Nondestructive Evaluation of Bridge Foundations – For Quality Assurance and Forensic Purposes

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Abstract

The use of NDE methods is well established for the evaluation of deep foundations for bridges and other structures. However, there is often misunderstanding as to which of the various methods can or should be applied to different foundation situations such as quality assurance testing of newly placed foundations, determination of unknown tip depths for existing foundations, forensic investigations of foundations with suspected issues, etc. This article presents an overview of the most common methods used, including summaries of the advantages and limitations of each method. Included is an overview of how the methods are applied, how the data is analyzed, sample test data from real-world examples, and an overview of the when and when not to use each method.

Introduction

Bridge foundations can be quite enigmatic – all you see above ground is the top of the foundation, if even that. Does the engineer or owner have to simply trust that what they expect (or are told by the drawings) is in the ground is actually what is present? And what about the not uncommon situation where there are NO drawings or information available? Determining the foundation tip depth, integrity, and even type can be a challenge, but this challenge can often be met with the use of one or more Nondestructive Evaluation (NDE) methods. There are three common, well-accepted methods for foundation evaluation. These include Crosshole Sonic Logging (CSL) and the similar Crosshole Tomography (CT) for quality assurance of new drilled shaft foundation construction, Sonic Echo/Impulse Response (SE/IR, also called "pile integrity testing") for checking the depth and integrity of both new and existing foundations, and the Parallel Seismic (PS) method for determining unknown depths of existing foundations.

Each of these methods has their strengths and weaknesses, and it is important to be aware of the limitations and capabilities in selecting the right method for the task at hand. The CSL and CT methods, as noted are used almost exclusively on newly-constructed drilled shafts for underwater concrete placement quality assurance (QA) due to the need for access tubes to be installed (although core holes can also work). These methods, however, offer the greatest sensitivity to problems in the concrete of all the methods available. The SE/IR method can be done on both newly placed as well as existing drilled shafts and driven piles, but there must be access to some portion of the foundation top or upper side to perform this method. Finally, the PS test method is the most versatile for unknown deep foundation depth determination as it can be performed on foundations where the foundation itself is inaccessible such as piles or shafts under a buried pilecap. However, this method is only used for pile tip/shaft bottom depth determination and does require a cased borehole be put into place near the foundation to be tested.

The NDE methods available for deep foundations vary in terms of access requirements, sensitivity, and also speed which translates into cost. This article will present an overview of each method, illustrate the advantages and limitations of each, and show some typical sample results to provide the reader with some idea as to what to expect (and not to expect) from each method.

Parallel Seismic Method

The PS test method is used to measure foundation tip depth when the SE/IR test method can't be done due to access, or doesn't apply due to foundation type or geometry. This method is commonly applied for scour safety analyses of older unknown bridge foundations, for determining if a foundation can handle an increase in loading, for re-use of existing foundations, or for any other situation where an unknown foundation tip depth is needed.

Previous research performed for under National Cooperative Highway Research Program (NCHRP) funding by Olson Engineering (1,2) has shown that of the various foundation evaluation methods available, the Parallel Seismic (PS) test method is the most versatile and reliable for tip depth measurements on existing bridges. The PS method is discussed in ACI 228.2R-16 (3) along with discussions of the SE/IR and CSL/CT methods presented in this article.

This method can be applied to a wide variety of foundation types, including steel piles, sheet piles, drilled shafts, timber piles, etc. and used for almost any foundation depth. This method also does not require direct physical access to the foundation being tested. As noted above, the most significant limitation to the use of the PS method is that it requires a cased borehole be placed in the ground next to the foundation in question which should extend at least 10 ft and preferably 15 ft below the minimum suspected/hoped for/required depth of the foundation.

The PS test is normally performed by impacting an exposed foundation top or side, or impacting a part of the structure above the foundation (such as a pile cap or column). The impacts can be either vertical or horizontal, and are typically done with an instrumented impulse hammer to generate compressional waves and trigger the data recording system. Testing can also be done with a non-instrumented hammer, using an accelerometer mounted nearby for the trigger source. The P-waves (compressional) generated by the impact travel down the foundation and couple into the surrounding soil as shown in Figure 1. The coupled waves are then picked up in the soil by a nearby hydrophone or tri-axial geophone receiver. A hydrophone receiver is typically suspended in a water-filled (or grouted if needed), cased borehole. The casing is typically a 2 inch internal diameter schedule 40 polyvinyl chloride PVC casing but steel casing can also be used), but a receiver can also be near the tip of an instrumented cone probe pushed into the ground. The data from typically 3 impacts is collected at each test depths as the receiver is retrieved from the casing bottom to the surface at vertical intervals of 1 to 2 ft and stored. This data is then used to create a plot of receiver signal arrival time versus depth, from which the analysis is performed.

A photograph of typical PS testing setup on a bridge deck (with no direct access to the foundation at all) is presented in Figure 2 below. As seen, the casing from the borehole is seen coming up through a hole drilled in the deck. The hydrophone receiver is seen on the deck next to the borehole, ready to be inserted. The impact hammer is visible in the background – it was used to impact the bridge deck on top of the bridge pier directly above the foundation element (pile) which was being tested that was located closest to the boring.

