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Engineering Notebook Issuance GT-16
Summary of the NCHRP 21-5 Interim Report
Determination of Unknown Subsurface Bridge Foundations

Chief, Bridge Division HNG-31
Office of Engineering

Regional Administrators
Division Administrators
Federal Lands Highway Program Administrator

Distributed with this memorandum is Geotechnical Engineering Notebook Issuance GT-16, "Determination of Unknown Subsurface Bridge Foundations." The GT-16 is a summary of the NCHRP 21-5 interim report of the same title prepared by Messrs. Larry D. Olson, Farrokh Jalinoos, and Marwan F. Aouad. The purpose of GT-16 is to provide bridge owners with interim information on available nondestructive test (NDT) methods for assessing unknown bridge foundations.

The NCHRP Project 21-5 involves a study of various types of NDT equipment which could be used in subsurface investigations of unknown bridge foundations. At this stage of the research, the general aspects of several types of NDT equipment have been assessed for applicability in the unknown bridge foundation area. Although no definite conclusions can yet be reached on the reliability of these NDT methods in all situations, enough data has been collected to provide interim information to highway agencies on the general aspects of these methods.

The February 26, 1998, memorandum by the Office of Engineering "Compliance with the National Bridge Inspections Standards; Scour Screening and Scour Evaluation of Bridges over Waterways" requested that State departments of transportation (DOTs) begin evaluation of bridges with unknown foundations. The bridge owners should determine whether the current technology is applicable for gathering information needed to conduct scour evaluations of their bridges with unknown foundations.

Two printed copies of the GT-16 is distributed with this memorandum. The FHWA Division Office should provide one copy to the State DOT. Primary distribution of GT-16 will be via electronic copies over the internet. The report will soon be posted to the

Bridge Division web site at: www.fhwa.dot.gov/geo.htm. Please distribute the information about GT-16 to holders of the Geotechnical Engineering Notebook and geotechnical and hydraulics engineers.

If any questions arise concerning this document, please contact Mr. Jorge Pagán-Ortiz at 202-366-4604 or Ms. Michelle Cribbs at 202-366-8792.

/s/

David H. Densmore

Attachment

U.S DEPARTMENT OF TRANSPORTATION

FEDERAL HIGHWAY ADMINISTRATION

GEOTECHNICAL ENGINEERING NOTEBOOK

Geotechnical Guideline No. 16

TITLE
“Determination of Unknown Subsurface Bridge Foundations”
A Summary of the NCHRP 21-5 Interim Report Prepared by
Larry D. Olson, Farrokh Jalinoos, and Marwan F. Aouad

Purpose: To provide interim information on available NDT methods for assessing unknown bridge foundations.

Background: The NCHRP Project 21-5 involves a study of various types of NDT equipment which could be used in subsurface investigation of unknown bridge foundations. At this stage of the research, the general aspects of several types of NDT equipment have been assessed for applicability in the unknown bridge foundation area. Although no definite conclusions can yet be reached on the reliability of these NDT methods in all situations, enough data has been collected to provide interim information to highway agencies on the general aspects of these methods.

Continuing Research: Based on the results of this report, a second phase of research was initiated. The phase II research will evaluate the validity and accuracy of some of the NDT methods researched during Phase I and to develop instrumentation for use by highway departments and agencies. The initial phase of the Phase II research was to determine the feasibility of adapting/developing practical methods and equipment for the determination of subsurface bridge foundation characteristics, particularly the depths of the foundations. The next part of the research involved semi-blind NDT studies of 20 bridges with known foundations to determine the accuracy of the methods. The final report presenting the research results is expected in the Spring of 1999.

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1.0 INTRODUCTION

There are approximately 580,000 highway bridges in the National Bridge Inventory. About 104,000 of these bridges are estimated have unknown foundations in terms of the type and/or depth. For a large number of older non-federal-aid bridges, and to a lesser extent federal-aid bridges, there are no design or as-built bridge plans available to document the type, depth, geometry, or materials incorporated in the foundations. There are two general cases for unknown bridge foundations:

1. the foundation type and depth are unknown; and,
2. the foundation type is known, but its depth is unknown.

These unknown bridge foundations pose a significant problem to state DOT's from a scour safety evaluation perspective. Because of the risk of scour undermining bridge foundations and the threat to public safety, the Federal Highway Administration (FHWA) and state transportation departments face the need to screen and evaluate all bridges, over rivers, streams, and in coastal areas, both on- and off-state systems, to determine their susceptibility to scour. The problem is that foundation type and depth information is needed to perform an accurate scour evaluation of each bridge. State bridge engineers are faced with the dilemma that their budgets cannot fund the required investigations with conventional excavation, coring, or boring methods to determine unknown bridge foundation conditions and simultaneously support normal maintenance operations at required funding levels.

The NCHRP 21-5 research project "Determination of Unknown Subsurface Bridge Foundations" was conceived to evaluate, develop, and test concepts, methods, and equipment that will allow the determination of subsurface bridge foundation characteristics where information is unavailable, unknown, or uncertain. The 21-5 project objective is to provide practical, accurate, and cost-effective means to determine unknown foundation conditions for as many different bridge types as feasible. The foundation data will be used as input into scour evaluation studies of existing bridges over water. This report is a summary of the NCHRP 21-5 research project Final Report.

1.1 Bridge Superstructure, Substructure, Geology, And Channel Variables

Before discussing possible approaches to the problem of unknown bridge foundations over water, it is useful to consider the components of the bridge system. The bridge superstructure is defined as all structure above the bridge bearing elevation and bridge substructure consists of everything below the superstructure. Therefore, bridge substructure incorporates all foundation elements such as columns, wall piers, footings, pile caps, piles, drilled shafts, etc. In this report, the terms "bridge foundation" and "bridge substructure" are used interchangeably. A simplified illustration of these definitions is shown in Figure 1.

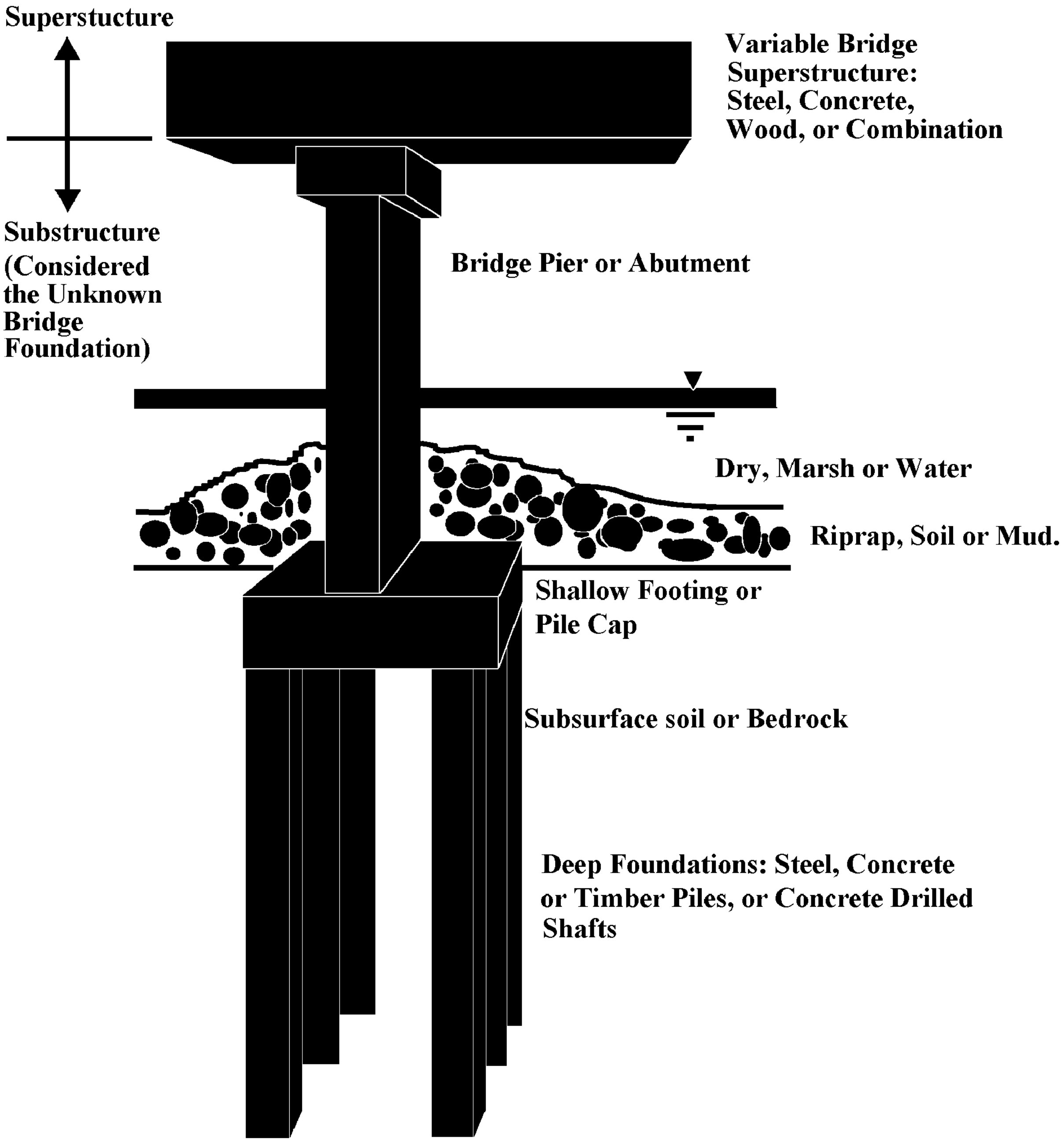


Figure 2- Variables of an Unknown Bridge Foundation Depicted on an Idealized Bridge Element

The challenge of nondestructive determination of unknown bridge foundation characteristics can be appreciated by considering the multitude of variables that could impact a given NDT method as listed below, and partially illustrated in Figure 1.

1. The bridge may be a single span with abutments only, or multiple spans with abutments and piers.

2. Foundation materials may be concrete, steel, timber, or masonry.

3. The tops of footings and pile caps may be buried below riprap, backfill, and/or channel soils.

4. The bridge channel conditions may range from dry riverbed to marsh to flowing water with water conditions ranging from fresh to brackish to saltwater.

5. Subsoil conditions may range from soft silts, clays, and loose sands to very stiff and dense soils to bedrock.

6. The foundation types may be shallow footings or deep foundations. Footings are most likely square or rectangular with some massive cofferdam footings, but pedestal stone footings may also exist. Piles might be timber, concrete (round, octagonal, and square), or steel (H and round pipe sections); with or without concrete pile caps; and may be battered or vertical. Other deep foundation types used for bridges recently are concrete drilled shafts and even more recently auger-cast concrete piles.

7. The bridge substructure and superstructure are highly variable in geometry and materials. The superstructure may consist of steel, concrete, timber, or a combination of materials. The substructure is generalized herein as an abutment or pier, which can be made of steel, concrete, masonry, and/or timber.

1.2 Physical Property Considerations of NDT of Unknown Bridge Foundations

The following items are considered important information in the evaluation of substructure elements:

1. Foundation Depth - bottom of footing, pile, or combined system;
2. Foundation Type - shallow (footings), deep (piles or shafts), or a combination;
3. Foundation Geometry - buried substructure dimensions, pile locations;
4. Foundation Materials - steel, timber, concrete, and masonry;
5. Foundation Integrity - corroded steel, rotted timber, cracked concrete, etc.

The foundation depth and the foundation type (if unknown) were consistently indicated by the NCHRP panel members and others to be the two most critical items on which bridge engineers want accurate data for input into scour studies. The other items may be judged to be of secondary importance, since the evaluation of scour susceptibility is less dependent on these variables, although knowledge of the foundation substructure geometry is certainly useful in scour evaluations. The ideal nondestructive test (NDT) should provide positive information concerning the first two critical items and indications concerning the latter items.

To decide which NDT methods might be useful in determining unknown bridge foundation conditions, first consider which physical properties can be nondestructively detected to delineate the unknown bridge foundation components from the water and earth environments around the foundation substructure. Secondly, consider what positive or negative impacts the differing geometry and materials of the bridge superstructure and substructure will have with varying water and subsurface geological conditions on the potential NDT methods.

An unknown bridge foundation almost always has different material properties from the surrounding geological and hydrological environment. The foundation material may be steel, wood, concrete, or masonry. The bridge foundation shape may be that of a footing, a pile, or a combination of the two. The environment around the bridge substructure is composed of air, water, riprap materials, soils, and/or rock and is generally approximated by a horizontally layered medium of these various materials. Thus, methods to detect and delineate a bridge foundation need to primarily consider the wide ranges of substructure, geological, and hydrological conditions at a particular bridge site. Depending on the NDT method, consideration may also need to be given to the superstructure conditions of a bridge.

The differing material types and geometries of foundations are the two most important factors to be considered in nondestructively determining bridge foundation data for widely varying geological and hydrological conditions. Superstructure type can have an adverse effect on the results of some NDT methods also. The above characteristics of the unknown bridge foundation environment provide the background used to identify NDT methods with potential applications for foundation type and depth determination. Any NDT methods must delineate between foundation substructure and surrounding subsurface conditions. A wide range of possible NDT technologies, based on stress waves, electrical/electromagnetic, magnetic, and gravity measurements to sense the difference between the foundation and its environment, were reviewed and investigated. Existing NDT methods that have been applied to unknown bridge foundations prior to this research are introduced below.

1.3 Conventional Investigation Methods

Excavation to expose a full-depth portion of a bridge foundation is the most positive means of determining unknown foundation conditions. However, there are several problems with excavation as the means to investigate unknown foundations. Excavations of bridge abutments and piers to examine their foundations are impractical without costly sheeting and dewatering operations at most bridges over water, and access for excavation equipment is difficult and will frequently require barges. The excavation work itself is hazardous for the workers and precautions must be taken not to undermine the foundation support. Excavation is thus cost-prohibitive for determining the depths of most shallow footings and even more costly to expose deep piles to verify whether or not they extend sufficiently below the scour zone so that bridge safety is not compromised. Probing with a hammer and rod, coring, or drilling through exposed bridge substructure from the bridge deck to determine the depth of concrete and masonry abutments and pier is also possible for more massive foundation elements. Table 1 compares conventional investigation methods.

Table 1- Comparison of conventional investigation methods

METHOD	REMARKS
Excavation	Positive identification of foundation, expensive, difficult,
Probing	Fast, inexpensive, only negative information obtained, not positive identification of foundation, limited depth capacities, possible false indications of foundation depth in rip-rap, rock and gravelly soils, and boulders,
Drilling/ Coring	Fast, reliance placed on penetration rate and examination of cuttings to determine foundation depth and type, no pile depth information, more positive that probing, more expensive, traffic is impeded, safety of workers is a concern, damage to the element must be repaired, unlikely that piles below the pier or abutment will be encountered by a single corehole, more expensive
Remote Subsurface Exploration	Expensive, time consuming, may require barge, multiple angled drill holes needed to confirm pile location and type, no pile depth information.

Conventional excavation, coring and boring excavations to determine unknown bridge foundation depths and types are thus seen to be expensive, destructive, and limited in their application to the unknown foundation problem. There is therefore a real need to research and develop lower cost nondestructive testing methods to provide foundation depth and type data on unknown bridge foundations to aid in scour safety evaluations.

1.4 Existing NDT Methods for Unknown Bridge Foundations

The past state-of-practice for nondestructive determination of unknown foundation conditions primarily involved two methods: the surface Sonic Echo/Impulse Response tests, and the borehole Parallel Seismic method.

The Sonic Echo/Impulse Response tests involve measurement of the echoes (reflections) of compression (longitudinal) stress waves from foundation bottoms. The Sonic Echo test for piles and shafts was first developed for quality assurance of the integrity and length of newly constructed driven piles (concrete and timber) and drilled shafts (concrete). The Parallel Seismic method has broad application to a wide range of substructure foundations. It involves impacting the exposed substructure to generate seismic wave energy that travels down the foundation and is sensed by a receiver in a nearby borehole.

Two additional methods have also been used to a lesser extent to indicate unknown foundation depths for specific types of piles: the borehole Induction Field method for piles containing a significant percentage of steel, and the surface Bending Wave (Flexural Wave) method for timber piles. The Induction Field method is only applicable to foundations of steel (H-piles, pipe piles, reinforced concrete piles, and shafts), and will not work on timber piles, plain concrete, or unreinforced masonry foundations because these foundations are non-conductive. The Bending Wave method is limited to more slender piles such as timber piles, and is similar to the Sonic Echo/Impulse Response tests.

1.5 THE NCHRP RESEARCH APPROACH

The first phase of the research involved:

> Review and summarize existing and potential technologies with promise for determining subsurface bridge foundation characteristics such as type, depth, geometry, and materials.
>
> Develop and apply a screening and evaluation process to the nondestructive testing technologies noting the advantages, limitations, development costs, initial and operational costs, as well as their applicability to different types of bridge substructure types and environments.
>
> Evaluate the capabilities of proposed NDT methods for determining unknown subsurface foundation conditions on a diverse group of bridges with varying substructures, foundations, and geology that had known foundations (i.e., at the least good design plans and at the best with as-built information). A summary of the proposed and actual research is presented in Table 2.

Table 2 - Summary of Research Objectives and Work Performance.

NDT Methods	**Research Objectives**	
	Proposed Research	**Actual Research (Independent Work)**
Sonic Echo/ Impulse Response Ultraseismic Bending Wave	Source/receiver configuration tests for 6 - 8 bridge sites. Analysis of processing techniques and feasibility evaluation of using neural network systems. Evaluation for piers and abutments on footings, steel piles, timber, piles and concrete piles/shafts, with and without caps, to evaluate different types of bridge substructures.	Data for the first 3 methods have been acquired at 17 substructures with wide range of foundation types shown in Tables 6 & 7. Theoretical modeling for Sonic Echo / Impulse Response and neural network feasibility study were completed. Bending Wave theoretical modeling plus field NDT of 2 timber piles performed at one site.
Dynamic Foundation Response	Determine feasibility by gathering data on basic responses from a bridge with footings and one with caps on piles. Source evaluation with impulse hammers and small vibrators, receiver evaluation. Compare the experimental results with the theoretical analyses of the bridge abutments/piers to evaluate the feasibility of determining deep versus shallow foundations.	Field studies at 7 sites have been completed. Theoretical modeling studies were performed of drilled shaft foundation in Texas for comparison with experimental results. Dynamic modeling was also performed of Coors bridge, and model bridge with and without piles below footings.
Parallel Seismic	Evaluation at 6-8 bridge sites with borings for footings, piles, caps, etc. In particular determine if a pile cap prevents identification of piles or if it is still clear. Also, examine processing with VSP data to provide image of edge of substructure.	Studies have been completed at the 5 sites shown in Table 8. (Five PS tests were performed at 5 Connecticut DOT bridge sites with unknown foundation depths.) Studies covered the range of the objective.
Borehole Sonic	Evaluation of existing geophysical tools at two bridge sites. Potentially limited experiments with a mock-up for feasibility. Conceptual design of a tool, if promising. Use of geophysical processing to analyze data, and software work if needed.	A prototype U. of Texas tool has been adapted for testing from two separate holes. Field testing has been completed at 3 substructure sites in Texas. A specialized full waveform sonic tool from Oyo Corporation was also used at the 3 sites in Texas from single holes.
Borehole Radar	Limited evaluation at 3 - 5 sites.	Field testing was performed at 4 sites shown in Table 9. (Testing was performed at 5 bridge sites in Connecticut with unknown foundation depths.)

In support of the extensive field NDT, theoretical studies were also conducted to improve the understanding of NDT results from the Sonic Echo/Impulse Response, Bending Wave, Parallel Seismic, and Dynamic Foundation Response tests. Theoretical 1-, 2-, and 3-D finite element modeling analysis research was conducted on these four methods. A feasibility study was also performed on the use of neural networks for analyzing Sonic Echo/Impulse Response data.

In addition, results of independent consulting investigations of unknown bridge foundations by Olson Engineering, Inc. are presented to illustrate real-world applications of some of the NDT technologies. Investigation results are presented from NDT of the abutments of 4 concrete and 1 masonry single-span bridges of the Connecticut DOT.

Table 3 - Summary of Tests Performed

Bridge Location	**Tested Unit**	**Applied NDT Methods**									
		Substructure NDT								**Soil NDT**	
		US	**SE/IR**	**BW**	**SR**	**DFR**	**PS**	**BHR**	**BHS**	**CH**	**SASW**
Golden (Colorado)	North Pier	X	X			X					
Coors (Colorado)	Pier 4	X	X		X	X	X	X		X	
	Pier 2	X	X		X	X		X			
Franktown (Colorado)	North east Wingwall	X	X	X							X
	Middle Pier	X	X								
Weld (Colorado)	West Abutment		X			X					
	West Pier	X									
Alabama	Bent 4	X	X				X	X			
Old Bastrop (Texas)	Caisson	X	X			X	X	X	X	X	
	Piles		X			X	X	X	X		
New Bastrop (Texas)	Drilled Shaft	X	X			X	X	X	X		

US = Ultraseismic;
SE/IR = Sonic Echo/Impulse Response;
BHR = Borehole Radar;
DFR = Dynamic Foundation Response;
BHS = Borehole Sonic;
PS = Parallel Seismic;
CH = Crosshole Seismic of Soils;
SASW = Spectral Analysis of Surface Waves of Soils;
BW = Bending Wave Method;
SR = Surface Radar.

The 5 bridges were tested with the Sonic Echo/Impulse Response, Ultraseismic (a new test developed in this research which is an extension of the Sonic Echo and Bending Wave tests), Parallel Seismic, Borehole Radar, and Spectral Analysis of Surface Waves (first applied by Olson Engineering independently). In addition, results of Parallel Seismic tests by Olson Engineering on a railroad bridge on the southern California coast are reported herein to illustrate the use of the method on timber piles.

