Using Crosshole Sonic Logging (CSL) To Test Drilled-Shaft Foundations

Concept of CSL

Crosshole Sonic Logging (CSL) is an accurate, cost-effective, and nondestructive means of investigating the integrity of concrete in drilled-shaft foundations. These guidelines are intended to enhance the quality of data acquired in CSL surveys by providing contractors with information on the preparation of shafts for CSL and the methods used to acquire CSL data. These guidelines are consistent with ASTM D 6760-021.

CSL establishes the homogeneity and integrity of concrete in a deep foundation and identifies anomalies, such as voids or soil intrusions, within the structure. In a CSL survey, the transit time of an ultrasonic compressional-wave (or p-wave) signal from a signal source in one access tube to a receiver in another access tube is measured from the bottom to the top of a foundation. Then, knowing tube separation distance, the p-wave velocity is calculated for each depth horizon. This results in a profile plot of velocity with respect to depth.

In a nominal foundation with uniform, "good"-quality concrete, the acoustic travel time between equidistant tubes will be relatively constant over the depth of the foundation. P-wave velocities for good concrete are on the order of 3,700 m/sec (12,000 ft/sec). Decreases in sonic-velocity from the local velocity average, accompanied by decreases in the signal energy, indicate a departure from uniform concrete quality. An improper concrete mix, voids, or other non-cemented intrusive materials can cause decreased-velocity anomalies. Complete loss of signal may indicate a severe defect.

<table>
<thead>
<tr>
<th>Material</th>
<th>Velocity (ft/sec)</th>
<th>Velocity (km/sec)</th>
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<tbody>
<tr>
<td>Good Concrete</td>
<td>12,000</td>
<td>3.7</td>
</tr>
<tr>
<td>Water</td>
<td>4,800</td>
<td>1.5</td>
</tr>
<tr>
<td>Air</td>
<td>1,100</td>
<td>0.3</td>
</tr>
</tbody>
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CSL testing is normally conducted as a part of Quality Assurance or Quality Control programs by an experienced independent testing firm such as Branagan & Associates, Inc. (B&A).

Preparing for CSL Testing

Preparing drilled-shaft foundations for CSL testing is a simple process. The contractor supplies and installs tubes around the perimeter of the reinforcement cage that is installed in the drilled shaft(s) to be tested. These tubes provide the source and receiver probes with access to the full foundation length from top to bottom. After placing concrete and waiting a minimum of 24 hours for concrete curing, CSL tests can be performed. The following sections provide specific guidelines for contractors to consider when planning and implementing a drilled-shaft foundation evaluation program.

Access Tube Specifications

Access tubes for CSL tests may be steel or PVC depending on the project specifications. In either case, the tubes must have end caps and couplers that are watertight. The tube inside diameter (ID) must permit the top-to-bottom free and unobstructed passage of CSL probes having dimensions of 1.41 inches diameter and 4 inches in length. Thus, the internal surfaces of the tubes must be clean and free of corrosion, defects and obstructions. Prior to CSL testing, tubes should have removable caps at the surface to prevent entry of foreign material which could obstruct the tube.

<table>
<thead>
<tr>
<th>Tube Composition</th>
<th>Tube ID (inches)</th>
<th>Approximate Time Window for Acquiring Optimal CSL Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schedule 40 Black Steel</td>
<td>1.5 to 2.0</td>
<td>24 hours up to 45 days</td>
</tr>
<tr>
<td>Schedule 40 PVC</td>
<td>1.5 to 2.0</td>
<td>24 hours up to 10 days</td>
</tr>
</tbody>
</table>

Good bonding between the tube and concrete is an important consideration. If de-bonding should occur, CSL data quality can be negatively affected. Therefore, external tube surfaces must be clean and free from contamination to ensure good bond between the concrete and the tubes. If PVC tubes are used, it is recommended that they be roughened by abrasion prior to installation to enhance bonding. There are trade-offs to consider if there is a choice in tube composition. PVC tubes cost less than steel but, due to the tendency of PVC tubes to de-bond more rapidly from concrete than do steel tubes, there is a shorter window for acquiring optimal-quality CSL data. Alternatively, steel tubes are more expensive but maintain a good bond for a significantly longer period.

