Nondestructive evaluation of concrete dams and other structures

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ABSTRACT

This paper presents an overview of several stress-wave based nondestructive testing methods which can be used to assess the condition of concrete structures such as dams, buildings, and foundations. The specific methods to be presented include the use of the Impact Echo (IE) and Spectral Analysis of Surface Waves (SASW) methods in the assessment of dam concrete condition (including freeze-thaw damage assessment), the use of Ultrasonic Pulse Velocity Tomography (UPV Tomography) in the 2 dimensional imaging of concrete defects in walls and foundations, and the use of the Crosshole Sonic Logging (CSL) method for rapid, accurate, and cost-effective quality assurance of drilled shaft foundations. Included in this paper are summary descriptions of each of the NDT methods used (including some underlying theory), along with brief case histories of the application of each of these methods to real-world problems. Case histories presented include the evaluation of the Rogers' Dam spillway for freeze-thaw damage and overall concrete condition, the use of the CSL method in quality assurance testing of foundations for the LA Metro Green Line, and the use of tomography for imaging a defect in a deep foundation.

Key Words
Impact Echo, IE, Nondestructive Testing, Tomography, Ultrasonic Pulse Velocity, Crosshole Sonic Logging, Concrete Testing, Spectral Analysis of Surface Waves, SASW

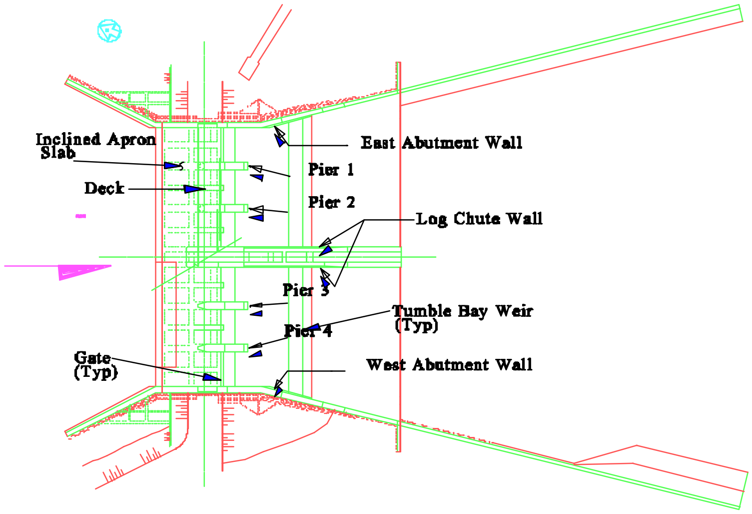
1. INTRODUCTION

A number of stress-waves based methods can be used for assessment of in-place condition of concrete structures. Of the many methods available, two have been found to be most useful in condition assessment of structures with access to only one side of the test members. These are the Impact Echo (IE) method and the Spectral Analysis of Surface Waves (SASW) method. The IE method has long been recognized as a powerful tool for the nondestructive testing of concrete members. It has the advantage of requiring access to only one side of a test member, and is capable of determining member thickness as well as flaw depth when used on members with simple geometries. A new scanning system has recently been developed which uses rolling transducers, water coupling, and solenoid-driven impactors to allow linear scanning of flat concrete members at test rates of over 2000-3000 points per hour. This Impact Echo scanning system is presented in detail in another paper at the SPIE conference (1). The SASW method is another powerful method for assessment of concrete when only one side is available for testing. The SASW method is capable of providing the shear wave velocity versus depth profile of a structure, including measurements of the velocity of soils or rock behind the structure, with no coring or other damage to the structure required. The shear wave velocity versus depth profile is useful in that the shear wave velocity of a material is directly related to the strength of a material if the Poisson's ratio and density are known. Thus, the SASW test method can be used the estimate relative strength of the concrete (and other materials) versus depth into the test surface. The first section of this paper presents a summary of a case history showing the use of the IE and SASW methods in tandem to assess the condition of a concrete dam with freeze-thaw and other internal damage.

When access is available to both sides of a member for testing, the Ultrasonic Pulse Velocity method has long been used for condition assessment. One limitation of this method has always been that if a defect is located, the depth, size, and shape of the defect cannot be normally be determined. A recent advance in the use of computer processing and rapid data acquisition methods has resulted in the ability to produce tomograms, or two dimensional images, of defects within a wall. The images are presented as a 2-D picture of the velocity versus location of the material within the wall along a given slice. Tomographic methods have also been used for imaging defects in deep foundations, with the data collected with the Crosshole Sonic Logging (CSL) method. This is a method normally used for inexpensive and rapid quality assurance of drilled shaft foundations. The CSL method uses ultrasonic pulses sent between cast-in-place access tubes to measure the compression wave velocity profile of a foundation from top to bottom. A modification in the way the data is collected can result in a tomographic-compatible data set in less than one hour of testing time. Processing of this data set will yield a "picture" of a defect in the shaft, including rough size, shape, and location information. A typical example of a tomogram from a drilled shaft defect is included in this paper.

