reduction limit of 6 dB. With the proposed rating scale, the FAT increases of 29, 28 and 12, and energy decreases of 7.3, 9.4, and 7.5 dB for approximate depths of 1, 7 and 10.5 m respectively would rate the upper two anomalies as Poor/Flaw, and the lower one as Questionable. The 9.4 dB at 7 m might cause an engineer to judge the local FAT selection more conservatively and might easily result in a Poor/Defect rating.

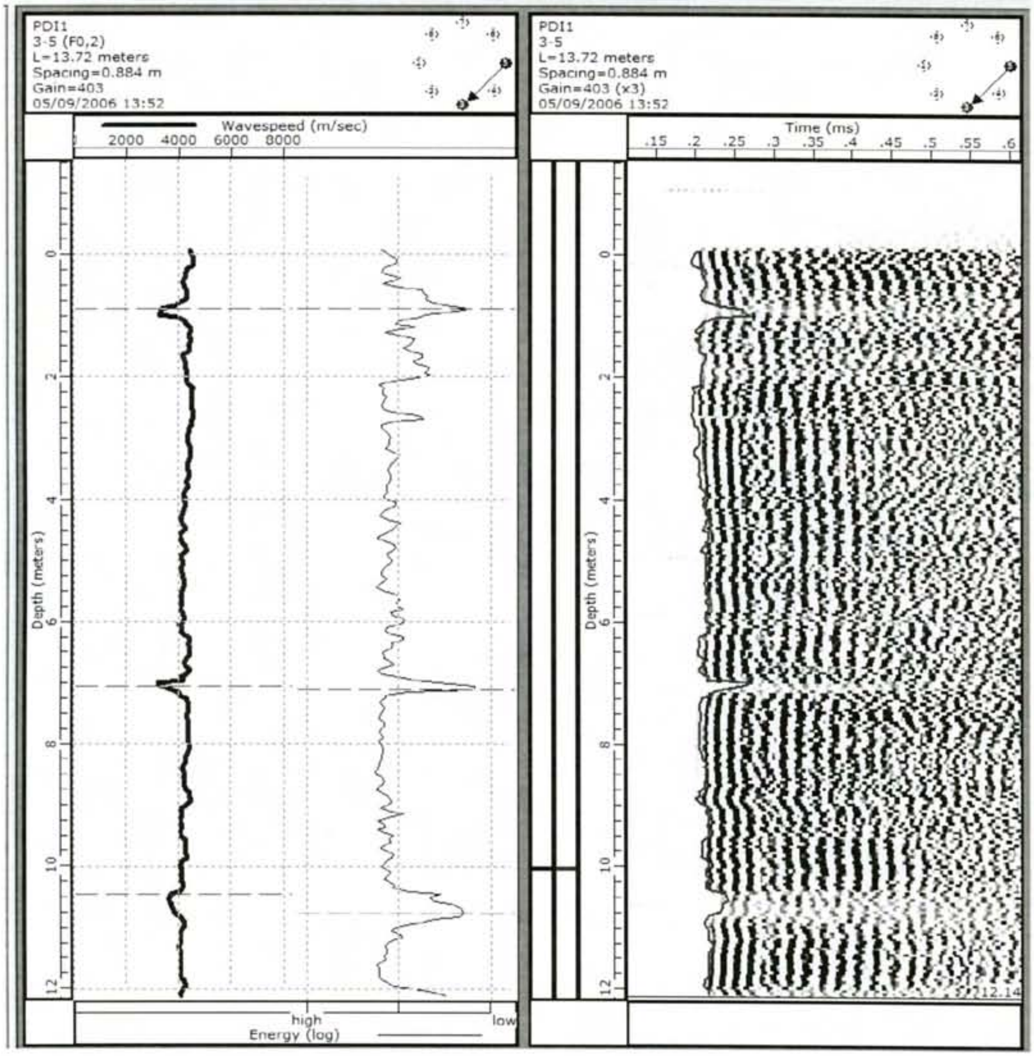

Figure 2: CSL "waterfall" diagram in right, processed results in left (wave speed heavy left line, energy thin right line)

TOMOGRAPHY

Although CSL data can be evaluated for each tube combination profile, combining and reviewing all available profiles leads to the best engineering evaluation. If a defect is found at the same depth in every profile, it is clear that the shaft has a defect covering the entire section and that remedial action is then required. Such action might include excavation and repair if the defect is near the top of the shaft, or perhaps coring and pressure grouting if the defect is at depth, or in some cases abandoning the shaft and constructing a replacement shaft(s). If no defect is found in any profile, then the entire shaft is satisfactory and acceptable and no additional analysis is necessary.