**Number and Spacing Angles of Tubes**

Project plans and specifications generally identify the number and spacing of CSL access tubes that provide good cross-sectional coverage of a given drilled-shaft foundation. The general guide, however, is to install one access tube per foot of shaft diameter (or one tube per 0.25 to 0.30 meters of shaft diameter) while maintaining equal spacing around the circumference. The figure illustrates typical tube configurations and CSL source-receiver raypaths that select tube configurations allow.

**Installation of Tubes**

The following general guidelines describe the installation of the access tubes and outline the sequential timing of the operations.

**Pre-construction Planning**

- Before construction begins, confirm with the project engineer the specified tube composition and dimension along with proposed method of tube installation.

**Tube Preparation**

- Fit access tubes with watertight cap on bottom and removable cap on top. Any couplers used to make full-length tubes must also be watertight. Butt welding of steel tube couplings is not permitted and couplers on plastic pipe shall be threaded or glued. Wrapping joints with tape is not permitted.

**Attaching Tubes to Reinforcing Cage**

- Wire-tie tubes to interior of cage at regular intervals along its length (e.g., every 3 ft) to maintain tube alignment during cage lifting, lowering and concrete placement. Tubes should be as vertical and parallel to each other as possible. Non-vertical or non-parallel tubes can adversely affect CSL data.

- The access tubes should be installed such that their bottom is close to the bottom of the concrete foundation thereby allowing the foundation's bottom condition can be tested. The generally accepted practice is to place tubes 0.5 ft above shaft bottoms and extend the tubes 2-3 ft above what will be the top of concrete.

- Access tubes placed on the reinforcement cage should have a minimum concrete cover of one tube diameter or approximately 3 inches.

- Use a regular and symmetrical pattern so that each tube is spaced a maximum distance possible from adjacent tubes. Number and spacing of tubes around cage perimeter must correspond to design drawings or to specifications.
**Placing Cage (Reinforcement Operations)**

- During the reinforcement cage installation, take care not to damage tubes.

**Filling Tubes with Water**

- *It is very important to fill tubes with clean water immediately before or within one hour after concrete placement.* This action inhibits de-bonding of concrete from the tube. Cap or seal tube tops to keep out debris.

- Removing and then replacing tube caps or plugs for CSL testing is normally done by B&A personnel. If for some reason the contractor needs to remove or replace tube caps, care must be taken to avoid applying excess torque, hammering, or other stresses that could break the bond between tubes and concrete.

**Tube Grouting**

- After CSL testing is completed and the engineer has accepted the shaft, remove all water from access tubes and any other drilled holes. Then fill tubes and holes completely with approved grout mix.

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**CSL Field Setup and Data Acquisition**

The earliest time that CSL tests can be conducted is 24 hours after the concrete has been placed. A longer cure time may be needed depending on if circumstances (e.g., larger foundation diameter, concrete mix design) cause the concrete to set more slowly. Working in coordination with the contractor, B&A tests shafts quickly and accurately as soon as possible after concrete is placed. For CSL testing, B&A uses a field-proven and industry-standard CSL system manufactured by Olson Engineering. The equipment, transported in an suitcase-size hard case, includes the following components:

- a depth wheel/counter cabling system for depths to 250 ft with depth-measuring increments from 0.6 to 3.5 in.;

- a microprocessor-based system capable of displaying individual records, converting data from analog to digital format, recording data, analyzing receiver responses, and printing logs;

- 35-kHz hydrophone source and receiver probes with diameter of 1.41 inches and length of 4 inches (i.e., sized for tube IDs of 1.5 to 2.0 in.);

- a synchronized triggering system that starts the recording system at the same time the source is excited; and

- a 12-volt DC battery power source that allows remote fielding of equipment for a limited time.

**CSL Testing Procedures**

The CSL testing procedures used by B&A are consistent with the recommended procedures of the manufacturer of the CSL equipment, ASTM (as described in D-6760-02), and the Federal Highway Administration (as described in publication FLH 521-01).

Either prior to or at the time of the CSL tests, the following information should be provided to B&A:

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bottom and top elevations of the foundation, or foundation length;
• concrete placement dates;
• any other pertinent data regarding unusual observations or events during construction.

Upon setting up in the field, B&A field personnel make a sketch of the tube configuration on each tested foundation and assign a systematic reference number to each tube. To calculate acoustic velocity, the distance between the all of the tube-pair combinations is accurately measured and recorded, as are the tube stick-ups above the top of concrete. Because field data-acquisition efforts are most effective and efficient if performed in a single mobilization, B&A routinely tests all possible tube pairs including major diagonals, minor diagonals, and periphery. These comprehensive CSL data sets may be useful in defining the extent of an anomaly should an acoustic anomaly be observed in the primary data set analyzed.

