NDT Diagnosis of Drilled Shaft Foundations

by

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ABSTRACT

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Nondestructive methods based on propagation of sonic and ultrasonic waves are increasingly being used in the United States and internationally for forensic investigations of existing structures and for quality assurance of new construction. Of particular interest is the quality assurance of newly constructed drilled shaft foundations. A large number of State Departments of Transportation specify NDT testing of drilled shaft foundations, particularly for shafts drilled and placed under "wet" construction conditions.

For quality assurance of drilled shaft foundations of bridges, the Crosshole Sonic Logging (CSL) and Sonic Echo/Impulse Response (SE/IR) methods are routinely used. The CSL method requires access tubes to be installed in the shaft prior to concrete placement. SE/IR measurements require that the top of the shaft be accessible after concrete placement. Discussed in this paper are proper test setups, specifications, and case studies to illustrate the advantages and disadvantages of each of these methods. Presented also are recommendations for repair when a defect is identified in a drilled shaft foundation. Based on our experience, the CSL method is more effective in locating defects than the SE/IR method.

CSL measurements are effective in determining anomalies and defects between two access tubes. However, an accurate image of the defect cannot be determined from just a CSL test. The Crosshole Tomography (CT) method uses multiple CSL logs with varying receiver locations to produce a 2-D image of the defect, and thus a better characterization of the defect. The CT method is briefly discussed in this paper along with presentation of one dataset obtained from a drilled shaft foundation. The CT method requires more time for data collection and analysis than the CSL method, and presently its use is justified only for critical drilled shaft foundations.

Key Words: Crosshole Sonic Logging, Sonic Echo/Impulse Response, Tomography, Quality Assurance, Drilled Shafts.

INTRODUCTION

Quality assurance of foundations, particularly drilled shaft foundations, is becoming an important part of the foundation installation process to ensure a good foundation that can transfer the applied loads to the surrounding soil or rock. Until the mid 1980's, quality assurance of driven piles and drilled shafts in the USA was performed at selected shafts and used the Sonic Echo and Impulse Response (SE/IR) test methods to identify anomalies or defects (Olson and Thompson, 1985; Davis and Dunn, 1974). The SE/IR method relies on reflection events from a change in impedance. Although the SE/IR method can be applied to identify defects, the method suffers from the following limitations: 1) the strength of the echoes depends on the surrounding soil, 2) echoes are frequently too weak to be distinguished when length to diameter ratios exceed 20:1, 3) the size and location of the defect cannot be determined, 4) defects located below a major defect cannot be identified, 5) defects at or near the bottom of the shaft cannot generally be identified, and 6) planned or unplanned diameter changes can appear to be defects even if the diameter is acceptable.

The drawbacks associated with the SE/IR method have led to the search for other alternatives and the development of the Crosshole Sonic Logging and Gamma-Gamma methods (Olson et. al, 1994) to identify defects in drilled shaft foundations by use of cast-in-place access tubes. One of the advantages of the CSL method over the Gamma-Gamma method is that a fairly complete coverage of the shaft conditions can be determined with the CSL method, while the Gamma-Gamma method determines the shaft conditions around the installed tubes in a drilled shaft. In addition, CSL is generally much faster to perform and does not use radioactive materials.

In this paper, the Crosshole Sonic Logging (CSL), Crosshole Tomography (CT) and Sonic Echo/Impulse Response (SE/IR) methods are discussed along with case studies to illustrate the use of each method. It should be mentioned that the CT method is not routinely applied to drilled shaft foundations, and its application is limited to critical structures to produce a better image of defects identified in CSL and SE/IR tests.

CROSSHOLE SONIC LOGGING METHOD

The CSL method was developed in the mid 1980's for quality assurance of drilled shaft foundations, slurry walls and seal footings. The CSL method relies on direct transmission of sonic/ultrasonic waves between access tubes placed in a drilled shaft prior to concrete placement. Figure 1 shows an illustration for a CSL test setup.

The number of access tubes per drilled shaft is dependent on the diameter of the shaft, typically 1 tube per 1 ft of diameter, and the tubes are installed around the perimeter of the shaft and tied to the inside (or outside) of the cage of the shaft. The tubes are usually 38 to 50 mm (1.5 to 2.0 in.) inside diameter schedule 40 steel or PVC pipe. Tube debonding from the surrounding concrete can occur at an earlier time in PVC tube as compared to steel tubes. Most State DOT's specify that CSL tests be performed in 10 days or less after concrete placement for PVC tubes and in 45 days or less for steel tubes to avoid problems associated with tube debonding.

To perform a CSL test, two probes (hydrophones) are lowered to the bottom of two access tubes, and are retrieved to the top of the shaft while CSL measurements are taken approximately every 50 mm (2 in.). The ultrasonic wave pulser is controlled by a distance wheel to trigger the transmission of waves at preselected vertical intervals. Automatic scanning of the collected records produces two plots, time (or velocity) and energy, versus depth. Anomalies and defects between tested tubes are manifested by time delays (or velocity decreases) and energy drops in the scanned CSL plot. Concrete velocities are calculated by simply dividing the distance between the two tubes by the time required for the wave to travel from the source hydrophone to the receiver hydrophone. CSL tests are typically performed between all perimeter tubes to evaluate the concrete conditions of the outer part of the shaft and between major diagonal tubes to evaluate the concrete conditions of the inner part of the shaft. Figure 2 shows an illustration for the interpretation of a CSL log. NDT methods which could be used in conjunction with the CSL method to better identify anomalous zones include Crosshole Tomography (CT), Singlehole Sonic Logging (SSL), Gamma-Gamma Nuclear Density Logging, Downhole Sonic and/or Sonic Echo/Impulse Response (SE/IR) tests. The CT and SE/IR methods are briefly discussed below.

CROSSHOLE TOMOGRAPHY METHOD

The Crosshole Tomography method uses the same equipment as the CSL method with more tests being collected (many source and receiver locations). Once a defect is identified in CSL tests, CT tests can be performed to produce an image of the defect between the test tubes. The CT tests are typically performed at depths extending few feet below and above the defect zone as shown in Figure 3.

Tomography is an inversion procedure that can provide for ultrasonic images of a concrete zone from the observation of transmitted compressional or shear first arrival energy. The CT data is used to obtain an image of the defect. The test region is first discretized into many cells with assumed slowness values (inverse of velocity) and then the time arrivals along the test paths are calculated. The calculated times are compared to the measured travel times and the errors are redistributed along the individual cells using mathematical models. This process is continued until the measured travel times match the assumed travel times within an assumed tolerance. Tomographic analysis was performed using two series expansion algorithms with a curved ray analysis from geotomography. The tomographic analysis presented herein was performed using a SIRT (Simultaneous Iterative reconstruction Technique, Herman 1980) based analysis program developed as part of a research project sponsored by the National Science Foundation to image defects in structural concrete (Olson et al, 1993).

SONIC ECHO / IMPULSE RESPONSE METHODS

Sonic Echo Test Method

The SE method is a low strain integrity test conducted from the surface. Test equipment includes an impulse hammer (optional, an ordinary plastic tipped hammer) and an accelerometer (or geophone) on the shaft top as shown in Figure 4. The impulse hammer has a built-in load cell that can measure the force and duration of the impact (needed for IR tests). The test involves hitting the foundation top with the hammer to generate wave energy that travels down the foundation. The wave reflects off irregularities and/or the bottom of the foundation and travels up the foundation to the foundation top. The receiver measures the vibration response of the foundation to each impact. The signal analyzer or PC processes and displays the hammer and receiver outputs. Foundation integrity is evaluated by identifying and analyzing the arrival times, direction, and amplitude of reflections measured by the receiver in time. The receiver output is usually integrated (if an accelerometer is used) and exponentially amplified with time (Koten and Middendorp, 1981) to enhance weak reflections. Digital filtering with a low-pass filter of about 2,000 Hz is usually applied to eliminate high frequency noise. In some cases, where reflections are difficult to identify, an impedance imaging procedure is used to obtain a 2-D image of the shaft (Paquet, 1991).