In terms of foundation substructures and materials, concrete substructure bridges which were nondestructively tested included spread footing (Golden), wall concrete pier and stub abutment supported by steel piles (Weld), shallow spread footing and pile cap supported by steel BP piles (Coors), a concrete pile foundation with a pile cap (old Bastrop), a concrete caisson foundation (old Bastrop), and a concrete drilled shaft foundation (new Bastrop). A timber bridge with a timber pile pier and abutment (Franktown) and a steel BP pile bridge (Alabama) were also tested. A summary of which tests where performed at each bridge is presented in Table 3.

1.6 RESULTS OF INITIAL RESEARCH

Summary of Results. The results of this research indicate that of all the surface and borehole methods, the Parallel Seismic test was found to have the broadest applications for determining the bottom depth of substructures. Of the surface tests (no boring required), the Ultraseismic test has the broadest application to the determination of the depths of unknown bridge foundations, but provides no information on piles below larger substructure units (pile caps). The Sonic Echo/Impulse Response tests, Bending Wave method, Spectral Analysis of Surface Wave (SASW) method, and Borehole Radar method all had more specific applications. A summary of all the methodologies considers in this research to evaluate their potential application to unknown bridge foundations is presented in Table 4. Summary evaluations of all tested NDT methods are presented in Tables 5a and 5b below for the surface and borehole tests, respectively.

Table 4 - Summary of Proven and Potential NDT Methods for Determination of Unknown Bridge Foundations (As of August 1995).

Proven/Potential Application to Bridge Foundations:	
	A. **Stress Wave Techniques**
	1. NDT Stress Wave Methods from Substructure or Superstructure
Proven*	a. Sonic Echo/Impulse Response with Compressional Waves
Proven*	b. Dispersion of Bending Wave Energy (recent research by others and in this study)
Proven*	c. Ultraseismic (new research after Sonic Echo and Bending Wave tests)
Potential*	d. Dynamic Foundation Response (new research for shallow/deep).
	2. Surface Seismic Methods for bridge substructures and ground
None	a. Refraction (more for soils)
Minimal	b. Reflection (footing/cap top at best)
Proven**	c. Spectral Analysis of Surface Waves (independent study case history)
	3. Borehole Methods
Proven*	a. Parallel Seismic (for foundation depth with hydrophones and new research with geophones)
Potential*	b. Borehole Sonic (new research for substructure image)
Potential	c. Crosshole Seismic Tomography/Imaging (multiple boreholes for image of substructure and soils/bedrock)
	B. **Electrical and Electromagnetic Techniques**
None	1. DC-Resistivity Method on Ground Surface (supporting soils data)
	2. Ground Penetrating Radar (GPR)
Minimal	a. Surface GPR (footing/cap top at best)
Proven*	b. Borehole GPR (substructure image)
Proven	3. Induction Electromagnetic Field Method with Borehole (steel rebar/pile required)
Minimal	4. Time Domain Reflectometry from Substructure (steel rebar required - may not work)
	C. **Magnetic Techniques**
None	1. Surface Magnetic Surveys (not applicable by modeling)
Minimal	2. Borehole Magnetic Surveys (steel only - other methods better)
	D. **Gravity Technique**
None	1. Micro-Gravity Surface Survey (not applicable by modeling)

(*NCHRP 21-5 research - **Olson Case History only)

Table 5 - Summary Evaluation of the Applicable NDT Methods. (August 1995)

Ability to Identify Foundation Parameters	Sonic Echo (SE)/Impulse Response (IR) Test (Compressional Echo)	Bending Wave (BW) Test (Flexural Echo)	Ultraseismic (US)Test (Compressional and Flexural Echo)	Spectral Analysis of Surface Wave (SASW) Test
Surface or Subsurface Test	Surface	Surface	Surface	Surface
Foundation Parameters:				
Depth of Exposed Piles	Fair-Excellent	Fair-Excellent	Fair-Excellent	N/A
Depth of Footing/Cap	Poor-Good	Poor-Fair?	Fair-Excellent	Fair-Good
Piles Exist Under Cap?	N/A	N/A	N/A	N/A
Depth of Pile below Cap?	N/A	N/A	N/A	N/A
Geometry of Substructure	N/A	N/A	Fair	Poor-Good
Material Identification	N/A	N/A	N/A	Good
Access Requirements:				
Bridge Substructure	Yes	Yes	Yes	Yes
Borehole	No	No	No	No
Subsurface Complications: Effect of soils on response	Low-Medium	Medium-High	Low-High	Low
Relative Cost Range:				
Operational Cost/SSU[*]	$1,000-$1,500	$1,000-$1,500	$1,000-$1,500	$1,000-$1,500
Equipment Cost	$15,000-$20,000	$15,000-$20,000	$20,000-$25,000	$15,000-$20,000
Required expertise:				
Field Acquisition	Technician	Technician	Technician	Technician-Engineer
Data Analysis	Engineer	Engineer	Engineer	Engineer
Limitations:	Most useful for columnar or tabular structures. Response complicated by bridge superstructure elements. Stiff soils and rock limit penetration.	Only useful for purely columnar substructure. Response complicated by various bridge superstructure elements, and stiff soils may show only depth to stiff soil layer.	Cannot image piles below cap. Difficult to obtain foundation bottom reflections in stiff soils.	Cannot image piles below cap. Use restricted to bridges with flat, longer access for testing.
Advantages:	Lower cost equipment and inexpensive testing. Data interpretation for pile foundations may be able to be automated using neural network. Theoretical modeling should be used to plan field tests.	Lower cost equipment and inexpensive testing. Theoretical modeling should be used to plan field tests. The horizontal impacts are easy to apply.	Lower equipment and testing costs. Can identify the bottom depth of foundation inexpensively for a large class of bridges. Combines compressional and flexural wave reflection tests for complex substructures.	Lower equipment and testing costs. Also shows variation of bridge material and subsurface velocities (stiffnesses) v.s. depth and thicknesses of accessible elements.

[*] SSU = Substructure Unit cost is for consultant cost only - DOT to supply 1-2 people + does not include drilling costs.   N/A = Not Applicable.

Table 5- Summary Evaluation of the Applicable NDT Methods. (August 1995)

Ability to Identify Foundation Parameters	Surface Ground Penetrating Radar (GPR) Test	Parallel Seismic (PS) Test	Borehole Radar (BHR) Test	Induction Field (IF) Test
Surface or Subsurface Test	Surface	Subsurface	Subsurface	Subsurface
Foundation Parameters:				
Depth of Exposed piles	N/A	Good-Excellent	Poor-Excellent	None-Excellent
Depth of Footing/Cap	Poor	Good	Poor-Good	N/A
Piles Exist Under Cap?	Fair-Poor	Good	Fair-Good	None-Excellent
Depth of Pile below cap	Poor	Good-Excellent	Fair-Good	None-Excellent
Geometry of Substructure	Poor-Good	Fair	Fair-Excellent	N/A
Material Identification	Poor-Fair	Poor-Fair	Poor-Fair	Poor-Fair
Access Requirements:				
Bridge Substructure	Yes	Yes	No	Yes
Borehole	No	Yes	Yes	Yes
Subsurface Complications: Effect of soils on response	High	Medium	High	Medium-High
Relative Cost Range:				
Operational Cost/SSU*	$1,000-$1,500	$1,000-$1,500	$1,000-$1,500	$1,000-$1,500
Equipment Cost	$30,000+	$15,000-$25,000	$35,000+	$10,000
Required expertise:				
Field Acquisition/SSU*	Technician-Engineer	Technician-Engineer	Engineer	Technician
Data Analysis	Engineer	Engineer	Engineer	Engineer
Limitations:	Signal quality is highly controlled by environmental factors. Adjacent substructure reflections complicate data analysis. Higher cost equipment.	Difficult to transmit large amount of seismic energy from pile caps to smaller (area) piles.	Radar response is highly site dependent (very limited response in conductive, clayey, salt-water saturated soils).	It requires the reinforcement in the columns to be electrically connected to the piles underneath the footing. Only applicable to steel or reinforced substructure.
Advantages:	Fast testing times. Can indicate geometry of accessible elements and bedrock depths. Lower testing costs.	Lower equipment and testing costs. Can detect foundation depths for largest class of bridges and subsurface conditions.	Commercial testing equipment is now becoming available for this purpose. Relatively easy to identify reflections from the foundation; however, imaging requires careful processing.	Low equipment costs and easy to test. Could work well to complement PS tests and help determine pile type.

*SSU = Substructure Unit cost is for consultant cost only - DOT to supply 1-2 people + does not include drilling costs.

N/A = Not Applicable.

2.0 NDT DETERMINATION OF UNKNOWN BRIDGE FOUNDATIONS

The results of experimental and theoretical research and unknown foundation case history results all serve to demonstrate that significant advancements have been made in research and application of NDT methods to the difficult problem of determining unknown bridge foundation conditions. Tables 5a and 5b qualitatively summarized the applicable surface and borehole NDT methods capabilities and use in terms of characterizing unknown foundation conditions, access requirements, subsurface complications, cost range for equipment and operations, required expertise, and the limitations of the methods. Summaries of the-state-of-the-art of the current capabilities of NDT methods to provide information on unknown subsurface foundation depths, type (shallow or deep), geometry, and materials are presented below.

Brief Description of Surface Methods.

- In the Sonic Echo/Impulse Response (SE/IR) test, the source and receiver are placed on the top and/or sides of the exposed pile or columnar shaped substructure. The depth of the reflector is calculated using the identified echo time(s) for SE tests, or resonant peaks for IR tests.

- The Bending Wave test is based on the dispersion characteristics and echoes of bending waves traveling along very slender member like piles. The method has recently been applied to timber piles. 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.

- The Ultraseismic test involves impacting exposed substructure to generate and record the travel of compressional or flexural waves down and up substructure at multiple receiver locations on the substructure.

- The Spectral Analysis of Surface Wave (SASW) test involves determining the variation of surface wave velocity v.s. depth in layered systems. The bottom depths of exposed substructures or footings are indicated by slower velocities of surface wave travel in underlying soils.

- The Dynamic Foundation Response test was proposed mainly in an attempt to differentiate between shallow foundations and foundations with piles or other deep foundations underlying the visible bridge substructure. The method is based on the differences in the dynamic vibration responses of a shallow footing on piles (pilecap) and without piles (footing alone) subjected to vertical and horizontal modes of vibrations.

Brief Description of Borehole Methods.

- A Parallel Seismic test consists of impacting an exposed foundation substructure either vertically or horizontally with an impulse hammer to generate compressional or flexural waves which travel down the foundation and are refracted to the surrounding soil. The refracted compressional wave arrival is tracked at regular intervals by a either hydrophone receiver suspended in a water-filled cased borehole or by a clamped three-component geophone receiver in a cased or uncased borehole (if it stands open without caving).

- The Borehole Sonic test is a proposed new method which involves lowering a source and a receiver unit in the same or separate boreholes and measuring the reflections of compressional or shear waves from the side of the bridge substructure foundation using essentially horizontal raypaths.

- The Borehole Radar test uses a transmitter/receiver radar antenna to measure the reflection of radar echoes from the side of the bridge substructure foundation.

2.1 NDT Capabilities for Unknown Subsurface Foundation Depths

Since determining foundation depths is a critical input into bridge scour vulnerability evaluations, this was a key focus of the research. The potential applicable surface NDT methods for foundation depth determination are: Sonic Echo/Impulse Response (compressional wave echoes from stiffness changes), Bending Waves (flexural wave echoes from stiffness changes), Ultraseismic Vertical Profiling with geophysical processing of the data (compressional and flexural wave echoes) and Spectral Analysis of Surface Waves. The stress-wave based surface NDT methods were found to be able to accurately determine the unknown depths of: exposed timber and concrete piles; drilled shafts; wall-shaped, shallow (less than 3 m embedment, although deeper tests may be possible) abutments and piers; and footings below columnar to semi-columnar substructures.

Prior to this research, only the Sonic Echo/Impulse Response and Bending Waves methods had been used to determine unknown foundation depths of largely columnar-shaped, exposed foundations. The Ultraseismic Vertical and Horizontal Profiling methods were conceived during this project and greatly helped to extend the use of compressional and flexural waves to more massive and wall-shaped substructures. The SASW method was found to be of real value in independent consulting investigations to determine the unknown depths of abutments and exposed footings/pilecaps which have flat, horizontal surfaces for testing. Thus, the use of surface NDT methods to determine unknown foundation depths has been greatly expanded from columnar substructure to include non-columnar, more massive and wall-shaped, shallow substructures as well.

The surface NDT methods are only able to discriminate the first major change in substructure stiffness (acoustic impedance) below the surface, such as the bottoms of piles, shafts, and footings and pilecaps below visible columnar to wall-shaped, more massive, but shallow abutments and piers. Unfortunately, none of the above surface NDT methods can detect or predict the depths of pile foundations underlying pilecaps of abutments and piers. This result is not surprising and was largely expected because the cross-sectional area of piles is much less than the area of pilecaps so that most of the energy is simply reflected from the bottom of the pilecap back up the substructure to the surface. This finding was confirmed by theoretical modeling results.

In support of the experimental investigation of surface NDT echo methods, research was also done on theoretical finite element modeling of compressional and flexural wave travel in columnar-shaped, slender to stubby substructures with and without model slabs/beams in-place. The theoretical modeling is of key importance in future research and practice to increase the understanding of the complex wave propagation phenomena that occurs in the many varied, simple to complex substructures of the unknown bridge foundation population.

The theoretical models greatly aid in interpretation of NDT results as well as in planning investigations. Theoretical modeling may also be used to train neural networks to analyze the data and predict foundation depths as was done in a feasibility study in this research (although it is best to use as much real data as economically possible in such training).

The applicable borehole NDT methods for determination of unknown foundation depths are: Parallel Seismic (direct measurement of compressional and shear wave arrivals to receivers in a borehole emitted by waves traveling down the foundation from an impact to the exposed substructure - wave arrivals are weaker and slower below the foundation bottom); Borehole Radar (reflections of electromagnetic wave energy are measured from nearby foundation substructure); and Induction Field (analogous to Parallel Seismic, but with the strength of a magnetic field induced around the steel of the pile or reinforced concrete foundations being measured (the field strength decreases significantly below the bottoms of the foundations - the method is not applicable to substructures without steel). Only borehole-based NDT methods were able to detect the presence and depths of piles below pilecaps, as well as the depths of truly massive, deep caisson foundations.

One borehole method, the Parallel Seismic test, was found to be able to predict the bottom depths of substructure foundations with good to excellent depth accuracy, and fair to excellent data quality, for all of the bridge substructures tested with boreholes. The method has worked well in the case history investigations, provided the boring extended beyond the foundation bottom (if a boring does not extend beyond the foundation bottom, then one can only conclude the foundation is at least as deep as the boring).

The Parallel Seismic research also introduced the use of 3-component geophone receivers which sense the vertical and two perpendicular horizontal components of motion in velocity amplitude of vibration units. The use of geophones in grouted, cased boreholes was found to aid in overcoming problems of non-uniform soil velocities. Since the geophones are clamped into the casing, no water need be placed in the casings and problems with tube waves traveling in the casing are minimized. The geophones also provided better resolution of shear wave arrivals than with the traditionally used pressure-sensitive hydrophones (which sense all-around pressure changes in the cased boring and thus are subject to tube waves that can mask any shear wave arrivals).

Another innovation in the research concerned theoretical modeling of Parallel Seismic test results. Results of limited, 3-D axisymmetric modeling studies for simple columnar foundations show considerable promise for improving the understanding of the Parallel Seismic test for more complicated substructures in the future.

The performance of a feasibility demonstration study of the use of a fairly recently developed omni-directional borehole radar tool was also a new application of technology to the unknown foundation problem. The Borehole Radar test should work best for steel substructures (high reflection contrast between soils and steel), but was not successful in the site soil conditions where HP- and BP-steel pile foundations were present. The success of radar is not as dependent on the reflecting characteristics of the foundation target as it is on the soils, water, and groundwater having low conductivity. Highly conductive saltwater, clay, and other conductive soils severely attenuate the radar signal so that even reinforced and steel substructure may not be detected.

As proposed, only a literature review was conducted of available research reports on the Induction Field method for steel piles and reinforced concrete piles and shafts. This method appears to work well at sites with more uniform soil conductivity conditions, but will only work where there is steel in the foundation that can be electrically connected to at the surface. The Induction Field method is potentially attractive for use in conjunction with the Parallel Seismic method. It could indicate whether steel is present or not, and might work better than the Parallel Seismic method for the case of slender steel H-piles below a pilecap. The custom equipment is lower cost, much easier to use and interpret than Borehole Radar, and requires less training and expertise to operate.

Feasibility tests of the Borehole Sonic technique (a new concept) showed only limited success for measuring "sonar-like" reflections from a massive caisson foundation. No reflections at all were measured from a 1.2 m diameter drilled shaft and a 356 mm square concrete pile. This method has some potential, but is at a very early stage of research and development.

2.2 NDT Capabilities for Unknown Subsurface Foundation Types

Whether a given bridge structure is on shallow footings or deep piles is a second critical question to be answered in scour vulnerability analyses. At present, no surface NDT method exists which is capable of answering this question for abutment and pier substructures. Only when the pile is visible can the depth of the piles be determined with surface NDT methods. Research to date has shown only some potential for the Dynamic Foundation Response concept to indicate foundation type (shallow or deep) from the surface. Theoretically, shallow footings have lower resonances than a similar size pilecap on piles in the same soils. Lower frequency, more powerful excitation is needed to excite needed low frequencies of bridges to verify how well the promise of theory agrees with the reality of field tests for modal vibration based discrimination of footing/pile foundation type.

Consequently, a surface NDT method is only recommended to be used to determine the depth of the partially visible substructure. Then, if the visible structure does not extend deep enough relative to the scour zone, one could check for the presence of any foundations that would extend below the scour zone with a borehole test.

The borehole test with the widest range of application is the Parallel Seismic method. The Borehole Radar and Induction Field methods can also be useful in uniform, lower conductive subsurface environments for radar, and only if steel is present in the substructure for the magnetic field measurements. The borehole methods also provide information on the subsurface that can be used in the scour vulnerability evaluations.

2.3 NDT Capabilities for Unknown Subsurface Foundation Geometry

Subsurface dimensions of unknown foundations can be an aid in scour vulnerability analyses, particularly for pilecaps and footings. The numbers of pile foundations and their geometry could also be useful in the analysis. Even thicknesses of visible portions of abutments can be useful in the analyses, as well as determining dimensions of any toe or heel of a footing/pilecap at an abutment.

Some success was achieved by using surface ground penetrating radar to estimate heel and toe dimensions for shallow footings at abutments, although the confidence level was low. The surface radar worked better for indicating the thicknesses of the abutment walls. Omni-directional Borehole Radar tests also had some success at indicating the heel footing thickness and horizontal extent from an abutment wall. Directed, focused Borehole Radar tests would in theory be able to see different piles, and their relative locations for uniform, low conductivity subsurface conditions. However, one still might have to use at least 2 boreholes to triangulate the locations of pile reflectors. Spectral Analysis of Surface Waves and Impact Echo (31) tests could also be used to indicate the thicknesses of exposed abutment substructure, if this is unknown.

2.4 NDT Capabilities for Unknown Subsurface Foundation Materials

The question of whether indicated foundation substructure is steel, reinforced or plain concrete, timber, or masonry can also be useful in deciding what type of foundation is present. The Spectral Analysis of Surface Waves method provides data on the change in velocity (stiffness) of foundation materials with depth without drilling a boring. The method is only applicable to massive, wall-like abutments and piers with good access for testing. However, the wave velocity does not uniquely define material types for a bridge substructure. Velocities of concrete and masonry bridge materials can be very similar. The SASW method is also useful in determining subsurface velocity profiles of local soils and bedrock, and layer thicknesses. This information can be used in modeling of NDT results, as well as in scour evaluations. None of the other surface NDT methods can be used to identify subsurface material types.

The borehole NDT methods may possibly provide an indication of subsurface foundation material types. SASW tests or Downhole Seismic tests can determine the variation of velocity with depth, and then adjust the Parallel Seismic test results to account for this variation to determine the velocity of the foundation element. However, stress wave velocities of concrete, timber, and masonry materials can be highly variable with only steel velocities being constant. Borehole Radar and Induction Field tests are both more sensitive to steel in foundations. However, for that sensitivity to translate into differentiation between steel H-piles, reinforced concrete piles, and timber piles would require performance of at least one of the two tests in conjunction with the Parallel Seismic test (most likely the Induction Field test which is less sensitive to soil conditions than radar). Local soil, water, and groundwater conditions could even then preclude a definitive answer as to material type, although this approach would be generally successful.

3.0 DESCRIPTION OF NDT METHODS

Discussions are presented of surface NDT methods first, followed by borehole NDT methods in each section below.

3.1 SONIC ECHO (SE)/IMPULSE RESPONSE (IR) METHOD

The Sonic Echo/Impulse Response (SE/IR) method was developed for testing the integrity and length of single, rod-like, columnar shaped deep foundations such as drilled shafts and driven piles. The method is based on the principle that stress waves will reflect from significant changes in stiffness (i.e., changes in acoustic impedances which is velocity *x* mass density *x* cross-sectional area for foundation substructures). <u>Much like sonar or a fish-finder, the Sonic Echo/Impulse Response test of bridge substructure involves measuring the velocity of wave travel in the known substructure, tracking the reflection events coming from either above or below the source/receivers locations, and then calculating the reflector depth corresponding to the foundation bottom (or other significant</u>

change in stiffness). The method is conceptually shown for application to the accessible tops of bridge substructure in Figure 2. Where top access is not available, or cap beams or superstructure is present that would complicate the interpretation of reflections greatly, testing can be performed on the sides of accessible substructure. However, in this case at least two receivers must be set at different elevations to determine if the reflection event is coming from above, or below the receivers as discussed below.