2.0 NDT OF ROGERS DAM WITH IMPACT ECHO AND SPECTRAL ANALYSIS OF SURFACE WAVES

The use of the Impact Echo and Spectral Analysis of Surface Waves methods for the condition assessment of a large concrete dam structure is illustrated by a case history of the evaluation and rehabilitation of the Consumers Power Company's Rogers Dam Hydroelectric Generating Plant, located on the Muskegon River in western Michigan. This dam was constructed at the beginning of this century. It consists of a powerhouse, a three-section earthen dam of 805 feet in total length, and a concrete spillway structure founded on timber piles driven to hardpan.



PLAN - ROGERS SPILLWAY

The concrete spillway structure is 156 feet wide, 193 feet long and 36 feet high. The structure supports six radial tainter gates, each 20 feet wide and 12 feet 6 inches high, and a central log chute, six feet wide. The general arrangement of the spillway is shown in Fig. 1. The spillway is constructed of unreinforced, mass concrete without air entrainment and has suffered freeze/thaw damage throughout its life. The concrete has frequently been repaired. Recent repairs in 1985 involved removing the damaged concrete and resurfacing it with shotcrete.

Field observation in 1991 revealed that the repaired spillway structure had extensively degraded. The characteristic patterns of alligator cracking were prevalent, and shotcrete surface at many locations produced a hollow sound when struck by a hammer, indicating that the surface shotcrete had debonded from the interior concrete.

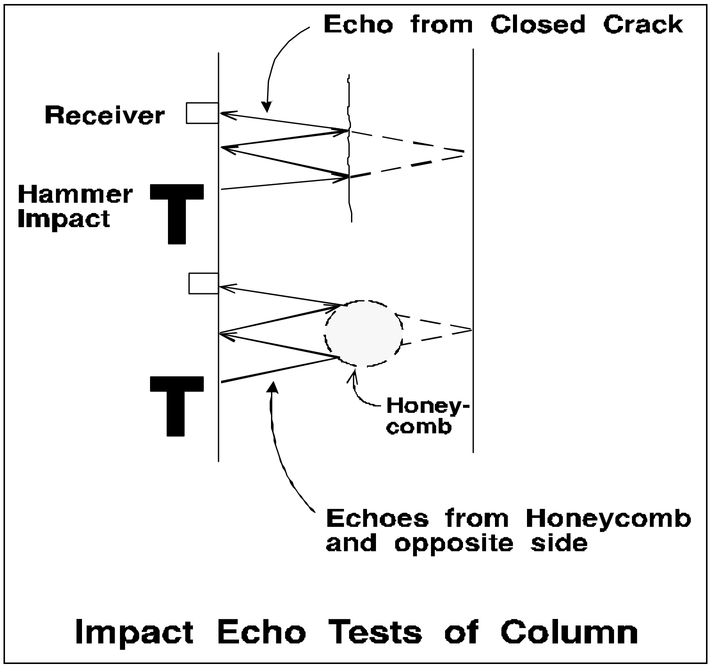
Because of the greatly varying concrete conditions found with a limited coring and visual inspection, Acres International recommended performing nondestructive testing (NDT) to better define the concrete conditions on a fine-grid pattern, so that the extent of structural rehabilitation could be assessed and the optimum repair method devised. Olson Engineering was retained to perform the NDT.

2.1 NDT test methods

Impact-Echo (IE) and Spectral-Analysis-of-Surface-Waves (SASW) test methods were chosen for investigating the spillway structure. The IE test method was used to determine the extent of concrete cracking and the SASW test, the thicknesses of the surface shotcrete and the underlaying layer of weathered/deteriorated concrete. Brief descriptions of the IE and SASW methods are included in the next two sections.

2.1.1 IE test method description

The IE test is a stress-wave based method for nondestructive condition assessment of concrete which requires access to only one side of a structure and is capable of measuring the depth to a flaw. The method and applications have been well described in previous publications (2,3). As stated, the IE method is performed by hitting the test surface at a given location with a small instrumented impulse hammer or impactor and recording the reflected wave energy with a receiver mounted to the test surface adjacent to the impact location. Since the reflections are more easily identified in the frequency domain, the time domain test data are processed by a signal analyzer for frequency domain analyses. For data collected with the impulse hammer and accelerometer, a transfer function (system output/input) is then computed between the hammer (input) and receiver (output) in displacement units as a function of frequency. If an impactor is used instead of an instrumented hammer, then just the linear spectrum of the receiver signal is computed and displayed. Reflections, or "echoes", of the compression wave energy are indicated by pronounced "echo" peaks in the transfer function or frequency spectrum test records. These peaks correspond to thickness or flaw depth resonant frequencies. If the velocity of the concrete is known or can be measured (as is usually the case), then the depth of a reflector can be calculated from the echo peak frequency. For sound concrete slabs or walls, the depth of the reflector will correspond to the local slab or wall thickness.



