Determination of Unknown Bridge Foundation Depths with NDE Methods

Larry D. Olson, P.E.
Olson Engineering
5191 Ward Road, Suite 1
Wheat Ridge, CO 80033
Ph – 303-423-1212
Fx – 303-423-6071
ldolson@olsonengineering.com

Abstract
This paper discusses the results of NCHRP 21-5 and 21-5(2) sponsored research on nondestructive evaluation (NDE) methods for determination of unknown bridge foundation depths. Surface and borehole NDE methods are reviewed below along with a discussion of the limitations and accuracy of the NDE techniques. The NDE methods found to be applicable to unknown foundation depth determination were the borehole methods of Parallel Seismic, Induction Field, and Ground Penetrating Radar, and the surface methods of Ultraseismic, Sonic Echo/Impulse Response, Spectral Analysis of Surface Waves and Bending Waves methods. The research further found that the Parallel Seismic and Ultraseismic were the most accurate and broadly applicable borehole and surface methods and these are discussed in detail herein.

INTRODUCTION

There are approximately 589,685 highway bridges in the National Bridge Inventory from December, 2001 FHWA data. The best estimate of the population of bridges over water with unknown foundations, as of April 15, 2000, is about 91,094 from FHWA data. These unknown bridge foundations pose a significant problem to the state departments of transportation (DOT's) because of scour vulnerability concerns. The foundation depth information in particular is needed to perform an accurate scour evaluation at each bridge site, along with as much other information on foundation type, geometry, materials, and subsurface conditions as can be obtained. This guideline document was prepared to aid state DOT's in the specification and performance of engineering investigations to determine unknown bridge foundation depths for bridge scour safety evaluations.

The National Cooperative Highway Research Program (NCHRP) 21-5 project "Determination of Unknown Subsurface Bridge Foundations" (final report dated August, 1995)[1] and the NCHRP 21-5(2) project "Unknown Subsurface Bridge Foundation Testing" (final report dated December, 2000)[2] were performed by the author and his firm to evaluate and develop existing and new technologies that can determine unknown subsurface bridge foundation depths. The NCHRP 21-5 Phase I research focused on the identification of potential NDE methods for determining depths of unknown bridge foundations at 7 bridges in Colorado, Texas and Alabama. The NCHRP 21-5 (2) Phase II research focused on evaluating the validity and accuracy of the identified NDE methods for determining depths of unknown bridge foundations. In this phase, 21 bridge sites were studied in North Carolina, Minnesota, New Jersey, Michigan, Oregon, Massachusetts and Colorado. Phase II research also involved the development of hardware and software needed to perform the NDE testing. Please note that this paper is intended to provide a simple, quick summary of the most important findings of the NCHRP 21-5 and 21-5(2) research. Full details of the findings, including additional data and full discussions of methods, test locations, etc., can be found the in the final reports (references 1 and 2) for each of these stages of the research.

This paper is focused on the use and specification of the borehole Parallel Seismic (PS) and surface Ultraseismic (US) methods. These two nondestructive evaluation (NDE) methods were found to be the most applicable methods for determination of unknown foundation depths in this research. A number of other NDE methods were also investigated in the research and found to have more limited applications. These more limited NDE methods are also discussed herein and include the Sonic Echo/Impulse Response (SE/IR)[3], Bending Waves (BW)[4], Spectral Analysis of Surface Waves (SASW)[5] surface methods and the Induction Field (IF)[6] and Ground Penetrating Radar (GPR)[7] borehole methods.

REVIEW OF SURFACE NDE METHODS

Brief discussions of the surface-based Sonic Echo/Impulse Response, Bending Wave, Ultraseismic, and Spectral Analysis of Surface Waves NDE methods for determination of unknown bridge foundation depths are presented below. Schematics of these four surface NDE methods are shown in Fig. 1.

Sonic Echo/Impulse Response Test

In the Sonic Echo/Impulse Response test, the source and receiver are placed on the top and/or sides of the exposed pile or columnar shaped substructure as shown in Fig. 1a. The depth of the reflector, e.g., a pile bottom, is calculated using the identified sound (compression) wave echo time(s) for SE tests, or resonant peaks for IR tests due to the applied source impact.

Bending Wave Test

The Bending Wave (BW) test is based on the dispersion characteristics and echoes of bending waves traveling along very slender members like piles. The method was first developed for timber piles[8]. The method involves mounting two horizontal receivers a few feet apart on one side of an exposed pile, and then impacting the pile horizontally on the opposite side of the pile a few feet above the topmost receiver in an attempt to identify an echo of bending wave energy from the pile tip as shown in Fig. 1b. Analyses may be performed on BW data by the Short Kernel Method in the time domain (similar to filtering in an SE test), or from modal analysis in the frequency response domain (like the Impulse Response method). The BW method was found in the research to be limited to comparatively short pile foundations in soft soil conditions.

Ultraseismic Test

The Ultraseismic test involves impacting exposed substructure to generate and record the travel of compression or flexural waves down and up substructure at multiple receiver locations on the substructure as shown in Fig. 1c. This test combines the capabilities of the SE/IR and BW measurements with geophysical processing to separate reflections of wave energy coming from foundation elements versus reflections from the top of exposed substructure. The US method was found to be more accurate and applicable than the SE/IR or BW tests.

Spectral Analysis of Surface Waves Test

The Spectral Analysis of Surface Waves (SASW) test involves determining the variation of surface wave velocity vs. depth in layered systems as shown in Fig. 1d. The bottom depths of wall shaped pier and abutment substructures or footings can be determined if they have suitable flat, horizontal and exposed surfaces for testing. The foundation element bottoms are indicated by the slower velocity of surface wave travel in underlying soils. This test was found to be very applicable for these types of foundations where the foundation depths were less than or equal to 2/3 the width of the accessible flat test surface.

REVIEW OF BOREHOLE NDE METHODS

Brief discussions are presented below of the borehole-based Parallel Seismic, Induction Field and Borehole Radar NDE methods for determination of unknown bridge foundation depths. Schematics of these three borehole NDE methods are shown in Fig. 2.