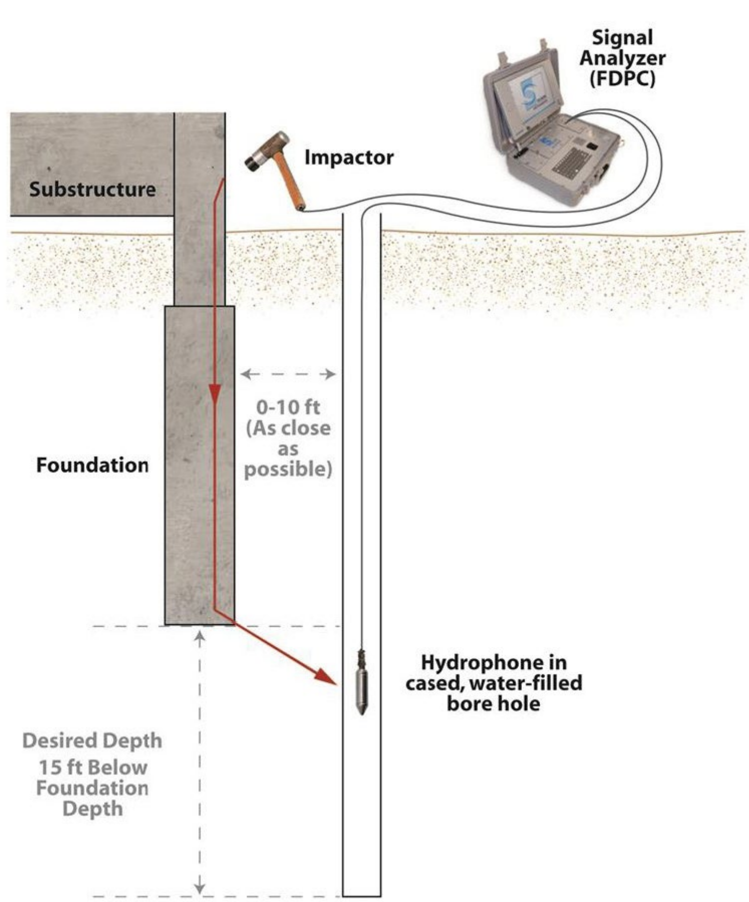

Figure 1. Parallel Seismic (PS) testing schematic diagram. P-waves travel through the foundation at a greater velocity than surrounding soil, and a "break" in the direct arrival times indicates the depth of the foundation along with a reduction in signal amplitude when the hydrophone receiver is below the foundation.

Figure 2 – Parallel Seismic (PS) test setup on a bridge deck with 3 lb impulse hammer, PC data acquisition system, hydrophone receiver and PVC boring casing filled with water.

Example PS Test Data – Concrete Bridge Foundation

An example record from a PS test performed through a bridge deck is presented in Figure 3 below. The hydrophone was retrieved from the casing bottom at 1 foot increments, and the bridge deck over the foundation was impacted typically 3 times at each hydrophone receiver depth. As seen in Figure 3, there is a clear constant slope in the upper half arrival time versus depth plot. This slope is due to the slowly increasing arrival times versus depth from the foundation element, with the slope equal to the compressional wave velocity of the foundation (for saturated soil conditions between the casing and the foundation). The measured velocity of about 13,400 feet per second (fps) is typical of a foundation for good quality and strength concrete. The plot also shows a clear change in slope at about 45.2 feet, indicating the foundation tip depth below the 0 depth reference. Below this tip depth, the velocity

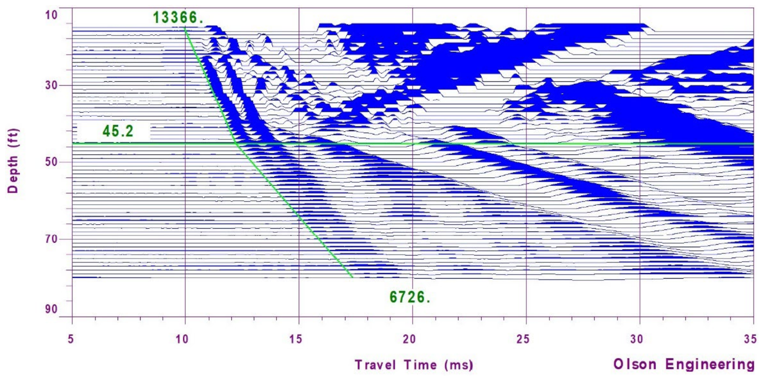

Figure 3. Sample Parallel Seismic (PS) Test Results for a Concrete Pile Foundation with a velocity of about 13,400 ft/s. Note the pile tip depth is indicated by the slower velocity below 45 ft deep and the weaker amplitude signals.