2.1.2 SASW test method description

The SASW method is a powerful NDT method which indicates material modulus (stiffness) versus depth while measuring from one surface and without any coring or other material intrusion required. The SASW method is based upon measuring surface waves propagating in layered elastic media and is pictured in

Fig. 2. The ratio of surface wave velocity to shear wave velocity varies slightly with Poisson's ratio, but can be assumed to be equal to 0.90 with an error of less than five percent for most materials, including concrete. Measurement of the surface wave velocity with the SASW method similarly allows calculation of compression wave velocity for use in IE test analysis. Knowledge of the seismic wave velocities (surface and compression) and mass density of the material layers allows calculation of shear and Young's moduli for low strain amplitudes (4,5,6).

Surface wave (Rayleigh; R-wave) velocity varies with frequency in a layered system with velocity contrasts, and this frequency dependence of velocity is termed dispersion. A plot of surface wave velocity versus wavelength is called a dispersion curve. The SASW tests and analyses are performed in up to three phases: (1) collection of data in situ; (2) construction of an experimental dispersion curve from the field data; and (3) inversion (forward modeling) of the theoretical dispersion curve, if desired, to match the experimental curve and provide the shear wave velocity versus depth profile.

The SASW field tests typically consist of impacting the test surface to generate surface wave energy at various frequencies that are transmitted through the material. Typically, two accelerometer receivers are evenly spaced on the surface in line with the impact point to monitor the passage of the surface wave energy. To obtain increasingly deeper data, several tests with different receiver spacings can be performed by doubling the distance between the receivers about the imaginary centerline between the receivers.

A PC-based data acquisition system digitizes the analog receiver outputs and records the signals for spectral (frequency) analyses to determine the phase information of the transfer function between the two receivers versus frequency. The dispersion curve is developed by knowing the phase shift (ö) in degrees at a given frequency (f) and then calculating the travel time (t) between receivers of that frequency/wavelength by:

$$t = \ddot{o} / 360*f \qquad (1)$$

Surface wave velocity (Vr) is obtained by dividing the receiver spacing (X) by the travel time at a frequency:

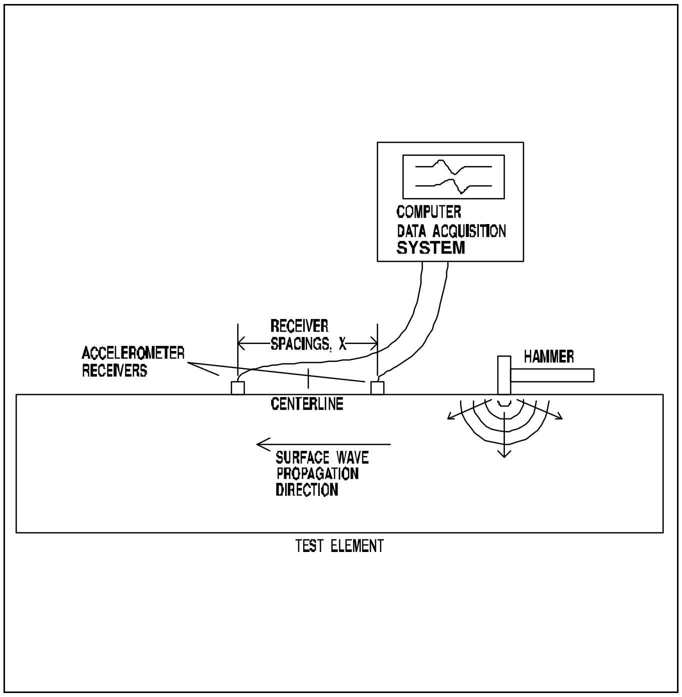
$$Vr = X / t(2)$$

The wavelength (Lr) is related to the phase velocity and frequency by:

$$Lr = Vr / f(3)$$

By repeating the above procedure for any given frequency, the surface wave velocity corresponding to the given wavelength is evaluated, and the dispersion curve is determined.

Forward modeling is the process of determining the "true" shear wave velocity profile from the "apparent" velocity of the dispersion curve. The forward modeling inversion process is iterative and involves assuming a shear wave velocity profile



and constructing a theoretical dispersion curve. The experimental (field) and theoretical curves are compared, and the assumed theoretical shear wave velocity profile adjusted until the two curves match. The SASW method and an interactive computer algorithm for both 2-dimensional and 3-dimensional analyses have been developed by Drs. Kenneth H. Stokoe II and Jose Roesset of the University of Texas at Austin (and their students) to compute a theoretical dispersion curve based upon an assumed shear wave velocity and layer thickness profile.

