NCHRP 21-5 Research Results on Determination of Unknown Bridge Foundation Depths

Larry D. Olson, P.E.
Marwan F. Aouad, Ph.D., P.E.

Olson Engineering, Inc.
5191 Ward Road, Suite 1
Wheat Ridge, Colorado 80033
Tel: 303/423-1212
Fax: 303/423-6071
e-mail: ldolson@olsonengineering.com

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ABSTRACT

This paper contains a summary of the NDT results of the NCHRP project 21-5 "Determination of Unknown Subsurface Bridge foundations". The NDT methods evaluated were divided into two categories: 1) Surface methods including the Sonic Echo/Impulse Response, Bending Waves with Short Kernel Method analysis, Ultraseismic, Spectral Analysis of Surface Waves, Surface Radar and Dynamic Foundation Response methods and 2) Borehole methods including the Parallel Seismic, Borehole Radar, Borehole Sonic and Induction Field Methods. Out of all the NDT methods evaluated, the Parallel Seismic and Ultraseismic proved to be the most applicable for Unknown bridge foundation depth determination.

Along the summary of results for the NCHRP project 21-5, case studies are presented to illustrate the use of the Parallel Seismic method and the two potential methods of Spectral Analysis of Surface Waves and Borehole Sonic for special types of foundations.

INTRODUCTION

Of the approximately 580,000 highway bridges in the National Bridge Inventory, many of the older, non-federal-aid bridges have no design plans available. Therefore, no information is available regarding the type, depth, geometry or material of the foundations (Elias, 1992; Watson, 1990). These unknown bridge foundations pose a significant problem to the state DOTs because of safety concerns and consequently the Federal Highway Administration (FHWA) is requiring state DOTs to screen and evaluate all bridges to determine their susceptibility to scour. The National Cooperative Highway Research Program (NCHRP) 21-5 project "Determination of Unknown Subsurface Bridge Foundations" (Olson et al, 1995) was conceived to address these urgent concerns to find accurate, cost-effective nondestructive testing (NDT) methods to determine unknown foundation conditions. A comprehensive evaluation of potential NDT technologies was made in this project. The project was carried in two stages. The first stage consisted of the review and evaluation of existing and proposed technologies having promise for use in determining unknown subsurface bridge foundation characteristics such as depth, type, geometry and material. The second stage of the project consisted of evaluating and testing as many of the recommended concepts, methods and equipment as was feasible under the remaining project budget.

Nine technologies were selected for the second stage of research work. They included five surface techniques (Sonic Echo/Impulse Response (SE/IR), Bending Waves (BW) with Short Kernel Method analysis, Ultraseismic (US), Spectral Analysis of Surface Waves (SASW), Surface Radar (SR) and Dynamic Foundation Response (DFR) methods) and four borehole techniques (Parallel Seismic (PS), Borehole Radar (BHR), Borehole Sonic (BHS) and Induction Field (IF) methods). The surface techniques require access to the exposed parts of the bridge substructure elements. The borehole methods require access through a nearby boring. The major objective of the research was to evaluate the capabilities of the various NDT methods that indicate depth and other information on unknown bridge foundation characteristics for widely varying known bridge substructure conditions.

RESEARCH SUMMARY

The major objective of the research work was to provide a broad evaluation of the capabilities of the various nondestructive testing methods to indicate the depth and any other information on unknown bridge foundation characteristics for widely varying, <u>known</u> bridge substructure conditions. 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.

The research involved field nondestructive testing investigations of bridges with detailed foundation plans, and frequently, as-built foundation depth information. The work also involved theoretical modeling of selected bridge substructure responses for the Sonic Echo/Impulse Response, Dynamic Foundation Response, and Parallel Seismic tests for comparison with field data. Nondestructive testing was performed at seven bridge sites with four bridges located in Colorado, two in Texas, and one in Alabama under NCHRP 21-5. Also, two investigation case histories to determine <u>unknown</u> bridge foundation depths and conditions were performed. The field work included the performance of the NDT selected methods (where possible) from the research planning stage at each bridge site. The following bridge substructure types have been tested at the seven bridges: 1) concrete bridge pier with columns connected by a breast wall on spread footing (Golden Bridge), 2) one concrete bridge pier with concrete columns on shallow footings, and a second pier on a concrete pilecap on BP steel piles (Coors Bridge), 3) timber beams on timber piles for a pier and abutment wing wall (Franktown Bridge), 4) concrete stub abutment on HP steel piles and a concrete wall pier on a concrete pilecap supported by HP steel piles (Weld Bridge), 5) bent with steel piles extending to the bottom of the substructure with concrete protective cap at ground level (Alabama bridge), 6) pier with concrete columns on concrete pilecap on concrete piles, and a pier with concrete columns with a wall on a massive concrete caisson foundation (Old Bastrop Bridge) and 7) a concrete pier with columns on concrete drilled shaft foundations (New Bastrop Bridge).