However, some CSL tests reveal defects in some profiles, but not in all profiles, and then the question arises as to the lateral extent and location of the defect. Certainly the magnitude of any FAT delay or energy reduction in any profile would enter into any evaluation. But the lateral extent of the defect across the section is also important. By visually reviewing all the profiles, the engineer can assess the possible size and depth of a defect. If the defect covers many profiles, or is near the shaft top, making it significant, it might seriously compromise the shaft integrity.

Since concrete strength is related to the concrete wave speed, a determination of wave speed at each point in the shaft can help assess the shaft acceptability. The severity of a local defect, defined by substandard concrete wave speed, can be assessed by both magnitude and lateral extent perhaps most easily by tomography. Arrival time data from all profiles, locations of each probe for each signal record, and tube geometry can be input into a single three dimensional analysis. For a grid of node points, the wave speeds in each node can be adjusted to minimize the errors between calculated and observed arrival times for all travel paths (Jie et al, 1998). Although there are other methods of tomography, this node matrix method, although computationally intensive, is the most reliable and therefore this paper focuses on this method. The tomography analysis results in a profile of wave speeds as a function of cross section and shaft length.

Tomography results can be shown in an overall 3-D presentation, or 2-D "slices" can be made either horizontally or vertically in the shaft. A horizontal 2-D slice at the depth of interest probably shows the most clear presentation of defect extent and location within the section, and is useful to guide the construction team into better selections of coring locations for verifications or remedial procedures. If a lower bound threshold of acceptable wave speed is defined, the analysis can calculate the percentage of the slice of cross section falling below this limit.

The data required for a tomography analysis depends on several factors. The more data that is available, the more accurate the analysis is likely to be. However, the amount of data available is practically limited by the number and locations of the access tubes. The more tubes that are available, typically true for larger diameter shafts, the more information that can be naturally available for the tomography analysis. For shafts with only 4 tubes, 6 possible tube combinations are possible with only 2 crossing the shaft interior, making the quadrant location of an interior defect difficult to determine with precision, while for 8 tube shafts there are 28 tube combinations, including 20 crossing the interior. Table 1 and Figure 3 relate the number of perimeter and the number of interior paths relative to the number of access tubes. Thus for shafts with preferably at least 6 tubes, any interior defect can be located quite well since it likely crosses many interior paths.

Table 1. Number of paths versus number of access tubes

Tubes	Perimeter paths	Interior paths	Total paths
4	4	2	6
5	5	5	10
6	6	9	15
8	8	20	28
10	10	35	45

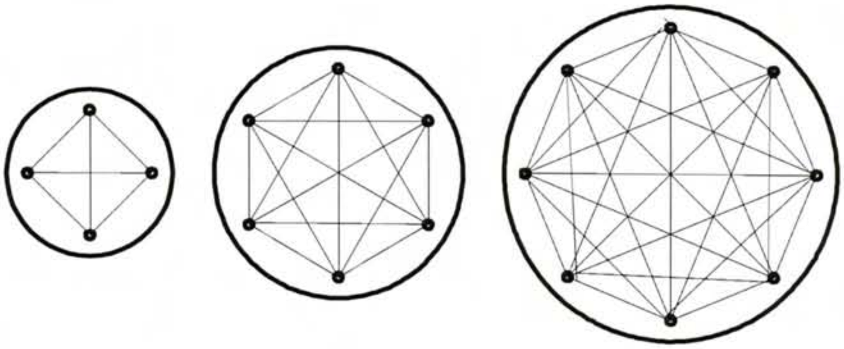

Figure 3: Potential scan paths for 4, 6 and 8 tube shafts

The exterior or perimeter paths however require extra considerations when locating a defect. When a defect is located in the perimeter in normal testing (probes being "parallel" or "level" in the tubes), it is generally not possible to tell if the defect is located closer to one tube or the other. However, if additional scans are made with an "offset" (e.g. one probe raised in relation to the other, and then repeated with the opposite probe raised), then these three measurements of parallel scans and two offset scans for each tube combination can help locate the defect relative to the tested tubes since the apparent depth location of the defect will shift as seen in Figure 4.

