EVALUATION OF DEFECTS AND TOMOGRAPHY FOR CSL

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ABSTRACT

Cross-hole Sonic Logging (CSL) transmits ultrasonic pulse waves between probes in parallel tubes that are embedded in drilled shafts. Due to ease of use, CSL has become the standard method to evaluate the integrity of drilled shafts. A study of steel and PVC access tubes installed in dry conditions shows no evidence of "debonding" for properly installed tubes, regardless of tube material. Interpretation of CSL results, while relatively straightforward, can lead to different conclusions. Numerical analysis tools have been developed in the Cross-Hole Analyzer (CHA) to aid the engineer in defect evaluation, either by reviewing each sonic logging test individually, or by combining several scans from the same shaft into a full three dimensional tomographic analysis. Thresholds for defects are discussed. Examples present the application, advantages and disadvantages of these advanced evaluation procedures.

Keywords: Cross-hole Sonic Logging, CSL, defects, integrity, tomography

1. INTRODUCTION

Drilled shafts are constructed by various methods depending on the site soil profile. In favorable soils, they are cast in dry conditions. However, shafts are often cast under wet conditions using slurry or polymers to keep the hole open during drilling and casting of the concrete. Wet casting makes inspection difficult as a tremie is used and the actual flow of concrete cannot be inspected, nor can the tremie tip be seen. Improper management of the tremie usually results in a defect. Even under dry conditions, visual inspection of the shaft is difficult. A casing is usually installed to facilitate keeping the hole open during the drilling process. In many cases only a partial casing covers the uppermost section of the pile, and caving in the lower portion of the shaft is then possible. The casing may be left in place, but usually it is temporary and is removed either during installation as the concrete is placed, or at the end of the shaft installation. Removal of the temporary casing sometimes pulls the reinforcing cage when the concrete cures rapidly. Baker (1993) and O'Neill (1999) have documented common defects and their causes.

Drilled shafts are expensive and generally carry large loads, often resulting in relatively few shafts and thus reduced redundancy in the foundation. With reduced redundancy, the performance of each drilled shaft is very important. Proper installation methods and inspection during construction, particularly when cast wet, are critical. The current consensus is that cross-hole sonic logging (CSL) is the best available method to verify shaft integrity, and therefore it is often specified. This method is discussed by Baker (1993) and O'Neill (1999). ASTM D6760 (ASTM 2002) provides guidance for this test.

CSL tests require access tubes attached to the full length of the reinforcing cage and cast into the pile during construction. The guideline is that there should be at least one tube for each foot of diameter of the shaft, with a minimum of four tubes. Probes are lowered into water-filled parallel tubes and traverse the length of the tubes. The quality and homogeneity of the concrete between the tubes is determined sending ultrasonic signals from one probe to the other and recording "first arrival time" (FAT) which can most reliably be determined by automatic signal processing (method built into CHA). The spacing between tubes (S) divided by first arrival time (t) results in the concrete wavespeed (S/t) which is a

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qualitative indicator of concrete quality. A low wavespeed indicates poor quality concrete or a defect. By observing the wavespeed versus depth between all possible combinations of tube pairs, the concrete homogeneity can be assessed for the entire pile by depth and by quadrant. The signal strength, defined by peak amplitude or by "relative energy" (calculated by integrating the signal absolute value over time), is also used to evaluate shaft quality. The CSL method can accurately locate multiple defects and is not limited by pile length or soil type, It is however limited to inspecting concrete between the tubes.

2. ACCESS TUBE COMPARISON

"Debonding" of the tubes from the concrete (usually localized in top ten feet of shaft) has often been reported for PVC access tubes, suggesting that testing in PVC access tubes is limited to the first few days after casting, and that steel access tubes are preferred. To prevent "debonding", which blocks CSL signal transmission, tubes should be filled with water either prior to concrete casting, or immediately afterwards so that temperature variations are minimized and the bond between the tube and concrete is not compromised. With good bonding, Figure 1 shows a typical CSL individual signal versus time from the receiver at arbitrary depth, with first arrival time (FAT) shown by the vertical dashed line.