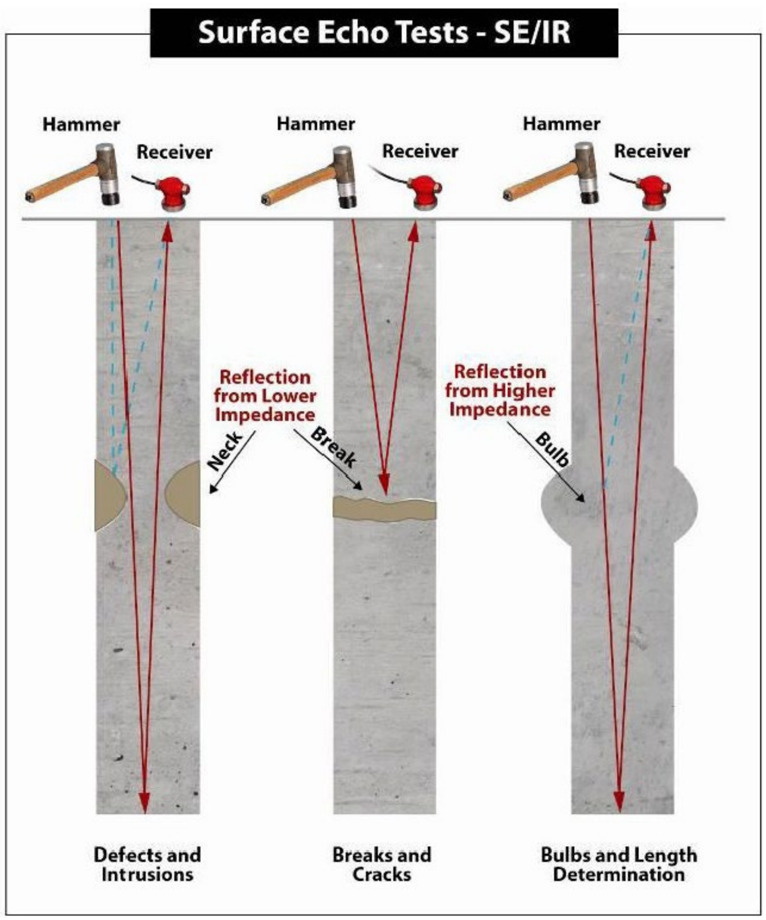

Figure 4. Sonic Echo/Impulse Response (SE/IR) shaft/pile integrity/depth test method.

is indicated to be about 6,200 fps, which is typical of weak bedrock (in this case, weak limestone). The tip depth is further confirmed by the clear drop in signal amplitude for depths below 45 feet as the compressional wave energy spreads out into the limerock below the pile tip and is no longer guided down the pile foundation.

As seen in this example, the PS test can be used for tip depth evaluation even in cases where there is absolutely no access to the foundation itself. In this case, testing was conducted from a bridge deck, with the borehole drilled through the deck concrete and then down into the soil/rock next to the foundation.

Sonic Echo/Impulse Response Method

The SE/IR pile integrity method is used to measure both depth and integrity of foundations and can be performed on both new foundation for quality assurance as well as on existing foundations. The method is referenced in ASTM D5882-16 (4). This method is relatively quick to perform, and does not require boreholes or access tubes. However, this method does normally require direct access to the foundation itself, either to some part of the top or to the upper side. Note that the SE/IR test method has been also conducted through either thin slabs or through smaller pile caps, but these cases require special care and will only be successful if certain pile cap or slab geometry constraints are met.

The SE/IR method is a low strain pile integrity test conducted from the top of a foundation as illustrated in Figure 4 below. Typical test equipment includes a 3 lb impulse hammer and an accelerometer mounted on the shaft top or on the upper shaft side. While the SE testing can be done with an ordinary hammer, the IR test hammer must have a built-in load cell that can measure the force and duration of the impact. The accelerometer receiver response is integrated from acceleration to be velocity vs. time in the SE data and it is more sensitive to echoes at shallow depths and from small defects than a geophone (velocity transducer). A geophone is often used in addition to an accelerometer to get better measurements of the foundation head flexibility/stiffness at low frequencies in the IR analyses. The test involves hitting the foundation top (or pile cap above the foundation top) with the hard-plastic tipped hammer to generate energy that travels to the bottom of the foundation. The wave reflects off irregularities (cracks, necks, bulbs, soil intrusions, voids, etc.) and/or the bottom of the foundation and travels back up along the foundation to the top. The receiver measures the vibration response of the foundation to each impact. The signal analyzer processes and displays the hammer and receiver outputs. Foundation length and integrity of concrete are evaluated by identifying and analyzing the arrival times, direction, and amplitude of reflections measured by the receivers in time.

For SE time domain data analysis, the echo depth (D) is calculated by multiplying the reflection time (t) by the compressional wave velocity (V) and dividing this quantity by 2 to account for the fact that the wave has gone down and reflected back (i.e. $D = V*t/2$). If possible, the compressional wave velocity should be measured on an exposed portion of the pile for wood and concrete, otherwise a typical velocity of 12,000 to 13,000 ft/s may be assumed. Note that steel piles have a constant velocity of 16,600 ft/s for an SE/IR test. The IR analysis uses the same data as the SE analysis, but the data processing is done in the frequency domain, i.e., the vibrations of the foundation measured by the receivers are processed with Fast Fourier Transform (FFT) algorithms used in modal vibration testing to generate mobility (velocity/force) and flexibility (displacement/force) vs. frequency