Parallel Seismic Test

The Parallel Seismic (PS) test consists of impacting exposed foundation substructure either vertically or horizontally with an impulse hammer to generate compression or flexural waves which travel down the foundation and are transmitted into the surrounding soil as shown in Fig. 2a. The refracted compression (or shear) wave arrival is tracked at regular intervals by a hydrophone receiver suspended in a water-filled cased borehole (original PS procedure) or by a clamped three-component geophone receiver (new procedure-better for shear wave arrivals) in a cased or uncased borehole (if it stands open without caving). The depth of a foundation is typically indicated by a weaker and slower signal arrival below the tip of the foundation. Diffraction of wave energy from the foundation bottom was also found to be indicative of its depth in PS tests as well. The PS test was found to the most accurate and widely applicable NDE method for determination of unknown bridge foundation depths of all tested NDE methods.

Induction Field Test

The Induction Field (IF) method is similar in its application to the Parallel Seismic method, but employs the use of electromagnetic waves instead of stress (sound) waves as shown in Fig. 2b. An electromagnetic field is set up in the ground between a steel pile (or electrically continuous reinforced concrete foundation) and a steel electrode (or other electrically isolated steel containing foundation). A triaxial magnetic field search coil is used to measure the field strength in a PVC cased boring drilled within 1 m (3 ft) or less of the foundation that extends about 3 m (10 ft) below the foundation bottom. When the coil goes below the foundation the field amplitude decreases to a minimum thereby indicating the depth of a steel pile or reinforced foundation. Interpretation of the data from the Induction Field method is complicated by the existence of ferrous or other conductive materials in the bridge structure, and the presence of conductors (such as cables or pipes) in the ground around the pile. The IF test is only applicable to reinforced concrete foundations or steel piles that have accessible, electrically connected rebar/steel.

Borehole Radar

The Borehole Radar (BHR) test uses a transmitter/receiver radar antenna to measure the reflection of radar echoes from the side of the bridge substructure foundation as shown in Fig. 2c. The BHR test is most sensitive to foundations of steel or with steel, as the electromagnetic wave energy reflects strongly from steel. The BHR method is limited in its application by wet, conductive clays and salt water as the wave energy is severely attenuated by these subsurface conditions with high dielectric constants.

SELECTION OF NDE METHODS FOR UNKNOWN BRIDGE FOUNDATION DEPTHS

The research showed that the borehole-based Parallel Seismic method was both the most accurate and most applicable NDE method for the determination of the depth of unknown bridge foundations for bridge scour safety evaluation purposes. This suggests that it would be valuable to initially perform at least one Parallel Seismic test for each bridge to check the accuracy of depth predictions from any other less costly surface methods that may also be applicable for a

given foundation type of the bridge being tested. Ultraseismic or other surface methods that are subsequently proven to be accurate based on a comparison with the Parallel Seismic results may then be used with greater confidence to evaluate unknown foundation depths of other abutments and/or piers on a bridge.

It should be noted that as local experience is gained with the use of any of the borehole or surface NDE methods for typical local bridge substructure types and subsurface conditions, the accuracy and applicability of the methods will become much better known to DOT engineers. This local knowledge can then be used to further optimize the selection of NDE methods from technical and cost perspectives. Knowledge of unknown foundation bridge substructure will range from knowing only what is visible to having design drawings and subsurface geology information without as-built plans.

PARALLEL SEISMIC NDE METHOD

Of all the NDE methods investigated during this research, the borehole Parallel Seismic (PS) method shown in Figure 2A was found to be the most applicable to all bridge foundation types. The PS method requires impacting the exposed portion of the substructure and monitoring the response of the foundation and surrounding soil with a receiver in a cased borehole drilled next to the foundation. As the wave energy is monitored by the receiver at depths parallel to and below the bottom of the foundation, it becomes typically weaker and slower below the foundation bottom. This change in the received signals with depth indicates the foundation depth.

Borehole Considerations

The location of the borehole to be drilled should be selected based on minimizing the impact to vehicular traffic. However, when the choice is between some traffic disruption during drilling and testing versus drilling from a barge when over water, it may be best to core and drill through the bridge deck if reinforcement can be avoided or cut with structural engineer approval. The PS method requires that a borehole be drilled next to the foundation to be tested, preferably satisfying the following conditions:

1.   The borehole needs to be drilled as close as possible, preferably within 0.9 to 1.5 m (3 to 5 ft) or less from the edge of the foundation to be tested. This requirement is to reduce the effect of the surrounding soil, particularly at sites with unsaturated soil conditions. Where saturated soil conditions exist, PS tests have been successfully performed with larger horizontal offsets from foundation edges.

2.   The borehole should extend at least 4.5 m (15 ft) below the minimum required foundation depth (from a capacity/scour perspective considering the subsurface geology) or suspected foundation depth, whichever is greater. This requirement is to ensure that data is collected to the depth of interest. If the borehole is not at least somewhat deeper than the foundation bottom, one can only determine that the foundation is at least as deep as the borehole.

3.   The borehole should be cased with a plastic PVC casing of sufficient diameter to insert

the NDE tools that will be used (typically 50 to 100 mm, i.e., 2 to 4 inch ID casing). Steel casing is not recommended for use since the steel has faster stress wave velocities than concrete and wood foundation materials, and it prevents the use of the Induction Field and Borehole Radar methods. For all foundation construction materials, the wave velocities through the material are higher than the velocity in the PVC casing. If steel casing is used, the wave traveling through the casing can be faster than the waves traveling through the foundation, thereby making the PS NDE results difficult to interpret.