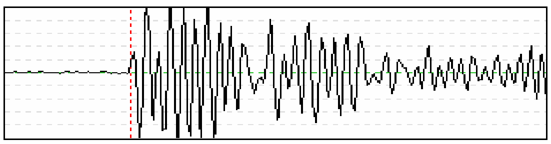

Figure 1: Individual signal sensed by receiver

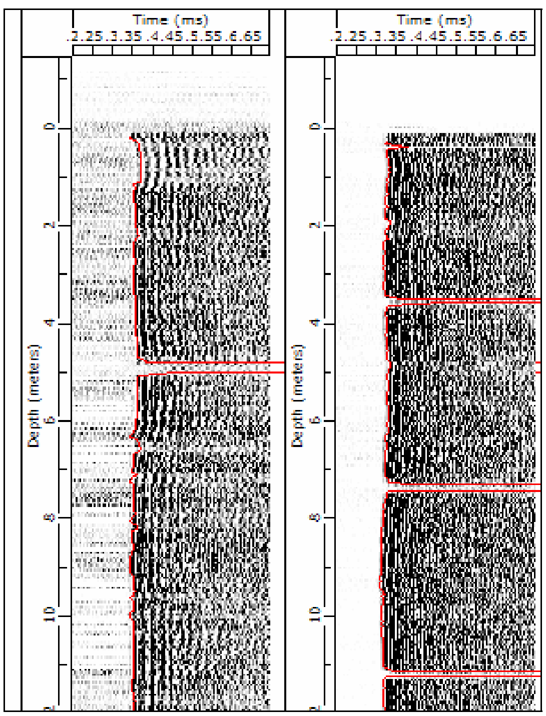

Figure 2: CSL waterfall (nested signals) from steel tubes (on left) and PVC tubes (on right)

Nesting the individual signals versus depth creates "waterfall diagrams" as in Figure 2 with the intensity of the graph relating to the individual signal strength and the left edge of the diagram is FAT. A drilled shaft with specially constructed defects and both steel and PVC access tubes was installed (in dry conditions) at the Pile Dynamics' facility, and periodically tested. "Waterfall diagrams" in Figure 2 from two different main diagonals of this shaft at almost 7 months after installation show no evidence of "debonding" for either steel or PVC tubes. No effort was made (e.g. roughening PVC tubes) to ensure a good bond other than filling the PVC tubes with water immediately after concrete casting, as recommended by ASTM D6760 (ASTM 2002).

Purposely constructed defects in this special test shaft (made by a foam layer wrapped over a short length of the even numbered tubes) are clearly indicated in Figure 2 by the horizontal gaps at different depths. The signals transmitted between the PVC tubes have double the amplitude and significantly less "noise" than those between the steel tubes. The advantages of PVC tubes are that they can be easily drilled out to allow access to pressure grouting of "soft toe" defects, and that they allow radioactive testing to assess concrete outside the cage. Steel tubes are preferred for wet cast shafts.

3. RESULT INTERPRETATION

In many cases, the waterfall diagram shows a "full layer defect" as in Figure 3 where all six possible scans of a four tube 35 m shaft show a similar defect at a depth of about 28 m depth. At the extreme right of Figure 3, the "processed data" for one scan shows graphs of FAT (left) and the log of relative energy (right). All defects have both delayed FAT and low relative energy. Shafts with no defects, or shafts as in Figure 3 that clearly show a major defect covering the entire cross section, need no further analysis. Defective piles can be cored and pressure grouted, or replaced.