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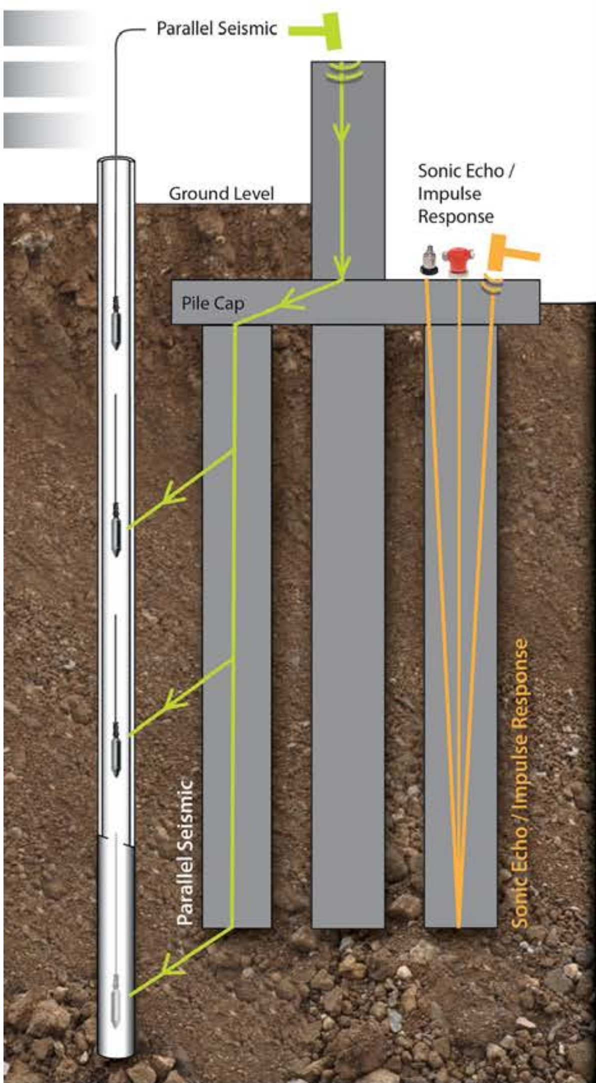
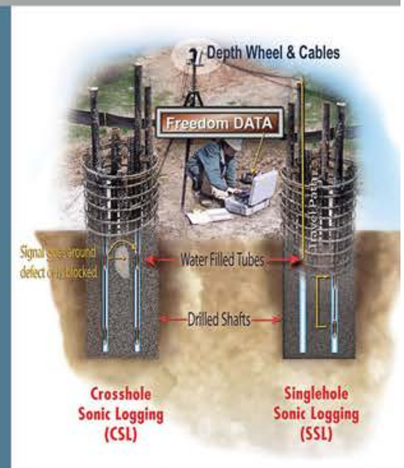


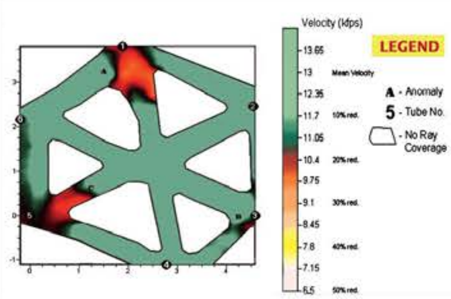
OLSON offers four *Nondestructive Testing Methods* to determine Deep Foundation Depth & Integrity:

» **Parallel Seismic (PS)** testing method is performed to determine unknown foundation depths when there is no direct access to the pile cap or on long, slender piles.

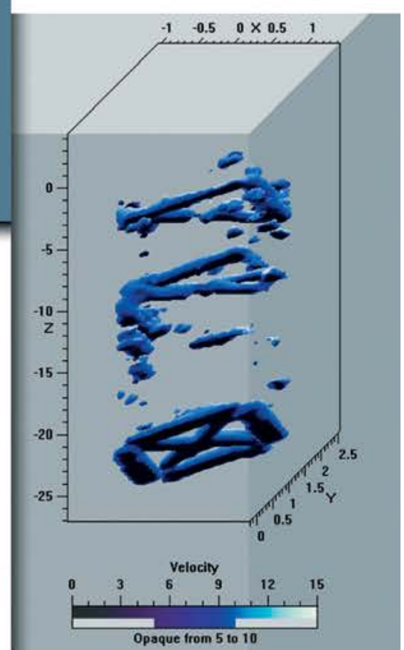
» **Sonic Echo/Impulse Response (SE/IR)** testing reveals integrity and depth information about a pile/shaft with or without a wall/column on top. SE/IR is usually performed as shown in the figure, where the instruments are mounted directly to a small pile cap or to the pile itself.

» **Crosshole Sonic Logging (CSL)** for testing the concrete ingtegrity of newly placed slurry drilled shafts. CSL requires that steel tubes be placed in the shaft prior to concrete placement.





Crosshole Tomography (CT) for 2-D and 3-D imaging of defects found by CSL



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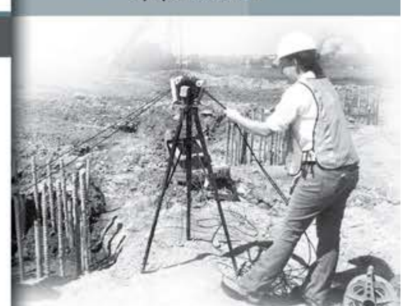

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transfer functions for analyses. The coherence of the impulse hammer impact and accelerometer receiver response data versus frequency is calculated to indicate the data quality. A coherence near 1.0 indicates good quality data. Because of the rod-like shape of a deep foundation, reflections are indicated by equally spaced resonant peaks that correspond to modes of vibration associated with the depth of the reflector. The inverse of the SE reflection time, t, is equal to the change in frequency, Δf, between the resonant peaks in the IR mobility plot. The reflector depth is then calculated as:

$D = V/(2*\Delta f)$.