Impulse Response (IR) Test Method

The IR method is also an echo test and uses the same test equipment as the SE method. The test procedures are similar to the SE test procedures, but the data processing is different. The IR method involves frequency domain data processing, i.e., the vibrations of the foundation measured by the receiver are processed with Fast Fourier Transform (FFT) algorithms to generate transfer functions for analyses. The coherence of the impulse hammer impact and accelerometer receiver response data versus frequency is calculated to indicate the data quality. A coherence near 1.0 indicates good quality data. In the IR records the linear transfer function amplitude is in velocity/force on the vertical axis (mobility) and frequency in Hz on the horizontal axis.

SE/IR Analyses

Analysis of the integrity of a foundation for both the SE and IR methods is based on the identification and evaluation of reflections. However, test results are analyzed in the time domain for the SE and in the frequency domain for the IR method. The reflections are shown as resonant frequency peaks in the frequency domain for IR test data. The two methods complement each other because the identifications of reflections are sometimes clearer in either the time or the frequency domain.

The SE and IR test methods are sensitive to changes in the shaft impedance (shaft concrete area * velocity * mass density where mass density equals unit weight divided by gravity), which cause the reflections of the compression wave energy. Compression wave energy (hammer impact energy) reflects differently from increased shaft impedance than from decreased shaft impedance. This phenomenon allows the type of reflector to be identified as follows. Soil intrusions, honeycomb, breaks, cold joints, poor quality concrete and similar defects (referred to herein as a neck) are identified as reflections that correspond to a decrease in the shaft impedance. Increases in the shaft cross-section or the competency of surrounding materials (referred to herein as a bulb) are identified as reflections corresponding to increases in the shaft impedance. A decrease in impedance is indicated by a downward initial break of a reflection event in an SE record and frequency peaks positioned in a record such that a peak could be extrapolated to be near 0 Hz in the mobility plot. Conversely, an increase in impedance is identified by an upward initial break for an SE reflector and frequency peaks positioned in an IR record such that a trough could be extrapolated to be near 0 Hz in the mobility plot.

CASE STUDIES

Discussed below are results from CSL and CT tests performed by Olson Engineering on two drilled shaft foundations in California. Also discussed are results from CSL and SE/IR tests performed on a drilled shaft foundation in New Mexico.

The CSL results between tube pair 1-4 of the first shaft in California are presented in Figure 5. A significant delay in arrival times of compression waves and a significant drop in energy were observed in this CSL log at depths ranging from 2.5 to 3.4 m (8.3 to 11.2 ft) below the top of the shaft. Although the anomaly depth is well identified in Figure 5, the exact location of the defect between tubes 1 and 4 cannot be determined. For a better characterization of the anomaly indicated in Figure 5, a tomograhic dataset was obtained by Olson Engineering. For this dataset, the source was pulled from a depth of 5.5 m (18 ft) below the shaft top and ending at the top of the tubes with the receiver moved at fixed interval locations of 57 mm (2.25 in.). A velocity tomogram between tube pair 1-4 is presented in Figure 6. The anomalous zone in Figure 6 is represented as the low-velocity area (light area) which extends from a depth of 2.8 m (9.3 ft) to a depth of 3.5 m (11.6 ft) below the top of the shaft. The apparent low-velocity regions in the middle at the top and bottom of Figure 6 are artifacts resulting from a low ray density in these areas (see Figure 6 for the distribution of the ray densities). Figure 6 clearly shows that the defect occupies the entire distance between tubes 1 and 4, which cannot be inferred from the CSL results. This was confirmed by subsequent excavation.

CSL results performed by Olson Engineering on a drilled shaft foundation at the Sargent Bridge on Highway 101 in Hollister, California identified a defect at depths ranging from 4.6 to 5.2 m (15 to 17 ft). The anomaly was more severe between tube pair 1-3 than between other tube pairs (Figure is similar to Figure 5 and not shown here). This anomaly was further confirmed by Gamma-Gamma testing and destructive coring showed it to be a soil intrusion. Tomograhic data was obtained between tube pair 1-3 with the source pulled from 5.8 m (19 ft) below the shaft top to the shaft top and the receiver fixed at 49 locations of 57-mm (2.25-in.) separation. Figure 7 shows the velocity tomogram obtained from this tomographic dataset along with the corresponding ray density plot. The anomalous zone in Figure 7 is represented as the low-velocity area which extends from a depth of 4.6 m (15 ft) to a depth of 5.2 m (17 ft) below the top of the shaft. Figure 7 shows that the defect is centered around the tubes with good quality concrete in the interior between the two tubes as opposed to the defect shown in Figure 6 which extended through the entire distance between the two tubes.

The CSL results between tube pair 1-2 of a shaft tested in New Mexico are presented in Figure 8. A significant delay in arrival times of compression waves and a significant drop in energy were observed in this CSL log at depths ranging from 10.4 to 11.6 m (34 to 38 ft) below the top of the shaft. The CSL results between other tubes showed similar anomalies at the same depths. Another commonly used display for CSL data is the banded time versus depth (also known as Z-axis modified). In this display, a line is plotted for each point of each record for which the positive or negative signal peaks are greater than the threshold value. This results in a series of bands vertically down the plot for a shaft with no defects. A defect will be seen as a disappearance of the bands at the defect depth. Figure 9 shows this type of display for the shaft tested in New Mexico with the negative peaks as the black bands. Sonic Echo/Impulse Response tests were performed on the same shaft. Echoes from a depth of 11 m (36 ft) were identified in the SE records as shown in Figure 10. The upper trace in Figure 10 represents the accelerometer output and the lower trace represents the upper trace after integration (to velocity) and exponential amplification. The IR results showed an echo from a depth of 10.8 m (35.3 ft) as shown in Figure 11. The upper trace in Figure 11 represents the coherence function to reflect data quality and the lower trace is the mobility function which is equal to velocity divided by pound force. No echoes from the bottom of the shaft at a depth of 18.9 m (62 ft) were identified in the SE/IR records. It was then concluded that the encountered defect is a major defect since bottom echoes could not be identified. Note also the good agreement between the CSL and SE/IR results. If there were additional defects below the major encountered defect at a depth of 11 m (36 ft), they most likely would not have been identified by the SE/IR method, but could easily have been identified with the CSL method.

SOLUTIONS TO ENCOUNTERED DEFECTS

When defects are encountered in drilled shafts, the design engineer is informed of the problem. The structural and geotechnical engineers usually check the axial and lateral capacity of the shaft after considering the size, depth and severity of identified defects plus actual load test results (if any), concrete strengths and volumes with appropriate safety factors. Based on the new calculations, the shaft is either accepted or rejected.

For shallow defects, the most common procedure is to excavate around the perimeter of the shaft until the defect area is exposed and repair procedures take place. For deep defects which still influence the capacity of the shaft, coring is usually performed and grout is injected using the coreholes. In other circumstances, two substitute shafts are drilled next to the defect shaft so that sufficient load can be transferred to the new shafts via a tie beam such that the defect shaft may carry no loads or reduced loads safely.