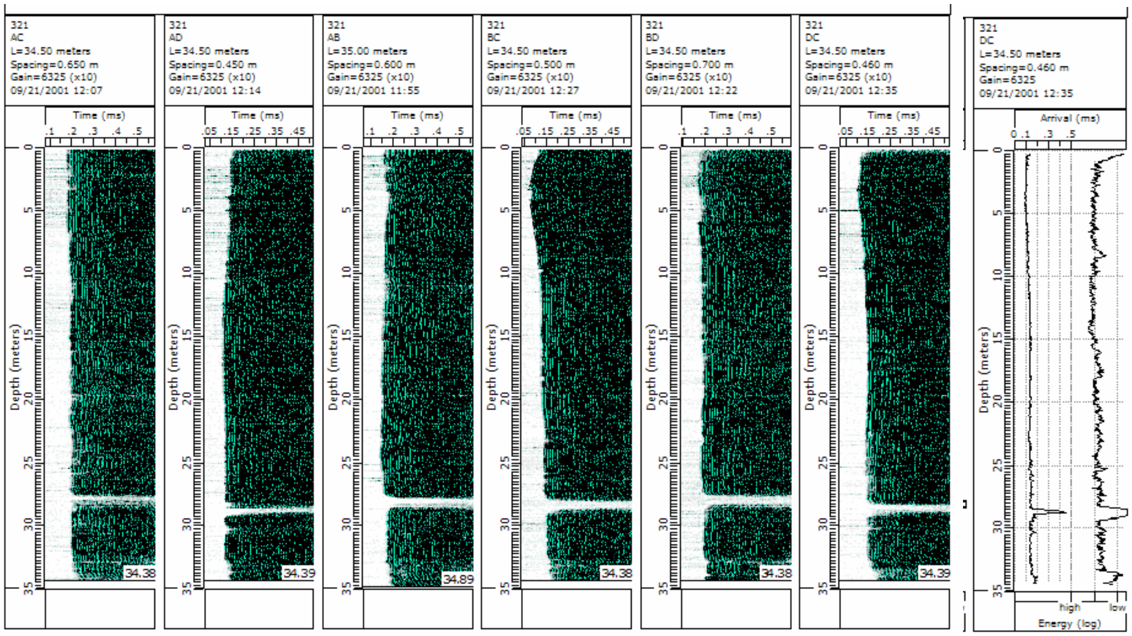

Figure 3: Example Case 1 with shaft containing a full section defect at depth 28 m