Although interior offset tests offer little benefit to tomography when the number of access tubes is 6 or more, offset tests are useful for the interior profiles in tomography for shafts with few tubes. The general suggested rule for shafts with 5 or fewer access tubes is that "offset scans" be performed for all tube combinations when a defect is located in that tube combination, while for shafts with 6 or more tubes, parallel scans are sufficient for the interior and the extra offset scans are necessary only for the perimeter. Of course there is no benefit to any offset scan for any tube combination if the parallel or level data does not reveal any defect. The goal is to obtain necessary and sufficient data for the analysis, without having to collect useless extra data that adds to the testing cost but provides no real resolution improvement.

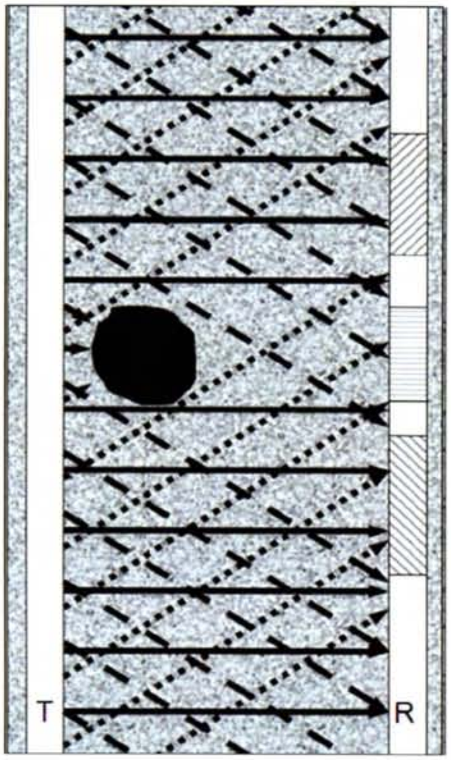

Figure 4: Effect of "probe offsets" in apparent defect location for transmitter (T) and receiver (R) in access tubes

In a perfect world, spacings between all tubes are equal and known with precision, the tubes are precisely parallel, and the probes are centered in the tubes. In the real world, tubes are often not uniformly spaced and not even parallel. Smart logic is required to correct for non-parallel tubes. The most accurate wave speed is determined by the main cross diagonals since the tubes are more parallel and the percentage distance traveled in concrete is larger due to the large spacing. Since the depth to each probe is measured, the actual travel distance in the concrete is also known from geometry, and the arrival time can be adjusted to compensate for the wave travel in water.

CASE HISTORY

The shaft with purposely installed defects built at the author's Ohio office for developing and testing the hardware and software can be effectively used to evaluate the methods. The shaft is 1.5 m in diameter and 12.2 m in length. It was cast with six steel and 2 PVC tubes, and it can be mentioned that even over three years later there is absolutely no evidence of "debonding" of the PVC tubes (cast in the dry method, and water in the tubes has been continuously maintained). Four major defects were installed in this test shaft. A soft toe was created on one quadrant only using sand bags. The previously mentioned defect at about 7 m depth was a 150 mm thick Styrofoam insert covering half the interior cage (e.g. "half moon" shape). Two 400 mm diameter buckets were inserted, one about 1.5 m above the bottom filled with soil, and one at 1 m below the top that was a true void. Both buckets and the half moon Styrofoam were seen in Figure 2, because they were located on the "direct path" between the tested access tubes for that profile. However, the soft toe defect was out of that plane, although a hint of a natural soft toe is observable in the energy graph. Because part of the wave front may pass outside the shaft bottom and thus reduce the energy content, the arrival time is given more emphasis at the shaft toe.