4.   A hydrophone receiver is used in the most commonly performed PS tests due to its omni-directional sensing capabilities and associated sensitivity to compression waves. The hydrophone receiver must be surrounded by water inside and outside the casing in order to respond to the arrival of the wave energy. A hydrophone in air (without water coupling) will not detect energy traveling through the soil that has been emitted from the foundation element. Water coupling of hydrophones in a boring is easy to achieve where the ground water level is high or the foundation is in water, since then boreholes can be drilled using slurry or just water methods. A PVC casing must be inserted and clean water added to the casing if it is solid. If comparatively clean ground water (minimal fines) is present in a boring, then water can also be allowed to flow in through small sawcuts in a casing. In dry soils with sufficient clay and silt fines so that the boring drains slowly, clean water can be added to the casing and into the boring annulus. However, in dry, free-draining sands and gravels it may be difficult to maintain enough water in the boring to permit testing with a hydrophone. Consequently, in dry soils the borehole annulus around the PVC casing may need to be grouted to ensure good coupling between the borehole casing and the surrounding material. The grouting material should be bentonite based or a lean bentonite-cement mix to avoid having a material that has a similar fast velocity to the foundation material. In a grouted casing, it can be filled with water for hydrophone PS tests (fastest), or left dry and sealed for tests with a triaxial geophone to permit both compression wave and shear wave measurements in the PS test. If a triaxial geophone is used, one can also impact the ground above and measure the compression and shear wave velocities in the soils with a Downhole Seismic test. This information is useful if theoretical modeling of the PS test is to be done and it also provides data on the stiffness of the soils.

5.   The casing should be water tight, capped at the bottom, water-filled and free of debris. The water tight casing is required if hydrophones are used as the receivers in the PS tests. Slots may be cut in the casing to permit easier filling provided there is no risk of sediments coming into the casing. Water pressure from the wave energy is measured by the hydrophones in the casing.

Required Parallel Seismic Test Equipment

When a PS test is performed, it is required to record the impact force and the responses of the receivers. The equipment needed to perform the data collection includes:

1.   Digital signal analyzer or PC based data acquisition system with a sampling rate of at least 100 kiloHertz (10 microseconds/12 bit digital data point) on at least 2 channels (4 channels needed for triaxial geophone) with at least 4096 data points per channel,

2.   Signal amplifier(s) for hydrophone or geophone (differential input recommended for best signal to noise ratio performance),

3.   Instrumented impulse hammers weighing 1.4 to 5.5 kg (3 to 12 lb) to measure impact force and trigger data acquisition upon impact,

4.   Hydrophone and/or triaxial geophone receivers with necessary cables, connectors, and power supply (battery, inverter or generator).

Parallel Seismic Data Interpretation

The main objective of Parallel Seismic tests is to determine the depth of the unknown foundations. Based on the NCHRP 21-5 and 21-5(2) research results, several criteria were established for determining the foundation depths based on Parallel Seismic data as follows:

1.   Breaks in the slope of the lines in a plot of depth versus recorded time (see Fig. 3),
2.   Drop in energy amplitude below the bottom of the foundation (see Fig. 4), and
3.   Diffraction of wave energy at the bottom of the foundation (see Fig. 5).

The vertical axes in Figs. 3-5 represent depth below the top of the casing. The horizontal axes represents recorded time in milliseconds (1 mSec = 0.001 seconds).

Examination of Figure 3 shows the case where subsurface conditions are uniform with depth (this usually means saturated soil conditions where the compression wave velocity is that of water, i.e. about 1500 m/s or 4900 ft/s). This allows one to determine the velocity of the foundation element, and to clearly see the foundation bottom as the point where the wave velocity is slower and the amplitude is weaker. The foundation bottom is then taken as the intersection of the foundation velocity line with the soil velocity line as shown in Fig. 3.

The break in the velocity slope is not as clear in the PS results shown in Fig. 4. However, there is a distinct drop in amplitude of the wave energy and a break in the data later in the record at 24 ft that indicates the foundation bottom. In Fig. 5, the arrival of the weaker and fastest compression wave energy is not visible at shallow depths as the data is dominated by tube waves traveling in the PVC cased boring. The tube waves were generated by the pilecap footing which acted as a "speaker" to emit wave energy into the soils that coupled into the cased borehole to generate the tube waves. However, some of the weaker compression wave energy did indeed reach the bottom of the steel H-piles whereby it diffracted into the surrounding soils and generated upward and downward going tube waves in the borehole as well. This arrowhead feature in Fig. 5 accurately indicated the depths of the steel H-piles. Steel H-piles have comparatively high attenuation of wave energy properties due to their comparatively large surface area to cross-sectional area ratio versus solid, round piles and other foundation shapes.

US METHOD FOR UNKNOWN BRIDGE FOUNDATION DEPTHS

The surface Ultraseismic (US) method was researched and developed during the NCHRP 21-5 research for determination of the unknown depths of bridge foundations. The Ultraseismic method is a sonic reflection technique that uses geophysical digital data processing techniques.

With the US method, one analyzes the propagation of induced compression and flexural waves as they reflect from foundation substructure boundaries (impedance changes, i.e. changes in the multiple of wave velocity x density x cross-sectional area). This is the same principle that the Sonic Echo/Impulse Response and Bending Wave methods rely on as well. However, the data acquisition and processing for the US method involves recording and display of multiple channels of data to better track the reflections from foundation element interfaces and bottoms as discussed below. The Ultraseismic Vertical Profiling method is shown above in Fig. 1C.

The Ultraseismic method was researched and developed by the authors to overcome the difficulties encountered by the Sonic Echo/Impulse Response method and the Bending Wave method tests on non-columnar and complex columnar bridge substructures. The Ultraseismic method is a broad application of geophysical processing to both the Sonic Echo/Impulse Response and Bending Wave tests in that the initial arrivals of both compression and bending waves and their subsequent reflections can be analyzed to predict unknown foundation depths.

Two types of Ultraseismic test geometries have been specifically introduced for this problem: US Vertical Profiling and US Horizontal Profiling. For a one dimensional imaging of the foundation depth and tracking the upgoing and downgoing events, the term Vertical Profiling (VP) test method is used as shown in Figure 3 below. In this method, the bridge column or abutment is hit from the top or bottom (both vertically and horizontally) and the resulting wave motion is recorded at regular intervals down the bridge substructure element. Typically, three-component recording of the wavefield is taken in order to analyze all types of ensuing wave motion. A VP line can be run in both a columnar (a bridge pier or pile foundation) and a tabular (a bridge abutment) structure.