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 will provide no information on piles below larger substructure (pilecaps). The Sonic Echo/Impulse Response, Bending Wave, Spectral Analysis of Surface Wave, and Borehole Radar methods all had more specific applications. A comparison is presented in Table I of the actual plan or as-built foundation element depths versus the NDT-based depth predictions. The results are arranged by NDT method for the seven study bridges. Summary evaluations of all tested NDT methods are presented in Tables II and III below for the surface and borehole tests, respectively.

Legend for Table I

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

Table I- Known Foundation Depths vs. 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

Table II- Summary Evaluation of the Applicable <u>Surface</u> NDT Methods.

Ability to Identify Foundation Parameters	Sonic Echo (SE)/Impulse Response (IR) Test (Compressional Echo)	Bending Wave (BW) Test (Flexural Echo)
Foundation Parameters:		
Depth of Exposed Piles	Fair-Excellent	Fair-Excellent
Depth of Footing/Cap	Poor-Good	Poor-Fair?
Piles Exist Under Cap?	N/A	N/A
Depth of Pile below Cap?	N/A	N/A
Geometry of Substructure	N/A	N/A
Material Identification	N/A	N/A
Access Requirements:		
Bridge Substructure	Yes	Yes
Borehole	No	No
Subsurface Complications:		
Effect of soils on response	Low-Medium	Medium-High
Relative Cost Range:		
Operational Cost/SSU*	\$1,000-\$1,500	\$1,000-\$1,500
Equipment Cost	\$15,000-\$20,000	\$15,000-\$20,000
Required expertise:		
Field Acquisition	Technician	Technician
Data Analysis	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.
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.

*SSU = Substructure Unit cost is for consultant cost only - DOT to supply 1-2 people. N/A=Not Applicable

Table II- Summary Evaluation of the Applicable Surface NDT Methods (cont).

Ultraseismic (US) Test (Compressional and Flexural Echo)	Spectral Analysis of Surface Wave (SASW) Test	Surface Ground Penetrating Radar (GPR) Test
Fair-Excellent Fair-Excellent N/A N/A Fair N/A	N/A Fair-Good N/A N/A Poor-Good Good	N/A Poor Fair-Poor Poor Poor-Good Poor-Fair
Yes No	Yes No	Yes No
Low-High	Low	High
\$1,000-\$1,500 \$20,000-\$25,000	\$1,000-\$1,500 \$15,000-\$20,000	\$1,000-\$1,500 \$30,000+
Technician Engineer	Technician-Engineer Engineer	Technician-Engineer Engineer
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.	Signal quality is highly controlled by environmental factors. Adjacent substructure reflections complicate data analysis. Higher cost equipment.
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) vs. depth and thicknesses of accessible elements.	Fast testing times. Can indicate geometry of accessible elements and bedrock depths. Lower testing costs.

Table III- Summary Evaluation of the Applicable <u>Borehole</u> NDT Methods.

Ability to Identify Foundation Parameters	Parallel Seismic (PS) Test	Borehole Radar (BHR) Test	Induction Field (IF) Test
Foundation Parameters:			
Depth of Exposed piles	Good-Excellent	Poor-Excellent	None-Excellent
Depth of Footing/Cap	Good	Poor-Good	N/A
Piles Exist Under Cap?	Good	Fair-Good	None-Excellent
Depth of Pile below cap	Good-Excellent	Fair-Good	None-Excellent
Geometry of Substructure	Fair	Fair-Excellent	N/A
Material Identification	Poor-Fair	Poor-Fair	Poor-Fair
Access Requirements:			
Bridge Substructure	Yes	No	Yes
Borehole	Yes	Yes	Yes
Subsurface Complications:			
Effect of soils on response	Medium	High	Medium-High
Relative Cost Range:			
Operational Cost/SSU*	$1,000-$1,500	$1,000-$1,500	$1,000-$1,500
Equipment Cost	$15,000-$25,000	$35,000+	$10,000
Required expertise:			
Field Acquisition/SSU*	Technician-Engineer	Engineer	Technician
Data Analysis	Engineer	Engineer	Engineer
Limitations:	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:	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.