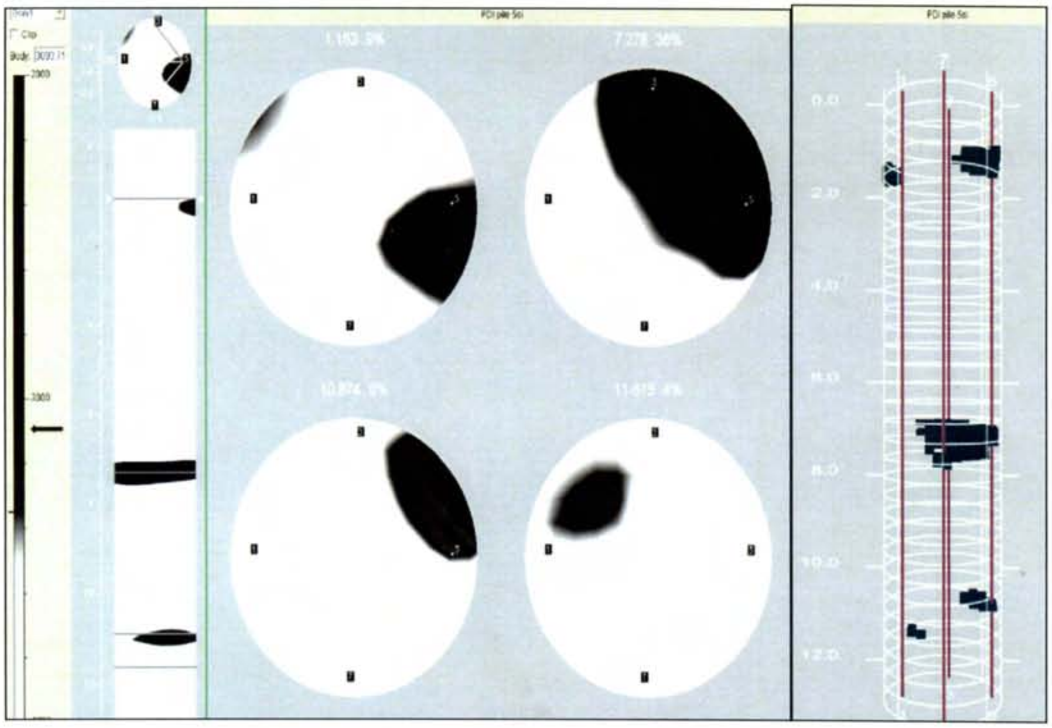

Figure 5: Tomography results for drilled shaft with four purpose built defects.

Because even numbered tubes had additional impediments attached to the tubes to test the tube-concrete interface, data from only the odd number tubes was subjected to a tomography analysis. Because only 4 tubes were selected, parallel and two offset scans were input for each tube combination as per the general recommendation. Results are shown in Figure 5 (usually results are in vivid colors, rather than the black and white required for this publication). "Black" was assigned to any wave speed less than 3300 m/sec, and "White" to wave speeds above 3500 m/sec, with transition "gray" in between. This wave speed scale is shown at the extreme left. Next on the left is a selected horizontal slice at the top and a selected vertical slice at the bottom (profiling tubes 3-5 in this case). The four large circles, or "slices", perhaps show best the analysis results at the depths of the four main defects. The soft toe defect is in the lower right, the half moon defect is in the upper right, and the bucket defects are the two on the left. While the buckets are not perfectly round, they do convey the general shape. The far right diagram is a 3D presentation showing the main defects. This frame can be animated, rotated, tilted, and zoomed/enlarged to view defects in the best angle. Other than one small "ghost" image (with wave speeds in the gray range) at the location of the upper bucket defect, no other defect can be observed. It is possible that the "ghost" could be some unplanned soil inclusion caused by removing the temporary casing (a common occurrence in drilled shaft installation).

CONCLUSIONS

CSL testing is an efficient tool to evaluate the integrity of drilled shafts. Since the occurrence of defects is relatively common, and is related to the skill of the contractor and the soil conditions of the site, CSL testing is also routinely applied. An improved evaluation standard is proposed that considers not only the traditional arrival time changes but also the signal strength, or signal energy reduction. The extra information is useful when the engineer evaluating the data applies judgment to selection of the arrival time, and to consider defects not on the direct path between tubes. A sufficiently large energy reduction, perhaps from a large defect not on the direct path, would define a defect even if the first arrival time were normal.

In cases of local defects which cover only part of the cross section, tomography analysis is very helpful to visualize and quantify the extent and location of the defect. Such information is useful when coring is required to assist remediation efforts, or when the structural engineer must assess the adequacy of the shaft to resist the applied loads.

The use of the new evaluation scale and tomography promise to provide the engineer with better evaluation tools for CSL test measurements.

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