2.2 NDT investigation summary and results

The NDT was conducted by Olson Engineering personnel assisted by Acres International and Consumers Power Company personnel. Altogether, 380 locations were tested using the IE method on the abutment walls, log chute walls, piers (both sides), tumble bay weirs, inclined apron slab and sill beams. The SASW testing was conducted in 131 locations on the abutment walls, log chute walls and piers. SASW receiver to receiver spacings were typically 1 and 3 feet.

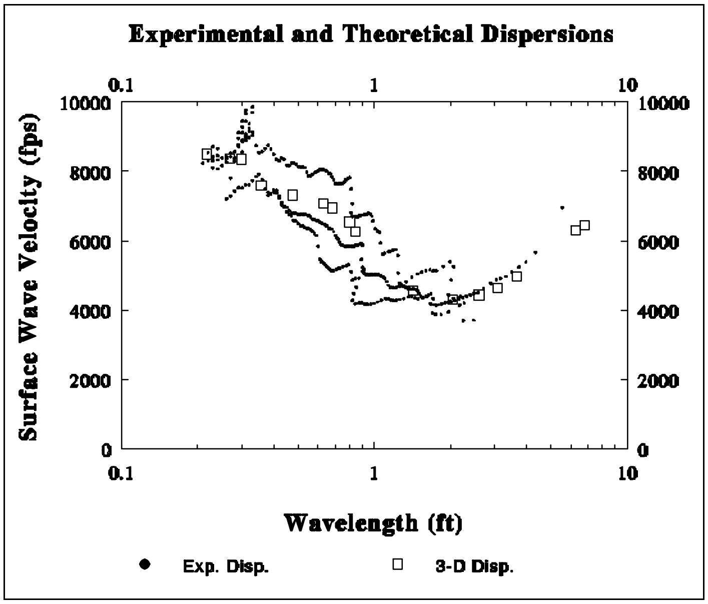
2.2.1 IE results

Overall, only 9% of the locations tested on the spillway with the IE method indicated sound concrete and 28% indicated minor to moderate cracking. Of the remaining points, 10% indicated severe cracking and 53% indicated severe front face delamination of the shotcrete. Of the areas tested, only the apron areas showed relatively sound conditions. Other significant findings include finding less than 20% of the points tested on the abutments indicating sound or even only minor/moderate cracking, all of which were located near the base of the abutments. Most points on the abutments, piers, and log chute walls were indicated to have severe surface delamination or cracking. This agrees with the findings of the SASW testing which showed that the sound shotcrete layer was relatively thin and had generally separated from the very low-strength, degraded material underneath. The only areas with mostly sound conditions were the apron and tumble weir areas. These areas are at ground level and thus are presumably exposed to different conditions than those experienced by the vertical members. The results of the NDT showed that the apron and tumble weirs needed significantly less rehabilitation than the other structural members.

2.2.2 SASW results

Spectral-Analysis-of-Surface-Waves (SASW) tests were performed at many of the IE test locations on the piers, abutment walls, and log chute walls. The SASW results were classified in 3 categories: sound shotcrete/concrete (good velocity throughout the depth profile), comparatively shallow degradation (1 foot or less of poor concrete with sound concrete below), and deep degradation (greater than 1 foot of poor concrete, with no sound concrete measured. Of the 99 SASW survey locations with good quality data, only 2 of the locations had comparatively high velocity, sound concrete, while 22 showed shallow degradation and 75 showed deeper degradation. The deteriorated concrete zones showed shear wave velocities of from 2,500 to 4,700 ft/sec, with thicknesses ranging from 0.5 to 1.5 feet and depths of up to 1.9 feet.

In addition to being used for estimating the depth of the weathered concrete zones, the SASW data was analyzed to determine the condition of the concrete below. Of the 99 SASW locations that could be analyzed, 51 locations showed an increase in apparent surface wave velocity below the low velocity zone. This finding is significant since it demonstrates that there was a higher velocity, relatively sound interior concrete core in the abutment walls and piers. For points where no increase with depth was noted, the most likely explanation is that the longer wavelengths required were not measured either because surface delaminations or perpendicular cracks were present or because the maximum attempted receiver spacing of 3 feet was too short to obtain deeper data in areas of severe near-surface degradation.