CONCLUSIONS

The CSL method is an excellent nondestructive method for identifications of anomalous zones in drilled shaft foundations. Many State DOT's are moving towards specifications for CSL tests on new construction of drilled shaft foundations. The method is effective at locating defects between tube pairs, defect depths and extent, but not exact locations of defects between tube pairs.

The CT can be used as a complimentary method to the CSL method to determine a better characterization of the defect. Because of the much greater time required to perform tomographic analyses, the method may not gain popularity and its application will be limited to the more critical structures. The SE/IR method can be used in conjunction with the CSL method to determine the nature of encountered anomalies. A good application for the SE/IR method is when the identified anomalies in CSL testing are due to tube debonding and do not represent any defects in the drilled shafts. An SE/IR test is usually performed and if no reflections are identified in the areas where tube debonding occurred in CSL testing, the shaft is considered to be sound.

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LIST OF FIGURES

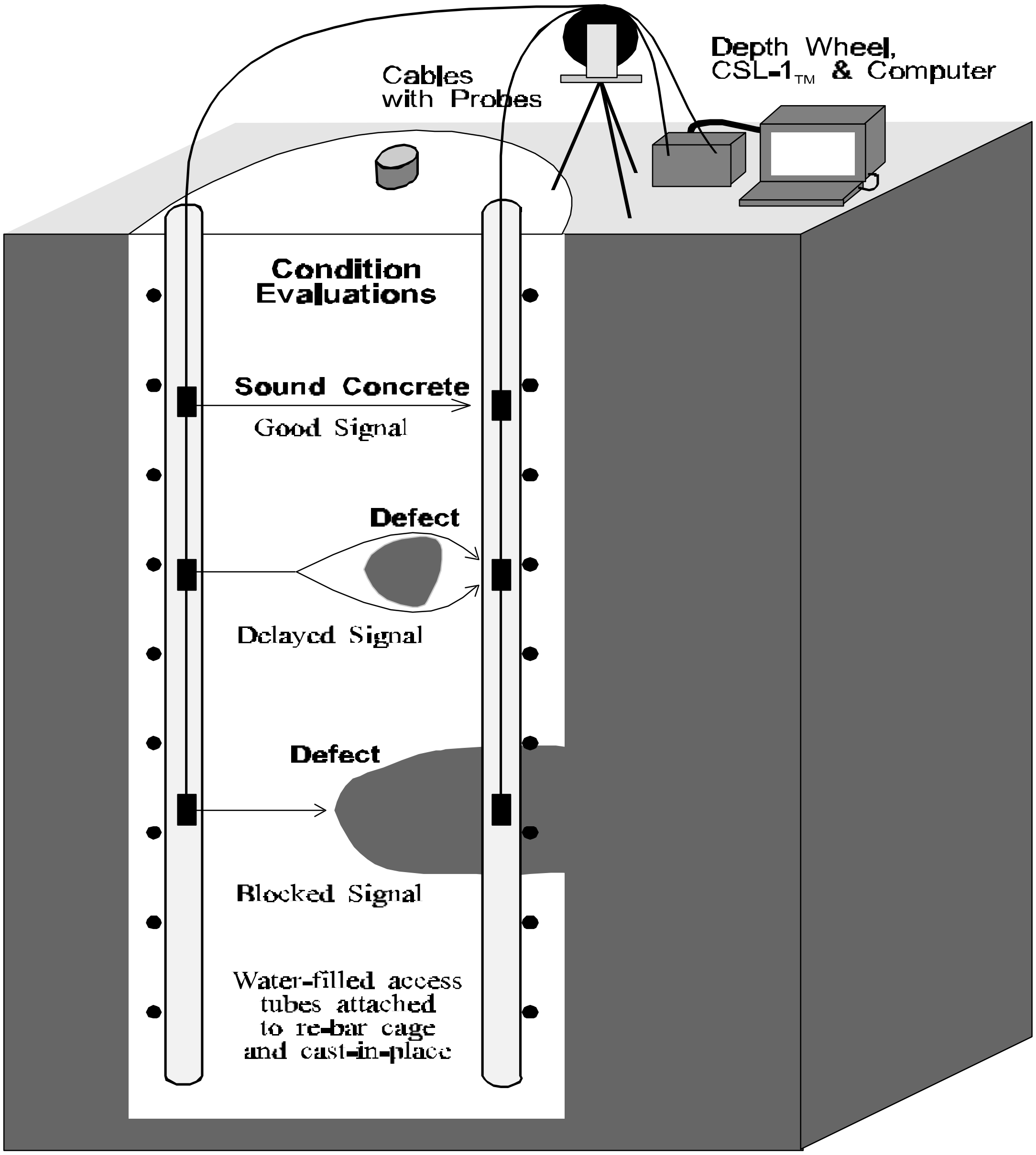
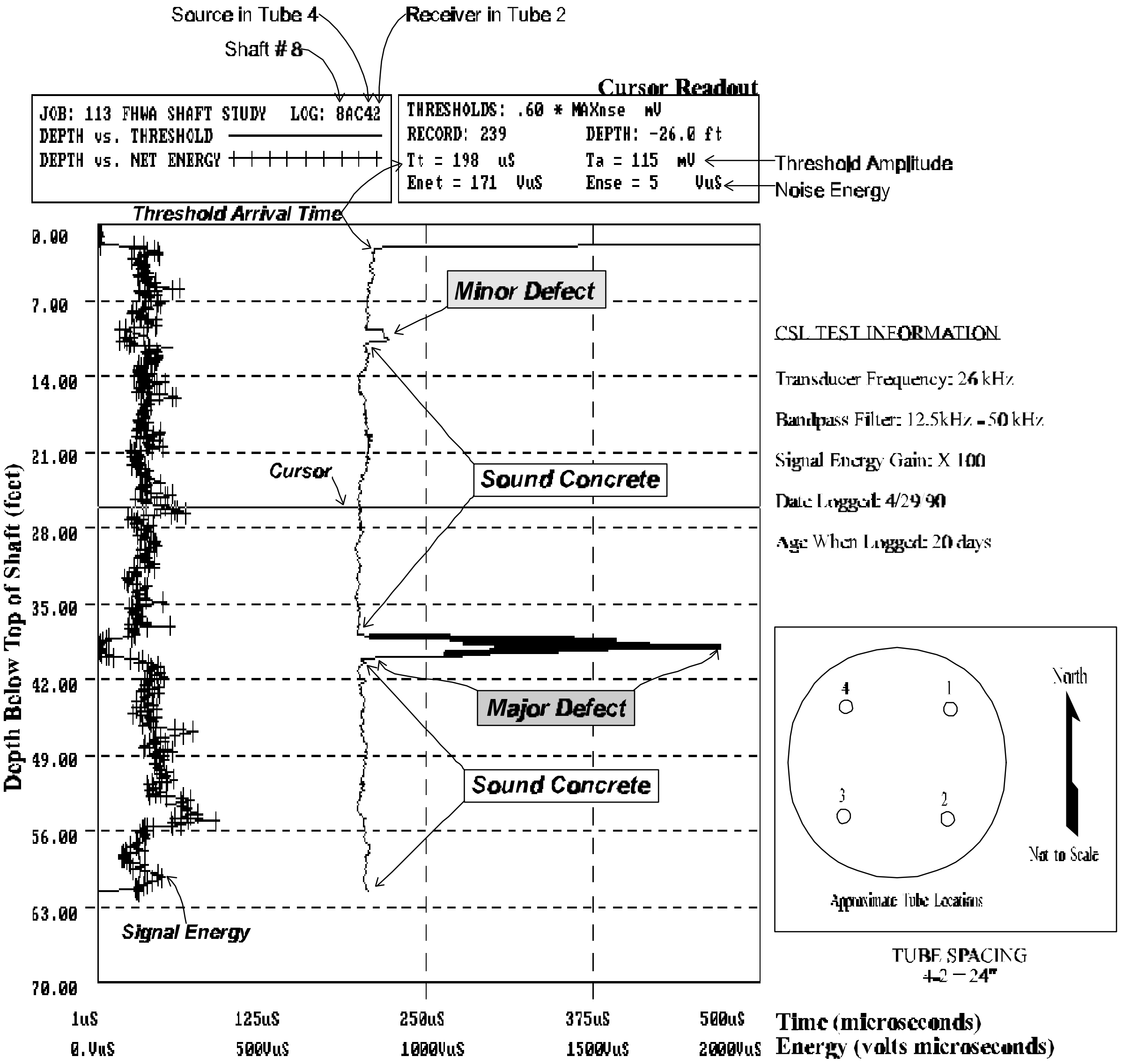


Figure 1- Crosshole Sonic Logging Test Setup.