For two-dimensional imaging of the foundation depth, the term Horizontal Profiling (HP) test geometry is used where there is flat, horizontal access for testing such as the top of an accessible pier or abutment. In this less commonly applicable US method, the reflection echoes from the bottom are analyzed to compute the depth of the foundation. The source and receiver(s) are located horizontally along the top of accessible substructure, or any accessible face along the side of the substructure element, and a full survey is taken along the top of the element.

The main objective of Ultraseismic tests is to determine the unknown depth of the foundation. Example US results from the NCHRP research are presented herein to illustrate the use of the method and the interpretation of the results. The source/receiver layout for Ultraseismic Vertical Profiling tests on one of the pier columns of Bridge No. 5188, Minnesota Highway 58 in Zumbrota is shown in Fig. 6. The source point was able to be located vertically on top of the concrete beam. Thus, impacts were applied with downward vertical impacts to the top of the beam over the column using a 1.4 kg (3 lb) impulse hammer with a hard plastic tip. A 3-component accelerometer was mounted on the side of the exposed portion of the column at intervals of 0.15 m (0.5 ft) from 1.5 m (5 ft) below the top of the beam to near the ground surface.

Field data for a Vertical Profiling test done to measure flexural waves is shown in Fig. 7. The depth shown in Fig. 7 represents the depth below the top of the concrete beam. All data were debiased to remove any DC shift and f-k filtered to enhance upgoing waves. After this

processing, two clear reflection events are apparent in the data. The first reflector corresponds to a depth of 2 m (6.5 ft) below Receiver 24 at a depth of 5 m (16.5 ft) below the top of the concrete beam as shown in Fig. 7. The flexural wave velocity of 1,770 m/sec (5,800 ft/sec) was determined from the slope of the initial downgoing and reflected upgoing waves. This reflection corresponds to a depth of 7 m (23 ft) from the top of the concrete beam. The actual depth of the foundation was equal to 9.4 m (31 ft).

Further examination of Fig. 7 shows there is a second reflector at a depth of 4.3 m (14 ft) below Receiver 24 at a depth of 5 m (16.5 ft) below top of concrete beam. This reflection corresponds to a depth of 9.3 m (30.5 ft) from the top of the concrete beam. The actual depth of the foundation was equal to 9.4 m (31 ft). The shallower reflection is most likely due to a change in the subsurface material properties at this depth which is below water. The most important thing to note in Fig. 7 is that the flexural wave energy is first tracked down the bridge substructure, and that upgoing events correspond to reflectors whose depth can be predicted with geometry as shown. Downgoing events from the bridge structure above the impact point can be eliminated in the US data with the use of f-k filtering.

CONCLUSIONS

The NCHRP 21-5 and 21-5(2) research resulted in greatly improved understanding of the applicability and accuracy of such NDE methods using sonic, ultrasonic, seismic, magnetic and electromagnetic techniques. Of all of the methods researched, the borehole Parallel Seismic Method was found to be the most accurate and versatile method for determining unknown foundation depths for the broadest range of foundation types. The surface Ultraseismic Method was found to be the most accurate method for determining single substructure element depths such as piles, piers, abutments, etc. However, the Ultraseismic method does not provide data on the elements below the first major change in cross-section, such as a pier with a pilecap on piles, where the piles will not be detected.

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Surface Echo Tests
Sonic Echo/Impulse Response
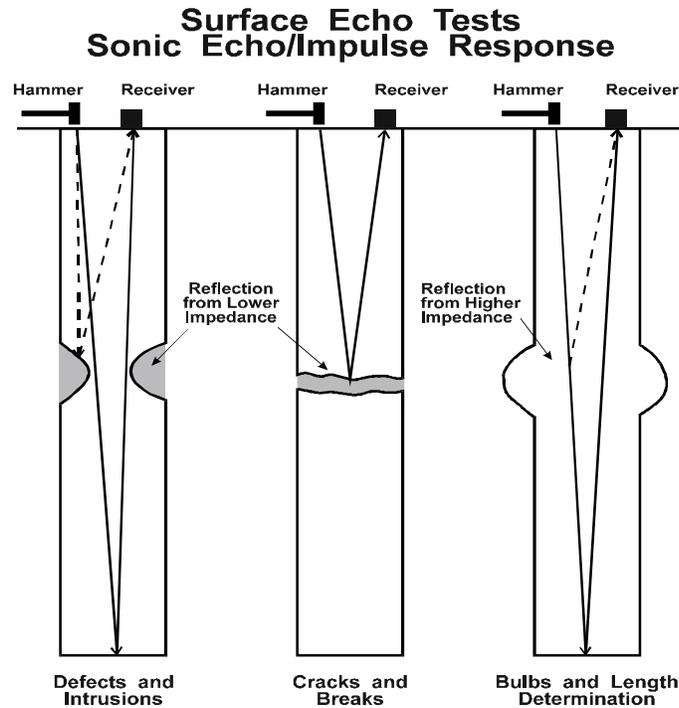
Figure1a - Sonic Echo/Impulse Response Method