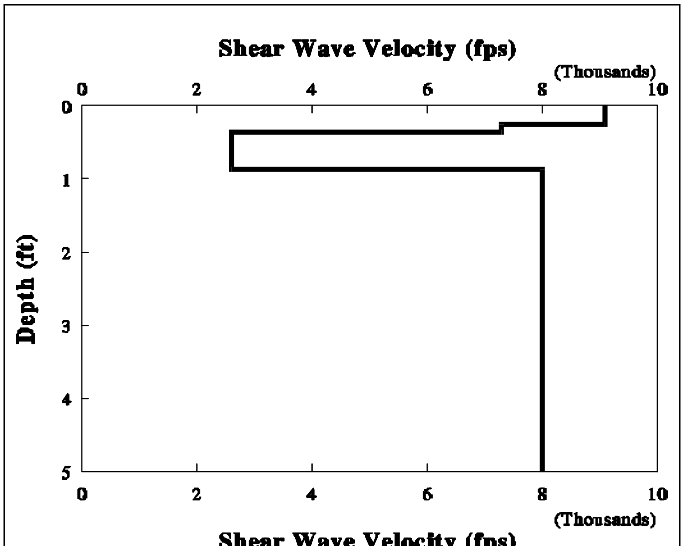


Sample SASW dispersion curve and velocity profiles are presented in Figs. 4 and 5 for a location with sound surface material, followed by a layer of degraded concrete, below which is sound core concrete. The field dispersion curve data, and 2-D and 3-D (more accurate) theoretical analysis, produced dispersion curves as presented in Figure 4 followed by the shear wave velocity profile versus depth plot in Fig. 5. The dispersion curve is plotted with surface wave velocity on the vertical linear axis scale and wavelength in feet on a horizontal logarithmic (base 10) scale (Fig. 4). The theoretical shear wave velocity profile is plotted on a linear scale with velocity on the horizontal axis and depth of each analysis layer on the vertical axis in feet (Fig. 5).

2.3 Comparison with as-found conditions (Pier 1 and East Abutment Wall)

During demolition in 1993, a pneumatic hammer was used to demolish the surface shotcrete, followed by hydroblasting to remove the deteriorated concrete layer below. The shotcrete came off very easily. After hydroblasting, an average of 10 inches of concrete/shotcrete was removed from the west face of Pier 1, less than 6 inches from the east face of Pier 1 and between 10 to 14 inches of average thickness from the various locations on the east abutment wall. The hydroblasting operation also removed all deteriorated (unsound, weathered) and low strength (less than 3,000 psi) concrete at the construction joints. For the east abutment wall, the construction joints were spaced about 3 feet apart. In many locations, the depth of concrete removed exceeded 30 inches and the width, one foot on the surface. These joints usually ran the entire length of the abutment wall and could have been unbonded but closed joints.

The ease of shotcrete removal verifies the IE results showing that the shotcrete was delaminated from the interior sound concrete. The depth of concrete removed at the test locations on the east abutment wall and on the east face of Pier 1 agreed well with the SASW test results.



2.4 Conclusions

For this investigation, the IE and SASW NDT methods were employed to investigate the concrete conditions of the Rogers Hydro Station's concrete spillway. The results showed that the surface shotcrete on the majority of the piers and walls was delaminated from the interior sound concrete and that there was a significant amount of sound concrete in the interior cores of the piers and walls. These results were verified during the hydroblasting operations, which showed that while the outer shotcrete was sound (and came off in large sheets), the material behind the shotcrete was significantly degraded and even rubble down to depths of 10-30 inches. Below this degraded material, as predicted by the SASW test results, the core of the concrete structures was sound.

3.0 FOUNDATIONS WITH CROSSHOLE SONICLOGGING AND TOMOGRAPHY

The quality assurance testing of drilled shaft foundations has become increasingly important to assure both owners and contractors that no hidden defects exist in the foundations after placement. For this task, the Crosshole Sonic Logging (CSL) method has proven to be both economical and very accurate in locating defects such as soft bottoms, caving, washouts, inclusions, and poor concrete quality from placement problems. Recent advances in technology now allow the use of tomographic methods to image defects in drilled shafts using data collected with the CSL equipment. A summary case history of a testing investigation using the CSL method is presented below, along with an example of a tomogram, taken during a different project, on a drilled shaft foundation which was found to have a defect.

The CSL case history to be presented is the quality assurance testing of foundations for the El Segundo Segment of Los Angeles Metro Green Line Rail Transit Project. In addition to normal visual inspection and measurement of concrete quantities, nondestructive testing of the foundations was ordered due to concerns based on the large diameter of the drilled shafts, potential caving of the soils, and the presence of ground water. Each of the large diameter, drilled shafts were tested by crosshole sonic testing in plastic tubes installed within the steel reinforcement cage.

3.1 Background

The Los Angeles Metro Green Line Rail Transit Project is a 32 kilometer (about 20 miles) light rail transit system that extends across southern Los Angeles County. Except for a 0.8 kilometer (0.5 mile) section of track leading to the Hawthorne Yard and Shops, the El Segundo Segment consists of dedicated aerial structures. There are also five elevated passenger stations along the El Segundo Segment.

The El Segundo Segment's 4.8 kilometers (3 miles) of elevated aerial structure provide a grade separation over existing major streets, intersections, and railroad tracks. These aerial structures are of reinforced concrete construction and are typically supported on single and two column bents. The foundations for these columns are typically large diameter, concrete drilled shafts that are essentially a continuation of the columns above grade.