Note: CSL Log from Shaft 8 of FHWA San Jose California Research Site
Drilled Shafts for Bridge Foundations (DTFH 61-88-Z-00040)
Shaft 8 is 3 ft diameter with known defects attached to the rebar cage during construction.

The Major Defect is a 1/6 diameter neck in at 40 ft depth (56% of shaft cross-section).
The Minor Defect is an elliptical inclusion at 12 ft depth (15% of shaft cross-section).

Figure 2- Example Crosshole Sonic Log.

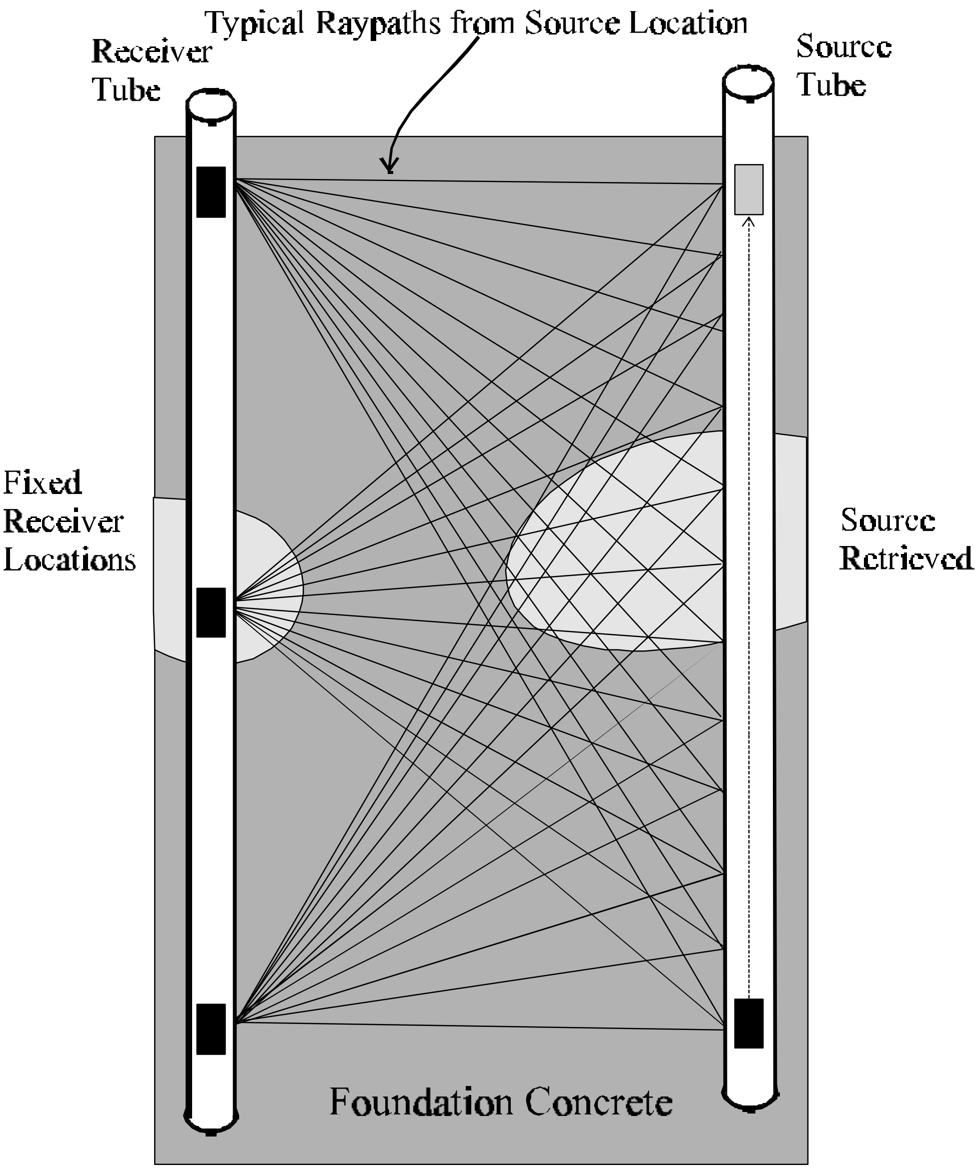


Figure 3- Crosshole Tomography Setup between Two Tubes of a Drilled Shaft.