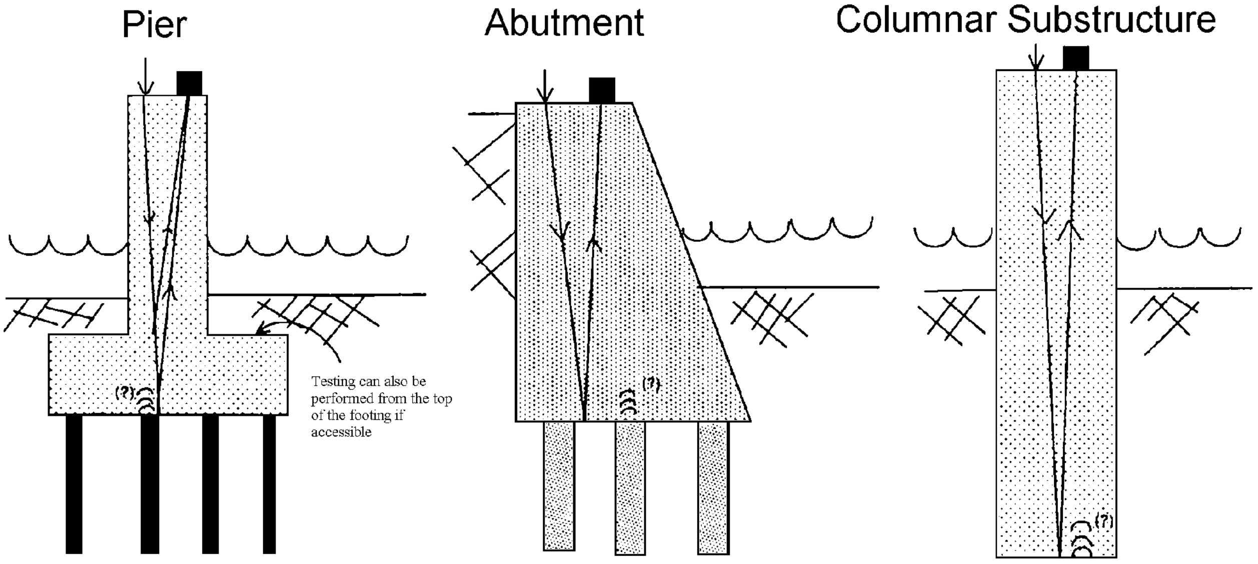


Figure 2 - SE/IR Method Diagram as Used on Bridges with Accessible Substructure.

3.1.1 Application of the Sonic Echo/Impulse Response Method

The Sonic Echo/Impulse Response method classically involves impacting the top of a deep foundation with a hammer to generate a downward traveling compressional wave (5,6). The wave energy reflects back to the surface from changes in stiffness, cross-sectional area, and density (i.e. the reflections are from changes in acoustic impedance). A neck or break has lower impedance relative to a sound pile section while a bulb or a much stiffer soil or bedrock layer has a higher impedance. The arrival of the reflected compressional wave energy is sensed by a receiver (accelerometer or vertical geophone). Analyses are done in the time domain for the Sonic Echo test and in the frequency domain (mobility transfer function, i.e. velocity/force) for the Impulse Response test. Examples of the Sonic Echo and Impulse Response results are shown in Figures 3 and 4 respectively.

A reflection is seen as an increase in amplitude and change in phase of the receiver response versus time in the Sonic Echo test. The same reflection event is seen as evenly spaced frequency peaks that correspond to the resonant echo in the Impulse Response test. Test equipment typically includes an impulse hammer (measures impact force), accelerometer (acceleration) and vertical geophone (velocity) receivers, and a microprocessor based recording and processing system, e.g., a dynamic signal analyzer.

The Sonic Echo/Impulse Response method (as shown in Figure 2) is most applicable to columnar substructures on drilled shafts or deep foundations that are exposed above the ground or water. The foundation element must be directly instrumented for the test to be successful. Side-mounting receivers and setting nails, screws, blocks, or other impact contact points can be accomplished without much effort for such conditions. Ideally, the compressional wave velocity is measured between the two side-mounted receivers to improve the accuracy of the length prediction. Using two receivers when testing on the sides of substructure is highly recommended to determine whether wave reflection events are coming from the bottom or top of the substructure.

Theoretical modeling studies were performed on Sonic Echo/Impulse Response test of piles. The theoretical finite element modeling was very useful in determining that the complex vibrations that result from column to beam interactions can mask the desired echoes from foundation bottoms in Sonic Echo tests. Impulse Response tests can be even more complicated, particularly if the testing is done in the middle of a column rather that towards the end.

3.1.2 Sonic Echo/Impulse Response Results

Table 6 summarizes the Sonic Echo/Impulse Response results for all the tested bridges. The results presented indicate the Sonic Echo/Impulse Response tests worked best on the rod-like Franktown bridge timber piles and the shallow west abutment of the Weld County bridge. The depth of the large north column on top of the Old Bastrop bridge caisson bell was also identified in Sonic Echo tests, however, the top of the caisson bell was only a few feet below the ground surface and no further information was provided on the depth of the bell and the underlying rectangular caisson section. The drilled shaft of the New Bastrop bridge showed a weak bottom echo, but even this result was complicated by the vibrations of the columns and beams of the substructure. The large concrete beams on top of columns of the Golden and Coors bridges masked the identification of any reflected wave energy corresponding to the footings/pile caps of these bridges. Similarly, although the top of the Old Bastrop bridge pilecap was exposed, no echoes indicative of the presence of the piles was recorded. The test results were instead dominated by reflections of the pier crossbeam and the pilecap had a large impedance contrast with the smaller section concrete piles that also trapped much of the energy in the pilecap. As a rule of thumb, when embedded length to diameter ratios are greater than 20:1 to 30:1 in stiffer soils, there will be no identifiable bottom echoes due to excessive damping of the compression wave energy in the Sonic Echo/Impulse Response tests. This problem is even worse for steel H-piles which have a larger surface area than square or round piles. Consequently, no reflections were identified with tests on either the Weld County or Alabama bridges with steel piles.

Velocity Calculation:
Δf = 330 Hz
Length = 25.5 ft
Compression Wave Velocity = Length x 2 x Δf= 16,830 ft/sec

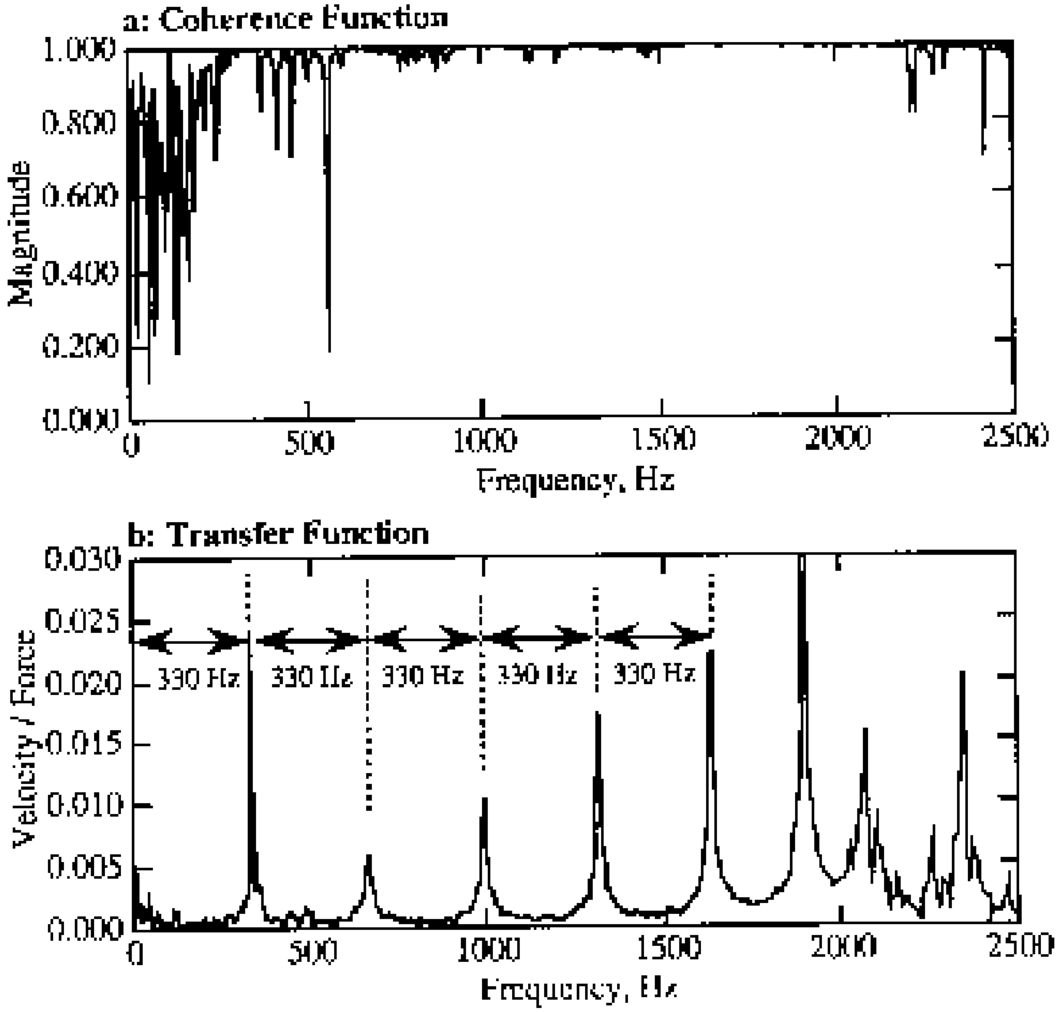


Figure 4 Impulse Response Test Results

Table 6 - Summary of Sonic Echo/Impulse Response Test Results

Bridge	Tested Unit	Substructure Type	Actual Depth (ft)	Predicted Depth (ft)
Golden (Colorado)	North Pier	Concrete Columns on shallow footings, connecting breast wall	(42.8' from top of beam to bottom of footing), embedded depth of 14.8'	No Success
Coors (Colorado)	Pier 4	Concrete columns on shallow footings supported by steel piles	(31.1' from top of beam to bottom of footing), embedded depth of 28.8', steel piles are 25' long,	No Success
	Pier 2	Concrete columns on shallow footings	(26' from top of beam down column to bottom of footing), embedded depth of 4.5'	No Success
Franktown (Colorado)	Northeast Wing (Abutment)	Exposed timber piles	28' embedded depth of 21'	29.8' (SE Tests) 27.9' (IR Tests)
	Middle Pier	Cap on top of exposed timber piles	28' embedded depth of 25'	23.8' (SE Tests) 23.2' (IR Tests)
Weld (Colorado)	West Abutment	Massive concrete abutment supported by steel piles	(6.0' depth of abutment) Steel piles are 34.5 ' long (1 ft in pilecap), embedded depth of 34'	6.6' (SE Tests) 6.5' (IR Tests) No success for steel pile length
Alabama (Alabama)	Bent 4	Steel piles extending from top to bottom	(39' from ground surface to tip of pile)	No success
Old Bastrop (Texas)	Caisson	Two circular columns connected by a breast wall supported by a belled concrete footing on a rectangular concrete footing	(38' from top of columns to top of bell section, 18' thick bell section, 16' thick rectangular section), embedded depth of 35'	35.9' (upper columns, SE tests) no success for the bell and rectangular sections depth determinations
	Piles	Concrete columns supported by a pile cap of concrete piles	3' thick pile cap, 32' long concrete piles, embedded depth of 33.3'	No success
New Bastrop (Texas)	Drilled Shaft	Concrete columns supported by shafts	45' long shafts, embedded depth of 38'	38' (Depth below grade, SE tests)

Velocity Calculation:

Δt = 3.03 ms

Length = 25.5 ft

Compression Wave Velocity = Length x 2 / Δt = 25.5 x 2 / (3.03 x 10^{-3}) = 16.830 ft/sec

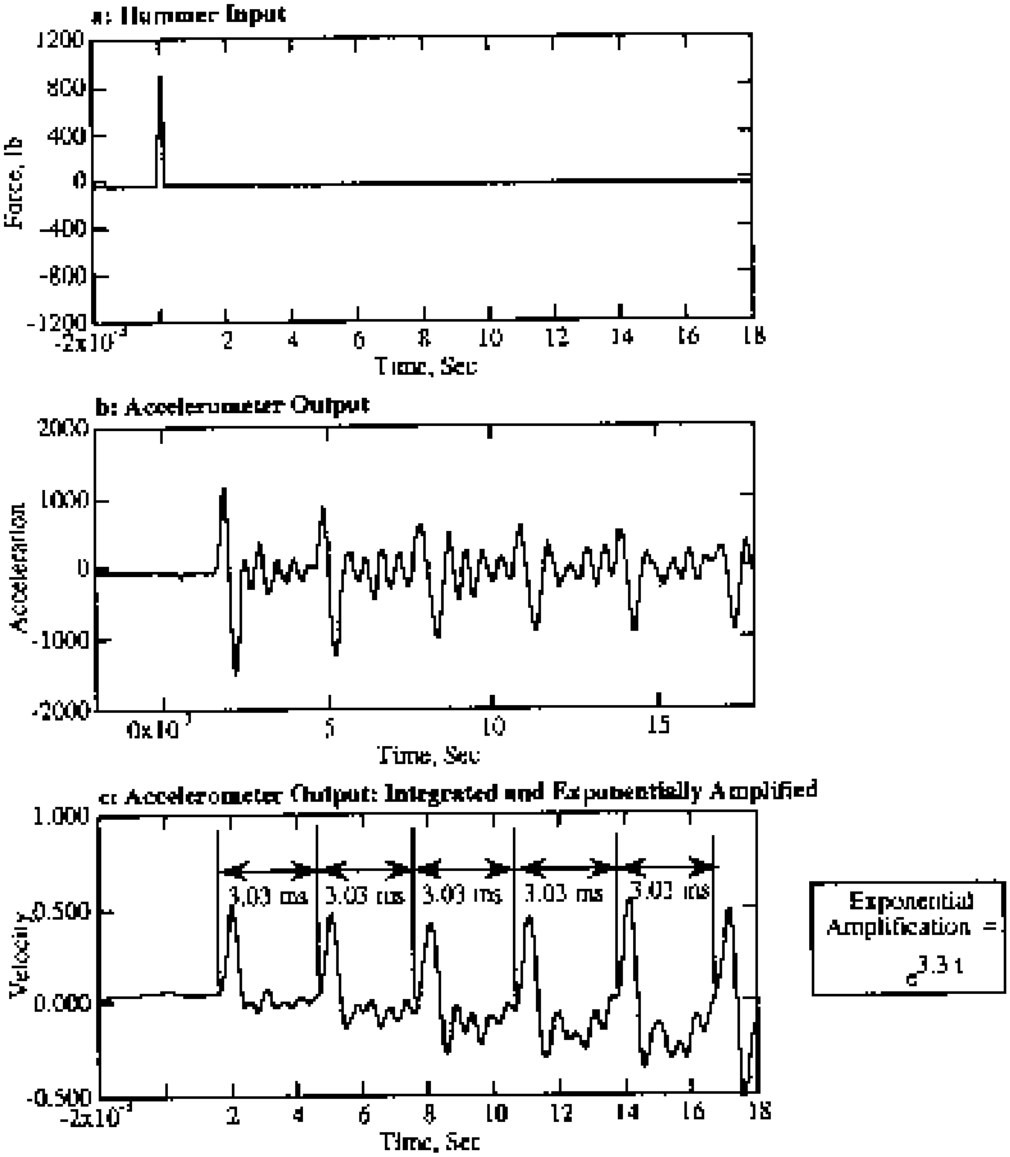


Figure 3 - Sonic Echo Test Results

3.2 BENDING WAVE METHOD AND RESULTS

This method was first researched to predict timber pile lengths on bridges. The method is based on the principles of bending wave propagation in slender, rod-like media so the pile must be directly instrumented. The Bending Wave method is illustrated in Figure 5 and involves horizontally impacting the pile to generate flexural or bending waves that travel up and down the pile. The bending wave propagation is monitored by two horizontal accelerometer receivers mounted on the same side of the pile from the impact as shown in Figure 5. The Bending Wave method with the Short Kernel Method analysis (10) can be thought of as being the bending wave equivalent of the Sonic Echo method, which uses the faster compressional (longitudinal) waves. Both methods involve determining the velocity of wave travel, then identifying initial wave arrivals and subsequent reflections (echoes), and finally calculating the depths and locations of the reflection events.

Modeling of the Bending Wave method was undertaken to theoretically explore the capabilities and examine the fundamentals of the method. Like the Sonic Echo/Impulse Response models, the theoretical 1-D bending wave model can be used to predict maximum detectable reflector depths for specific pile types, cross section, and top condition for estimated or measured soil properties (density, Poisson's ratio, and shear wave velocity profile).

3.2.1 Bending Wave Method and Review of North Carolina State University Research

Research and development of the use of dispersion of bending (flexural) wave energy to predict pile depths has been detailed (10,11). Dispersion of stress waves means that the velocity of wave travel is not a constant, but is a function of frequency or wavelength. Stress wave velocity (V), frequency (f) and wavelength (λ) are related by the following equation:

$$V = f \lambda$$

Bending waves in piles are highly dispersive. The bending wave velocity decreases with increasing wavelength with most of the velocity decrease occurring at wavelengths that are longer than the pile diameter. These longer waves propagate as flexural or bending wave energy. Correspondingly, as wavelengths become shorter than the diameter of a pile, the bending wave velocity limit is approximately that of the surface (Rayleigh) wave velocity, and this wave energy propagates as surface waves. Compressive waves are also dispersive in piles, but in a different way that in practice results in a bar velocity decrease only when a deep foundation has a low length to diameter ratio of about 2:1 or less which is uncommon for deep foundations.

The technology is based on measuring the dispersion of bending wave energy in a timber pile due to a horizontal impact with small to large hammers. The passage of the bending wave energy up and down the timber piles is monitored by two accelerometer receivers positioned a few meters (few feet) apart and mounted on the heads of roofing nails driven radially into the pile. The receivers are in-plane with the hammer blow on the same side of the pile as shown in Figure 5. Equipment consists of a recording oscilloscope or dynamic signal analyzer, small to large hammers or other impactors that can have different tips ranging from rubber to hard plastic to steel, cushioning materials to protect and dampen the blow to the timber pile for metal tipped hammers (if needed), two accelerometers to measure initial bending wave arrivals and subsequent reflections, and the necessary cables, tape measure, and other supporting tools. The data can be processed with appropriate software on a portable or laptop PC in the field or at the office.

The Short Kernel Method (SKM) was used to analyze the data (10,11). The method is similar to narrow band cross-correlation procedures between the input (the hammer blow) and the output (receiver response(s)). However, instead of measuring the hammer blow, a periodic function of 1 or more cycles is used as a "Kernel Seed", and a number of seeds of frequencies ranging from 500 to 4000 Hz may be cross-correlated with the receiver responses. The SKM correlation procedure amplifies bending wave energy responses with the selected seed frequency and in a way bandpass filters the response data since frequencies higher and lower than the seed frequency are filtered out. Two receivers are used to measure the bending wave velocity (distance divided by elapsed time for between the bending wave arrival peaks) between them as determined from the peak responses in the cross-correlated data of the two receivers. The use of two receivers also allows one to determine whether the reflections of the bending wave energy are traveling back up the pile (the bottommost receiver senses the wave energy first) after reflection from the pile bottom, or if the bending wave energy is traveling back down the pile (the topmost receiver senses the wave energy first) after reflection from the pile top or beam. This is identical to the procedures used in Sonic Echo tests when 2 receivers are used. The dispersion of the bending wave velocity is thus accounted for by calculating the bending wave velocity for each Kernel seed frequency.

3.2.2 Bending Wave Test Results

Only a limited field demonstration study was proposed with the Bending (Flexural) Wave method for this research. Accordingly, tests were only performed of one of the Franktown bridge timber piles, and a steel H-pile in air at the Weld bridge. The same timber pile was also tested with the Sonic Echo and Impulse Response methods. For this timber pile, the best Kernel seed was found to be 1-cycle of a 500 Hz sine wave. The bending wave velocity was found to be 2,480 ft/sec for the initial bending wave arrival time peaks in the SKM cross-correlation records. Pile 2 of the Northeast Wing was predicted to have a depth of 27.3 ft which agrees well with the design depth of 28 ft and the depths of 29.8 and 27.9 ft predicted by the Sonic Echo and Impulse Response tests, respectively.

The Bending Wave test results predicted a pile length of 26 ft for the Weld H-pile in air which agrees well with the actual length of 25.5 ft. Unfortunately, because only 1 ft of the steel piles stuck up above ground after driving, no tests could be done of the driven piles. Bending Wave tests of driven steel H-piles would be expected to show high attenuation of bending wave energy just like compression wave energy as compared to nondestructive testing results of timber and concrete piles. This is because of the greater surface area of steel piles per unit length.

Forty timber piles were previously tested with the Bending Waves method using the short kernel analysis (10). The timber piles ranged in length from 6 to 60 ft. Five of the timber piles have known depths with the remaining 35 of unknown depths. Of the 40 piles tested, 26 piles permitted comparison between the measured lengths and lengths from records or after pulling the piles. The percent difference between the computed lengths and lengths from records or after pulling the piles ranged from -11.8% (too short) to 8.7% (too long) for the 16 piles supported by shear.