3.2 Drilled shaft installation

Virtually all of the drilled shaft foundations were 2.44 meters (8 feet) in diameter with shaft lengths of 15.2 to 27.4 meters (50 to 90 feet). A few drilled shafts were 1.22 meters (4 feet) in diameter. Because of the sandy nature of the soils along the alignment, large diameter temporary casing was used to support the sides of the upper portions of the drilled shafts above the water level. In some cases, multiple casing was used because of the lengths involved. Below the water level, drilling mud was introduced into the drilled shaft to maintain the stability of the sides of the hole until the bottom elevation was reached.

The drilling mud did not allow for visual observation of the bottom of the shaft to ensure that loose materials were properly removed. Furthermore, the presence of the drilling mud and the casing that was left in place during the concrete pour did not allow for any opportunity to confirm that the sides of the drilled shaft were not compromised and that voids or soil inclusions were not present within the drilled shaft.

3.3 Nondestructive testing for quality assurance

Because of the uncertainties involved with drilled shaft installation operations, it was determined that there was a need to have broad quality assurance procedures. Several options were explored but nondestructive testing using the crosshole sonic logging technique was recommended because it provided a proactive means to assure quality of the newly placed concrete in the deep drilled shaft foundations.

Crosshole sonic logging is performed by sending and receiving an ultrasonic pulse through the concrete between source and receiver probes placed in water-filled tube pairs. The set-up for CSL is similar to that of Crosshole Tomography as shown in Fig. 6, except that the source and receiver are moved at the same horizontal level for CSL. To reduce noise, the receiver response is electronically bandpass filtered around the receiver's resonant frequency. Data from the receiver probe is recorded and processed by a portable computer. The logging is conducted as the probes are simultaneously withdrawn from the tubes at a rate such that the measurements are obtained every 3 to 6 centimeters (0.1 to 0.2 feet) coming up the drilled shafts.

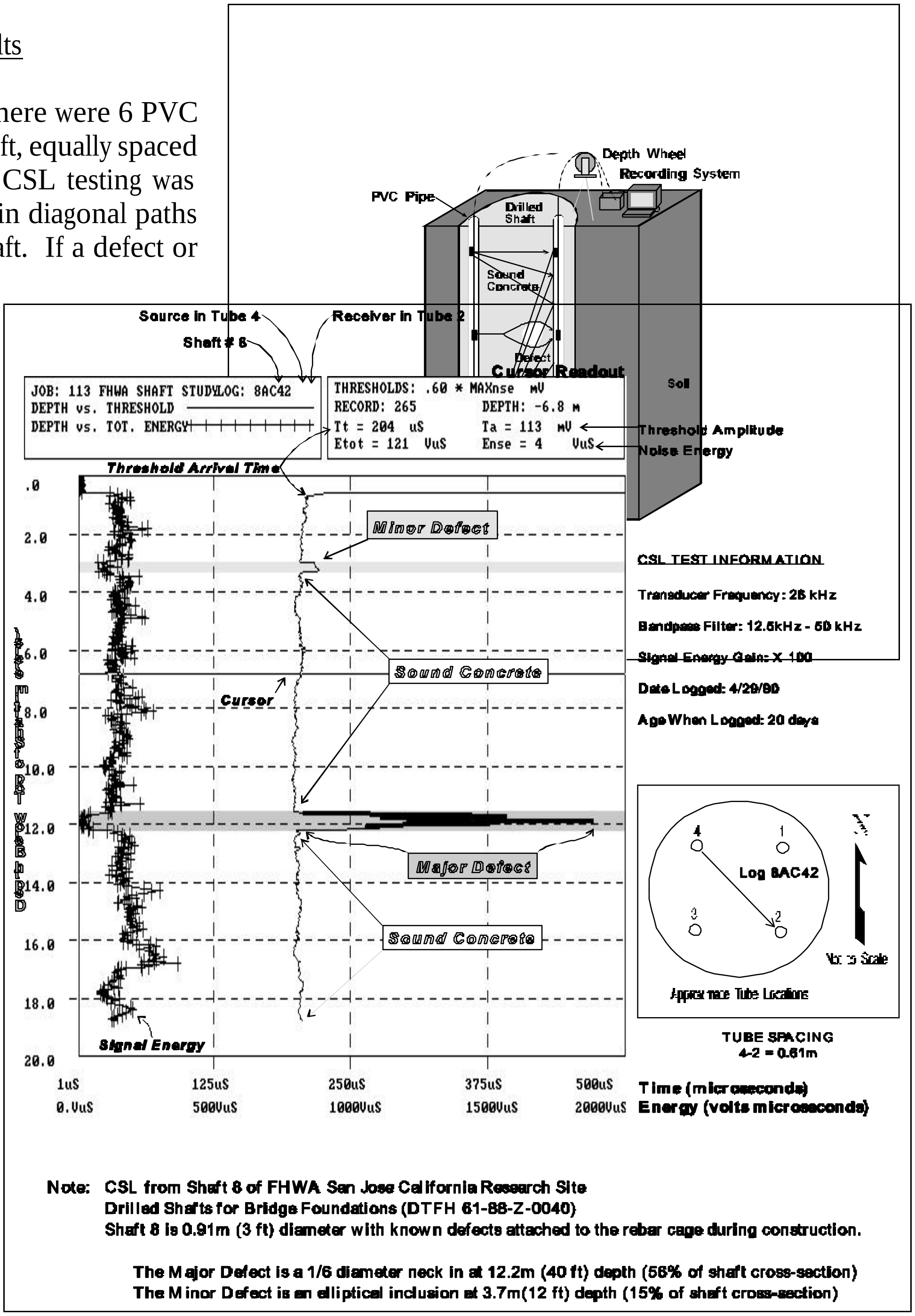
Analyses to evaluate the integrity of the concrete include measurement of wave travel times between the source and receiver, calculation of corresponding wave velocity, and receiver response energy. Longer travel times and corresponding slower velocities are indicative of irregularities in the concrete between the tubes, provided that good bonding is present between the tubes and concrete. The complete loss of signal is indicative of a significant defect in the concrete between one or more tube pair combinations. An example log, with annotations, from a typical CSL test of a shaft with known defects is presented in Fig. 7.