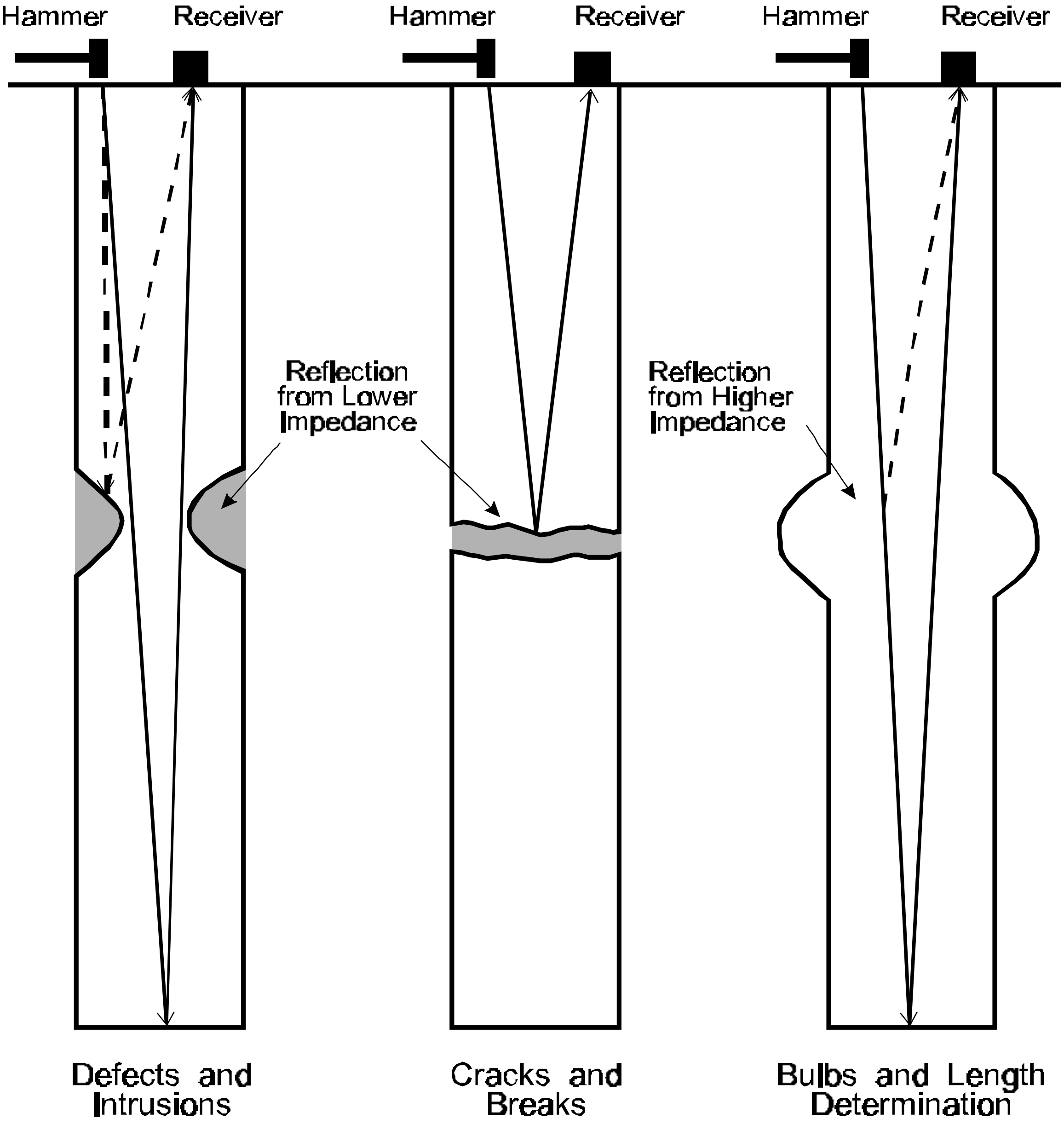


Figure 4- Sonic Echo/Impulse Response Test Method.

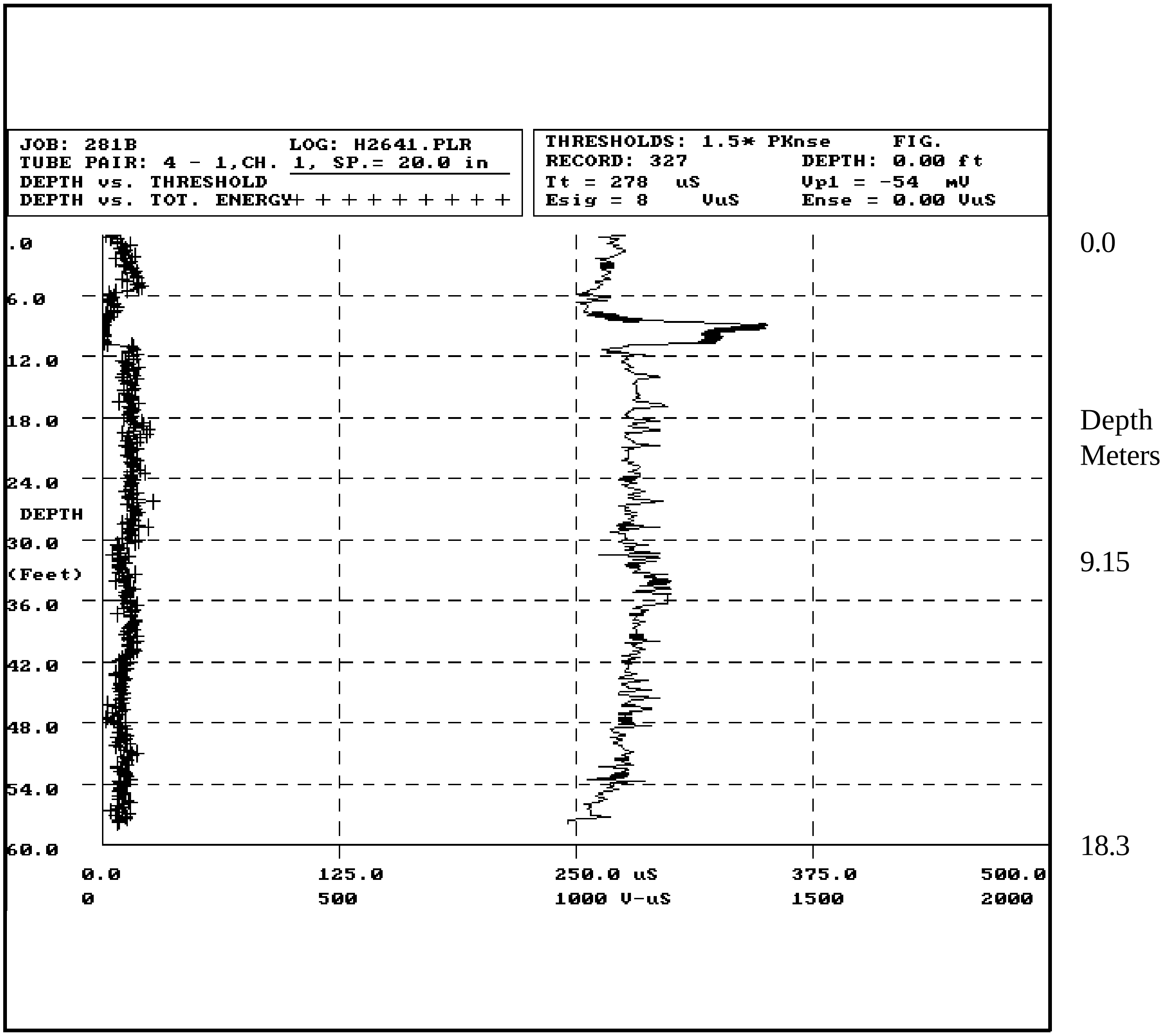


Figure 5- CSL Results Between Tubes 4-1 in a Drilled Shaft in California.