Analysis of the length determination and the integrity evaluation of a foundation for both the SE and IR methods is based on the identification and evaluation of reflections. The hammer impact energy reflects differently from increased foundation acoustic impedance (velocity*mass density*area) than from decreased foundation impedance. This phenomenon allows the type of reflector to be identified as follows. Soil intrusions, honeycomb, breaks, cracks, cold joints, poor quality concrete and similar defects (often referred to as a neck) are identified as reflections that correspond to a decrease in the foundation impedance. Increases in the foundation cross-section or the competency of surrounding materials such as an increase in shaft cross-sectional area (referred to as a bulb) or bedrock and other much stiffer soil strata are identified as reflections corresponding to increases in the foundation impedance.

One of the limitations of the SE/IR method is based on the length versus diameter ratio of the foundation. As a rule of thumb, when embedded foundation length to diameter ratios exceed about 20:1 to 30:1 for foundations in stiffer soils/bedrock, the attenuation of compressional wave energy is high and bottom echoes are weak or unidentifiable in SE/IR test results.

Example SE/IR Test Data – Timber Pile Bridge Foundation

An investigation of two timber piles was carried out in a recent project to determine the unknown lengths of the piles. At the time of testing, about 2 ft of the upper sides of the piles were exposed in an excavation. The piles were nominally 12 inches in diameter and appeared to be creosote treated. The tops of the piles were embedded in a concrete pile cap, requiring side-mounting of the accelerometer receivers used for the SE/IR measurements. Figure 5 shows photographs of the side-mounted accelerometers as well as the hammer impact location on the top of the pile cap above each of the tested piles.

An example SE (time) record from a test on one of the piles is presented in Figure 6 below. As seen, there are a series of very clear downward-breaking echoes from the apparent pile tip at about 9 feet below the accelerometer. Since this SE record is from the bottom accelerometer receiver set at 1.5 feet below the bottom of the pile cap, the indicated pile length of about 10.5 feet below the bottom of the pile cap. Processing of the SE data from 3 impacts produced the IR mobility and coherence plots versus frequency presented in Figure 7. The coherence of the impulse hammer impact and accelerometer receiver near 1.0 indicates good quality data. For foundations in air or in relatively soft soils, the coherence will typically only be near 1.0 at frequencies for which the mobility is non-zero.

Figure 5. SE/IR testing on timber pile – left photo shows 2 accelerometer receivers mounted on blocks with wood lag bolts on the timber pile side at 4.5 and 5.5 ft below the top of the concrete pile cap. The right photo shows the 3 lb instrumented impulse hammer impacting the 4 ft thick concrete pile cap directly over the timber pile.

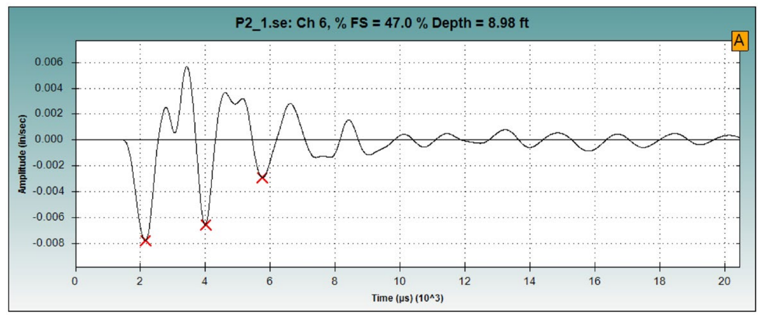

Figure 6. Sample SE from a timber pile with a side-mounted accelerometer and pile cap top impact. The initial accelerometer response is shown by the first X followed by 2 multiple X marked (and more unmarked) echoes, indicating the pile tip to be at 10.5 ft below the bottom of the pilecap (9.0 ft below the lowest receiver on the pile side).

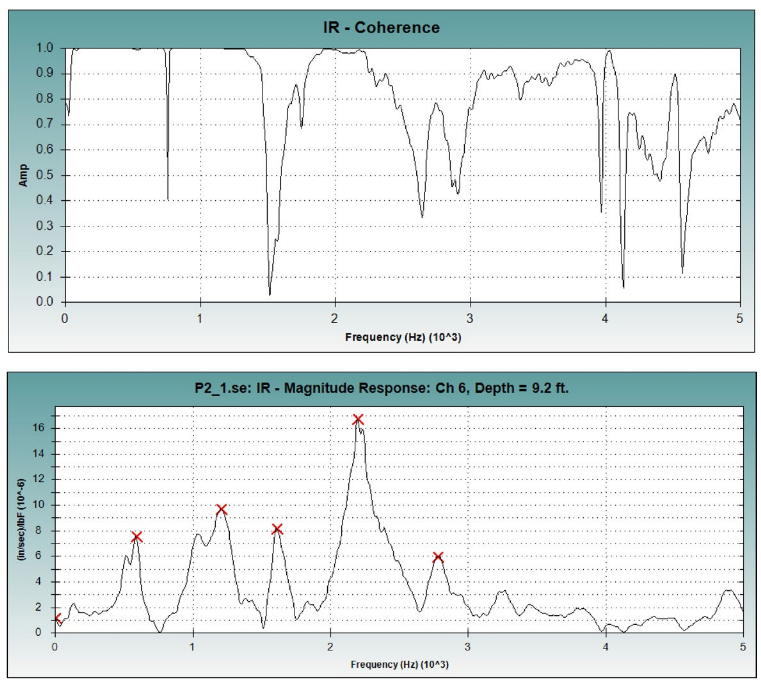

Figure 7. Sample IR Record from the Figure 6 SE data (3 impacts) with the coherence plot on top and the mobility plot (velocity/force) vs. frequency on the bottom. The evenly spaced resonant peaks correspond to an echo depth of 9.2 ft below the lowest receiver.