CASE STUDIES AND EXAMPLE RESULTS

Case studies are presented in this paper to illustrate the use of the borehole Parallel Seismic and Borehole Sonic methods and the surface Spectral Analysis of Surface Waves methods.

PARALLEL SEISMIC METHOD AND TEST RESULTS

The Parallel Seismic (PS) test method was researched and developed specifically to determine the depths of unknown foundations by the CEBTP research organization headquartered in Paris, France (Stain, 1982). The PS test method is based on the principle that an impact to the exposed structure generates wave energy that travels down the foundation which can be tracked by depth with receivers in a nearby parallel boring to determine when the signal weakens and slows down. This indicates the receiver has gone beyond the bottom of the foundation, and the depth is therefore determined.

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

The PS test involves impacting the side or top of exposed bridge substructure with a 1.4 kg (3 lb) or 5.6 kg (12 lb) 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 or by a clamped, 3-component geophone receiver in a cased or uncased borehole. A hydrophone receiver is sensitive to pressure changes in the water-filled tube, but it is also subject to contaminating tube wave energy. A clamped 3-component geophone receiver in cement-bentonite, bentonite, and sand-backfield, 10 cm (4 in.) ID, PVC cased borings was also used to better examine the wave propagation behavior with reduced tube wave energy noise. The boring is drilled typically within 1 to 1.5 m (3 to 5 ft) of the foundation edge and should extend at least 3 m (10 ft) deeper than the anticipated and/or minimum required foundation depth for the depth to be determined. Example results from geophone use are presented below.

By using a 3-component geophone receiver in cased borings with good contact between the casing and soils, improved quality of PS results were obtained at a field site with variable soil velocity conditions. This is because hydrophones only work well as receivers for soils of constant velocity (or saturated soils) surrounding the foundation. For soils with varying velocities, a break cannot be identified from the erratic arrival times unless the recorded traces are time corrected for the variations in the soil velocities, or if the borehole is placed very close to the foundation in question. As a result, traditional Parallel Seismic analysis of the foundation data, by picking the first arrival travel times and plotting time vs. depth, did not provide the clearest data of the foundation characteristics. Moreover, the bridge foundation shapes were mostly nonuniform (in cross section), due to existence of a footing or pile caps and so forth, so that travel time plot vs. depth along the length of the foundation frequently deviated from a straight line.

However, it was observed that the bottom of the foundation can act as strong source of energy, especially in more massive foundations. The foundation tip acts as a point diffractor in emitting both upward and downward traveling waves into the borehole. This diffraction event is best seen by using 3-component geophone in a cased, grouted borehole. The diffraction results in a steep

V-shaped hyperbolic event in the recorded seismic section. The bottom of the foundation is then identified by noting the depth where the peak of the hyperbolic event occurs. Example results from geophone use are presented below.

The source/receiver layout for parallel Seismic tests performed on the west abutment of the Hamden bridge is shown in Fig. 1. The top of the abutment was hit horizontally and vertically and a 3-C geophone response was measured at 22 receiver locations in 0.3 m (1 ft) intervals. The Parallel Seismic data for the horizontal hammer hit and horizontal component recording is shown in Fig. 2. The shear wave velocity arrival suggests a bottom depth of 3.4 m (11 ft) below the top of the pavement based on the indicated time shift of the shear wave arrivals. This corresponds to a bottom depth of 2.6 m (8.5 ft) calculated below the top of the abutment which is in good agreement with the 2.7 m (9 ft) depth determined from by the SASW tests discussed later.

BOREHOLE SONIC METHOD AND TEST RESULTS

Like Sonar, the Borehole Sonic (BHS) test is based on the principle of generating sufficient compression wave 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. This method involves lowering a source and a receiver unit in the two separated boreholes and measuring the reflection echoes from the side of the bridge foundation substructure.

The BHS test system evaluated in this paper was a mocked-up prototype of Dr. Stokoe's at the University of Texas at Austin Geotechnical Engineering Center (so-called UT system). 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. Figure 3 shows a schematic of the BHS test performed at the Old Bastrop Bridge in Texas.