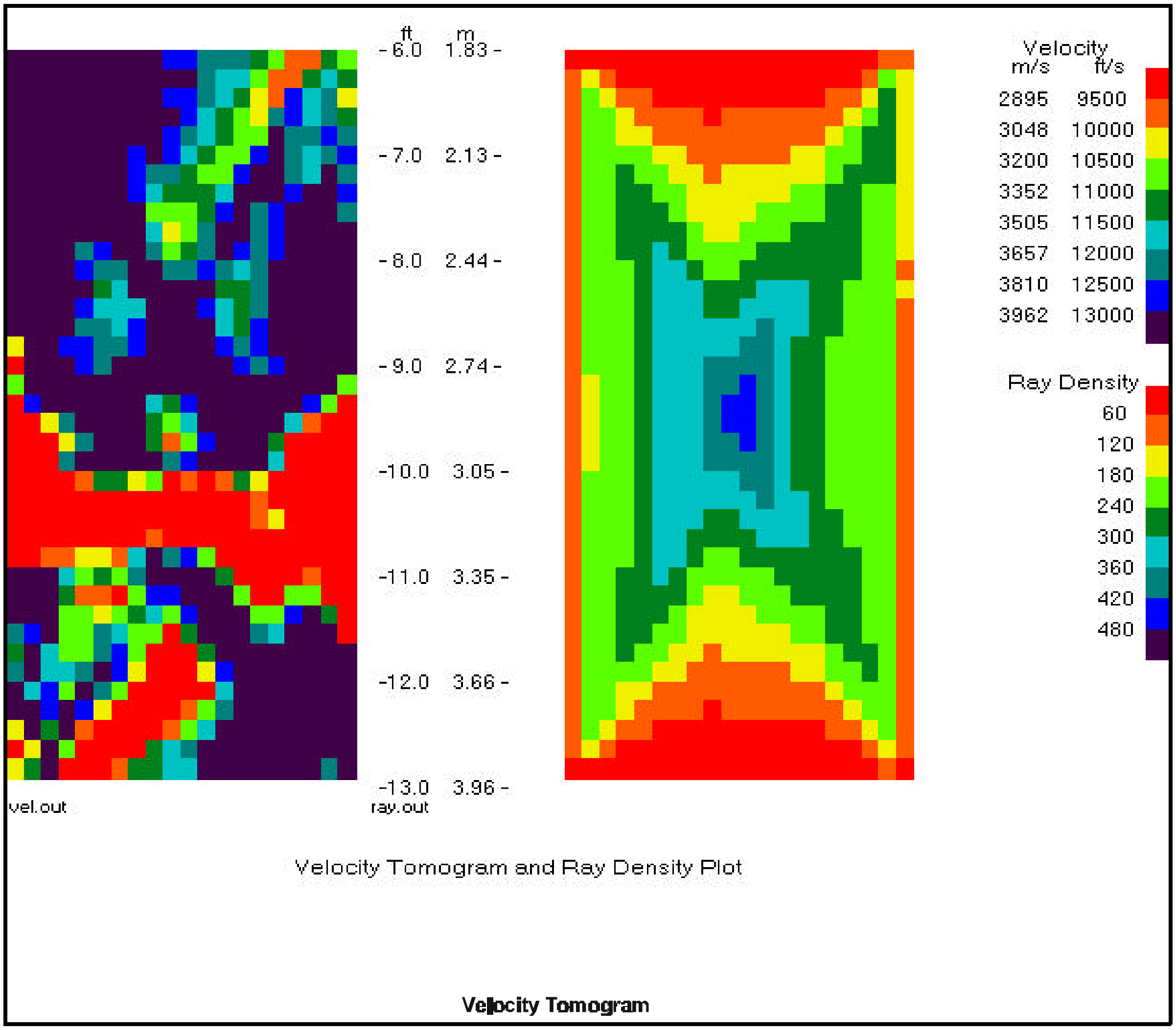


Figure 6- Velocity Tomography Results from the First Drilled Shaft in California.

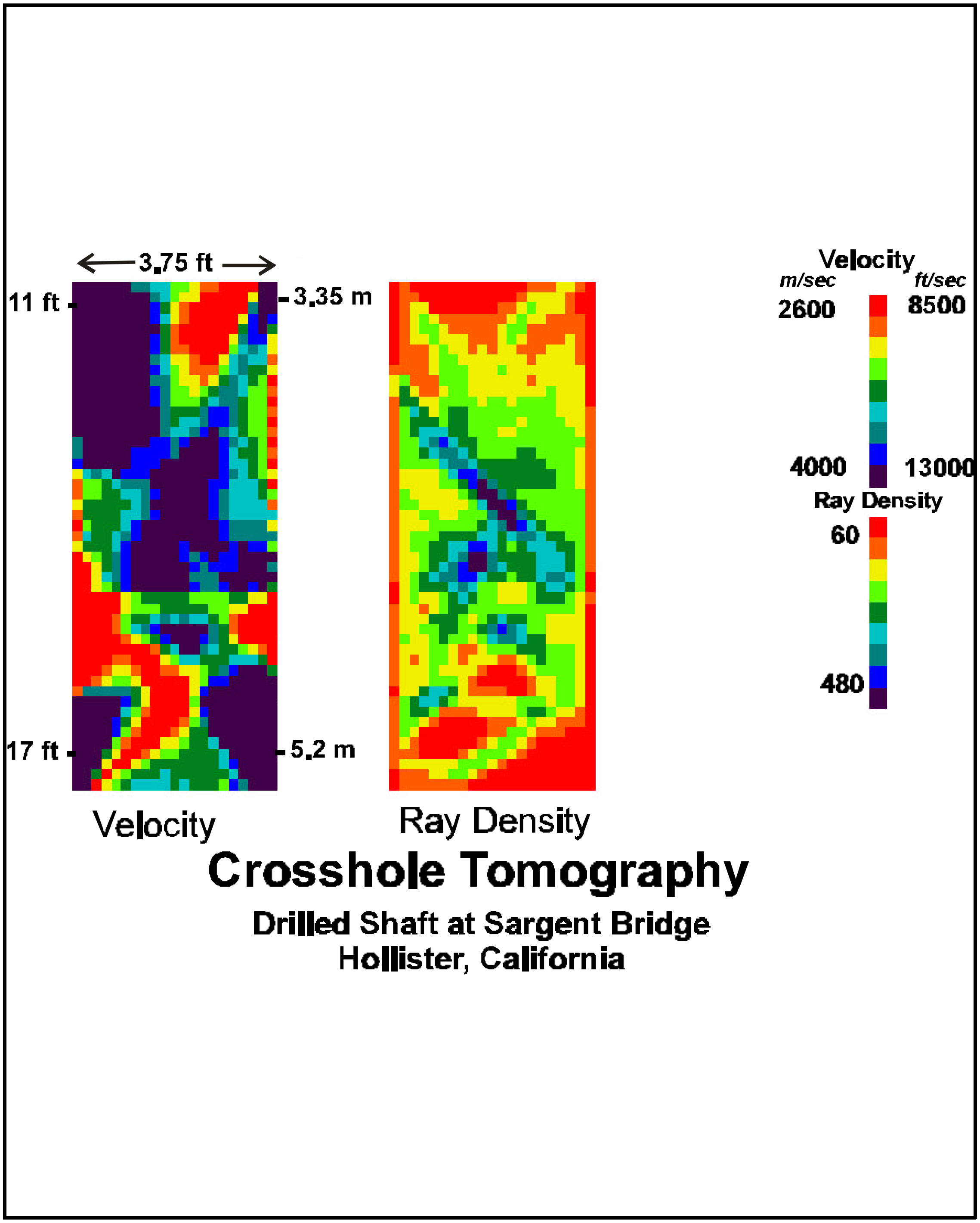


Figure 7. Velocity Tomography Results from the Second Drilled Shaft, Hollister, California.