3.3 Ultraseismic Method and Results

The Ultraseismic (US) method was researched and developed during the NCHRP 21-5 research for determination of the unknown depth of bridge foundation. The Ultraseismic method is a sonic reflection technique that uses geophysical digital data processing techniques to analyze the propagation of induced compressional and flexural waves as they reflect from foundation substructure boundaries (impedance changes). This is the same principle that the Sonic Echo/Impulse Response and Bending Wave methods rely on as well, but the data acquisition and processing for the US method involves recording and displaying of multiple channels of data as discussed below. The Ultraseismic method was researched and developed in response to the difficulties encountered by the Sonic Echo/Impulse Response method and the Bending Wave method tests on non-columnar and complex columnar bridge substructures. This test requires an accessible vertical surface of at least 4-5 ft or more.

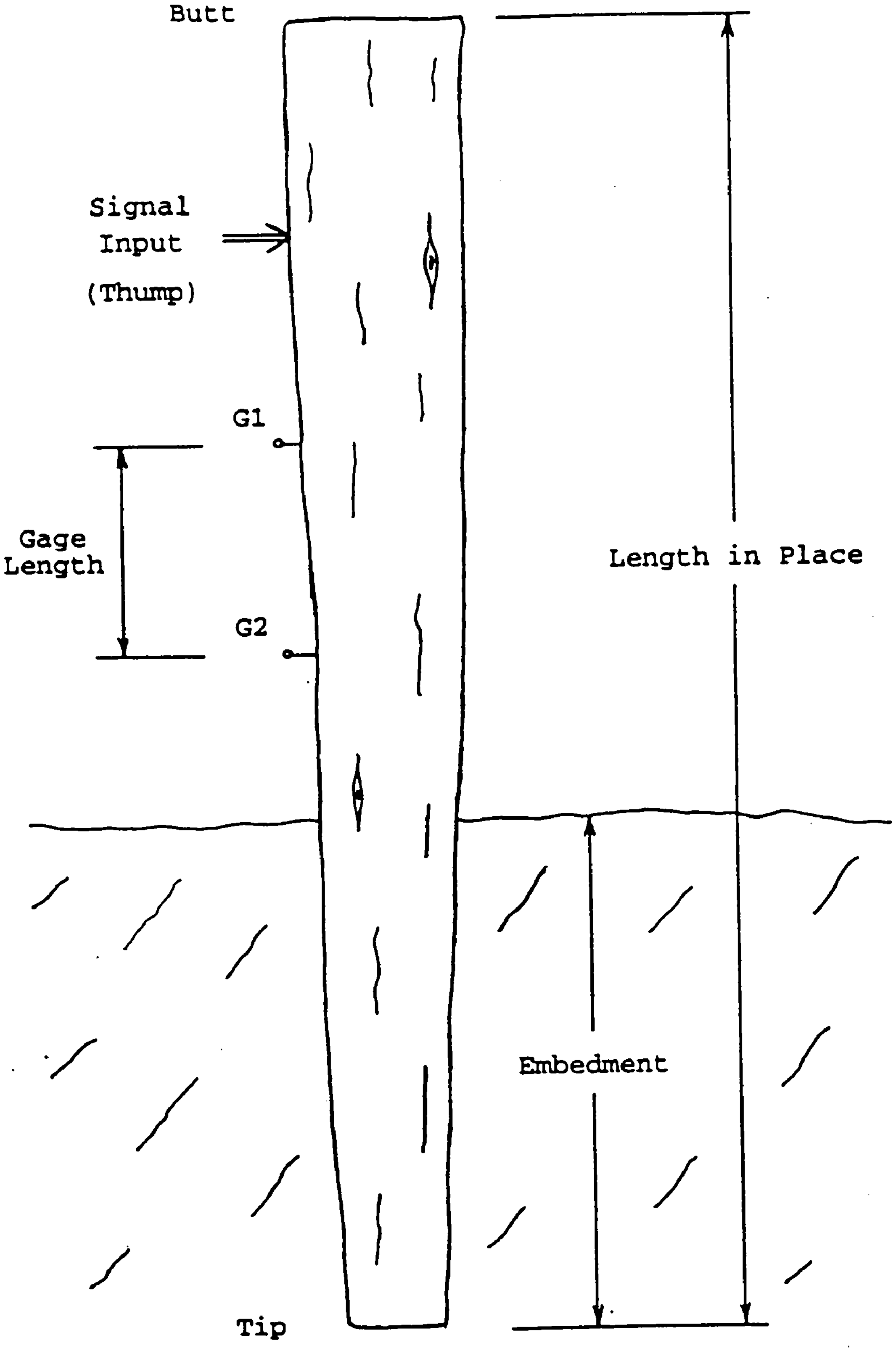


Figure 5 - Illustration of the Bending Wave Method for Piles

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 compressional and bending waves and their subsequent reflections are analyzed to predict unknown foundation depths. Two types of Ultraseismic test geometries have been specifically introduced for this problem:

1. 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. 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 to analyze all types of ensuing wave motion. A VP line can be run in *both* a columnar (like a bridge pier or pile foundation) and a tabular (like a bridge abutment) structure.

2. For two-dimensional imaging of the foundation depth, the term Horizontal Profiling (HP) test geometry is used. In this 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.

3.3.1 Ultraseismic Method with Vertical Profiling Example Results

The Ultraseismic method uses multi-channel, 3-component (vertical and two perpendicular horizontal receivers, i.e., triaxial receiver) recording of acoustic data followed by computer processing techniques adapted from seismic exploration methods. Seismogram records are collected by using impulse hammers (0.2, 1, 3, and 12-lb hammers were experimented with) as the source and accelerometers as receivers that are mounted on the surface or side of the accessible bridge substructure at intervals of 1-ft or less. The bridge substructure element is used as the medium for the transmission of the seismic energy. All the usual wave modes traveling down or reflected back (echoes from the bottom) can be recorded by this method. As will be shown, the seismic processing can greatly enhance data quality by identifying and clarifying reflection events that are from the foundation bottom and minimizing the effects of undesired wave reflections from the foundation top and attached beams. For concrete bridge elements, useful wave frequencies up to 4-5 kHz are commonly recorded.

The Vertical Profiling test geometry is presented in Figure 6. The impact point can be located either at the top or the bottom of the receiver line. Vertical impacts to the substructure are comparatively rich in compressional wave energy, although more flexural/Rayleigh (surface) wave energy is generated. Horizontal impacts are rich in flexural wave energy when the impacts generate wavelengths that are longer than the thickness of the substructure element. Impacts that generate wavelengths shorter than the thickness will be rich in Rayleigh wave energy. The VP lines are useful in differentiating downgoing events from the upgoing events based on their characteristic time moveout, and accurately measure their velocity. A VP line is also used to tie reflection events from the bottom to a corresponding horizon in a HP section.

For a medium with a bounded geometry, such as a bridge column, four types of stress waves are generated that include longitudinal, torsional, surface (Rayleigh) and flexural (bending) waves (13). In longitudinal vibration, each element of the column extends and contracts along the direction of wave motion which is along the column axis. In torsional vibration, each transverse section of the column remains in its own plane and rotates about its center. Finally, in flexural vibration, the axis of the column moves laterally in a direction perpendicular to the axis of the column. Each wave type can independently provide information about the depth of the foundation or the presence of significant flaws within the bridge substructure. However, practically, longitudinal (P-wave, compressional) and flexural (bending) waves are much easier to generate on bridge substructures than torsional. Consequently, compressional and flexural wave energy was generated by orienting impacts to substructures vertically and horizontally, respectively.

The Ultraseismic Vertical Profiling Tests on the South Column of Pier 4 of the Coors bridge showed no evidence of the steel piles underlying the pilecap. Vertical Profiling test lines can also be run from the side of a massive abutment and other tabular type structures. VP test lines are also used in tieing reflection events from the top and bottom of the structure to the events in a Horizontal Profile (HP) section, which will be described next.

3.3.2 Ultraseismic Horizontal Profiling Method

This method was developed for potential use on massive abutment and wall substructure elements which typically have greater widths of top or side surface access to permit a line of receivers to be placed at the same elevation. The HP method uses the same basic equipment as the VP test, but since the receivers are at the same elevation, reflection events from footing bottoms should have the same arrival time in the seismic records.

3.3.3 Ultraseismic Results

A summary of all the Ultraseismic test results at the seven bridge sites is shown in Table 7. Review of Table 7 indicates that fairly accurate predictions of the unknown foundation depths of buried footings, pilecaps, single piles, caisson, and drilled shaft foundations were able to be made with the Ultraseismic method using either compressional or flexural wave energy. These results were very encouraging, as the Ultraseismic method was found to be able to accurately estimate depths for all tested substructures except for the Wing timber pile of the Franktown bridge where the results were dominated by flexural wave reflections from the ground surface. However, as previously stated, the method can not detect a pile foundation under a pile cap. The Ultraseismic method was much more successful at testing the more complex columnar piers of the Golden and Coors bridges than the Sonic Echo/Impulse response methods.

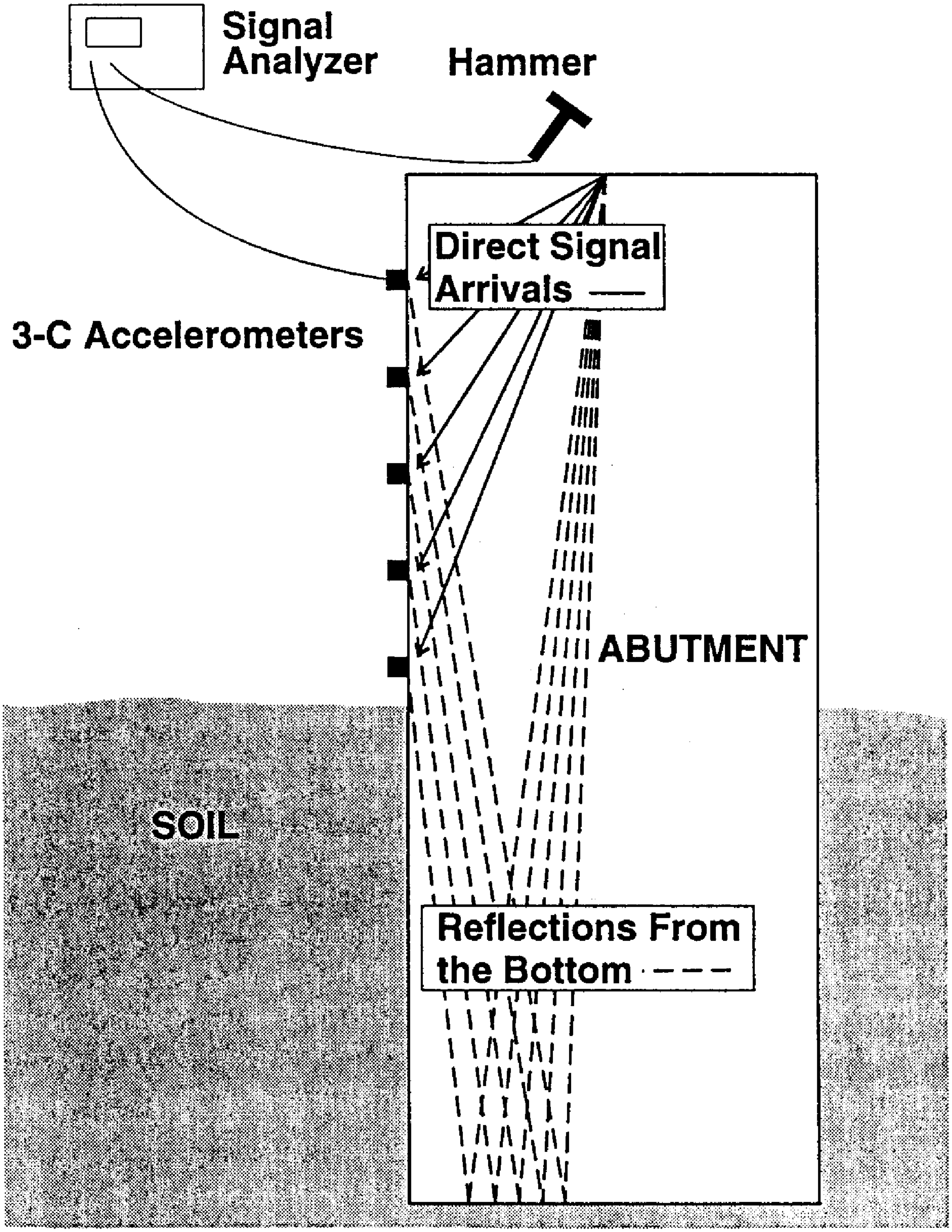


Figure 6 - Ultraseismic Test Method with Vertical Profiling Test Geometry

Table 7 - Summary of Ultraseismic Test Results.

Bridge Location	Tested Unit	Substructure Type	Actual Depth (ft)	Predicted Depth (ft)
Golden (Colorado)	North Pier	Concrete Columns on shallow footings, connecting breast wall	(42.8' from top of beam down column to bottom of footing), embedded depth of 14.8'	42.0' (P-Wave) 42.9' (Flexural Wave) (from top of beam)
Coors (Colorado)	Pier 4	Concrete columns on shallow footings supported by steel piles	(31.1' from top of beam down column to bottom of footing), Steel piles are 25' long, embedded, depth of 28.8'	31.1' (P-Wave) 29.7' (Flexural Wave) 33.9' (Frequency) (from top of beam)
	Pier 2	Concrete columns on shallow footings	(26' from top of beam down column to bottom of footing), embedded depth of 4.5'	25.9' (Flexural Wave) (from top of beam)
Franktown (Colorado)	Northeast Wing (Abutment)	Exposed timber piles	28' embedded depth of 21'	Not successful
	Middle Pier	Cap on top of exposed timber piles	28' embedded depth of 25'	23.0' (Compression) (from top of pile)
Weld (Colorado)	West Pier	Concrete wall on concrete footing supported by steel piles	(18.9' from top of wall to bottom of footing), Steel piles are 25' long, embedded depth of 34.6'	18' (from top of wall) (Flexural)
Alabama (Alabama)	Bent 4	Steel piles extending to the bottom of the superstructure	(39' from ground surface to tip of pile)	34'-35' (compression) 35' (flexural) (from ground surface)
Old Bastrop (Texas)	Caisson	Two circular columns connected by a breast wall supported by a bell shape concrete footing supported on a rectangular concrete footing	(38' from top of columns to top of bell section, 18' thick bell section, 16' thick rectangular section), embedded depth of 35 '	two depths: 37' (from top of bell section) and 18.6' (from top of bell section) Both depths are from flexural waves
New Bastrop (Texas)	Drilled Shaft	Concrete columns supported by shafts	45' long shafts, embedded depth of 38'	45'(from top of shaft) or 38' (from ground surface) Flexural

3.3.4 Summary of Ultraseismic Case History Results

Ultraseismic surveys were performed of the eight concrete and two masonry abutments of the five single-span Connecticut DOT bridges. Horizontal Profiling surveys were also taken at the bridges. The Ultraseismic results were found to be conclusive for all five bridges. Good agreement in terms of the predicted foundation depths is seen between the Ultraseismic test results and the borehole Parallel Seismic test results, as well as with the other NDT results. The Ultraseismic data quality ranged from fair to excellent with reflector events tending to be clearer in the Horizontal Profiling flexural wave results, but some bridges had the best results with the Vertical Profiling method.

3.4 Spectral Analysis of Surface Waves Method And Results

At the time of the Interim Report, the Spectral Analysis of Surface Waves method was primarily viewed as a supporting method to determine the shear wave velocity profile versus depth from the ground surface without drilling a boring. Subsequent independent consulting experience by the authors for determining unknown foundation depths has shown that SASW tests can be quite useful in determining the depths of more massive abutments, piers, and footings provided the substructure geometry allows for proper access. Access for the SASW test in terms of unknown bridge foundations means that the foundation is more massive (a wall, abutment, pier, or exposed footing/pilecap) and has an exposed fairly flat ledge or top surface on which impacts are applied and a pair of receivers placed. The SASW method is shown in Figure 7 below. This method is based on the principle that the foundation substructure materials have different stress wave velocities (stiffness) than the underlying supporting soil and bedrock, which typically have slower velocities, that is they are less stiff than the foundation materials. The SASW method measures the variation in surface wave velocity with depth in layered materials as discussed below.

3.4 .1 Spectral Analysis of Surface Waves Method

Research on the SASW method was initiated in the late 1970's (14,15). The SASW method has unique capabilities to nondestructively determine layer thicknesses and velocity (stiffness) versus depth for soft over stiff over soft layers that other methods such as Seismic Refraction are not capable of doing unless velocity increases with depth. One advantage of the SASW method for investigation unknown foundation depths of bridges is that measurements are performed using a source and two receivers which can be placed on top of a horizontal surface such as the exposed surface of an abutment. In the last 16 years, active research has been conducted to improve the theoretical and practical aspects of the method (16,17,18). The method has been successfully applied for the determination of shear wave velocity profiles for soils (19) and for pavement systems (20). Lately, the SASW testing has been adopted for offshore/underwater use (21).

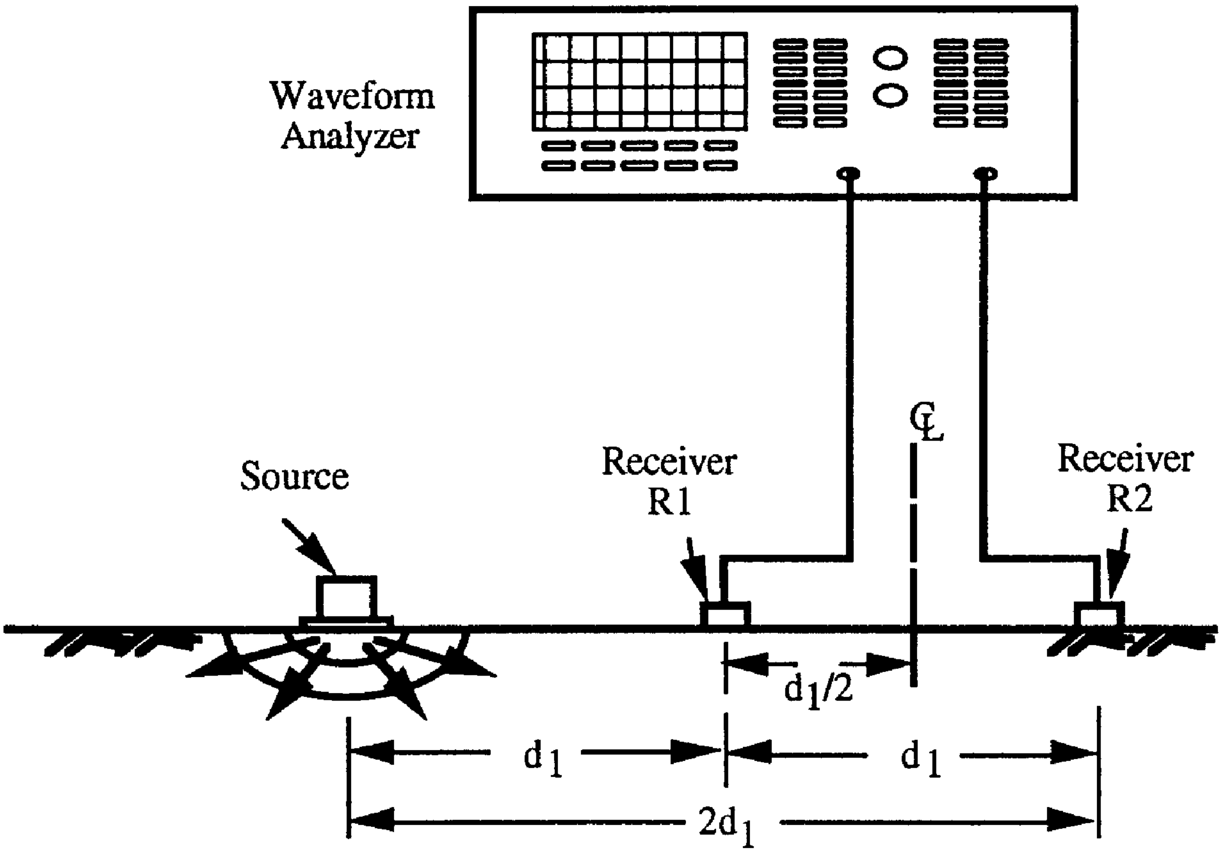


Figure 7 - Source/Receivers Array Used in SASW Measurements

When SASW measurements are performed, a source and two receivers are placed in-line on the surface such that the distance from the source to the first receiver (D) is equal to the distance between the two receivers. This general source-receivers array is illustrated in Figure 7. Testing is performed by impacting the surface and recording the passage of predominant Rayleigh (surface) wave energy past the two receivers. A series of receiver spacing is used, and testing is performed in forward and reverse directions at each receiver spacing.

A dynamic signal analyzer is used to capture and process the receiver outputs. The time domain outputs are then transformed to the frequency domain using a Fast Fourier Transform. This is then used to calculate the cross power spectrum between the two receivers. The surface wave velocity and wavelength associated with each frequency are then calculated and a plot of the surface wave velocity versus wavelength, called a dispersion curve, is prepared. The surface wave velocity is calculated from the phase plots (for one receiver spacing).

Once the dispersion curve is determined, the shear wave velocity profile of the structure or soil being tested can be obtained. This is accomplished through a process called forward modeling. Computer programs for the forward modeling procedure have been developed (22, 23). When a good match is obtained between the experimental and theoretical dispersion curves, the assumed profile is considered to be a good representation of the actual profile. Accuracies of velocity profiles and layer thicknesses vary with the variability of the pavement/soil/bedrock or other layers being tested, but theoretically modeled values are typically accurate to within 10 to 15% of actual values. This is excellent accuracy considering that no borings have been drilled.