Figure 4 shows the BHS records at the caisson of the Old Bastrop Bridge, Texas. The source and the receiver were oriented in a direction orthogonal to the line separating the two boreholes so that horizontally polarized (SH) waves were recorded. The SP mark in Fig. 4 denotes depths in feet from the top of the borehole; Therefore, SP 14 indicates the seismic trace recorded at 14 ft from the top of the borehole. A clear indication of direct source to receiver shear energy arrivals is shown. The first arrival travel times and amplitudes of the shear wave energy are indicated to be fairly constant, about 8,000 µsec to a depth of 8.3 m (27 ft) and gradually decrease up to a depth of 11 m (36 ft), which is the depth of the shale bedrock, and remain constant therefore. A strong second event starting at about 27,000 µsec indicated the correct travel times corresponding to a possible reflected event from the 3 m (10 ft) wide foundation wall. This event is indicated to end at about 10.7 m (35 ft) from the top of the borehole. This result agrees with the actual as-built depth of the foundation, which is 10.9 m (35.6 ft) from the top of the boreholes. It should be noted that the BHS is applicable to wall-shaped foundations (large lateral extent) so that body waves can reflect from this boundary and can be identified in the time records. For smaller foundations such as concrete piles, the waves can go around the piles (depending on the wavelength of the generated waves) and thus go unidentified as reflections.

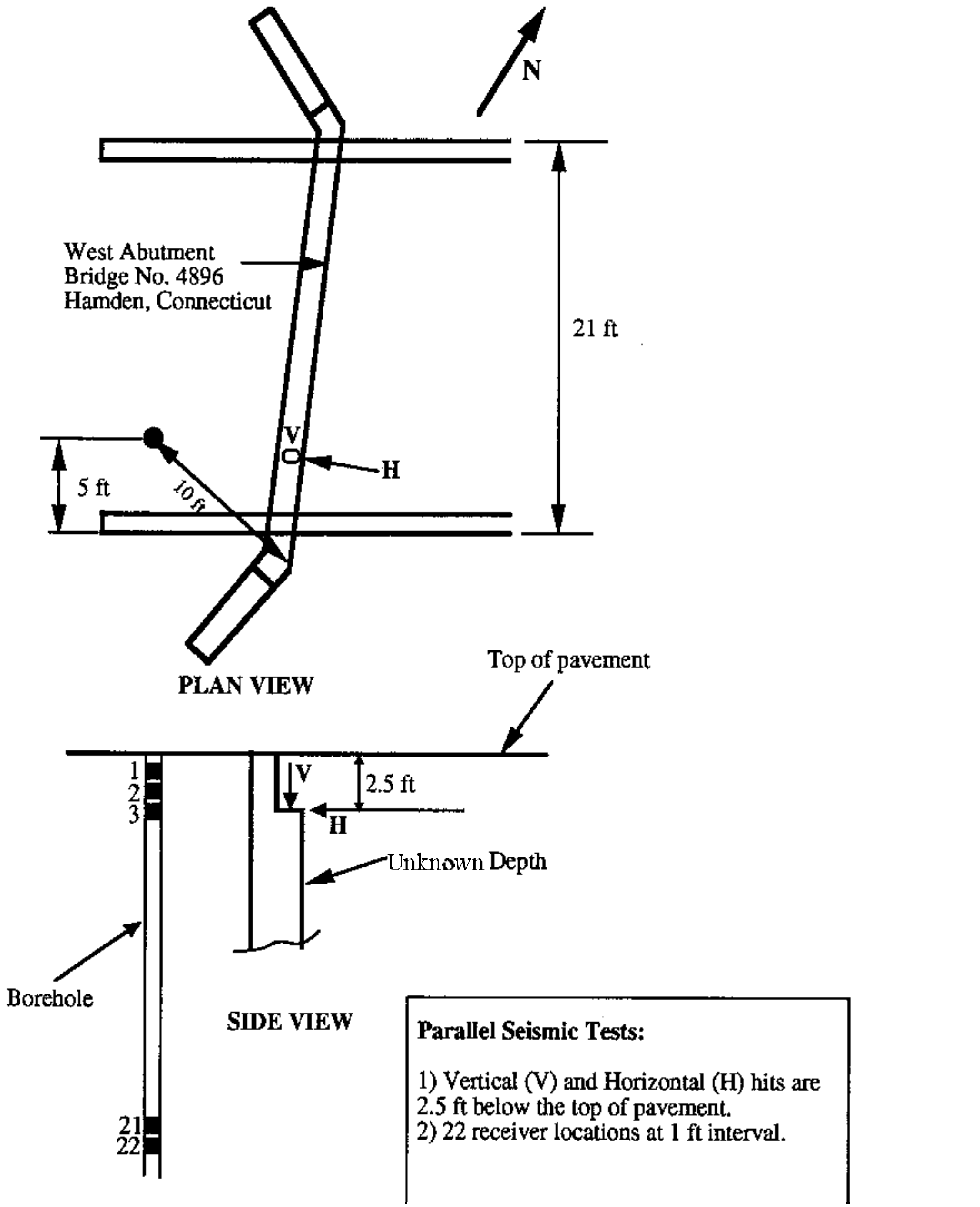

Figure 1- Source/Receiver Layout for Parallel Seismic (PS) Tests for Bridge No. 4896, West Abutment, Hamden, Connecticut