Bending Waves Method
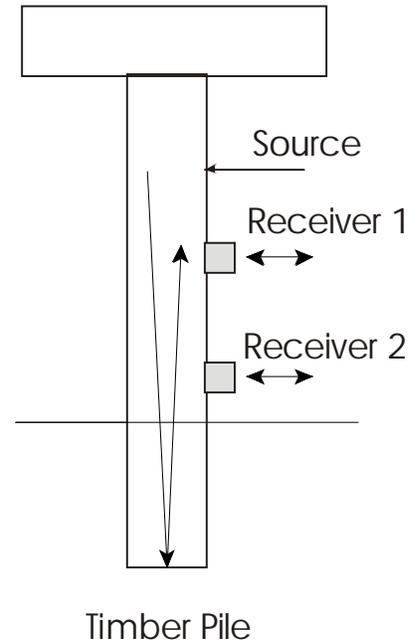
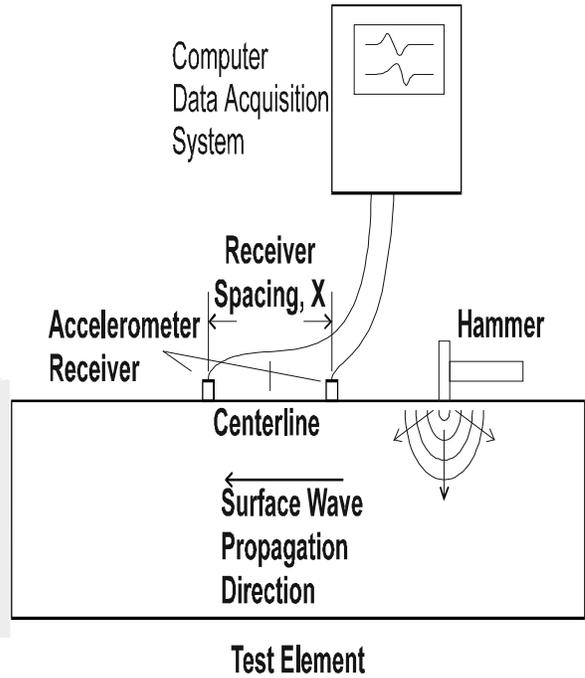Figure 1b - Bending Waves Method
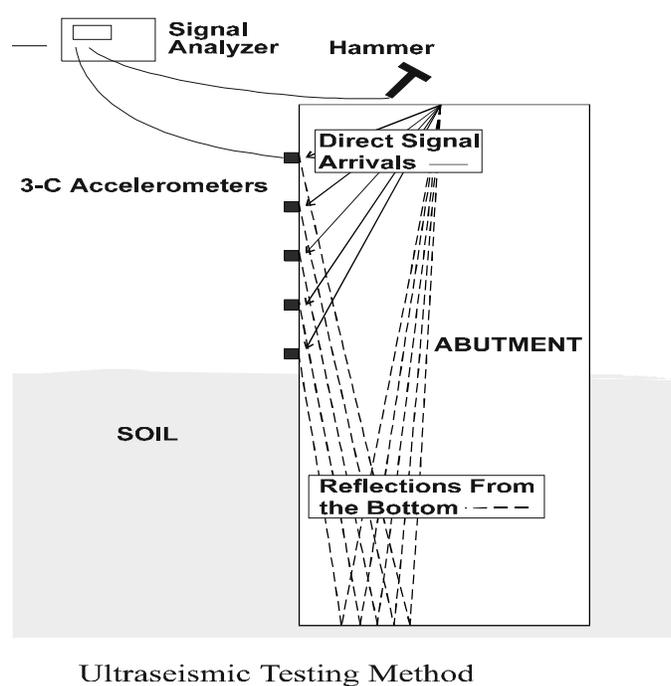
Ultraseismic Testing Method

Figure 1c - Ultraseismic Method – Vertical Profiling

Figure 1d - Spectral Analysis of Surface Waves

Figure 1 – Surface-Based NDE Methods

Choose tapping to
maximize current A

Transformer

Oscillator
Detector

Output

Input

A

Superstructure

Signal
Analyzer

Return
Electrode

Search
Coil

Suspended hydrophone
or clamped 3-
component geophone

Pile of
interest
(steel)

PVC cased
hole
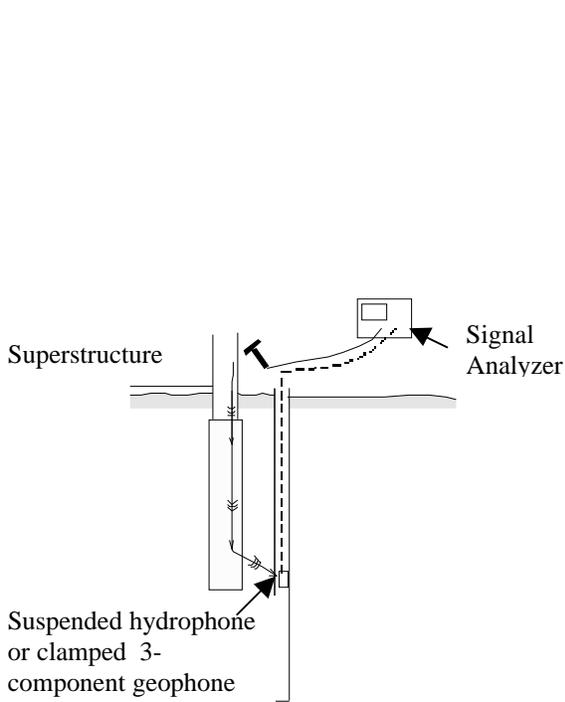
Figure 2a - Parallel Seismic Method
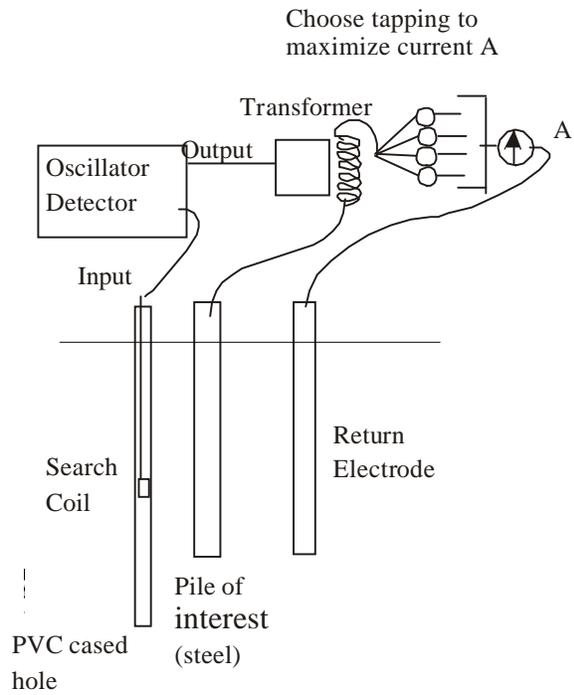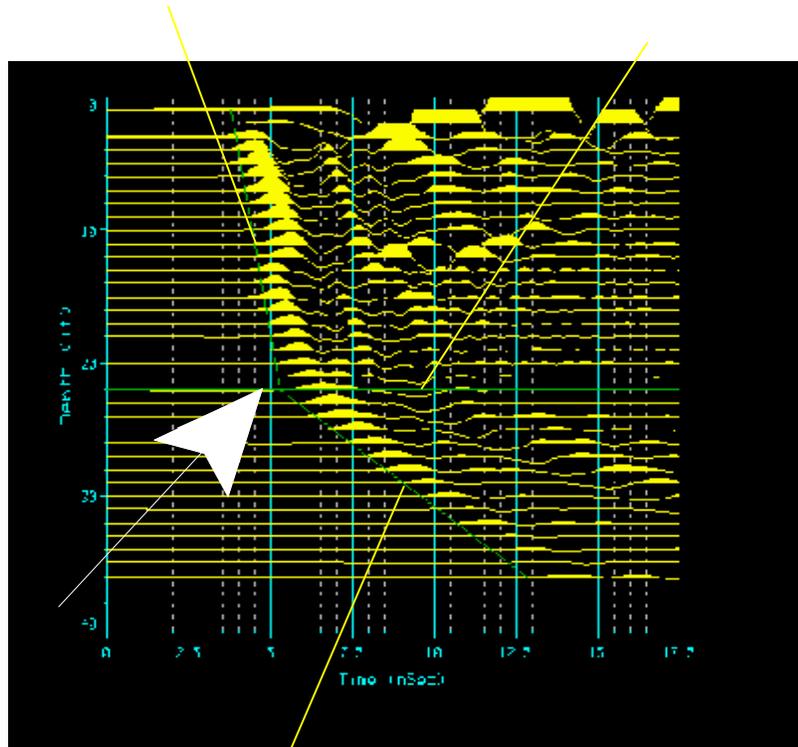
Figure 2b - Induction Field Method