The CSL method is particularly suited to quality assurance because results that indicate good conditions can only occur when sound concrete conditions exist. Any intrusion of soil, washout zone, honeycomb, or otherwise contaminated concrete between a tube pair will have a slower compression wave velocity and longer signal travel time. Additionally, because the CSL method measures the condition of the material between the tubes, the results from several tube combinations can be combined to define the extent and severity of any flaws encountered. Should more position detail be needed, new technology allows the collection and processing of tomographic imaging data between pairs of tubes. The resulting tomogram will present a 2-dimensional slice of the image of the defect shape, size, and location.

3.4 CSL testing program results

For this investigation there were 6 PVC access pipes placed in each shaft, equally spaced around the rebar cage. The CSL testing was conducted along the three main diagonal paths through the center of each shaft. If a defect or other anomaly was identified in any of the 3 primary paths, additional CSL logs were taken around the perimeter and through the secondary diagonals to determine the location and severity of the anomaly or defect.

During the course of the investigation 97.5% of the drilled shafts placed were identified to be sound with no significant flaws. Of the remaining 2.5% with anomalies, the majority were minor defects that required no remediation due to their small size or location in the shaft. Only one drilled shaft was identified as having a major flaw. A discussion of the shaft with a major defect follows.



Note: CSL from Shaft 8 of FHWA San Jose California Research Site
Drilled Shafts for Bridge Foundations (DTFH 61-88-Z-0040)
Shaft 8 is 0.91m (3 ft) diameter with known defects attached to the rebar cage during construction.

The Major Defect is a 1/6 diameter neck in at 12.2m (40 ft) depth (56% of shaft cross-section)
The Minor Defect is an elliptical inclusion at 3.7m (12 ft) depth (15% of shaft cross-section)

3.4.1 Major defect description - poor quality concrete

A major defect was identified in Shaft 39 Left. CSL, angled CSL, and Singlehole Sonic Logging (SSL) were used to define the defect in this drilled shaft. The final analysis of the logs indicated the defect was located at 3.0 to 3.6 meters (10 to 12 feet) below the shaft top, which is immediately below the hinge cage (upper rebar cage). The defect was identified in the center of the shaft, which ruled out the possibility of a soil intrusion or other caving problem. Review of the inspection logs revealed that the driller had been unable to place the hinge cage deep enough in the shaft during concrete placement. The hinge cage was then removed and small 1.22 meter (4 foot) bucket was used to drill down the center of the shaft to the necessary depth. A new hinge cage was set in place and concrete placement was completed. Therefore, it was determined that this defect was a problem related to the concrete placement and that further investigation would occur.