3.4.2 Spectral Analysis of Surface Waves Results

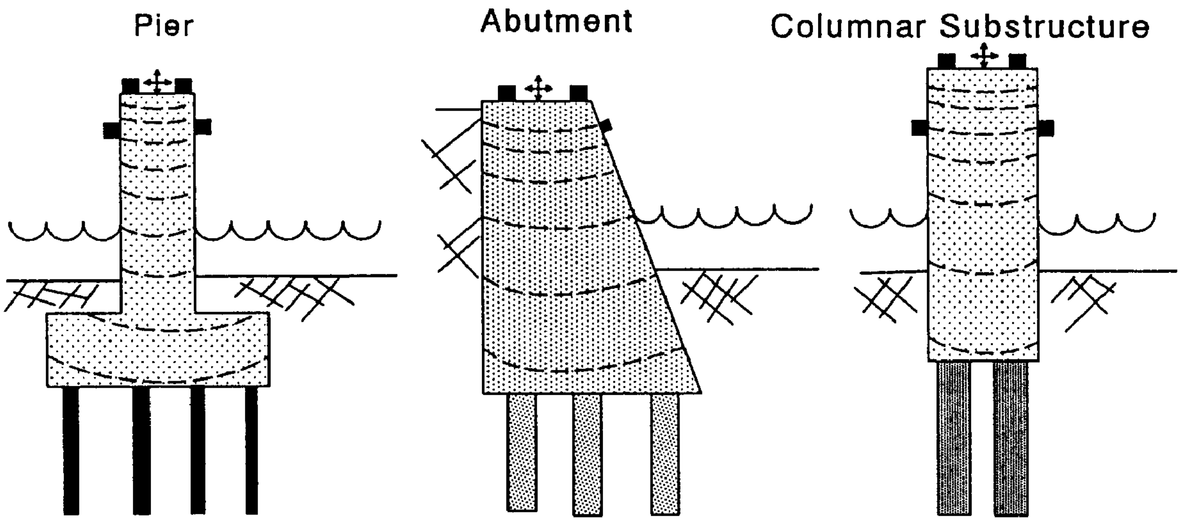
The SASW method was not applied to any of the NCHRP 21-5 research bridges because this research was not initially proposed (the only bridges that it would have been interesting to try SASW on would be the Weld County and Old Bastrop Caisson). However, the SASW method was applied to the tops of the two concrete abutments of the Hamden bridge on the bearing ledge between the girders, and on the tops of the exposed concrete footing ledges of the 2 Newton bridge abutments.

Examination shows a good comparison of the SASW predicted unknown foundation depths with the other NDT predicted depths. The clarity of the SASW data was good to excellent, and it should work well on similar, more massive bridges that have a ledge, shelf, or top for testing access. One limitation of the method could occur if a bridge substructure is much deeper than its length. In this case, the length of the substructure may be too short to generate the required longer wavelengths necessary to reach the bottom of the foundation and penetrate into the supporting strata.

3.5 Dynamic Foundation Response Method And Results

None of the surface methods discussed to this point, Sonic Echo/Impulse Response, Bending Wave, Ultraseismic, and Spectral Analysis of Surface Waves, were able to detect the presence of piles underlying pilecaps at the Coors (Pier 4), Weld County, or Bastrop (pile bent) bridges. The Dynamic Foundation Response (DFR) method was proposed in an attempt to address this problem and differentiate between shallow, footing foundations, and shallow pilecaps supported on piles for more massive bridge substructures. The method is based on the principle that all other things being the same, then the vibration response of a given bridge substructure will exhibit lower resonant frequency responses when excited for a shallow foundation versus the comparatively higher resonant frequency response of a deep foundation system. The application of the method is conceptually shown in Figure 8.

The method is unproven for this use in bridges, but is based on the dynamic analysis theory for vibration design of foundations (soil dynamics) and geotechnical analyses of foundations subjected to earthquake loading based on the theoretical work (24,25). Novak analyzed the problem of a simple shallow footing foundation with and without piles for



Notes:

- * Target: Shallow/Deep Foundation discrimination by measuring excited vibration modes and Amplitudes
- * Works with all bridge material types (concrete, timber, masonry, and steel)
- * Environmental (geological/hydraulic) factors must be known or measured
- * Depth of pier, abutment and columnar substructure, and ideally dimensions must be measured with other surface NDT methods

Figure 8 - Dynamic Foundation Response (DFR) Method.

vertical and horizontal modes of vibrations on the ground surface and embedded. Novak found that the vibration response of the pile foundations differ from the response of shallow foundations. The pile foundation is more rigid and exhibits higher amplitudes of vibrations than the shallow foundations. The pile supported foundations also have a much higher natural frequency than the footing foundations which reflects the greater stiffness of the piles on a rigid strata versus the footings in soil.

3.5.1 Dynamic Foundation Response Method and Example Results

A 12-lb impulse hammer with a built-in dynamic force transducer was used as the vibration source and a triaxial block of seismic accelerometers as receivers, all from PCB Piezotronics. Typically a bridge was excited at 5 to 6 locations and the triaxial response was measured at 5 to 6 locations giving rise to 25 to 36 source-receiver combinations. The bridges were excited in the vertical and horizontal directions to excite these modes as well as rocking modes along the frame of the substructures. This type of testing is known as modal testing, and when the impulse force is measured and the resultant vibration response is measured, then the transfer function can be calculated like the

Impulse Response test. In its most basic form, a transfer function is calculated by taking the Fast Fourier Transforms of the input (impact force, F) and the output (accelerometer receiver responses in acceleration units, (A) as functions of frequency (f), and dividing the output by the input to get the transfer function, A/F. Plots of the transfer function versus frequency indicate the frequencies and amplitudes of resonances for a tested structure. Problems were encountered exciting frequencies of the bridges with good data coherence (near 1) at frequencies of less than 18 to 30 Hz for all of the tested bridges. Larger, more powerful vibration excitation sources would be needed to excite these desired lower frequencies.

The dynamic foundation response of bridges, especially bridge piers, is much more complex than simple footing and pile foundation cases. Consequently, there will be many resonances present in transfer function results. Also, fundamental resonances of bridges are generally less than 20 Hz, and frequently less than 10 Hz. To determine the various resonances and their vibration mode shapes, the transfer function test must excite the range of frequencies of interest, and a number of locations must be tested to identify the mode shapes. The process of determining the full vibration behavior of a bridge abutment or pier, then requires curve fitting of the experimental data, and can also involve theoretical dynamic analysis of the bridge with dynamic structural analysis programs.

The Dynamic Foundation Response method showed some sensitivity in the response of the foundation as a function of depth and existence of piles, particularly for vertical vibrations. However, in practice the bridges generally could not be excited with the 12-lb hammer at frequencies comparable to the natural frequencies identified in the theoretical modeling. More research is needed to explore different sources to generate the very low frequencies required for the experimental modal tests and then to perform curve fitting techniques to experimental data to be able to extract the mode shapes from the experimental data to compare with the theoretical mode shapes as analyzed by Loris.

3.6 PARALLEL SEISMIC TEST METHOD

The borehole Parallel Seismic (PS) method was researched and developed specifically to determine the depths of unknown foundations (26). <u>The Parallel Seismic method is based on the principle that an impact to the exposed structure generates wave energy that travels down the foundation and can be tracked by depth with receivers in a nearby parallel boring to determine when the signal weakens, and slows down which indicates the receiver has gone beyond the bottom of the foundation, and the depth is determined</u>. The method is illustrated in Figure 9. The method has been previously used in a number of consulting projects to determine the depths of unknown foundations below buildings and bridges (26,27). The method has been used with good success for determining the unknown depths of rod-like deep foundations, like driven piles and drilled shafts, but not as much is known about its capabilities for the full range of substructure types that make up the unknown bridge foundation population.

3.6.1 Parallel Seismic Method and Example Results

Typical Parallel Seismic (PS) test equipment includes an impulse hammer, hydrophone or geophone receiver, and dynamic signal analyzer or oscilloscope as illustrated in Figure 9. A portable PC-based digital oscilloscope was used to record the Parallel Seismic data in this study.

The Parallel Seismic (PS) method involves impacting the side or top of exposed bridge substructure with a 3-lb or 12-lb (preferred) hammer to generate wave energy which travels down the foundation and is refracted to the adjacent soil. The refracted wave arrival is tracked by a hydrophone receiver suspended in a water-filled cased borehole in the conventional approach to the test. A hydrophone receiver is sensitive to pressure changes in the water-filled tube, but it is also subject to contaminating tube wave energy. Research was performed during this project on the use of clamped three-component geophones in empty 4-in. ID, PVC cased borings grouted with a cement-bentonite, bentonite, or sand-backfilled mixture, to better examine the wave propagation behavior with reduced tube wave energy noise. The boring is drilled typically within 3 to 5 feet of the foundation edge and should extend at least 10 feet deeper than the anticipated and/or minimum required foundation depth for the depth to be determined.

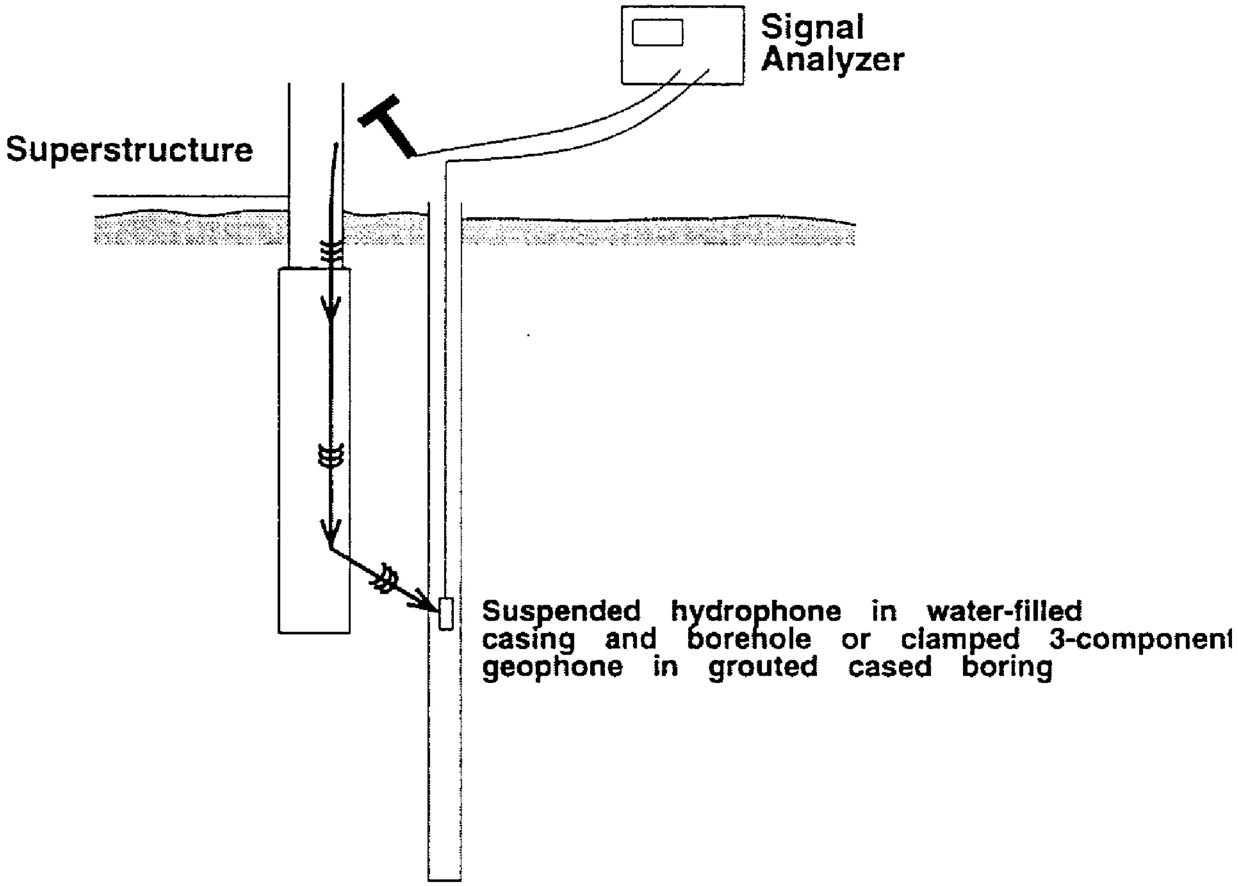


Figure 9 - Parallel Seismic Test Method

Preferably all borings for the Parallel Seismic (PS) test should be cased (either with plastic or steel) with inside diameter 50 mm (2-in.) or larger. Open hole PS test is also acceptable but this requires mechanical clamping geophones and the user runs the risk of losing the tool due to soil caving. The <u>casing and boring</u> must be filled with water before testing if hydrophones are to be used. The casing should be dry if geophones are to be used (the preferred method). Borings should be drilled with as little deviation from vertical as possible. The void between the soil and casing should ideally be cement-grouted for obtaining the best PS results with geophones. Grouting must be done in compliance to ASTM D 4428/D 4428M standard for Crosshole Seismic Testing.

For fully saturated sites below the water-table, the use of geophones and grouting is not as critical; a number of PS tests have been performed with hydrophones in slotted plastic casing and no grouting at these sites. The water couples the compressional wave energy through the soils to the hydrophones in the water-filled boring and casing. In partially saturated soils, loose sand has been used to fill the void between the soil and the casing but this practice is obviously not as satisfactory for the use of geophones and grouting with a cement-bentonite mixture.

The PS test typically involves lowering the receiver (hydrophone or geophone) to the bottom of the borehole, impacting the substructure as close to the ground surface as practical, recording the receiver response and then raising the receiver to the next test depth, typically in 2-5 ft increments depending on the desired accuracy. This test sequence is repeated until the top of the cased boring is reached. Downward, vertical impacts are ideal to generate compressional waves, but angled to horizontal impacts to substructures work also. A horizontal impact is used to generates flexural waves, and a second opposing horizontal impact may be used to cause a reversal of polarity in the soils shear wave arrival at the receiver to enhance its identification. Geophysical seismic processing was used to display and analyze the data.

3.6.2 Parallel Seismic Results

Parallel Seismic tests were run at three concrete foundations at the Old and New Bastrop bridges in Texas (with concrete pile, caisson, and drilled shaft foundation types); a concrete pilecap on steel H-piles foundation at the Coors bridge in Colorado, and a steel pile bridge in Alabama. Table 8 below summarizes all the predicted v.s. actual foundation depth test results. Good predictions of the foundation depths were able to be made from the Parallel Seismic test results for all of the tested foundations. The depth predictions are marked as either a hydrophone test or a geophone test.

3.6.3 Summary of Parallel Seismic Case History Results

Independent Parallel Seismic tests were performed in a cased borehole at one abutment for each of the 4 concrete and 1 masonry Connecticut DOT bridges. Conclusive depth information was obtained from all of the bridges, except the Newton bridge where the borehole did not extend beyond the bottom of the foundation due to drilling refusal. Review indicates the Parallel Seismic depths from geophone tests are consistent with other NDT foundation depth predictions. One interesting finding for these saturated subsurface conditions was that one could impact even the next to the outside and the outside battered piles and detect their lengths with the hydrophone suspended in the boring between the two center piles for boring to pile distances of well over 10 ft.

Table 8 - Summary of Parallel Seismic Test Results

Bridge Location	Tested Unit	Substructure Type	Actual Depth (from top of ground surface(ft))	Predicted Depth (ft)
Coors (Colorado)	Pier 4	Concrete columns on shallow footings supported by steel piles	28.8'	27' (Geophone) 29' (Hydrophone)
Alabama (Alabama)	Bent 4	Steel piles extending to the bottom of the superstructure	East Pile: 39' Middle Pile: 39'	East Pile: 30' (Geophone) Middle Pile: 31.6' (Geophone) 34.6' (Hydrophone)
Old Bastrop (Texas)	Caisson	Two circular columns connected by a breast wall supported by a bell shape concrete footing supported on a rectangular concrete footing	35'	Borehole 1: 35.3' (Geophone) 38.3' (Hydrophone) Borehole 6: 35' (Geophone)
	Piles	Concrete columns supported by a pile cap of concrete piles	33.3'	32' (Geophone) 33' (Hydrophone)
New Bastrop (Texas)	Drilled Shaft	Concrete columns supported by shafts	38'	35.3' (Geophone)) 38.3' (Hydrophone)

3.7 Borehole Sonic Test

The Borehole Sonic (BHS) method was proposed for research as a promising, but unproven approach for application in the determination of unknown bridge foundation depths, and perhaps even foundation geometry. Like Sonar, the method is based on the principle of generating compression wave energy of sufficient energy and frequency so that such waves will reflect back from the much stiffer bridge foundation substructure to be sensed by receivers in the BHS tool. The complication is that soil is a highly attenuative media for stress wave travel, even when saturated, which limits the bandwidth of the received signal. The method involves lowering a source and a receiver unit in the same borehole and measuring the reflection echoes from the sides of the bridge foundation substructure using near horizontal raypaths as conceptually shown in Figure 10.

Two potential systems for performing Borehole Sonic tests were evaluated in field tests of the concrete caisson and pile foundations of the Old Bastrop bridge and the drilled shaft foundation of the New Bastrop Bridge. The first system evaluated was a mocked-up prototype of source and receiver components for Crosshole Seismic Testing to determine shear and compression wave velocities in soils between two borings. The source uses a solenoid impactor to strike a casing wall to generate compression and shear wave energy. The receiver was a 3-component geophone that was also used in the Parallel Seismic tests. The second system evaluated was a commercial full-waveform, single hole sonic logging tool known as the PS Suspension logging tool by the OYO Corporation of Japan.

3.7.1 University of Texas at Austin BHS Test Results

A mock-up of a prototype Borehole Sonic device consisting of the crosshole source and geophones component geophone receiver was assembled for field testing at the Bastrop bridges. By testing at the Bastrop sites, three different sizes of foundations were available for evaluating the capabilities of the tested systems: the massive caisson (plan dimensions of 10 ft by 32 ft), the 4-ft diameter drilled shaft, and the 14-in. square concrete piles. In addition, the ground water table at about 16 ft deep offered the opportunity for tests above and below the water table. Tests of saturated soils with the systems would presumably have the best chance of recording and generating compression wave reflections that would travel at the velocity of water. Unfortunately, no identifiable reflections of compression or shear wave energy were measured from either the concrete pile or the drilled shaft due to their small sizes, only from the massive caisson.

3.7.2 OYO PS Logging Tool Test Results

The results of the Texas Bastrop bridge data was compared with another approach for Borehole Sonic BHS testing using a commercial full-waveform logging tool from Oyo Corporation lowered in the *same hole*. Oyo's PS logging tool is designed to measure the direct compressional and shear wave energies of soil and rock by means of a source and receiver system suspended in a water-filled borehole. The tool is quite long with a source to receiver spacing of 1 and 2 m (2 receivers). The tool works by exciting a horizontal force in the water that travels out into the surrounding soils through the casing wall. Isolation is built into the tool to minimize the effects of tube waves on the receivers. The full seismic time history is recorded by this system. The data was translated into a geophysical format. The purpose of this test was to investigate whether any reflections from any of the three
Bastrop bridge foundations was also present in the time records in addition to the direct measurements of compression (P) and shear (S) wave velocities.

Generally speaking, very weak reflections would be expected to be recorded with this tool as most of the energy is directed vertically up the borehole from the source to the receiver rather than horizontally to the foundation. Thus, it is unclear whether the apparent reflection is real or not. This tool was, however, very effective for measuring the in-situ shear wave velocities in the surrounding soils for which it is designed.

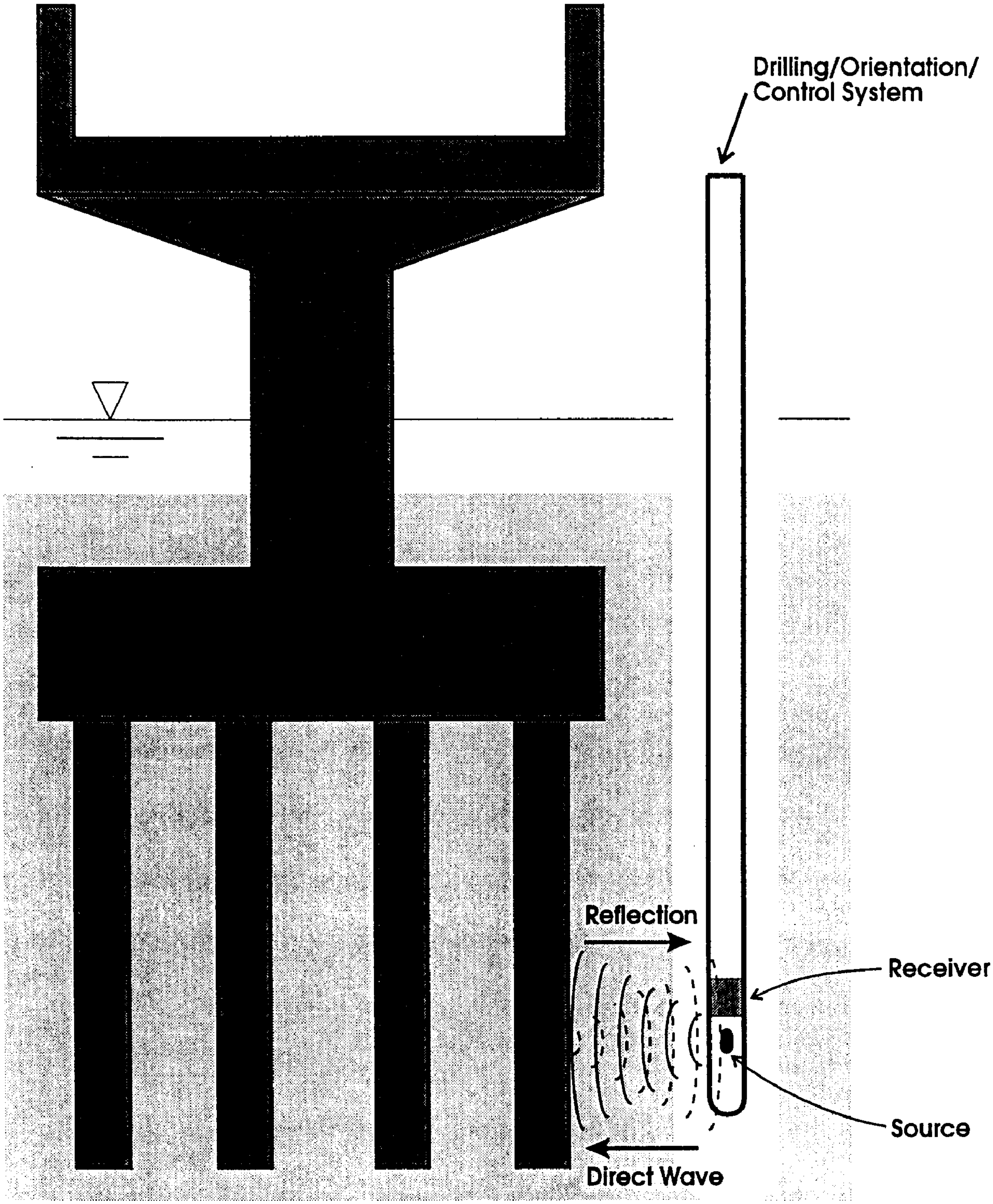


Figure 10 - Idealized Schematic of Borehole Sonic Method.