CSL computer equipment is routinely operated off of DC power (vehicle power outlet). Thus, vehicle access to the foundation provides the most convenient approach for data-acquisition operations. However, on-board system batteries can provide a limited amount of power for inaccessible locations. The CSL system can also be run off of commercial or generator-supplied 110-volt 55-60 Hz AC power. A tripod is setup at the foundation being tested and cabling is spooled from the computer, over the tripod depth wheel, to each of the source and receiver probes.

The probes are lowered to the full depth of each tube pair being tested. Standard CSL tests are carried out with the source and receiver probes in the same horizontal plane. The cables attached to the probes are simultaneously hand-pulled over the depth wheel to steadily bring the probes to the surface. Prior to pulling, any slack in the cables is removed to ensure accurate depth measurements in the CSL records. While traversing a tube pair, CSL acoustic travel time measurements are made at depth intervals of 0.2 ft or less from the bottom to the top.

While in the field, B&A personnel evaluate the measured data as well as the derived sonic velocities in terms of completeness and accuracy. A preliminary evaluation of the integrity of the concrete in the foundations tested can generally be provided in the field. However, such preliminary assessments do not preclude B&A's systematic evaluation of the data in the office setting and final documentation of the results.

**CSL Reporting**

As previously described, for each CSL tube-pair combination on each foundation that is tested, transit times and signal strength are measured over the full length of the foundation. Experienced B&A personnel then analyze the data and prepare a written report which, in addition to general descriptive information, includes the following specific information for each foundation tested:

• interpretation of velocity profile logs with regard to the integrity of the concrete with standard ratings of Good, Questionable, Poor, or No Signal applied to report the quality of the concrete.
• identification of the depth interval and tube pair that includes a sonic anomaly and, when appropriate, the influence of construction techniques or events on the results; and
appendices which include profiles of the initial acoustic pulse arrival time versus depth, and pulse energy/amplitude versus depth.

Additional Testing
Accuracy of the derived areal location of a defect in a foundation depends on the number and location of tubes within each foundation. If CSL results indicate the presence of significant anomalies, other techniques can be applied to improve location accuracy and to further characterize the feature. The additional information can reduce the uncertainty in coring and remediating the defective area. Additional non-destructive testing methods that could be used include Angled Crosshole Sonic Logging, Crosshole Tomography, Singlehole Sonic Logging, Gamma-Gamma Nuclear Density Logging, and Sonic Echo and Impulse Response tests.

Acceptance or Rejection of Foundations
Coring of a foundation may be specified if CSL anomalies indicate Questionable or Poor Quality concrete. If coring is to be performed, B&A’s CSL report provides the approximate location of the anomaly for coring to target. To intercept an anomaly located in a portion of a foundation, efforts should be made to maintain a vertical corehole to enhance the likelihood of target interception. In general, if a defect is confirmed, coring costs are the responsibility of the contractor. If no defect is encountered in the coring process, the owner is responsible for coring costs and grouting of all coreholes.

It is the responsibility of the project engineer or structural engineer to accept or reject a foundation. Such acceptance is based on the reported results of the CSL testing, coring results, and all other available information on the shaft construction. Rejection of a foundation based on CSL testing requires conclusive evidence of a defect that will result in inadequate or unsafe performance of the structure under service loads. Should a drilled-shaft foundation be deemed unacceptable, the standard practice is for the contractor to submit a plan for remedial action to the engineer for approval. All modifications to the foundation and load transfer mechanisms caused by the remedial action require calculations and working drawings stamped by a registered professional engineer for all elements affected. Typically, the labor and materials required to perform foundation remediation or replacement are provided at no cost to the owner and with no extension of the contract time.

About Branagan & Associates, Inc.

Branagan & Associates, Inc. (B&A) is a Las Vegas, Nevada-based consulting research and engineering company formed in 1993 to provide technical services to clients engaged in scientific and engineering projects in specialized geotechnical testing associated with the construction industry and in hydrocarbon exploration and production. B&A has performed hundreds of Crosshole Sonic Logging surveys for clients throughout the U.S.