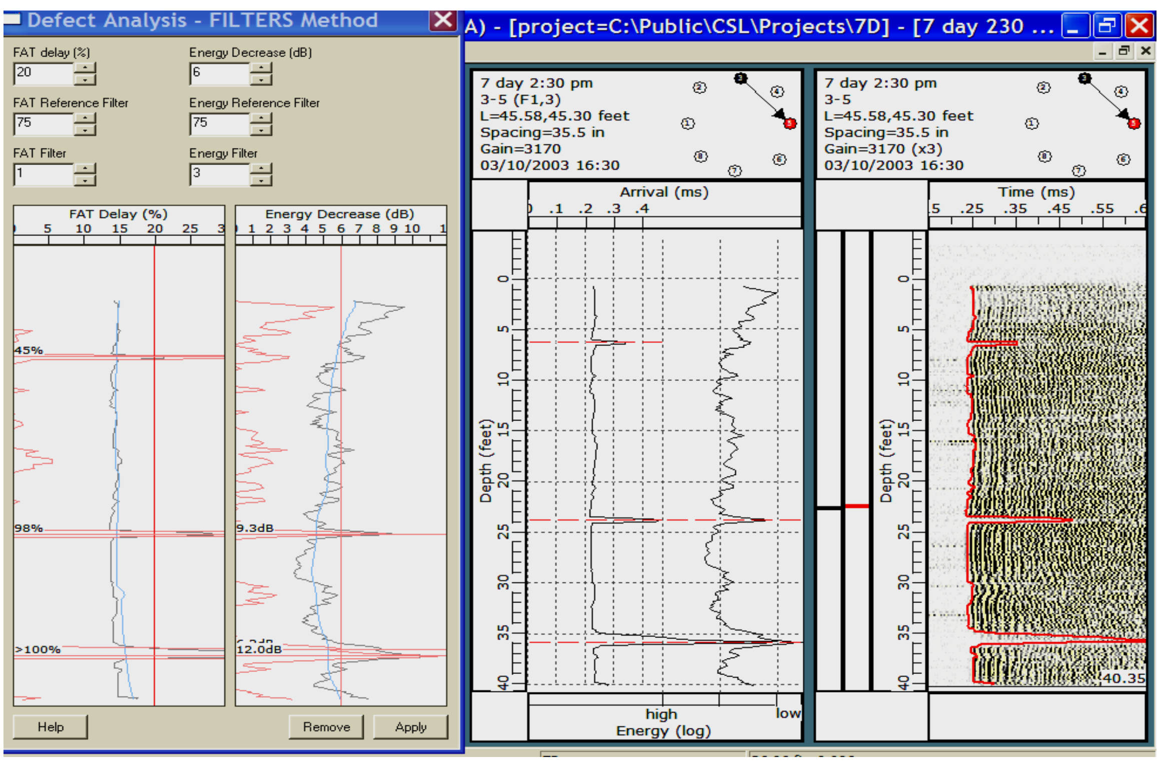

Figure 4: Example Case 2 showing automatic defect analysis of data

When a local necking defect is observed in only some of the scans (e.g. in a local quadrant), a better grasp of the location (quadrant and depth) and extent of each defect is needed so that the shaft can be structurally evaluated to determine if it is satisfactory for the loading conditions, or if it needs remedial action. Figure 4 presents a scan (7 days after casting) for tube pair 3-5 for the shaft shown in Figure 2. In Figure 4, the waterfall diagram is at the far right, and both FAT and log energy are displayed in the center. The left portion of Figure 4 displays the “Defect Analysis” including user-selected threshold values for both FAT and energy decrease used to define a “defect”. In this Defect Analysis, the actual signal is compared with a “reference filtered curve” (e.g. running average of the signals that allows for gradual variations with depth such as the tubes not being parallel or even bowed). When the difference between the signal and reference curves exceeds the assigned thresholds, a “defect” is noted at that location with a dashed line and the numeric amplitude of the defect. The numeric information of depth and magnitude is then automatically assembled for all tube pairs into a final summary table.

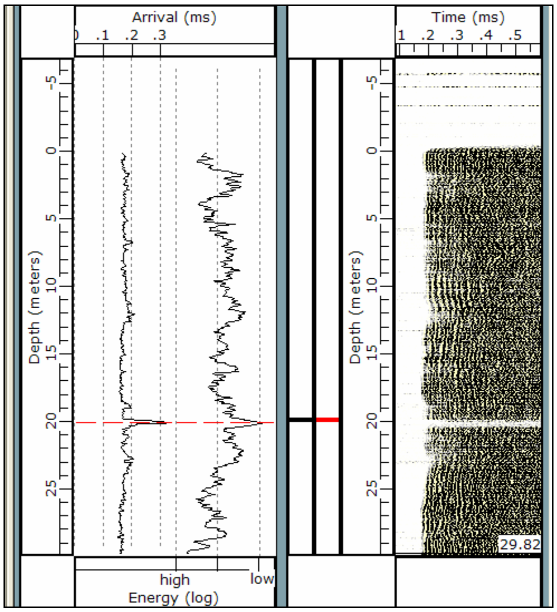

Figure 5: Example Case 3

In Example Case 3, during the casting of a 2.4 m (8 ft) diameter shaft of 30 m depth, the tremie tube was stuck. After attempts to free the tremie, it was eventually abandoned and the shaft completed with another tremie. The result of CSL testing on a perimeter tube pair is shown in Figure 5. All other tests in perimeter tube pairs and main diagonals were similar, with defects up to 1 m in thickness shown by a major loss of signal at about the 20 m depth below top of concrete. This major defect in the shaft was at the depth where the first pour was terminated and the second began. It is probably due to contaminated concrete or lack of a clean and level starting surface at the start of the second pour. Full section defects have also been caused by pulling the temporary casing which disturbs the reinforcement cage, or when the concrete partially sets prior to extraction of the casing.