3.8 Borehole Radar Method and Results

The Borehole Radar method was unproven in its application to the determination of unknown bridge foundations. The method is conceptually illustrated in Figure 11. The method is analogous to the Borehole Sonic Method in that it depends on reflections of waves from materials of differing properties as well, only the difference in those properties is not stiffness, but dielectric constants that cause reflections (28). Ground Penetrating Radar (GPR) employs radio waves in the frequency range of 1 to 2,000 MHZ to map structures in the ground. Surface radar studies have been done to investigate conditions of scour around bridge piers (29), but surface radar has limited application to unknown foundation depth determination because the reflecting targets tend to be largely vertical. In addition, adjacent substructure can complicate the results and make resolution of even shallow footings difficult. Borehole radar is unproven in its application to the determination of unknown foundation conditions, but it has the promise of being able to obtain direct reflections from the vertical foundation substructure. Borehole Radar has been used in Europe for mining studies (30) with a directional tool in both single hole and crosshole studies. Considering the above, the proposed research on the Borehole Radar work was to take data from the PVC cased borings used for the Parallel Seismic and Borehole Sonic tests at the Coors, Alabama, and Bastrop bridges (steel casing kills the electromagnetic wave propagation by reflecting most of the energy back to the borehole) and see how it worked. In addition, limited surface Ground Penetrating Radar surveys were done as well in an attempt to obtain the footprint of a footing and pilecap at the Coors bridge and Connecticut bridges.

3.8.1 Borehole Radar Method and Example Results

In this project, an omni-directional borehole radar system with a monostatic (zero-offset) antenna were used in 4-in. diameter, PVC-cased boreholes at the Coors, Alabama and Bastrop, Texas bridges. The tool is nominally 3-in. in diameter and is about 3.5-ft long. A surface ground penetrating radar system was also used at the Coors bridge piers in an attempt to detect the footprint of a pilecap and footing.

For the Borehole Radar (BHR) test the reflection from the soil/foundation boundary (the abutment) is of interest. The soil dielectric constant is a direct function of the water content, i.e., as the water content increases, so does the dielectric constant. This results in a decrease of radar velocity or longer travel paths through the same thickness of soil. The increase of water content also increases the electrical conductivity in soil which increases the intrinsic attenuation of the radar signal resulting in reduced depth of penetration of the radar signal. Typical radar records include a constant transmit pulse at early parts of the record as well as the deeper reflected events from the subsurface or the bridge abutment. Thus, environmental factors such as salt water, conductive soils, ground moisture conditions, buried electrical power lines, etc., can critically limit and/or confuse radar signals.

3.8.2 Borehole Radar Results

No interpretable quality data was obtained at either the Coors or the Texas bridge sites, most probably due to conductive and clayey soil conditions at the Bastrop bridges, and underground power lines noise source at the Coors bridge. Less clayey, but buried power line conditions were found in electromagnetic conductivity survey data at the Coors bridge site, particularly at Pier 4. The interference from these man-made noise sources resulted in very ringy, poor quality data in borehole and unclear surface radar surveys at the Coors bridge. In addition to the natural clayey conditions at the Bastrop bridges, all PVC cased boreholes at the Texas Bastrop bridge were either bentonite (Borehole 1) or bentonite cement-grouted (the rest) which could have further contributed to the severe damping of the radar signal. Consequently, borehole radar data is not presented for the Texas Bastrop or Colorado Coors bridge sites in this report. A summary of all the Borehole Radar results is shown in Table 9 below.

3.8.3 Summary of Borehole and Surface Radar Case History Results

Borehole and surface radar tests were run at the five independently investigated bridge sites in Connecticut with <u>unknown</u> bottom foundation depth characteristics. Borehole Radar tests were run in the 4-in. diameter PVC cased boreholes drilled at one abutment for each of the four concrete and one masonry bridges.

Review of a summary of all of the NDT depth prediction for the 5 bridges indicates Borehole Radar depth predictions are consistent with the other NDT results at the Hamden, Darien and Shelton bridges, not as accurate for the exposed footing of the Newton bridge, and inconclusive for the Oxford bridge. Depth prediction with Borehole Radar was good at these bridge sites and this is attributed to the generally less conductive soil and bedrock conditions. The water table depths were also apparent in the results.

The surface GPR radar surveys were run along the top of the roadway and across the exposed width of each abutment in the stream and river channel areas (above water). The surface tests were performed to obtain the thicknesses of the abutments and in an attempt to check for the toe or heel of any footings that might have been present. Borehole Radar test data was also analyzed to check for any detectable changes in the substructure geometry. A comparative summary for the Borehole and GPR results indicates confidence levels in the data ranged from low to high for the Borehole Radar depth predictions and footing thickness estimates. Confidence levels for surface GPR results ranged from low-medium to medium-high for the stem widths, but were low for the toe and heel widths. In summary, the Borehole Radar was effective at depth prediction, and less effective at footing thicknesses. The surface GPR was effective at thickness predictions for the stem widths, and not very effective for heel and toe widths due (probably due to poorer access and deeper targets).

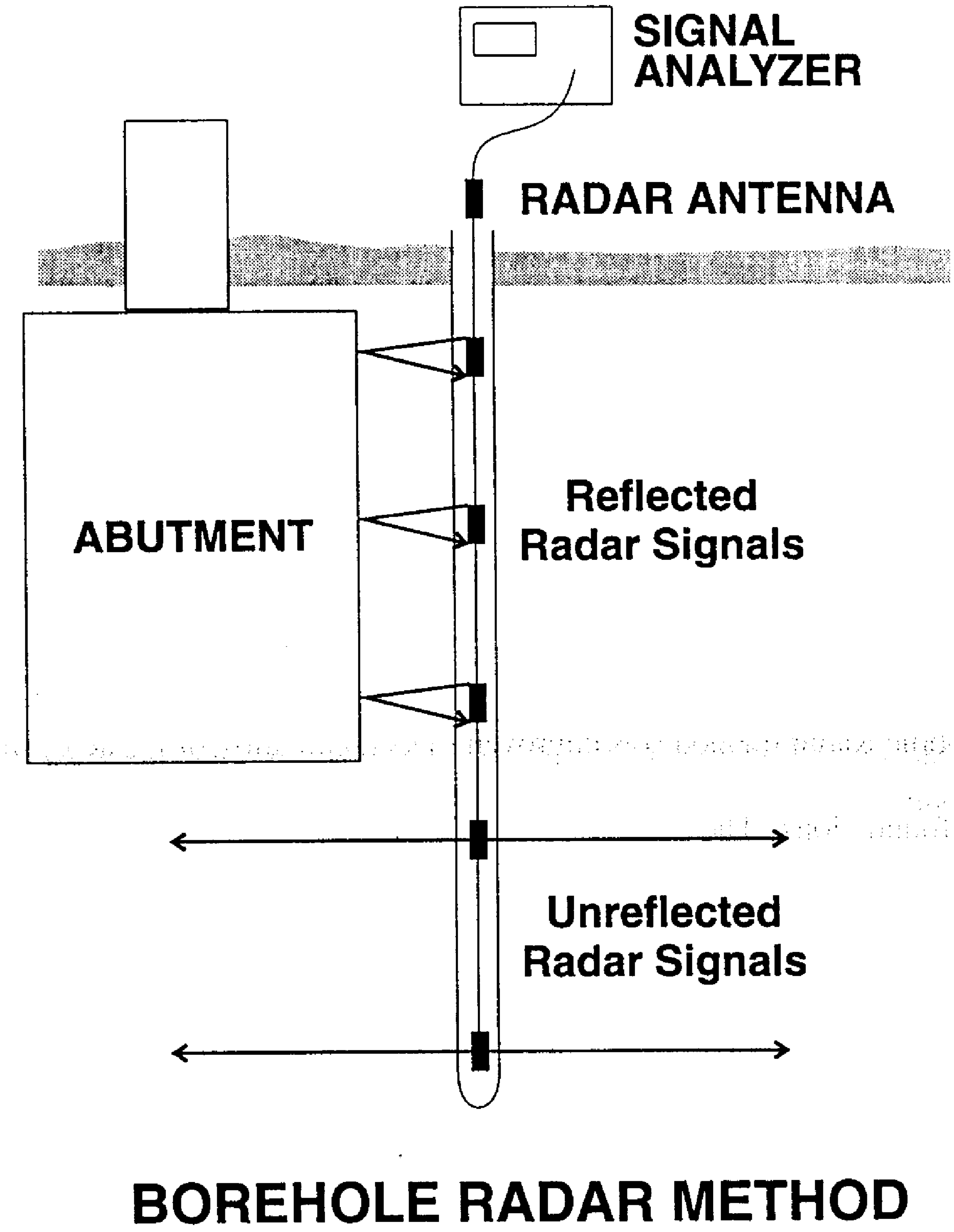


Figure 11 - Borehole Radar Method

Table 9 - Summary of Borehole Radar Test Results.

Bridge Location	Tested Unit	Substructure Type	Actual Depth (from ground surface (ft))	Predicted Depth (ft)
Coors (Colorado)	Pier 4	Concrete columns on shallow footings supported by steel piles	28.8'	Not successful (man-made noise sources)
	Pier 2	Concrete columns on shallow footings	4.5'	Not successful (man-made noise sources)
Alabama (Alabama)	Bent 4	Steel piles extending to the bottom of the superstructure	East Pile: 39' Middle Pile: 39'	East borehole: 31' Middle Pile: 28.1'
Old Bastrop (Texas)	Caisson	Two circular columns connected by a breast wall supported by a bell shape concrete footing supported on a rectangular concrete footing	35'	Borehole 1: Not successful Borehole 6: Not successful (clayey site conditions)
	Piles	Concrete columns supported by a pile cap of concrete piles	33.3'	Not successful (clayey site conditions)
New Bastrop (Texas)	Drilled Shaft	Concrete columns supported by shafts	38'	Not successful (clayey site conditions)

3.9 INDUCTION FIELD METHOD

Although no research was performed or proposed on this method, the two available technical research reports from New Zealand were obtained and reviewed during the course of the research. A summary of this borehole-based method is included herein because it is one of the four NDT methods that had been used to determine unknown foundation depths prior to beginning this research.

In the Induction Field (IF) method, an AC current flow is impressed into a steel pile (or the rebar in a reinforced concrete pile) from which the current couples into the subsurface and finally to a return electrode. The return electrode can be another pile, or it can be a pipe or piece of rebar driven into the ground. A receiver coil which is suspended in a nearby boring is then used as a sensor of the magnetic field induced by the alternating current flow in the pile, as shown in Figure 12. The basic limitation of this method is that the foundation substructure must contain electrically continuous steel for it's entire length, and the steel used must be accessible at the top to allow the electrical connection. Steel pile and reinforced concrete pile depths can be obtained from this type of survey. However, it is doubtful that the distribution of piles can be discerned. In addition, piles which are not electrically connected to a pile cap will not be seen unless some other electrical connection can be made to the pile steel directly.

This method was developed in New Zealand for foundation length determination of reinforced concrete piles and steel piles (3,4). The method is the electromagnetic analog to the Parallel Seismic (PS) test. A current is passed down the reinforcement or steel of a deep bridge foundation to a return electrode which can be a metal object with an area of about 1 m^2 (11 ft^2) or an adjacent deep foundation having no direct electrical contact with the test foundation as shown in Figure 12. A magnetic field is generated alongside the pile, by the current flowing vertically down the pile steel, that is measured using a search coil in a boring. This search coil is then connected to a detecting instrument which shows the relative field strength of the magnetic field. As the depth of the search coil increases, the induced voltage decreases linearly down the length of the pile, provided there is a constant current leakage down the pile.

By plotting the magnitude of the induced voltage versus the depth of the search coil, an indication of the length of the pile is provided. The presence of a ground water-table will somewhat affect the results of this measurement, but as long as the foundation bottom is not at the exact depth of the water-table, this should not be a big factor. Once the search coil is below the bottom of the foundation, the measured induced voltage tends to stabilize at a low value because of the residual conductivity of the soil or bedrock. A tangent point to the linear portion of the curve is then used to estimate the foundation depth at the inflection point of the change in voltage with depth

One important consideration with respect to unknown bridge foundations is that while the method could detect the presence of piles under a buried footing, that the piles must be electrically connected through the footing to the bridge superstructure or some other accessible element to allow connection of the current source. Another important consideration is that the method requires a boring. However, the method could be performed in conjunction with the Parallel Seismic method or the Borehole Sonic method, which also require a borehole.

3.10 Summary of Test Results

A summary of the known foundation depths v.s. NDT predicted depth for each bridge is shown in Table 10.

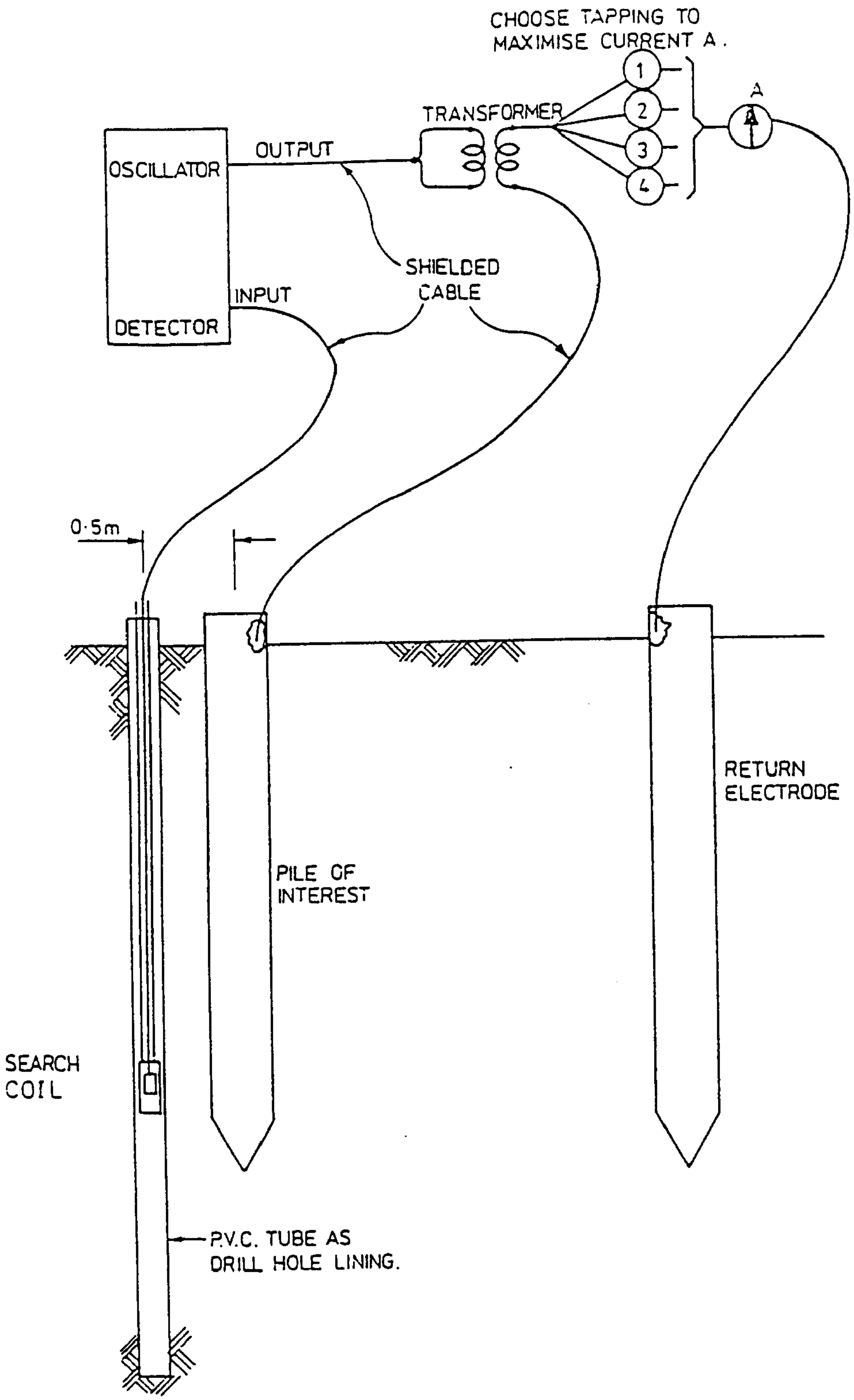


Figure 12 - Induction Field Method

Table 10 - Known Foundation Depths v.s. NDT Predicted Depths by Substructure

Substructure & Bridge	Substructure Description	Plan Depth (ft)	NDT Foundation Element Depths (below-grade in ft)							
			SE	IR	USC	USF	BW	PS	BHR	BHS
Concrete North Pier Golden, CO	Columns on footings with breast wall	14.8	inc	inc	14.0	14.9	--	nb	nb	nb n/a
Pier 4 Coors, CO	Concrete columns to pilecap	4.8	inc	inc	4.8	3.4	--	inc	inc	n/a
	Columns to pilecap to steel piles	28.8	n/a	n/a	n/a	n/a	n/a	29_h 27_g	inc	n/a
Pier 2 Coors, CO	Concrete columns on footings	4.5	inc	inc	inc	4.4	--	--	inc	n/a
NE Wing/ Middle Pier Franktown, Colorado	Exposed timber piles in wingwall	21.0	22.8	20.9	inc	inc	20.3	nb	nb	nb n/a
	Cap beam on timber piles	25.0	20.8	20.2	20.0	inc	--	nb	nb	nb n/a
West Abutment/ West Pier Weld, CO	Stubwall on H-piles (top @ 0 ft)	6.0	6.6	6.5	--	--	--	nb	nb	nb
	Concrete wall on pilecap H-pile	10.7	--	--	inc	9.7	--	nb	nb	nb n/a
Steel Pile Substructure Bent 4 Alabama	East Battered Steel BP pile	39	inc	inc	--	--	--	30_g	31	n/a
	Center Vertical Steel BP Pile	39	inc	inc	34-35?	35?	--	34.6_h 31.6_g	28.1	n/a
Concrete Caisson Old Bastrop, Texas	N. Column top to Bell top @ 0 ft	0	+2.1	inc	--	--	--	n/a	n/a	n/a
	bottom of bell shaped section	18	--	--	inc	18.6?	n/a	inc	inc	inc
	bottom of rectangular footing	34	--	--	inc	37.3?	n/a	37.3_h 34.3_g	inc	33.3-33?

Piles Old Bastrop, Texas	Column on exposed pilecap on concrete piles	33.3	inc	inc	n/a	n/a	n/a	33_h 32_g	inc	inc
Drilled Shaft New Bastrop, TX	Concrete Beams on columns on shafts	38.0	38.0	inc	inc	38?	n/a	38.3_h 35.3_g	inc	inc

Legend for Table 10

SE - Sonic Echo

IR - Impulse Response

USC - Ultraseismic Vertical Profiling with Compressional Waves

USF - Ultraseismic Vertical Profiling with Flexural Waves

BW - Bending Wave with Short Kernel Analysis

PS - Parallel Seismic with hydrophone (h) or geophone (g)

BHR - Borehole Radar

BHS - Borehole Sonic

inc - inconclusive test results for foundation element depth prediction

n/a - the method was judged to not be applicable for depth prediction of the substructure

nb - indicates no borehole tests were performed because no boreholes were drilled

-- - indicates the nondestructive test was not performed for that substructure

? - tentative, weaker prediction that may or may not be accurate

+- distance above top of bell

29_h - denotes a foundation element depth prediction from a hydrophone PS test

27_g - denotes a foundation element depth prediction from a 3-component geophone PS test

4.0 APPRAISAL OF NDT METHODS CAPABILITIES AND LIMITATIONS

NDT methods researched in this study, and other methods applicable to the unknown bridge foundation problem, are discussed below in terms of their capabilities and limitations. The six surface methods (Sonic Echo/Impulse Response, Bending Wave, Ultraseismic, Spectral Analysis of Surface Waves, Ground Penetrating Radar, and Dynamic Foundation Response). The four borehole methods (Parallel Seismic, Borehole Radar, Borehole Sonic, and Induced Electromagnetic Field). Most of the methods are primarily used for unknown foundation depth determination, but some of the methods can be used to provide additional information on foundation type, geometry and materials.