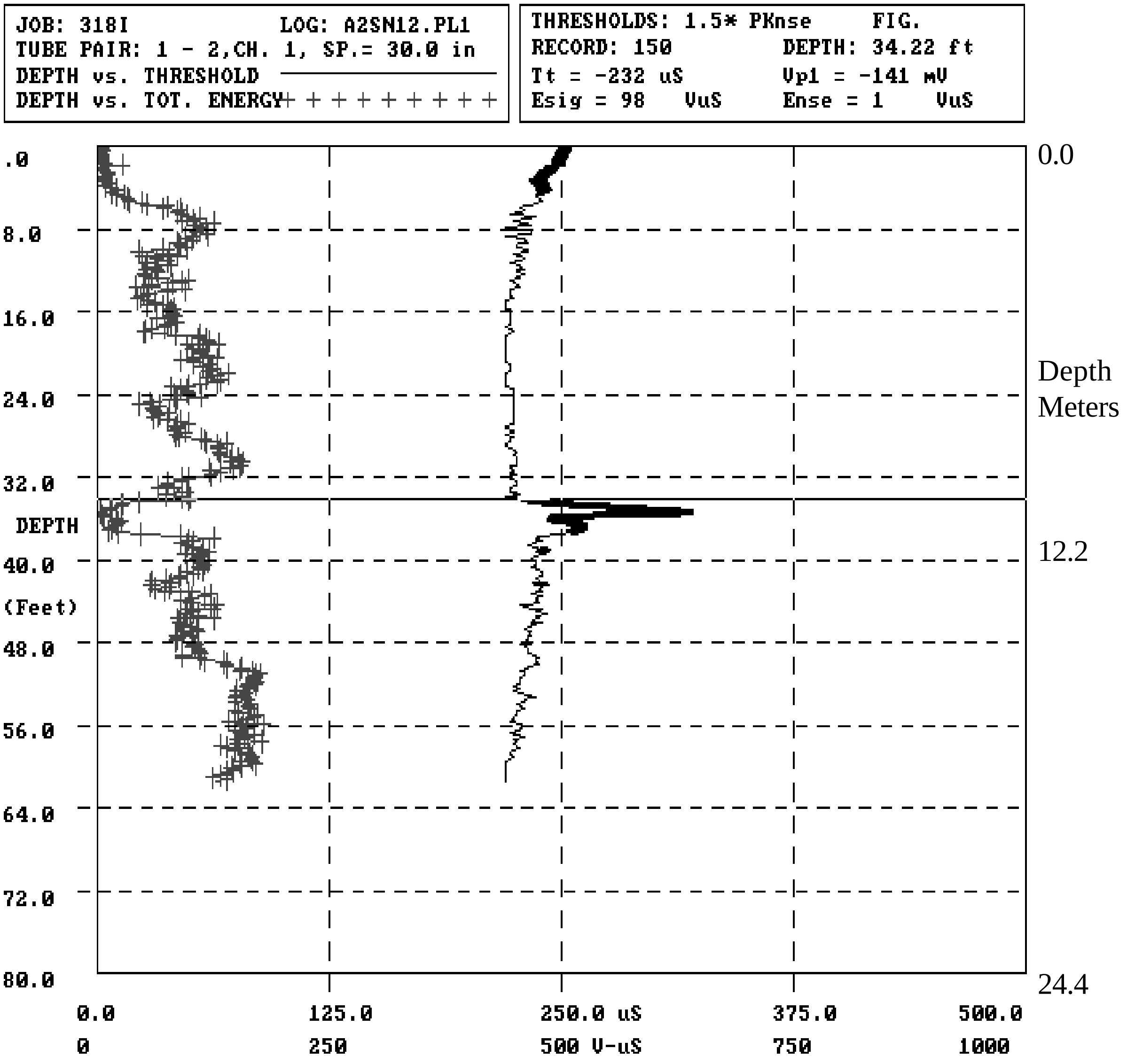


Figure 8- CSL Results Between Tubes 1-2 in a Drilled Shaft in New Mexico.

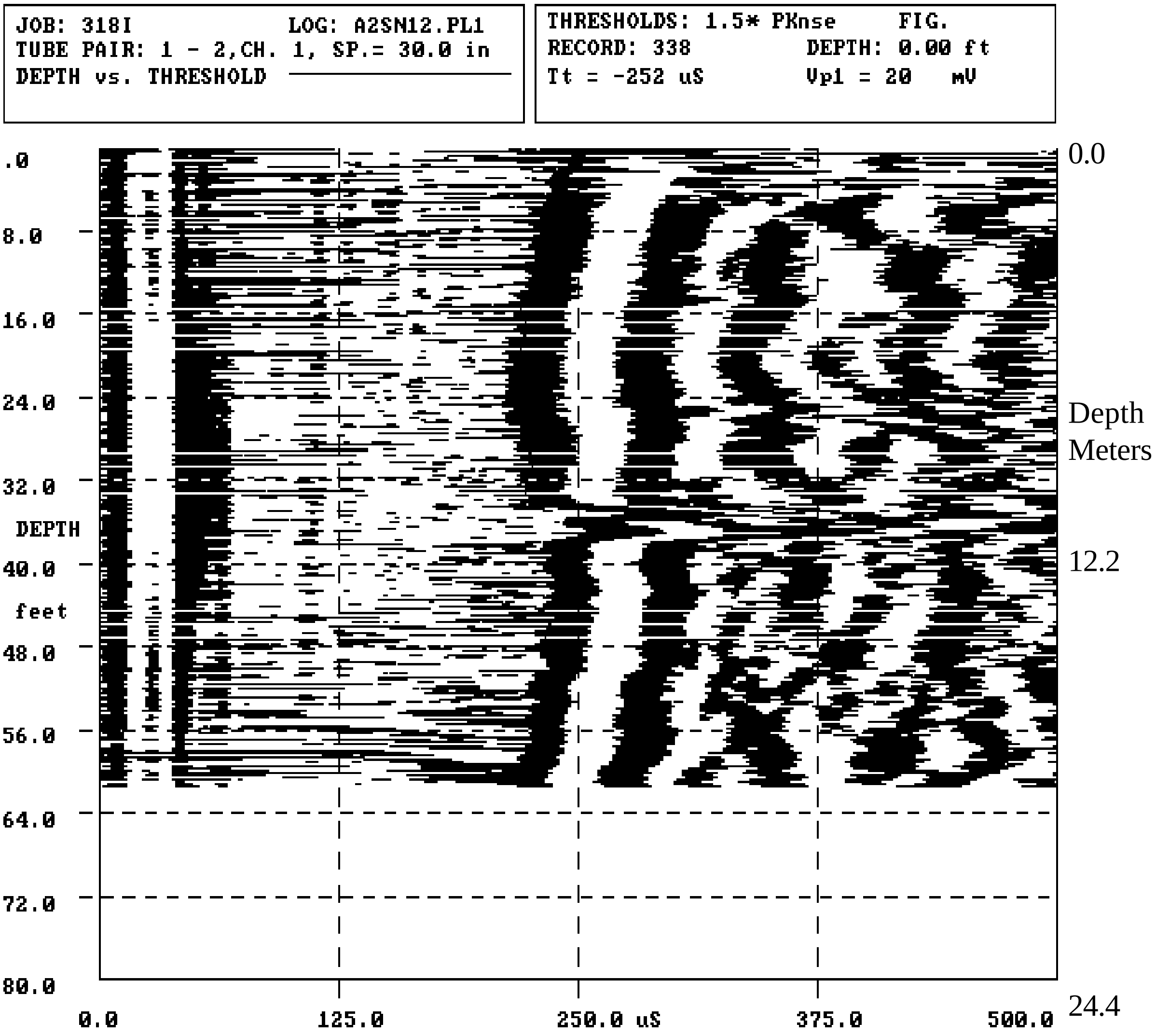
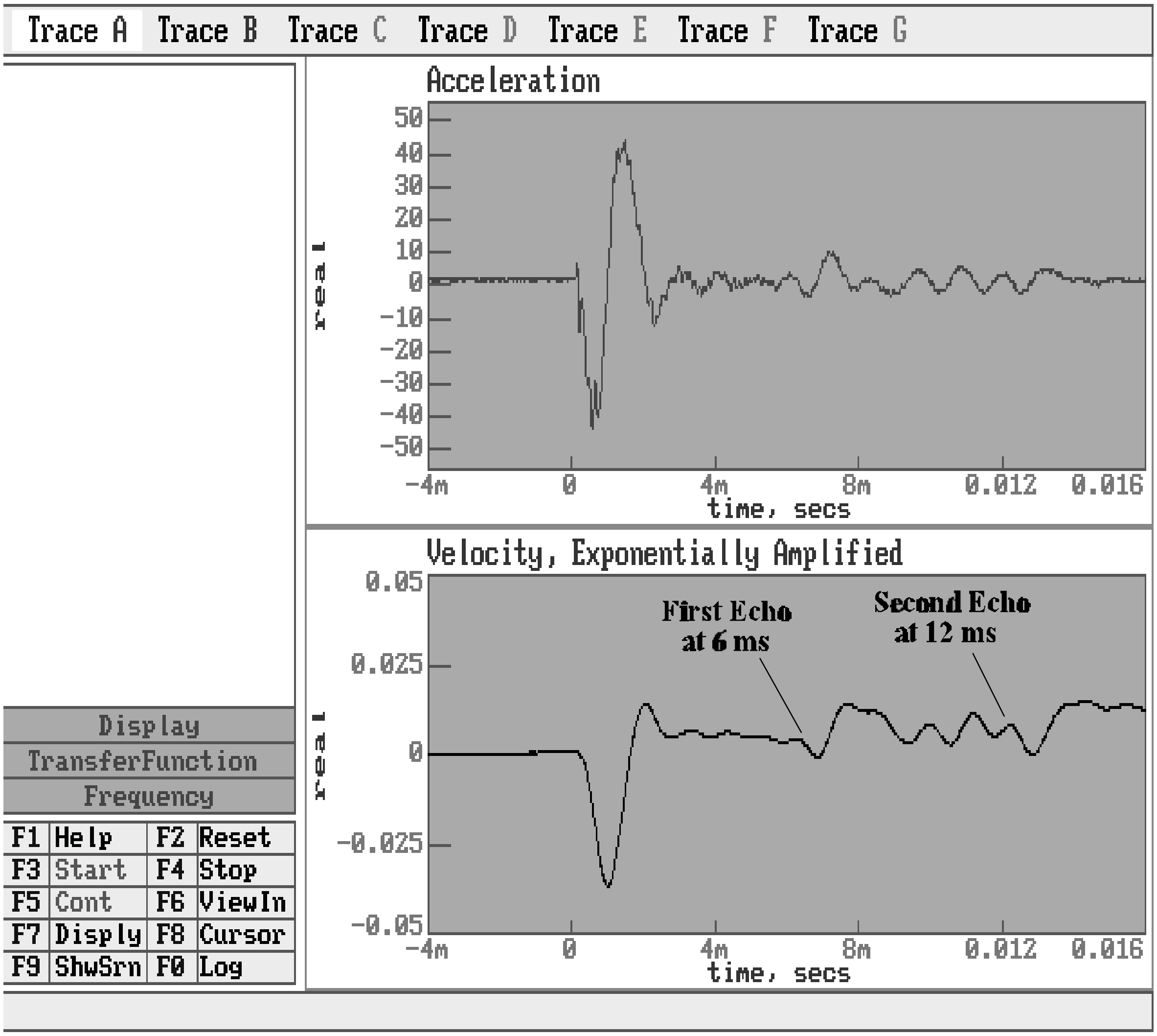