In the IR records the linear transfer function amplitude is in inches/second/pound force on the vertical axis (mobility) and frequency in Hz on the horizontal axis. Because of the rod-like shape of a deep foundation, reflections are indicated by equally spaced resonant peaks that correspond to modes of vibration associated with the depth of the reflector. The inverse of the SE reflection time, t, is equal to the change in frequency, Δf, between the resonant peaks in the IR mobility plot. The reflector depth is then calculated as: D = V/(2*Δf) and the resonant echo depth of 9.2 ft in the IR results agrees well with the SE results.

Crosshole Sonic Logging (Csl) and Crosshole Tomography (Ct) Methods

The CSL test is a downhole method for quality assurance testing of drilled shaft foundations and concrete slurry walls per ASTM D6760-16 (5). Access tubes, typically PVC or steel, must be cast-in-place in the concrete during construction or coreholes must be cut to permit logging as illustrated in Figure 8. For a CSL test, logging involves passing an ultrasonic pulse through the concrete between source and receiver probes in a water-filled tube pair as the probe cables are pulled back to the surface over a depth measurement wheel. The CSL method thus tests the quality of the concrete lying between a given pair of access tubes which are typically 2 inch ID schedule 40 black steel pipes (bonds better with concrete than PVC pipes). A minimum of 2 tubes is required for the test and typically 1 tube is installed per foot of drilled shaft diameter. Normally CSL is done of the perimeter tube pairs and diagonally opposing tube pairs (4 tubes have 6 logs and 6 tubes have 9 logs, although 6 more sub-diagonal tubes can be done of a 6 tube shaft – 6 ft diameter).

Analyses to evaluate the integrity of the concrete from CSL data include measurement of wave travel times between the source and receiver, calculation of corresponding wave velocities, and measuring receiver response energies. Longer travel times and corresponding slower velocities are indicative of irregularities in the concrete between the tubes. The complete loss of signal is indicative of a significant defect in the concrete between one or more tube pair combinations. The energy of the signal in an anomaly zone can be used to give an indication of the type of defect. As an example, a water-filled void will have a low velocity but a high signal amplitude, while a soil-filled void will have a low velocity and a low signal amplitude.

Desirable results show consistent pulse arrival times with corresponding compressional wave velocities that are reasonable for concrete. Defects such as water or slurry contaminated weak concrete and soil intrusions will result in delayed arrivals (slower velocity) or no arrivals in the defect zone. The signal energy level is a secondary indicator of concrete quality with low energy also indicating poorer quality concrete in the case when the time of arrival is delayed (but not in the case of a good arrival time). The wave velocity increases

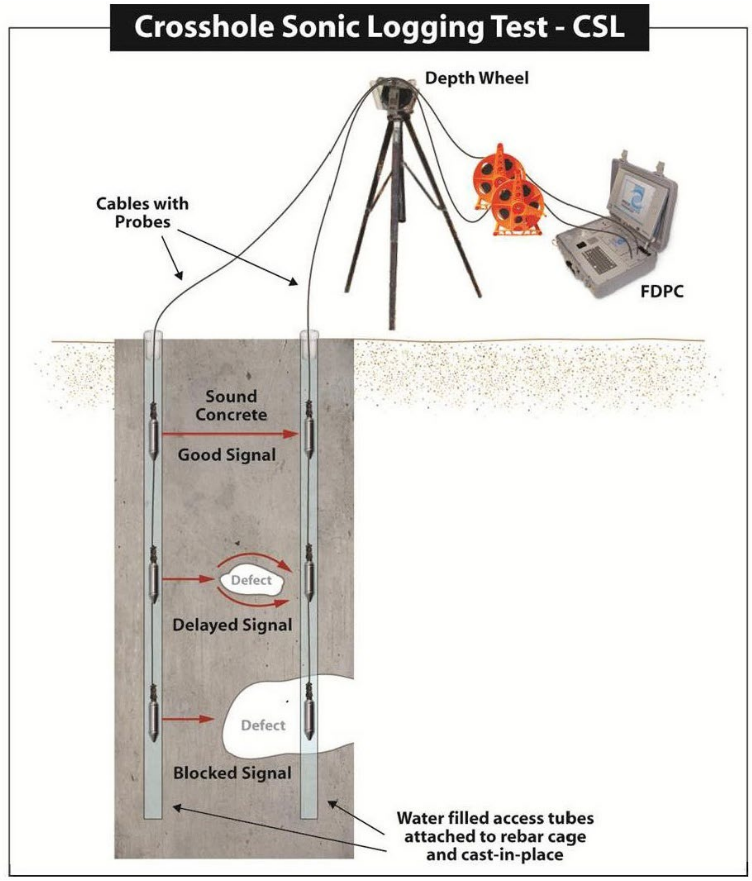

Figure 8. Crosshole Sonic Logging (CSL) test method diagram.

with time in concrete as it matures, particularly in the first few days of curing as the concrete hydrates and strength develops.

If an anomaly is found with the single-path CSL testing, additional information about the size, shape, and severity of the anomaly can be obtained by performing Crosshole Tomography (CT) testing. This testing uses the same hardware as the basic CSL test, but the data is collected at a series of different transducer offsets to obtain angled source and receiver. The collected CT data is processed with a tomography modeling program which then creates a 2-D or 3-D image of the anomaly.