4.1 Sonic Echo/Impulse Response Method

Capabilities - Unknown Depth. These two tests are best used for determining the depths of rod-like, columnar substructure shapes such as timber piles, concrete piles, and drilled shafts that extend up above the ground or water surface. The Sonic Echo test can also be used to determine the depths of shallow, wall-shaped abutments, and piers. If tests are performed on the side of a pile, then the Sonic Echo test should be used with 2 receivers to track upgoing v.s. downgoing wave reflections. This also permits the measurement of compressional wave velocity, which is used to calculate reflector depths such as the pile bottom. Bottom echoes can be obtained for embedded length to diameter ratios of 20:1 or less in most soils, but results have been obtained for slenderness ratios greater than 50:1 in extremely weak, soft soils. Use of theoretical models allows one to evaluate the likelihood of success with the methods prior to going to the field, and modeling also aids in interpretation of results. Impulse Response tests will generally only be useful when performed near the tops of piles and shafts as the resonant responses are clearest there. The two methods are fairly fast as both tests can be done by a two-person crew in 15 to 30 minutes depending on bridge access conditions and difficulties of mounting receivers.

Limitations. The Sonic Echo/Impulse Response methods will not work well when tests are attempted through more massive and complex members, such as beams and pilecaps, to detect echoes from smaller, columnar piles and shafts. Modeling and field tests have shown that the compressional wave energy is trapped in the larger element because of the impedance contrast (larger cross-sectional area). Bottom echoes will likely not be measured for embedded length to diameter ratios much greater than 20:1 to 30:1. Reflections will also not be identified when the stiffness of soils and bedrock begins to approach that of the foundation element. Complex substructure shapes can cause multiple reflections that make interpretation of the data difficult, and even impossible. Generally, no reflections will be identified below the first major change in stiffness (impedance). Thus, if one is testing a column on a buried pilecap on piles, one would only typically be able to identify the pilecap, but would not know if the piles were even present, let alone how deep they were. Finally, the methods do not work well on more massive, deep substructures.

4.2 Bending Wave Method

Capabilities - Unknown Depth. This method uses bending (flexural) waves instead of the compressional wave energy used in the Sonic Echo/Impulse Response methods. It is limited to applications on rod-like deep foundations such as timber piles, concrete piles, and drilled shafts that extend above the surface and water. Experimentally, it has been applied to largely timber piles, but will also work on other, more slender members. The method has been used on timber piles of up to 60 ft in length (10). The main advantage of the method is that only a horizontal blow is required, which is easy to apply to the side of a substructure.

Limitations. For a 12-m long, 1-m diameter concrete shaft, theoretical studies show that depth predictions may not be able to be made for depths greater than 5 m due to the high attenuation associated with flexural waves as compared to compressional waves traveling down a rod. Stiff soil layers can also result in apparent short pile lengths. More experimental and theoretical research is needed to compare the capabilities of the Bending Wave method to the compressional wave based Sonic Echo/Impulse Response methods.

4.3 Ultraseismic Vertical Profiling Method

Capabilities - Unknown Depth. This method has all the capabilities of the Sonic Echo/Impulse Response method with compressional waves, as well as the capabilities of the Bending Wave method with flexural waves. The method was found to be less affected by the presence of large beams on top of columnar substructure than the Sonic Echo/Impulse Response methods. The advantage of this method, as compared to the Sonic Echo/Impulse Response and Bending Wave methods, is that it uses multiple receiver (or source) locations to perform multi-channel, geophysical processing of the data. The additional data is processed to separate out upgoing and downgoing waves, to minimize noise from attached substructure reflections, and to permit "tracking" the wave travel to determine the reflector locations. The Ultraseismic method worked much better than the other methods for determining the depths of shallow abutment walls and pier walls, and also was much more useful for columnar substructure on footings with large beams on top. A typical dataset requires about 1 hour in the field to collect, depending on access.

Limitations. The method will not work well for foundations embedded in very stiff materials since little energy, if any, will be reflected. It also showed difficulties in identifying flexural wave reflections from more massive, deep foundations. It requires only a little more time to acquire and process data than the Sonic Echo/Impulse Response and Bending Wave tests, and data reliability is typically increased. An accessible vertical surface of at least 4-5 ft or more in length is needed for testing. Like the Sonic Echo/Impulse Response and

Bending Wave methods, Ultraseismic tests will not generate sufficient energy to penetrate below significant changes in stiffness (impedance). Thus, pile can not be detected below a buried pilecap.

4.4 Spectral Analysis of Surface Waves (SASW) Method

Capabilities - Unknown Depth, Geometry, and Materials. The SASW method has been found to be capable of determining the depths of shallow abutments, pier walls, and other solid substructures with a flat surface from which testing can be performed. Such flat surfaces could be the top of an abutment between girders, a ledge or step, or even the top of an exposed footing or pilecap. It can also be used to determine unknown thicknesses of abutment breastwalls and wingwalls, exposed footings and pilecaps, and indicate material properties in terms of stiffness (velocity) for substructures and surrounding soils and rock. It is estimated that SASW tests cannot penetrate depths that are much greater than the longest substructure dimension available for testing. Where substructure geometry has enabled the SASW test to be used, clear indications have been provided as to the depth (boundary) of the substructure abutments (faster velocity), and the underlying soils and bedrock (slower velocity).

Limitations. The main limitations of the method are geometric. Flat access is required to generate the surface wave energy. Maximum foundation depths that can be determined are estimated to be not much deeper than longest test horizontal surface on the tested substructure. The substructure must also be solid for the surface wave energy to travel down through it and interact with the underlying soils.

4.5 Surface Ground Penetrating Radar (GPR) Method

Capabilities - Geometry. The surface GPR method is mainly useful for determining the thicknesses of abutments from the wall surfaces, or the roadway. It can also be used to attempt to penetrate through the earth to detect the footprints of reinforced concrete footings or pilecaps, and perhaps the tops of steel piles themselves, but this will be highly site dependent in terms of its success.

Limitations. The main limitations on the use of radar are environmental effects that attenuate or complicate the GPR signals. Radar is severely attenuated by salt water, brackish water, conductive clays and other soils, moisture in the ground, and noise sources such as buried power lines. Consequently, the use of radar is best at sand sites and others with low conductivity.

4.6 Dynamic Foundation Response Method

Capabilities - None Confirmed, Some Potential. This test was proposed in an attempt to distinguish whether or not piles were present below a footing by vibrating a bridge substructure to measure its natural frequencies. Footings have lower resonant frequencies than pilecaps on piles in soils. It was hoped that this difference would be substantial enough to discriminate between shallow and deep foundations from the surface for substructures like walls (none of the other surface methods can do this). Although some promise was shown in the experimental, theoretical modeling, and dynamic analysis results, the method is still considered unproven in its potential for indicating foundation type, i.e., shallow or deep.

Limitations. Some promise was shown in the research, but additional work is needed before the feasibility of this method is established in being able to be used to detect the presence of piles below a footing/pilecap. One problem encountered was the difficulty in exciting the bridges at their very low natural frequencies with 12-lb impulse sledgehammers. The use of large, truck-mounted geophysical vibrators (a Vibroseis) as vibration sources needs to be researched.

4.7 Parallel Seismic Method

Capabilities - Unknown Depth. This borehole based method has the widest range of application of any of the methods for determining unknown foundation bottom depths regardless of depth, substructure type, geology, and materials. The use of geophones was found to extend the range of the method to identify foundation bottoms under a wider range of conditions than with hydrophones alone. Both compressional and shear waves can be used with the method as generated by vertical and horizontal impacts. The method can be used to depths of 100 ft, or more, if required.

Limitations. The main limitation of this method is that currently a borehole must be drilled and cased to protect the tools and keep the hole open. This can be quite costly in the river environments of bridges. Highly variable soil velocity conditions also complicate the results, but this can be compensated for in the future (regardless, foundation bottoms were accurately identified at all bridges tested with this method). Also, larger impact forces should be investigated so that greater energy is transmitted through pilecaps to piles.

4.8 Borehole Radar Method

Capabilities - Unknown Depth, Type, and Geometry. Borehole Radar can provide a great deal of data if subsurface conditions are conducive to the radar signal, i.e., low conductivity (conversely, high resistivity) subsurface conditions which allow good penetration of soils by the electromagnetic wave energy. Radar also works well at detecting steel and reinforced concrete because the steel reflects the signal strongly. It can be used to estimate the thicknesses of toes and heels of footings, as well as indicate depths of unknown foundations. The testing is fast to perform and data can be digitally recorded.

Limitations. The main limitation for Borehole Radar test is that the radar transmission is highly environmentally dependent. Radar is severely attenuated by salt water, brackish water, conductive clays and other soils, and moisture in the ground. Consequently, the use of radar is best at sand sites and others with low conductivity, and where the reflections targets include steel, which strongly reflects the signal. A borehole must be drilled and cased with a 4-in. diameter, PVC casing. Finally, since an omni-directional radar transmitting and receiving antenna was used in this study, received signals were the average of all reflections coming from around the borehole. The use of a directional, focused radar antenna could potentially improve the results. Unfortunately, the only available directional radar system is currently quite expensive, on the order of $250,000.

4.9 Borehole Sonic Method

Capabilities - None Confirmed, Some Potential. Only basic feasibility research was done on this method. Some promise was shown, but reflections were measured from only a very large caisson target. No reflections were measured from a 4- ft diameter drilled shaft or a 14-in. square concrete pile.

Limitations. Some promise was shown in the research, but additional work is needed to evaluate possibilities of high frequency sources before the feasibility of this method in being able to determine depths of unknown foundations is established. For small targets, such as concrete or steel piles, it is difficult to obtain reflections without generating higher frequency, shorter wavelengths in the soils. This problem can be even more severe when one does not know where to drill to look for piles. The location and orientation of piles are generally not known in unknown foundation substructure investigations. The use of Borehole Sonic requires a PVC-cased boring.

4.10 Induction Field Method

Capabilities - Unknown Depth. The Induction Field method is a proven technology for the determination of the depth of steel piles and reinforced concrete piles. One important consideration with respect to unknown bridge foundations is that the method requires a non-ferrous cased boring (typically PVC). The method could be performed in conjunction with the Parallel Seismic method or the Borehole Sonic method, which also require a borehole. The method works best in soils of more uniform conductivity.

Limitations. Interpretation of data from the Induction Field method is complicated by the existence of ferrous materials in the bridge structure. Also, these tests can only work for reinforced concrete or steel piles that are electrically connected to rebar or other metal which can be accessed at the surface. It will not work for unreinforced concrete, masonry, or timber. The boring must be drilled within 0.5 m (1.6 ft) of the foundation and should extend about 4 m (13 ft) below the bottom of the foundation.

5.0 RECOMMENDED NDT METHODS FOR UNKNOWN FOUNDATIONS

In this section, general nondestructive testing approaches are outlined for NDT investigations of unknown bridge foundation conditions. There are two classes of nondestructive testing methods that can be utilized at a given bridge site: 1. Those that require access from the exposed parts of the bridge substructure elements (surface methods); and, 2. Those methods that require access from a nearby borehole (borehole methods).

5.1 Recommended Surface NDT Methods

The recommended surface methods are Sonic Echo/Impulse Response, Bending Wave, Ultraseismic Vertical Profiling, Spectral Analysis of Surface Waves, and Ground Penetrating Radar. The recommended applications of these methods are discussed in terms of the NDT "target" of interest below.

5.1.1 Unknown Foundation Depths.

Sonic Echo/Impulse Response and Bending Wave methods both are applicable to determining the depths of timber and concrete piles, concrete-filled steel pipe piles, and drilled shaft foundations that extend above the ground or water surface. Since the tests can be complimentary, and use similar equipment, it is suggested that both tests be performed together using two vertical receivers and two horizontal receivers to better track wave travel up and down piles. It is also expected that the Sonic Echo/Impulse response method with compressional waves will be able to identify greater pile bottom depths than the Bending Wave method. In addition, the Sonic Echo method is applicable for determining the depths of shallow, wall-shaped, and more massive abutments and piers.

In the future, the processing of these two methods may be combined with the geophysical processing and display of the Ultraseismic Vertical Profiling method to provide detailed, accurate, and economical testing in one system. Ultraseismic testing could also be of use on piles, particularly if there is a need to track more complex reflections and arrivals than is possible with the simpler methods. The determination of unknown depths of steel H-piles is likely to be limited to very shallow depths at most sites. This is because of the high attenuation of stress wave energy over the large surface area of H-piles.

Finite element modeling of wave propagation behavior in foundation substructure was found to be of real value in planning NDT programs and analyzing NDT results for compressional and flexural waves.

Ultraseismic Vertical Profiling with compressional and flexural waves is recommended for determining the depths of the more complex columnar- and wall-shaped piers and abutments. Ultraseismic Horizontal Profiling was also found to be useful for these types of bridge substructures. Ultraseismic tests are also recommended for combined shallow/deep foundation substructures, e.g., columnar or wall substructures on pilecaps to determine the pilecap depth. However, for more massive and deep substructures, Ultraseismic tests are in need of more research.

For the special case of bridge substructures with exposed footing/pilecap tops, the two surface methods of surface radar and the spectral analysis of surface wave (SASW) methods can be employed in determining the depth of the footing/pilecap, using different physical principles. The SASW method uses the dispersive properties of Rayleigh surface waves to determine the concrete-soil depth (bottom of the footing). Spectral Analysis of Surface Waves (SASW) tests can work very well for foundation depth determination of concrete and possibly masonry bridge substructures that are more massive and wall-like in shape. A horizontal, flat access area is needed for testing, and the substructure should be of solid construction. For example, the method may not work well for a bridge substructure that consisted of a layer of masonry above earthfill, followed by a bottom layer of masonry. Also, the bottom depth of the substructure that can be detected with the SASW tests is likely to be not much greater than the longest accessible horizontal test surface of the substructure.

Surface ground penetrating radar records the reflection echoes from the concrete-soil boundary to determine the unknown depth. However, because of reflections from adjacent, exposed substructure, it can be difficult to determine the depths of even shallow footing foundations with radar.

To summarize, a good measure of the unknown depth of the foundation can be obtained in a large subset of bridges by utilizing the Sonic Echo/Impulse Response/Ultraseismic, SASW, and Ground Penetrating Radar methods. However, none of these methods are able to detect foundation elements below the first major change in stiffness, i.e. the presence of piles underlying a buried footing/pilecap can not be detected.

5.1.2 Foundation Type

The next question concerns detecting the possible existence of piles underneath a footing/pilecap, in other words, determining whether the substructure foundation system is shallow (footing), deep (pile) or a combination (pilecap on piles). The dynamic foundation response (DFR) test was proposed to determine whether a substructure element is on a footing or on a pilecap supported by piles. The surface methods can determine the unknown depth of shallow bridge foundations or exposed piles, but not of buried piles underneath a footing. These methods can, therefore, be used for the bridge substructures that do not contain piles or have exposed piles and are susceptible to scour. For the other bridges with footing on pile substructure, the borehole methods must be used. The Dynamic Foundation Response test shows some potential, but the method is not yet conclusive in this regard. For a complex bridge structure, the foundation system typically exerted a relatively minor influence on the total dynamic response of the system.

None of the researched surface methods can directly determine whether piles exist underneath a footing at this time. However, there are other criteria that can aid in the selection of a subset of bridges that require subsequent borings. For example, the depth to bedrock can be obtained near a bridge abutment or pier using surface radar, SASW, or seismic refraction tests. This information, combined with the results of the Ultraseismic and/or SASW methods, can determine whether the footing rests on bedrock. A bridge engineer can then assess the susceptibility of the foundation to scouring using this and other hydraulics parameters. Obviously, if a footing is resting on competent bedrock, it is very unlikely that piles were driven into the bedrock below the footing.

5.1.3 Geometry

Several NDT methods are applicable to the problem of determining unknown subsurface bridge substructure geometry. The nondestructive testing investigation to determine unknown foundation conditions of the Connecticut bridges was performed to determine unknown foundation depths. The investigation was also performed to determine as much other unknown abutment geometry as possible, such as thicknesses of stem walls and the extent of a footing heel and toe, if present. For the Connecticut bridges, this was attempted with surface ground penetrating radar with some success. Surface radar test methods can be used to determine stem wall thicknesses and inclinations. This can be done by running two or more test lines across the (exposed) front side of the stem wall of an abutment and recording the echoes from the (soil covered) back side. Similarly, the extent of the toe can be determined by running a surface radar line over the top of the bridge and also along the ground near the base of the existing substructure (abutments or piers). The signals are examined for the reflection event from the top of the toe, although interpretation of these results is a more challenging task because of reflections from the adjacent substructure. However, radar will not work well at sites with conductive soils, and its use on more reinforced abutments and piers, or around steel piles may produce data dominated by echoes from the steel.

Stress wave based tests such as Spectral Analysis of Surface Waves and Impact Echo (essentially high frequency Impulse Response testing (31)) can also be used to indicate the thicknesses of exposed substructure of abutments. Ultraseismic tests with high frequency impacts are also applicable to thickness measurements.

5.1.4 Materials

The Spectral Analysis of Surface Waves test can provide data on the change in the stiffness of foundation materials with depth without drilling a boring by measuring the dispersion curve (velocity versus wavelength). No other NDT methods provide such direct data on changes in subsurface substructure properties.

The other aspect of the unknown foundation problem concerns the local soil and bedrock geology conditions. The SASW method is useful in this regard as one can determine layer thicknesses and the shear wave velocity profile v.s. depth without drilling a boring. Shear wave velocity of the soil is a key input into the finite element modeling of compressional and flexural wave propagation behavior for bridge foundation substructure. The SASW method is also uniquely capable of being able to measure the velocity of soft soils underlying stiffer soils. Surface Seismic Refraction surveys can also indicate the variation of velocity with depth, but only if the soil velocity increases with depth. Electromagnetic Induction surveys can be run to measure the ground water-table depth, bedrock, and soil conductivity to predict the depth of radar penetration prior to radar measurements.

5.2 Recommended Borehole NDT Methods

The recommended borehole methods are Parallel Seismic, Borehole Radar, and Induction Field. The recommended applications of these methods are discussed by the NDT "target" of interest below.

5.2.1 Unknown Foundation Depths

Of all the NDT methods, the Parallel Seismic method was found to most accurately indicate unknown foundation bottom depths for the broadest range of bridge substructures and subsurface geologic conditions. The borehole should be drilled within 3 to 6 ft of the substructure and extend at least 10-15 ft beyond the minimum acceptable foundation depth from a scour standpoint. Parallel Seismic tests with hydrophone or geophone receivers produced good to excellent depth predictions for every bridge foundation tested as shown in Table 10. Hydrophone receivers will work well in saturated soils and other uniform velocity soil conditions where compressional wave first arrival times are a linear function of the foundation depth. Geophone receivers should be used in grouted, cased holes in variable velocity soil conditions, or if the arrivals of both compressional and shear wave energy are to be determined. Under ideal circumstances of uniform seismic soil velocities, the Parallel Seismic test can provide an image of the shape and orientation of a foundation. However, such subsurface uniformity occurs rarely in nature for any significant depths. An image can be provided in non-uniform soils by correcting for varying soil velocities v.s. depth based on the results of Downhole Seismic or SASW tests.

The Borehole Radar method produced results ranging from excellent to none in terms of foundation depth predictions at the study and case history bridge sites. The method will work best where some steel is present in the foundation; and soils, water, and groundwater all have low conductivity. Attenuation of the radar signals is severe in salt water, conductive clays, and other conductive soils, to the point where the radar penetration may be only a foot or two. However, Borehole Radar worked well in 3 of 5 sites in Connecticut where local geology conditions were favorable. Electrical conductivity surveys of the ground can indicate whether a site is suitable for radar or not. Analogous to the Parallel Seismic method, the Borehole Radar will work best in soils with near-constant electromagnetic wave velocities. At sites with such uniform conditions, Borehole Radar can even provide an "image" of subsurface foundation elements that vary in shape (i.e. footing heel beneath abutment wall) and orientation (i.e. battered steel BP-pile). With directional Borehole Radar (as opposed to the omni-directional tool used in this study), one might be able to check the depths of several piles from the same borehole under ideal test conditions. However, if the pile shape is such that it is not round, or square to the measurement, little energy may be reflected back towards the tool.

The Induction Field test is the electromagnetic analog to the Parallel Seismic method. It is only applicable to steel piles or reinforced concrete piles that are able to be electrically connected to the surface. It also requires the boring to be PVC-cased and drilled within less than 2 ft of the pile for the search coil. It should be noted that for embedded pilecaps on steel H-piles, the steel H-piles would not be detected by this method unless they were electrically connected to the reinforcing of the pilecap up to the exposed substructure. Consequently, this method is much more limited in its application.

5.2.2 Foundation Type

The next question concerns detecting the possible existence of piles underneath a footing/pilecap, i.e., determining whether the substructure foundation system is shallow, deep, or a combination (pilecap on piles). To answer this question, it is best that an appropriate surface NDT method be used in conjunction with Parallel Seismic tests (or Borehole Radar tests if subsurface conditions are favorable). However, in a simple sense, drilling the boring and performing the borehole NDT will indicate whether a foundation is deep or shallow simply by the indicated bottom depth.

5.2.3 Geometry

The nondestructive testing investigation to determine unknown foundation conditions of the Connecticut bridges also involved attempting to identify if a footing heel and toe were present. Borehole radar measurements gave a fair indication of the extent and thickness of the footing heel.

5.2.4 Materials

Both the Borehole Radar and Induction Field method are sensitive to steel in foundations. However, for that sensitivity to translate into differentiation between steel H-piles, reinforced concrete piles, and timber piles would require the performance of at least one of the two tests in conjunction with the Parallel Seismic method. Even then, local conditions may prevent a definitive answer.