SIGNAL
ANALYZER

RADAR ANTENNA

ABUTMENT

Reflected
Radar Signals

Unreflected
Radar Signals

BOREHOLE RADAR METHOD

Figure 2 - Schematics of Borehole-Based
NDE Methods
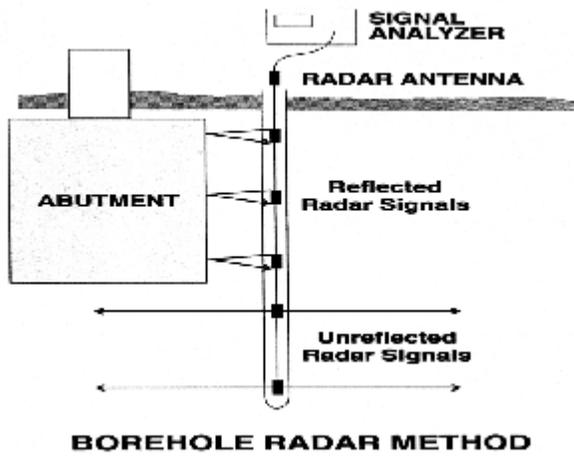
Figure 2c - Borehole Radar Method

Compression Wave Velocity in timber
pile = 13,500 ft/sec

Pile tip at a depth of 22 ft

Figure 3 - Parallel Seismic Result for Bridge Timber Pile Foundation Data from a 12-lb Horizontal Hammer Hit and Vertical Geophone Component, Wake County Bridge # 251, North Carolina

Comments:

Depth shown in figure is depth below top of borehole
Drop in amplitude below a depth of 24 ft
Bottom depth = 24 ft (reference is top of borehole)
Top of borehole is 2.6 ft below top of pile
Pile length = 24+2.6 = 26.6 ft (reference is top of pile)
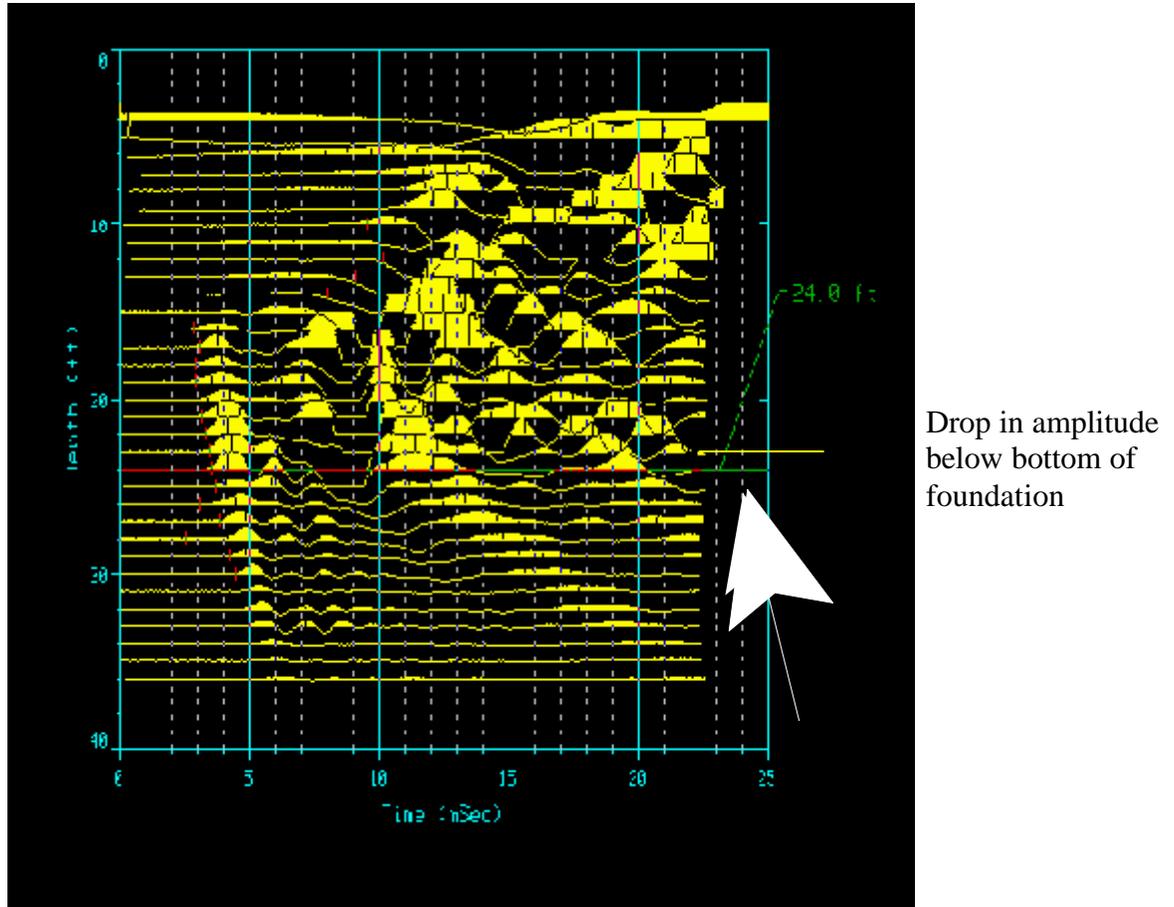
Figure 4-   Parallel Seismic Data from a 12-lb Vertical Hammer Hit
             and Vertical Component Recording of Geophone
             Wilson County Bridge # 5, Bent 1, East Pile, North Carolina
             Example of Drop in Amplitude below Bottom of Foundation.