Example CSL and CT Test Data – Concrete Drilled Shaft Foundation

A demonstration of the both the CSL and CT methods was conducted on a drilled shaft that had "artificial" defects built into it. The defects consisted of sand bags both tied to the rebar cage (to simulate a soil intrusion) and piled at the bottom (to simulate a "soft bottom" condition. These are the two most common types of defects seen in newly-placed drilled shafts. The shaft had 3 access tubes installed for CSL and CT testing. A photograph of the drilled hole showing the cage and the sandbag defects is presented in Figure 9 below.

The CSL testing was done first, and showed the presence of both the mid-height sandbag on one side of the shaft, as well

Figure 9. CSL and CT test shaft with sand bag defects that were installed at known depths prior to concrete placement.

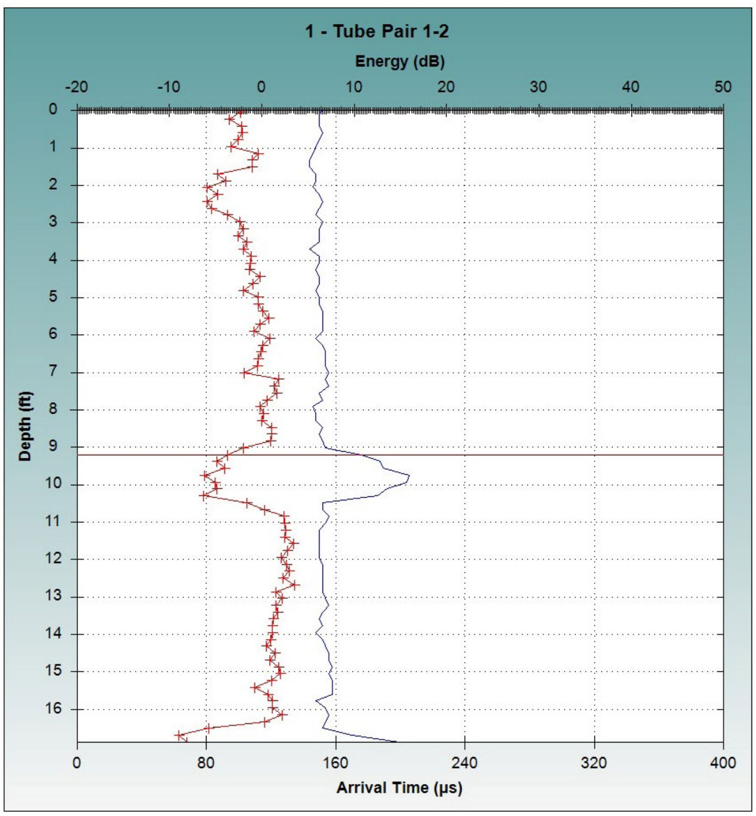

Figure 10. CSL Test Shaft result log with Sand Bag Defects identified at 9-10.5 and 16.5-17 ft deep.

as the "soft bottom" condition from the pile of sandbags at the shaft bottom. A sample CSL log showing these two conditions is presented in Figure 10 below. The blue line is the signal arrival time versus depth. The two anomalous areas at 9-10.5 and 16.5-17 feet deep are where the arrival time increases are from the two defect zones created by the sandbags. The red line is the signal energy (amplitude) and shows a clear drop in energy in each of the two defect zones.

The shaft was next tested with the CT method, with the tomography data collected between each of the three tube pairs at 7 angles per tube pair. For this shaft, the 7 pulls were done at offset angles of 0, +/- 15 , +/30, and +/- 45 degrees from horizontal. After data