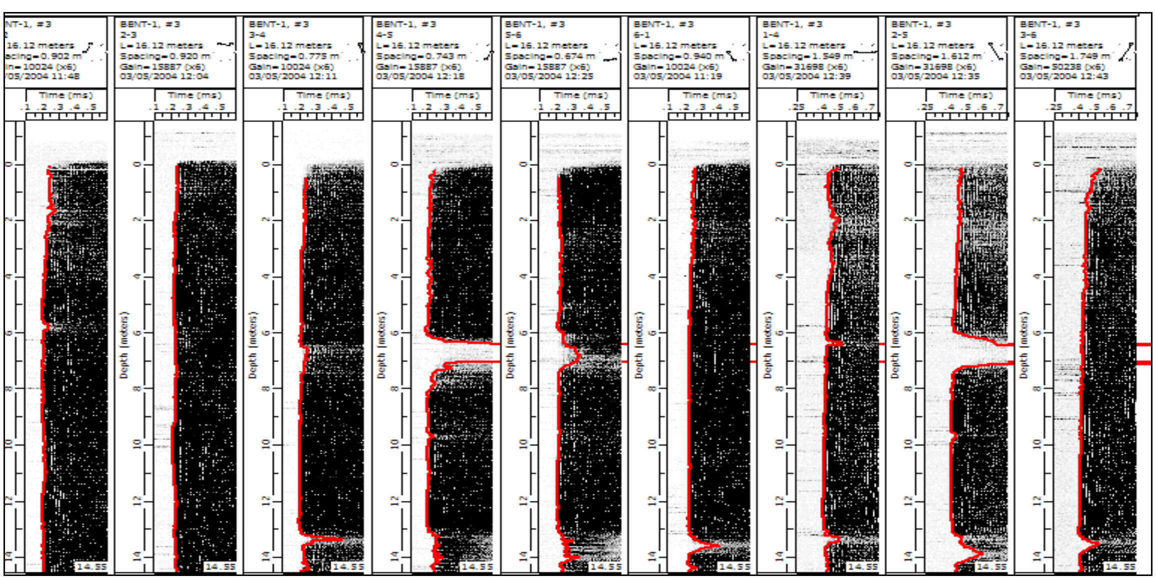
Figure 6: Example Case 4

For Example Case 4, the six perimeter tube pair scans and three scans of the major diagonals are given in Figure 6 for a 6 tube 2.1 m (7 ft) diameter shaft. This data, and the other 9 minor diagonals (not shown), demonstrate two major local defects, one near the pile midpoint, primarily near tubes 4 and 5, and a second defect about a meter above the toe in many, but not all, tube pair scans. The pile was cast with a tremie pipe under slurry with a very short temporary casing (which ended above the depth of the problems). In spite of the slurry and casing, this shaft required an extra 44% concrete volume above the theoretical volume of the shaft, and still there were such local problems due to loose caving soils.

CSL testing is straightforward. However, there is no general common consensus (in most parts of the world) concerning what reduction in amplitude or delay in first arrival time defines a defect. Many engineers rely on judgment on a project by project basis. The elastic modulus and concrete strength are related to the concrete wavespeed. Low wavespeeds generally indicate concrete of poor quality. However, because testing is often done when the shaft is only a few days old, the wavespeed might be relatively low or the shaft have sections where the concrete is insufficiently cured. Re-testing after further wait is often recommended. Strict limits on allowed wavespeed are discouraged. FAT threshold [relative] delays between 10 to 30% have often been used to define a defect. Lower FAT delays like 10% are sometimes referred to as “anomalies”. A 20% FAT delay is a commonly suggested limit for a defect (e.g. French code AFNOR NF P94-160-1). Of course, non-parallel tubes require comparison of delays over a relatively short shaft depth, and the reference filter curve in the Defect Analysis method allows accurate analysis even for non-parallel tubes. Evaluation of either the signal amplitude or relative energy is highly useful. Defects result in energy reductions of more than 6dB. China building codes (2003) require statistical evaluation methods. There, the wavespeed average and standard deviation are computed. If the wavespeed at some depth is below the average minus a code specified multiple of the standard deviation, then a defect is contained at that depth. Similarly, if the amplitude of the signal is more than 6dB less than the average amplitude, then it is considered a defect. Although this works well for parallel tubes, this purely statistical Chinese approach has some problems for non-parallel tubes.