5.3 NDT Investigation Approaches to Unknown Subsurface Foundations

The interpretation of all the NDT and geophysical results is recommended to be done by a specially trained engineer within the DOT or in conjunction with an outside consultant. Although many challenges still remain in determining all the unknown bridge parameters under all geological/hydraulic conditions, it is hoped with more research, these methods can be used routinely at many bridge sites.

Generally speaking, the most critical item to be determined is the unknown depth of the bridge foundation to compare with predicted scour depths in scour vulnerability analyses. Consequently, the selection of the NDT methods should reflect knowledge of the exposed substructure, local geology conditions, and the criticality of the bridge. Surface NDT methods will generally be more economical than boreholes because there are no drilling costs. Although the borehole methods are generally considered to be more expensive due to the associated cost of a boring, there are other means to mitigate their costs. For example, Parallel Seismic tests can now be run from 2-in. slim holes. Portable light-weight drilling units exist that can be mounted on the back of pick-up trucks. These units can be operated by DOT personnel in drilling slim holes economically at large number of bridge sites. Jetting, drilling and/or driving of probes and/or casings may be possible in the future.

As an unknown foundation investigation is planned, one must first decide what needs to be learned. Is the most important parameter the: depth of an abutment/pier, pile depths, foundation type, subsurface substructure geometry, material types, geotechnical data on subsurface conditions, or geophysical surveys for soil velocity and bedrock depths? For the sake of economy, only the depth information may be needed for many bridges with unknown foundations, and engineers will be left to make reasonable assumptions about other variables in their scour vulnerability analyses. Critical bridges may require as much information as possible. Also, in general it is good practice in nondestructive testing to use two or more NDT methods to check the results to verify that they are consistent.

6.0 NDT IMPLEMENTATION- EQUIPMENT, TRAINING, OPERATIONS

In this section, the applicable surface and borehole NDT methods are appraised in terms of their system costs, training requirements, time required to complete a test (including the analysis time), and level of expertise needed. A distinction is made below in terms of "commercial" equipment, i.e., a system which is available for purchase designed specifically for the method, v.s. "custom" equipment, i.e., a system which can be assembled by purchasing individual system components, and writing any software needed to process the data.

All the surface tests (Sonic Echo/Impulse Response, Bending Wave, Ultraseismic, and Spectral Analysis of Surface Wave methods) require accelerometers or geophones that are coupled or hand-held on the top or the side of the bridge substructure. Ordinary water-pump grease was used as the couplant. In one Ultraseismic experiment, the triaxial accelerometers were bolted directly into the bridge column to study the effects of receiver coupling. When comparing the data from that test with another where only hand-held, grease-coupled accelerometers were used, the results were found to be comparable. Bolted accelerometers tend to pick the low frequencies below 80 Hz and high frequencies above 2 kHz better. Since most of the useful amplitudes lie between 80 Hz to 2 kHz, no clear advantage in bolting the receivers at each location was noted, and the use of hand-held accelerometers with good couplant was concluded to be adequate in most concrete structures—and probably the same in stone, timber or steel structures.

The surface tests require access to the top and the side of bridge substructures. If necessary, lifts are needed to lower the field engineer from the bridge deck to the side of the bridge abutment or column and boats and ladder to test from the water level. These support costs (where necessary) for lift, boats, ladders, generator, and traffic control are not included in the cost estimates below.

6.1 Sonic Echo/Impulse Response/Bending Wave/Ultraseismic Tests

The Sonic Echo/Impulse Response and Bending Wave tests are generally limited in their applications to determining unknown depths of timber and concrete piles, drilled shafts, and columnar substructure exposed above the ground or water surface. The Ultraseismic test will work on columnar substructure and piles as well, but will also indicate unknown depths of abutments and piers that are wall-like in shape. The Ultraseismic tests uses compressional and flexural waves.

Commercial equipment is available for the Sonic Echo/Impulse Response systems, but it is typically only 2 channels. Consequently, only the impulse hammer input and 1 accelerometer input are available. It is likely that the desired additional receiver channel(s) could be added by the manufacturers if the market demand warranted it. The costs for commercial Sonic Echo/Impulse Response systems are on the order of $15,000 to $20,000. The systems typically include an impulse hammer, accelerometer, and micro-processor based digital data acquisition, analysis and modeling software (for rod-like deep foundation shapes).

Custom equipment can be readily assembled for the Bending Wave method. The system includes impact sources, accelerometers, and data acquisition hardware plus some software programming. The costs for the custom system are estimated to be on the order of $15,000 to $20,000.

Custom equipment and software was used in the research on the Sonic Echo/Impulse Response, Bending Wave, and Ultraseismic Vertical and Horizontal Profiling methods with compressional and flexural waves. Ultraseismic testing requires the use of fast sampling, multi-channel digital data acquisition cards. These methods require impacts to the substructure to generate wave energy that travels down into a foundation and up into the superstructure. However, reflections may occur from the bottom of a foundation and the top of the superstructure. When this occurs, Sonic Echo/Impulse Response and Bending Wave records can be greatly complicated by the simultaneous reflection of energy up from the foundation and back down from the superstructure. Because of this and other problems, the multi-channel Ultraseismic method is proposed.

A future system could be developed which would allow all three tests to be performed since they are all based on either compressional or flexural waves and use similar hardware to perform. The custom equipment used for all three tests in this research included 3- or 12-lb impulse hammers, 2-three component accelerometers (or more as needed) and conditioners, an analog filter/amplifier, and a dynamic signal analyzer card (4 channel) or digital oscilloscope card with processing software for each of the tests. The estimated custom system cost to perform all three tests is on the order of $25,000 to $30,000 including a portable PC with a card which acts as a digital oscilloscope. The analysis of the Ultraseismic data requires the use of commercially available, specialized geophysical software which costs an additional $5,000. A complete system for the three tests would therefore cost on the order of $30,000 to $35,000. The estimated custom system cost for the Ultraseismic equipment alone is $20,000 to $25,000.

Training on the equipment and tests is estimated to require from a few days to 2 weeks depending on the equipment and NDT methods. The training should also include field NDT of suitable bridge substructures. Training costs are not included in the above cost estimates. A trained technician with previous NDT, instrumentation and PC expertise within the owner's organization (DOT) is a suitable candidate for <u>collecting</u> the field data.

The cost of performing the NDT with one of these surface NDT methods by an outside consultant is estimated at $1,000 - $1,500 per bridge substructure units for ½ day of field testing and ½ day of analysis plus whatever report time is required. These cost estimates assume that the DOT provides the necessary support personnel (1-2 persons depending on the bridge conditions). All consulting costs presented in this section assume that at least a few bridges would be tested in a single contract. Costs can likely be lowered by testing a greater number of bridges per contract. At present, the interpretation of the Ultraseismic records requires a seismic geophysicist or engineer with appropriate NDT experience. The estimated training time for the basic processing of the Ultraseismic data is about one week.

6.2 Spectral Analysis of Surface Waves (SASW) Test

The SASW test has applications for unknown foundation depth determination where flat, wide substructure access is available for geometry determination of abutment wall thicknesses and exposed footings/pilecaps, for determining substructure material properties v.s. depth, and for measurement of the variation of stiffnesses (velocity) of soils and bedrock with depth. The custom equipment for the SASW method includes hammers ranging from 1-lb to a 4-lb hand sledge to a 12- lb sledgehammer (vibrators can also be used), a dynamic signal analyzer, and two seismic accelerometers (or suitable geophones for greater depths and for testing of soils). The estimated cost for this custom equipment with processing software (WINSASW, a windows program from the University of Texas at Austin) is about $15,000 to $20,000 and includes a portable PC.

With the exception of the seismic accelerometers and processing software, all of the other SASW system components are identical to those of the Sonic Echo/Impulse Response and Ultraseismic methods outlined above. Thus, if a combined custom system was developed for all four stress-wave based surface tests, its total cost might be on the order of $35,000 to $40,000 with all needed software. An SASW only system is estimated to cost on the order of $15,000 to $20,000.

The cost of performing this test by a consultant, where applicable, is estimated at $1,000 to $1,500 per bridge substructure unit for ½ day of field testing and ½ day of analysis by a consultant (assumes 1 DOT person for support at DOT cost) plus whatever report time is required. Depending on access, from 1-2 bridges and 2-4 substructures could be tested per day. Training time is estimated to be about 1-2 weeks to train DOT technicians in proper field procedures and data collection. Data analysis must be performed by a specialist consultant or a trained DOT engineer.

6.3 Surface Ground Penetrating Radar

Surface radar is primarily useful for determining the thicknesses of the breast walls of abutments, exposed footings/pilecaps, and possibly the width of a footing toe or heel. It may also be used to determine the depth to bedrock if suitable subsurface conditions are present for the use of radar (low conductivity soils and water). Commercial surface GPR antennae are available in both monostatic (single transmitter/receiver) and bistatic (separate transmitter and receiver systems). The full system costs, including a graphical interface, range from $30,000-$80,000. A system with a 500 MHZ monostatic antenna is adequate for the required testing at a cost of about $30,000. Radar processing software is available from the equipment manufacturer or other commercial software houses for about $1,000 to $5,000. With processing software, costs are typically on the order of $40,000 to $50,000 for a system.

The cost of performing a GPR test is estimated at $1,000 to $1,500 for ½ to 1 day of field testing in which 1-2 bridges and 2-4 substructures could be surveyed with 1 day of analysis. Data analysis must be done by a trained DOT engineer or geophysicist. Estimated training time is about one week for training of technicians and engineers in the performance and analysis of radar survey results.

6.4 Parallel Seismic Test

The Parallel Seismic test requires the drilling and casing of a boring to determine unknown foundation depths. If a hydrophone receiver is used, a 2-in. ID schedule 40 PVC casing with saw-cuts every few feet is capped on its bottom and installed in the borehole to keep it open. If a 3-component geophone receiver is use, a 2-in. minimum ID schedule 40 PVC casing is capped on its bottom and grouted in the hole with a cement-bentonite mixture (this may kill the radar signal - so clean sand backfill may be needed for radar holes). Alternatively, the tests can be performed in similar size or larger steel casings left-in-place by the drilling company. In this case, clean water must be placed in the steel casing for hydrophone testing. No water is desired for geophone testing, but tests can be done below water with water-proof geophones.

The custom equipment required for this method includes 3 to 12-lb impulse hammers (or similar size hammers with a triggering device to start recording on impact to the substructure), a recording oscilloscope or digital data acquisition card in a PC or dynamic signal analyzer, differential amplifiers/filters, and a hydrophone receiver and/or a 3-component geophone receiver to go in the casings. The estimated sale price for a portable PC- based system for only Parallel Seismic tests is about $15,000 with 2-hydrophones to $25,000 with 2- three component geophones.

With the exception of the hydrophone and geophone receivers (with rods to orient the geophones or casing wheel guides for inclinometer type casing), most of the other system components are identical to the Sonic Echo/Impulse Response and Ultraseismic methods outlined above. A multi-purpose equipment system could be developed to perform Sonic Echo/Impulse Response, Bending Wave, Ultraseismic, Spectral Analysis of Surface Waves and Parallel Seismic tests with an estimated sales price under $50,000.

The cost of performing Parallel Seismic tests by a consultant is estimated at $1,000 to $1,500 for ½ day of field testing in which 2-4 substructure units of 1 bridge could be tested (2 borings) with ½ day of analysis plus any required time for the report. This assumes 1 person is provided by the DOT to assist in the testing. The field testing can be done by a trained technician. It is recommended that the data analysis be performed by an outside consultant or a trained engineer within the DOT. Training time for DOT engineers and technicians is estimated at about 1-2 weeks. Drilling costs are estimated to be on the order of $1,000 to $2,000 per borehole if drilling can be done with a truck-mounted rig. Drilling costs will be much higher if a barge must be used for drilling in water.

6.5 Borehole Radar Method

At bridge sites with low conductivity soils and water, Borehole Radar may be used to determine unknown foundation depths and attempt to estimate the thickness and lateral dimensions of footings and pilecaps. Several custom Borehole Radar tools for geotechnical applications have been assembled by the USGS in Denver. The borehole system used in this study was an omni-directional 120 MHZ Borehole Radar system, after the USGS work, which sells for about $10,000 for the Borehole Radar antennae, plus $50,000 for the high-end two channel recording/display system ($23,000 for the single channel system). The monostatic system utilizes the same antenna acting as both transmitter and the receiver in a borehole.

Another borehole radar tool, one that is directional, is available from Sweden, but this system is currently expensive, about $250,000. The Borehole Radar (BHR) method can be very useful in discriminating vertical bridge members such as piles. It is, however, highly dependent on environmental factors such as the presence of conductive and clayey soils and saltwater.

The cost of performing borehole radar tests for a consultant is estimated at $1,000 to $1,500 for 2 hours per borehole per bridge substructure unit so that 2 bridges or more may be done in a field day with ½ day of analysis plus whatever report time is required. This assumes 1 person is provided by the DOT to assist in the testing. It is recommended that data acquisition and interpretation be performed by an outside consultant, or a trained geophysicist/engineer within a DOT. The required training time for a DOT specialist is estimated to be about one week.

6.6 Induction Field Test

This test is analogous to the Parallel Seismic test, but is only useful for determining unknown depths of steel piles and reinforced concrete piles that are electrically continuous to the surface. Custom equipment must be developed and assembled. Equipment components were shown in Figure 12. Costs for this system are estimated at less than $10,000. The cost of performing Induction Field tests for a consultant is estimated at $1,000 to $1,500 for 2 hours per borehole per bridge substructure unit so that 2 bridges or more may be done in a field day with ½ day of analysis. This assumes 1 person is provided by the DOT to assist in the testing. Drilling costs are estimated to be on the order of $1,000 to $2,000 per borehole if drilling can be done with a truck-mounted rig. Drilling costs will be higher if a barge must be used for drilling. The required training time for a DOT engineer/geophysicist and technician is estimated to be about 2 days.

7.0 REFERENCES

1. Elias, V. A., "Strategies for Managing Unknown Bridge Foundations", FHWA-RD092-030 report, Washington, D.C., January 1992.

2. Brooks, R., Engineering Data Management, Inc., "Determining In-Situ Timber Pile Length Using Stress Wave", Timber Bridge Initiation Special Projects Program, USDA Forest Service, Morgantown, West Virginia, 1992.

3. Beattie, G. J. "Pile Length Determination - Induction Field Method," Technical Note 5-3, Works Consultancy Services, Central Laboratories, Gracefield, P.O. Box 30-845, Lower Hutt, New Zealand, (1982).

4. Wright P.D., "Rangitaiki River Bridge, Te Teko, Pile Length Investigations", Ministry of Works and Development, Central Laboratories Report 5-79/9, Lower Hutt, New Zealand, 1979.

5. Koten, H. van and Middendorp, P., "Testing of Foundation Piles", HERON, joint publication of the Department of Civil Engineering of Delft University of Technology, Delft, The Netherlands, and Institute TNO for Building Materials and Sciences, Rigswijk (ZH), The Netherlands, vol. 26, no. 4, 1981.

6. Davis, A.G. and Dunn, C.S., "From Theory to Field Experience with the Non-Destructive Vibration Testing of Piles," Proceedings, Institute of Civil Engineers, Part 2, (Dec 1975), pp. 571-593.

7. Sibbald, A., Armstrong, D.M., McAvitt, N., and Forde, M.C., "Use of Cepstrum Analysis and Liftered Spectrum to Detect Structural Changes in Masonry Ring Sewers," Civil NDT of Structures Conference Proceedings, University of Edinburgh, Scotland, June 1993.

8. Paquet, J., "Une Nouvelle Orientation Dams le Controle D'Integute des Pieux par Sollicitation Dynamique: Le Profil D'Inpedana", Frud Colloque International, Foundation Profondes, Paris, (1991), pp. 1-10 (French).

9. Federal Highway Administration, "Drilled Shafts for Bridge Foundation", Publication No. FHWA-RD-92-004, (August, 1993), 335 pp.

10. Douglas, R. A., and Holt J. D., "Determining Length of Installed Timber Pilings by Dispersive Wave Propagation Methods", Report: Center for Transportation Engineering Studies, North Carolina State University, June, 1993.

11. Holt, J.D. and Douglas, R.A., "A Field Test Procedure for Finding the Overall Lengths of Installed Timber Piles by Dispersive Wave Propagation Methods, Technical Report No. NC/R&D/94-001, ITRE, University of North Carolina, March, 1994.

12. Liao, S. T., "Nondestructive Testing of Piles", Dissertation Submitted in Partial Fulfillment of the Doctor of Philosophy Degree, The University of Texas at Austin, Austin, 1994.

13. Kolsky, H., Stress waves in solids: Dover Publ., Inc., New York, NY, 1963.

14. Heisey, J. S., Stokoe, K. H., Hudson, W. R., and Meyer A. H., "Determination of In Situ Shear Wave Velocity from Spectral Analysis of Surface Waves", Research Report 256-2, Center for Transportation Research, The University of Texas at Austin, Austin, 1982.

15. Nazarian, S., and Stokoe, K. H., "Nondestructive Testing of Pavements Using Surface Waves", Transportation Research Board, Record 993, Washington, D. C., 1984.

16. Nazarian, S., "In Situ Determination of Elastic Moduli of Soil Deposits and Pavement Systems by Spectral Analysis of Surface Waves Method", Dissertation Submitted in Partial Fulfillment of the Doctor of Philosophy Degree, The University of Texas at Austin, Austin, 1984.

17. Sheu, J. C., "Applications and Limitations of the Spectral Analysis of Surface Waves Method", Dissertation Submitted in Partial Fulfillment of the Doctor of Philosophy Degree, The University of Texas at Austin, Austin, 1987.

18. Rix, G. J., "Experimental Study of Factors Affecting the Spectral Analysis of Surface Waves Method", Dissertation Submitted in Partial Fulfillment of the Doctor of Philosophy Degree, The University of Texas at Austin, Austin, 1988.

19. Stokoe, K. H., II, Nazarian, S., Rix, G. J., Sanchez-Salinero, I., Sheu, J.C., and Mok, Y.J., "In Situ Seismic testing of Hard-to-Sample Soils by Surface Wave Method", Proceedings, Earthquake Engineering and Soil Dynamics II, ASCE Specialty Conference, Utah, (1988), pp. 264-278.

20. Aouad, M. F., "Evaluation of Flexible Pavements and Subgrades using the Spectral Analysis of Surface Waves Method", Dissertation Submitted in Partial Fulfillment of the Doctor of Philosophy Degree, The University of Texas at Austin, Austin, 1993.

21. Stokoe, K. H., II, Wright, S. G., Roesset, J. M., Gauer, R. C., and Sedighi-Manesh, M., "In-Situ Measurement of Stiffness Profiles in Ocean Bottom Materials Using the

SASW Method", 22nd Annual Offshore Technology Conference, Houston, Texas, (1990), pp. 299-305.

22. Chang, D. W., "Nonlinear Effects on Dynamic Response of Pavements Using the Nondestructive Testing Techniques", Dissertation Submitted in Partial Fulfillment of the Doctor of Philosophy Degree, The University of Texas at Austin, Austin, 1991.

23. Foinquinos, R. M., "Analytical Study and Inversion for the Spectral Analysis of Surface Waves Method", Thesis Submitted in Partial Fulfillment of the Master of Science Degree, The University of Texas at Austin, Austin, 1991.

24. Novak, M., "Dynamic Stiffness and Damping of Piles", Canadian Geotechnical Journal, Vol II, (1976), p. 574.

25. Novak, M. and Aboul-Ella, F., "Impedance Functions of Piles in Layered Media." Journal of Engineering Mechanics, ASCE, Vol. 104, No. 3, (1978), pp. 643-661.

26. Stain, R.T., "Integrity Testing", Civil Engineering, New York, NY, (April, 1982), pp. 53-73.

27. Olson, L.D., Wright, C.C., "Nondestructive Testing of Deep Foundations with Sonic Methods", Proceedings, ASCE Geotechnical and Construction Divisions Specialty Conference, Northwestern University, Evanston, Illinois, 1989.

28. Duke, S. K., "Calibration of Ground Penetrating Radar and Calculation of Attenuation and Dielectric Permittivity Versus Depth", Mater's Thesis# T-3920, Colorado School of Mines, Golden, Co, (1990), 236 pp.

29. Haeni, F.P., Placzek, G., Trent, R.E., "Use of Ground Penetrating Radar to Investigate Refilled Scour Holes at Bridge Foundations", Geophysical Survey of Finland, Special Paper 16, (1992), pp. 285-292.

30. Olsson, O., Falk, L., Forslund, O., Lundmark, L. and Sandberg, E. "Borehole Radar Applied to the Characterization of Hydraulically Conductive Fracture Zones in Crystalline Rock", Geophysical Prospecting, 40, (1992), pp. 109-142.

31. Pratt, D., and Sansalone, M., "Impact Echo Interpretation Using Artificial Intelligence," ACI Materials Journal, Vol. 89, No. 2, (1992), pp. 178-187.

32. Ghaboussi, J., "An Overview of the Potential Applications of Neural Networks in Civil Engineering," Proceedings, Structures Congress XI, ASCE, Irvine, California, April 1993.

33. Meier, R.W., “Backcalculation of Flexible Pavement Moduli from Falling Weight Deflectometer Data Using Artificial Neural Networks,” Ph.D. Dissertation, Georgia Institute of Technology, Atlanta, GA, 1995.

34. Hecht-Nielsen, R., Neurocomputing, Addison-Wesley, New York, 1990.

35. Rumelhart, D. E., Hinton, G. E., Williams, R. J., “Learning Internal Representations by Error Propagation,” Parallel Distributed Processing, Vol. 1, (D. E. Rumelhart and J. L. McClelland Eds.), MIT Press, Cambridge, pp. 318-362, 1986.

36. Werbos, P. J., “Beyond Regression: New Tools for Prediction and Analysis in the Behavioral Sciences,” Ph.D. Dissertation, Harvard University, Cambridge, 1974.