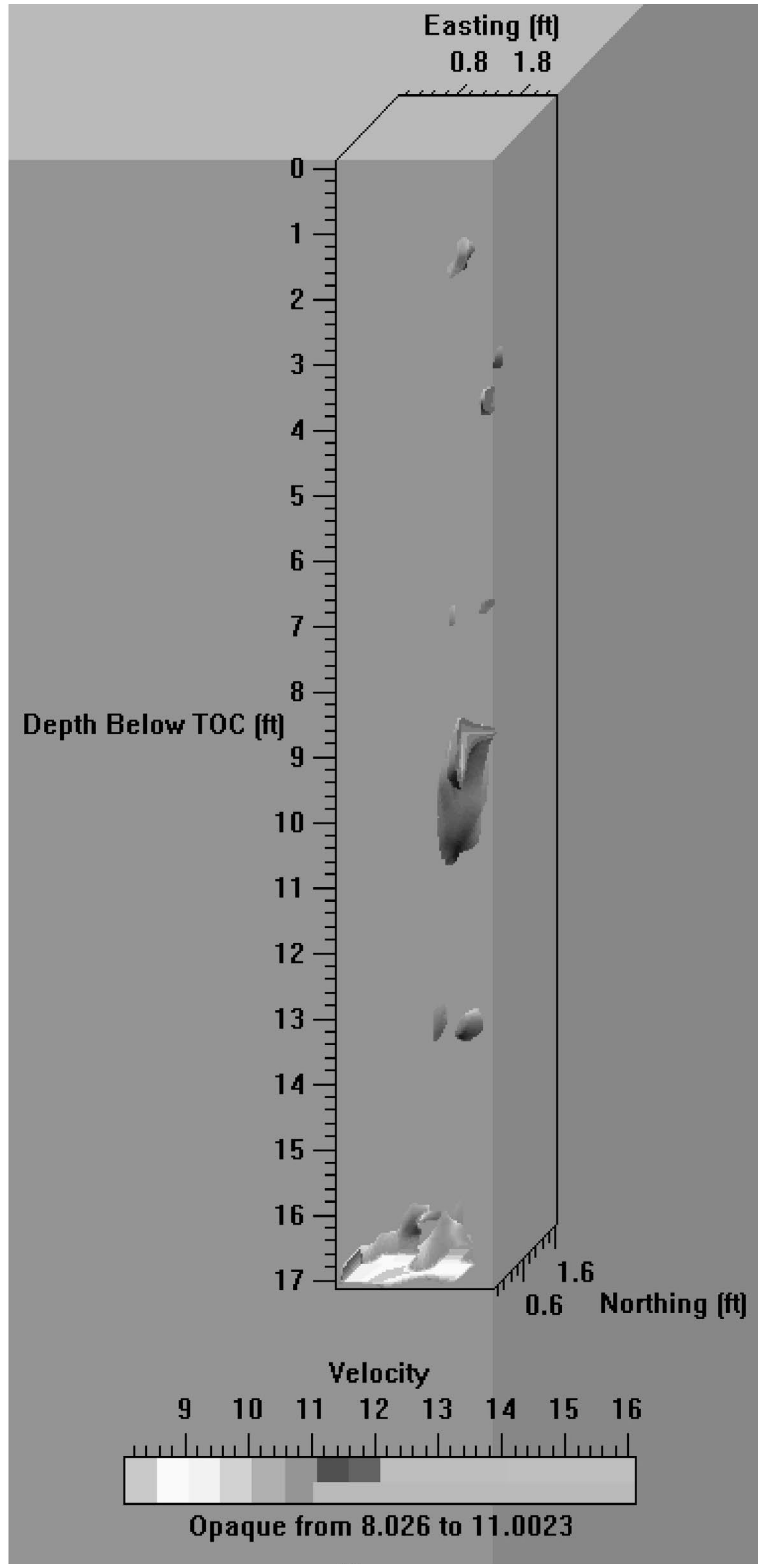

Figure 11. CT Test Shaft velocity tomogram result showing 3-D image of sand bag defects with velocity scale in thousands of ft/s.

collection, the full data set was processed with the GEOTOM CG tomography software package from GeoTom, LLC of Apple Valley, Minnesota to generate a 3-D tomography output data set. This output was then displayed with the Slicer Dicer imaging software by PIXOTEC, LLC of Renton, Washington to produce the final result seen in Figure 11 below. As seen, the large sandbag at 9-10.5 feet is clearly visible, including a reasonable estimate of its actual shape. The soft bottom from the pile of sandbags at the shaft bottom center is also clearly visible.

Discussion and Conclusions

There are a number of NDE methods available for evaluation of deep foundations. The methods can test a wide variety of foundation types, including drilled shafts, steel piles, timber piles, sheet piles, slurry and diaphragm walls, etc. However, as discussed in this article, it is important to recognize the strengths and limitations of each method so that the correct method (or combination of methods) can be selected for a given foundation. The Parallel Seismic (PS) method has been found to be the most accurate and versatile method for unknown foundation length determination, since it does not even require direct access to the foundation being tested. However, the PS method requires a cased borehole be installed next to the foundation, and this method is not very useful for locating smaller defects in a shaft. The Crosshole Sonic Logging (CSL) and Crosshole Tomography (CT) methods have the highest sensitivity to defects, and can even provide an image of a defect. These methods, however, require that access tubes (or coreholes) be present to allow testing and thus these methods are normally only performed on newly-placed drilled shaft foundations. The SE/IR method is generally the fastest and least expensive method for foundation length and integrity, but it is limited to drilled shafts and timber and concrete piles where access to the top or upper side is available.

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Larry D. Olson, P.E., is nationally and internationally known for his expertise in nondestructive evaluation (NDE) and performance monitoring of civil infrastructure including dams, bridges, buildings, foundations, pavements, tunnels, etc. He is a past director of EEGS and a member or past member of several committees including: ASCE's Geophysics Committee, Transportation Research Board (TRB) Committee AFF60 Tunnels, AFF40 on Field Testing and Nondestructive Evaluation of Transportation Structures and its Nondestructive Evaluation (NDE) subcommittee as well as the Earth Exploration Committee AFP20 and its Geophysical subcommittee. He has been an instructor in the American Society of Civil Engineers seminar on "Structural Condition Assessment of Existing Structure" since 1997 and in 2009 developed a new ASCE seminar "Bridge Condition Assessment and Performance Monitoring". He was the primary instructor in an Engineering Education of Australia seminar series on Nondestructive Evaluation of Concrete, Asphalt and Wood in Sydney and Melbourne in 2010 and for the two ASCE seminars in Brisbane and Sydney in 2014 and again in 2015 and 2017. He holds BS and MS Geotechnical Engineering degrees from the Civil Architectural and Environmental Engineering Department of the University of Texas at Austin which honored him as a distinguished alumnus in 2006. Olson Engineering has its main office in Wheat Ridge CO (metro Denver) with a branch office in Rockville MD (metro Washington, DC). Mr. Olson founded Olson Instruments, Inc. to manufacture NDE and seismic geophysical instruments in 1995 with national and international sales.