Depth = 29 ft

Diffraction of
wave energy at
bottom of
foundation

Tube Wave
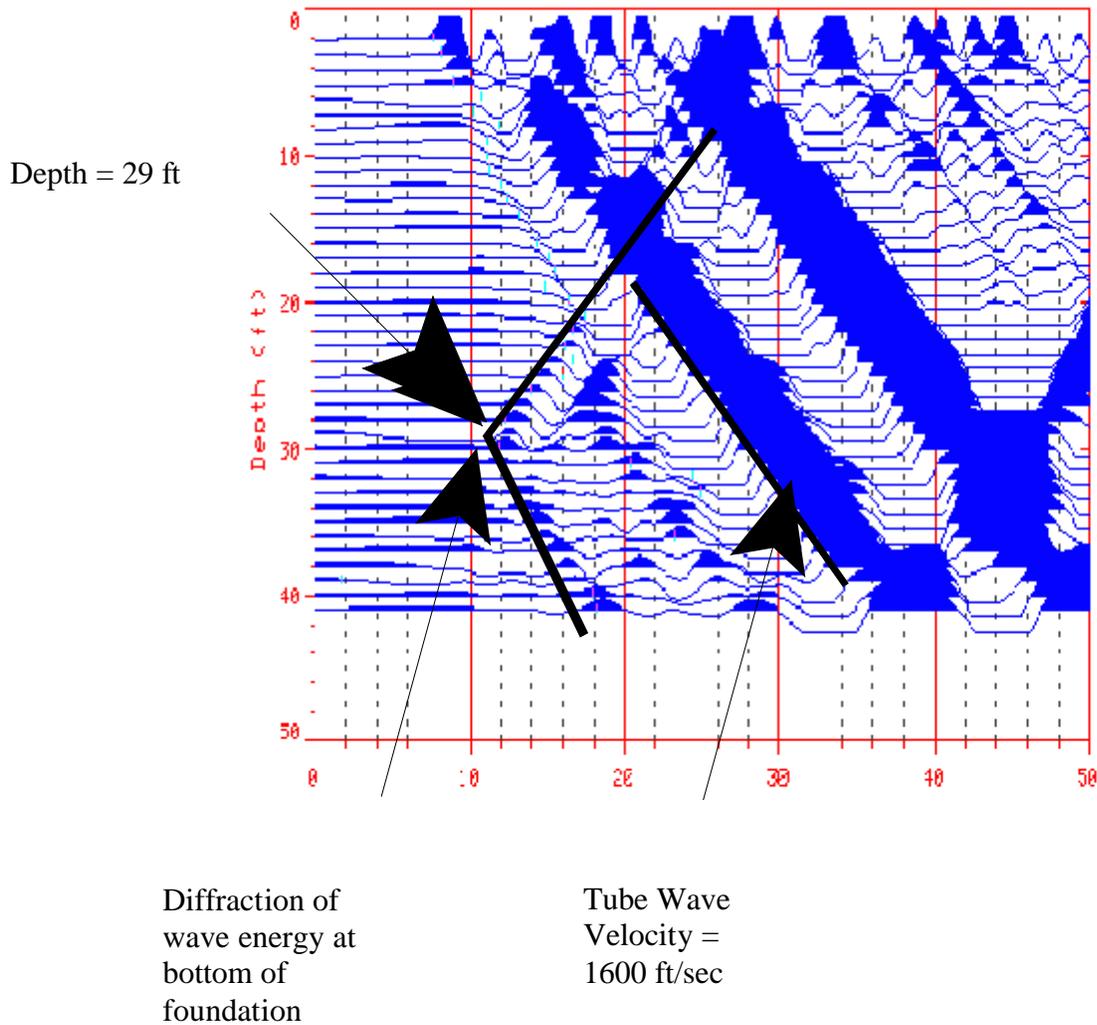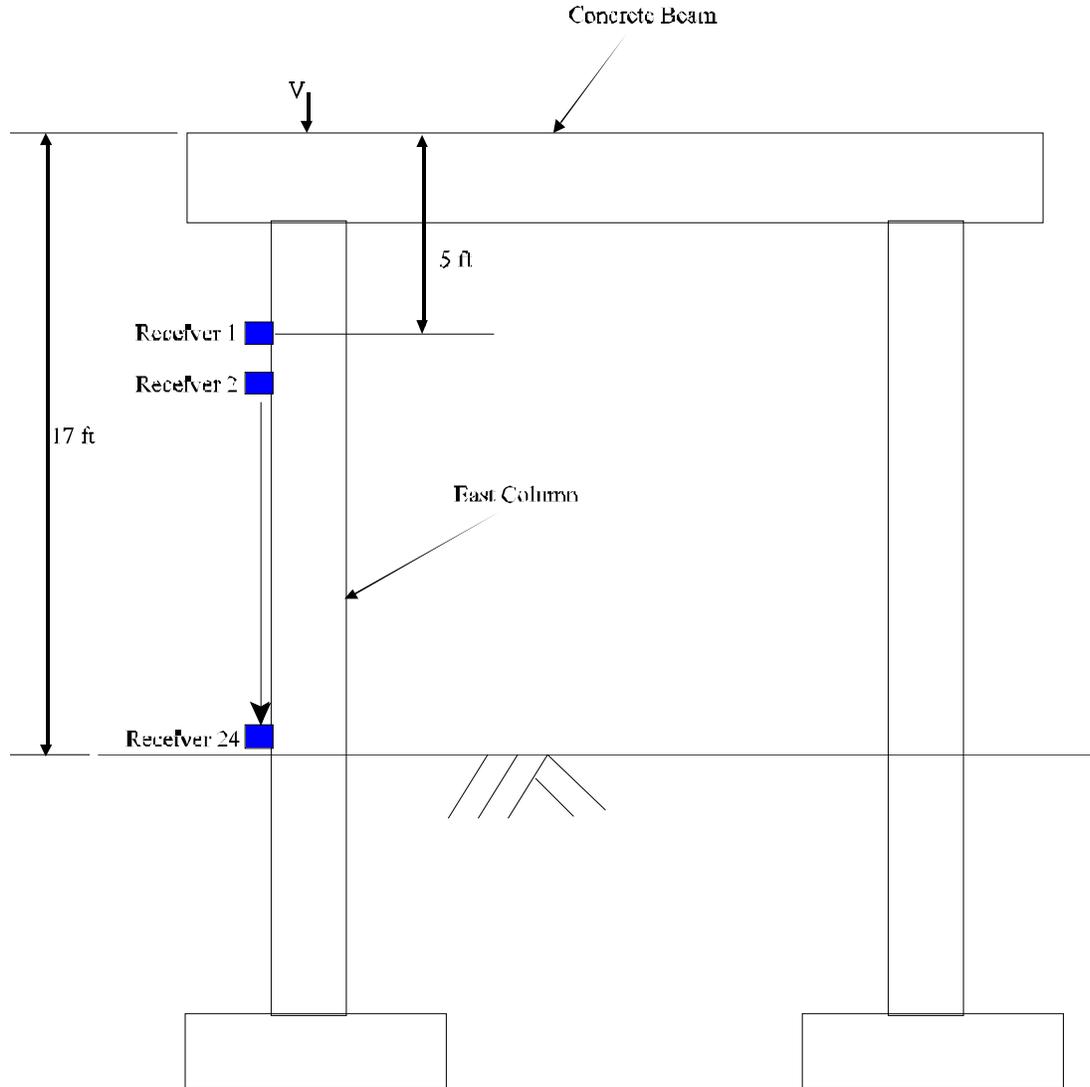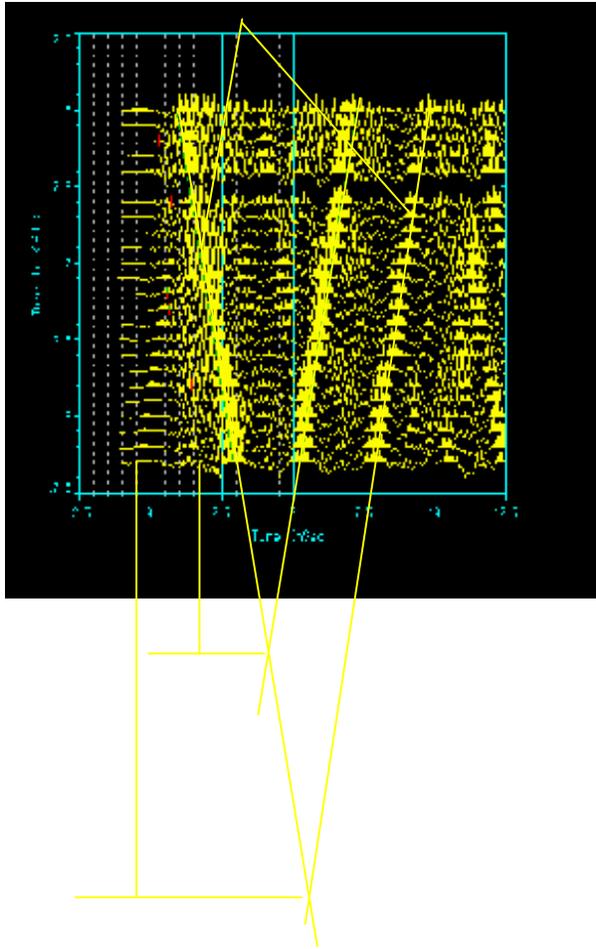Velocity =
1600 ft/sec

Figure 5-   Parallel Seismic Data from a 12-lb Hammer Horizontal Hit
              and Single Hydrophone Recording,
              Steel H-Pile Foundation with Concrete Pilecap on Top
              Coors Bridge, Golden, Colorado
              Example of Diffraction of Wave Energy at Bottom of Foundation.

Concrete Beam

V

5 ft

Receiver 1

Receiver 2

17 ft

East Column

Receiver 24

V = Vertical Hammer Hit Location
24 Accelerometer Receiver Locations at Intervals of 0.5 ft

Figure 6 - Source/Receiver Layout for Ultraseismic Tests Performed at Bridge No. 5188
Minnesota Hwy 58, Zumbrota, Minnesota

Flexural Velocity at top arrows equals 5,800 ft/sec
Depth shown in Figure is depth below top of pier
Depth of first reflector = 16.5 + 6.5 = 23 ft (reference is top of pier)
Depth of second reflector = 16.5 + 14 = 30.5 ft (reference is top of pier)

Figure 7 - Ultraseismic Data from a 3-lb Vertical Hammer Hit
and Radial Component Recording f-k Filtered to Enhance Upgoing Waves
Bridge No. 5188, Minnesota Highway 58, Zumbrota, Minnesota