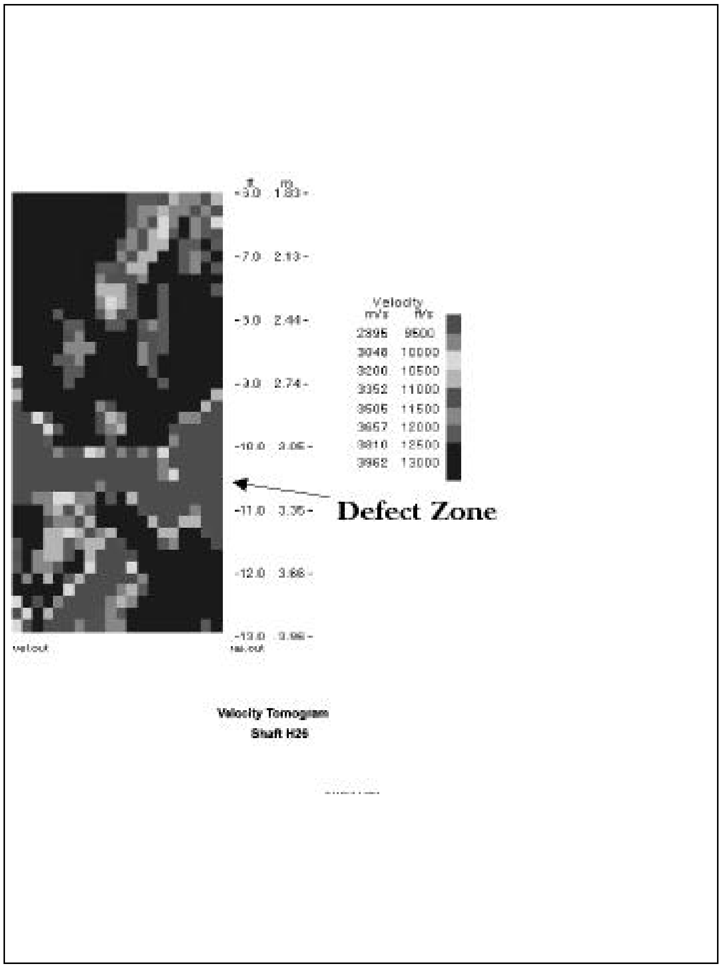
Because of the unusual construction circumstances and the location of the defect in the shaft, four NX cores were cut down through the defect zone. Review of the cores show that each core was broken at the defect zone and had some gravel retrieval in the defect zone. It was uncertain if the cores broke during drilling or if there was a weaker material in the indicated defect zone. Additional CSL logs were performed between the coreholes. The results again indicated a serious defect in the shaft center. High pressure grout was then injected into the coreholes to attempt remediation. Grout flow between the coreholes was observed at this time. Subsequent CSL testing between additional coreholes indicated that the problem remained. Finally a 0.5 meter (20 inches) core was taken down the shaft center. This revealed that air bubbles the size of pin heads had been whipped into the concrete. This 'whipped' concrete was extremely light weight and could be easily crushed with bare hands. Apparently, the bottom of the smaller drilled out hole was not adequately cleaned out before the new concrete was placed. The final remediation to the shaft required the removal and replacement of the top 3.6 meters (12 feet) of the shaft.

This defect was obviously very unusual in its cause, but it does illustrate the effectiveness of the CSL method to locate and identify defects in a shaft. It also illustrates the effectiveness of CSL testing for quality assurance of concrete repairs and how the results from traditional inspection and destructive testing (coring) can be integrated with nondestructive testing to amplify and clarify the results from both.

<u>3.5 Tomography of drilled shafts</u>

The CSL testing on the LA Green line was performed before the development of tomographic techniques (7) that could be applied to deep foundation defect imaging. If the techniques had been available for imaging the defect in Shaft 39, much of the uncertainty about the defect, and the subsequent coring, might have been avoided. The tomographic processing technology was used recently on a drilled shaft foundation for which a defect was located during routine CSL quality assurance testing. The CSL test results indicated a defect between 9.5 and 11 feet below the top of the shaft, but could not define the shape or exact cross-sectional location.

To better define the defect, a tomographic data set was collected along a path which intersected to largest extent of the defect, and a tomogram produced. Collection of the data required about 45 minutes of field time to collect data for several thousand unique ray paths. Tomographic analysis requires this many unique paths to construct an accurate image. It should be noted that prior to the development of



high-speed ultrasonic data acquisition systems such as the CSL testing system, several man-weeks were required to collect the data needed to produce a single tomogram.

The resulting tomogram from the shaft is presented in Fig. 8. This tomogram is a plot of material compression wave velocity versus 2-D position in the shaft concrete. A sound concrete shaft would show a constant color shade throughout the interior. The tomogram in Fig. 8 shows a clear cross-section of the defect just below the center of the tomogram. It should be noted that shaded areas near the top and bottom of the shaft are artifacts of the processing program, and do not represent real data. Artifacts are common at the top and bottom of tomograms due to the sparcity of the data density at these locations. In other words, artifacts result because fewer data ray paths cross the top and bottom of the tomogram area. The defect, evident as a lighter-shaded area below the center of the diagram, is in an area of high ray density, and is an accurate representation of the expected shape of the defect. For this shaft, the tomogram showed that the defect does indeed cover the complete shaft cross-section along this vertical slice. The CSL method alone, while fast and relatively accurate, can only give the height extent of the defect and approximate the area affected. Tomography can indicate where and how extensive the defect is in the shaft cross-section, as well as giving it's shape.

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