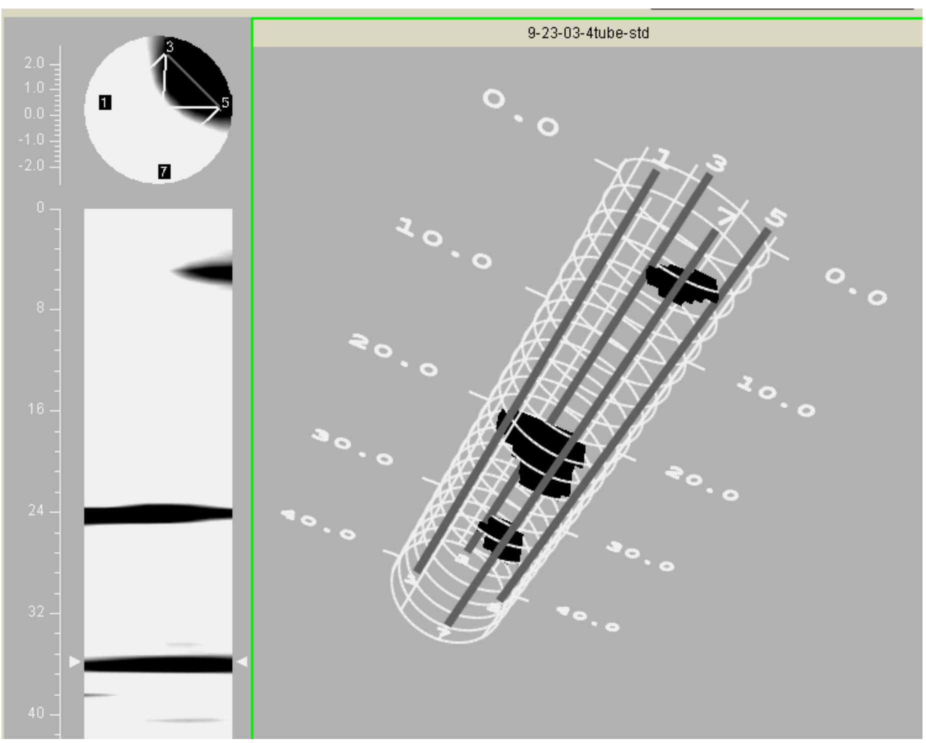

Figure 7: defective shaft with 3D tomography “body view” of defects on right

4. TOMOGRAPHY

A three dimensional (3D) tomographic image helps evaluate the extent of local defects, as in Example Case 4 above, and is promoted by the Federal Highway Administration (Haramy, 2000). Tomography is a mathematical procedure that operates on the measured data where the shaft is models the shaft as a grid, with each node point given an assigned wavespeed. An inversion routine of observed arrival times (FAT) of all data points in all tube combinations with known probe locations is employed to solve for the wavespeeds at each node point. Uniform wavespeeds generally produce straight ray travel paths, but variable wavespeeds allow refractions, causing curved ray paths. Curved ray analysis logic, gradient methods and smoothing allow the wavespeed to be mapped continuously even to node points that are not directly on lines dissected by the data ray paths. Tomography analysis is described by Jie (1998).

Tomography analysis using only the four odd numbered tubes (a reasonable number of tubes for this size shaft) was performed for the special test shaft at Pile Dynamics. (Analysis of only the odd numbered tubes avoids local foam wrapping defects placed exclusively on even numbered tubes, as investigated in Figure 2). The resulting sample 3D tomography output of an overall "body" image of the entire shaft is shown in the right side of Figure 7 with defects defined by low concrete wavespeeds (corresponding to low concrete strength) shown in black. These defects were purposely created by installing large sand filled buckets at depths 5 and 36 ft, and a thick Styrofoam layer covering half the cross section (affecting tubes 2, 3, 4, 5 and 6) at about the 24 ft depth. The tomography analysis correctly identified these defects and their approximate size and location in the shaft. While Figure 7 is presented in black and white mode due to publication limitations, generally the output is in vivid rainbow colors. The user may select various viewing angles, or sections of the shaft, or look at "slices" (either horizontal or vertical), or wrap-around diagrams showing the full perimeter. A horizontal slice at 36 ft depth is shown in the upper left of Figure 7, and a vertical slice between tubes 3 and 5 is shown in the lower left. Thus the presentation may be detailed or global to clearly show extent and locations of defects.

5. CONCLUSIONS

Structures supported by drilled shafts have less redundancy and thus higher risk. It is critical that each shaft perform satisfactorily. CSL testing is the preferred method to evaluate the integrity of drilled shafts as it can accurately locate multiple defects by depth or quadrant and is not limited by pile length. Access tubes can be either steel or PVC, although PVC provides better CSL signals, allows gamma-gamma testing, and gives the possibility of easier access for later pressure grouting repairs should a defect be found. Filling the access tubes immediately after casting the concrete avoids "debonding" of the tube, and is particularly important for PVC tubes. Steel tubes are preferred for CSL testing of wet cast shafts.

Shafts with no defects, or defects across the entire cross-section requiring replacement or repair, need no further analysis of the data. An automated Defect Analysis can assess the CSL data for concrete wavespeeds (and hence concrete quality) and provides numeric and graphical presentations when defects are found. Shafts with local partial defects can be analyzed by 3D tomography to give clear visual spatial presentations of defects, allowing more effective remediation or analysis by the structural engineer.

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