Figure 9- Alternative Banded Time Display of CSL Results Between Tubes 1-2 in a Drilled Shaft in New Mexico.



The lower trace shown is the same data as the upper trace after it has been integrated and exponentially amplified.

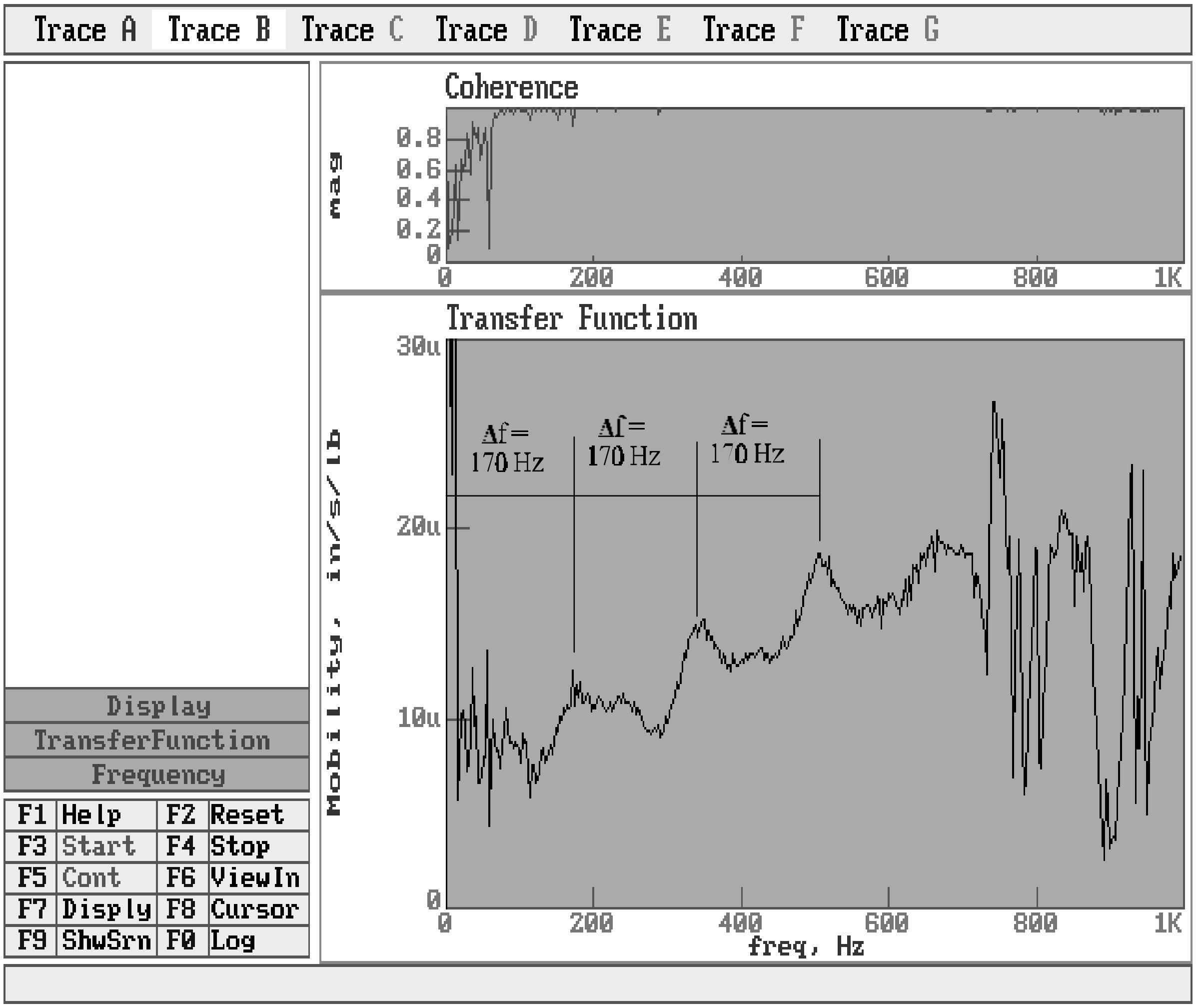
T_1 = 6 ms T_2 = 12 ms

Compression Wave Velocity = 3658 m/sec (12,000 ft/sec)

Depth of Reflector = V_C * T1/2 = 3658 * 0.006/2 = 11 m (36 ft)

The reflection is from an anomaly located at about 11 m below the shaft top

Figure 10- Sonic Echo Test Results, Drilled Shaft in New Mexico.



The upper trace shown is the coherence function to reflect data quality.
The lower trace is the mobility function used to obtain reflector depth

)f = 170 Hz
Compression Wave Velocity = 3658 m/sec (12,000 ft/sec)
Depth of Reflector = V_C/)f* 2 = 3658/ 170* 2 = 10.8 m (35.3 ft)
The reflection is from an anomaly located at about 11 m below the shaft top

Figure 11- Impulse Response Test Results, Drilled Shaft in New Mexico.