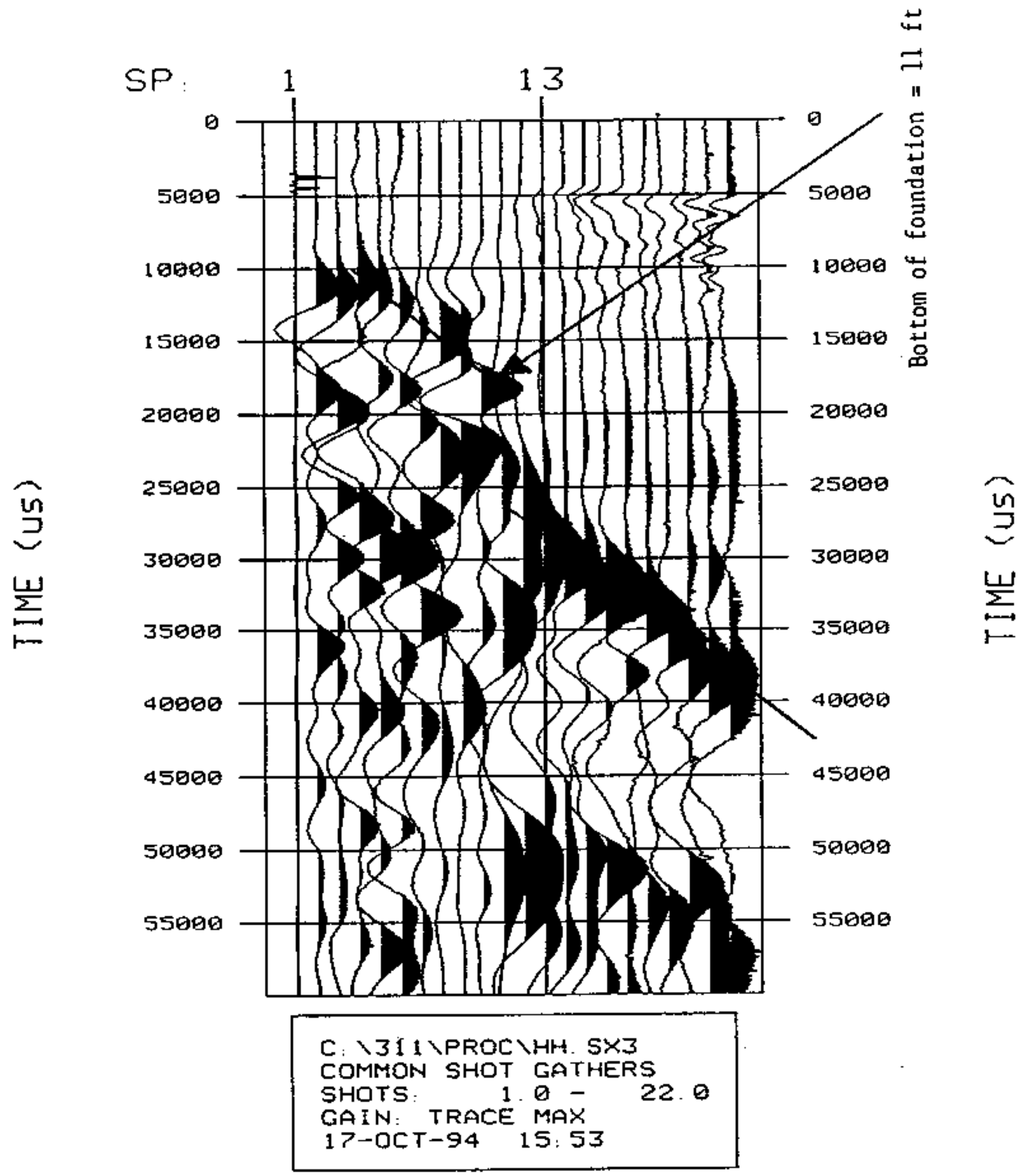

Figure 2- Parallel Seismic Field Records from Bridge No. 4896, West Abutment, Hamden, Connecticut

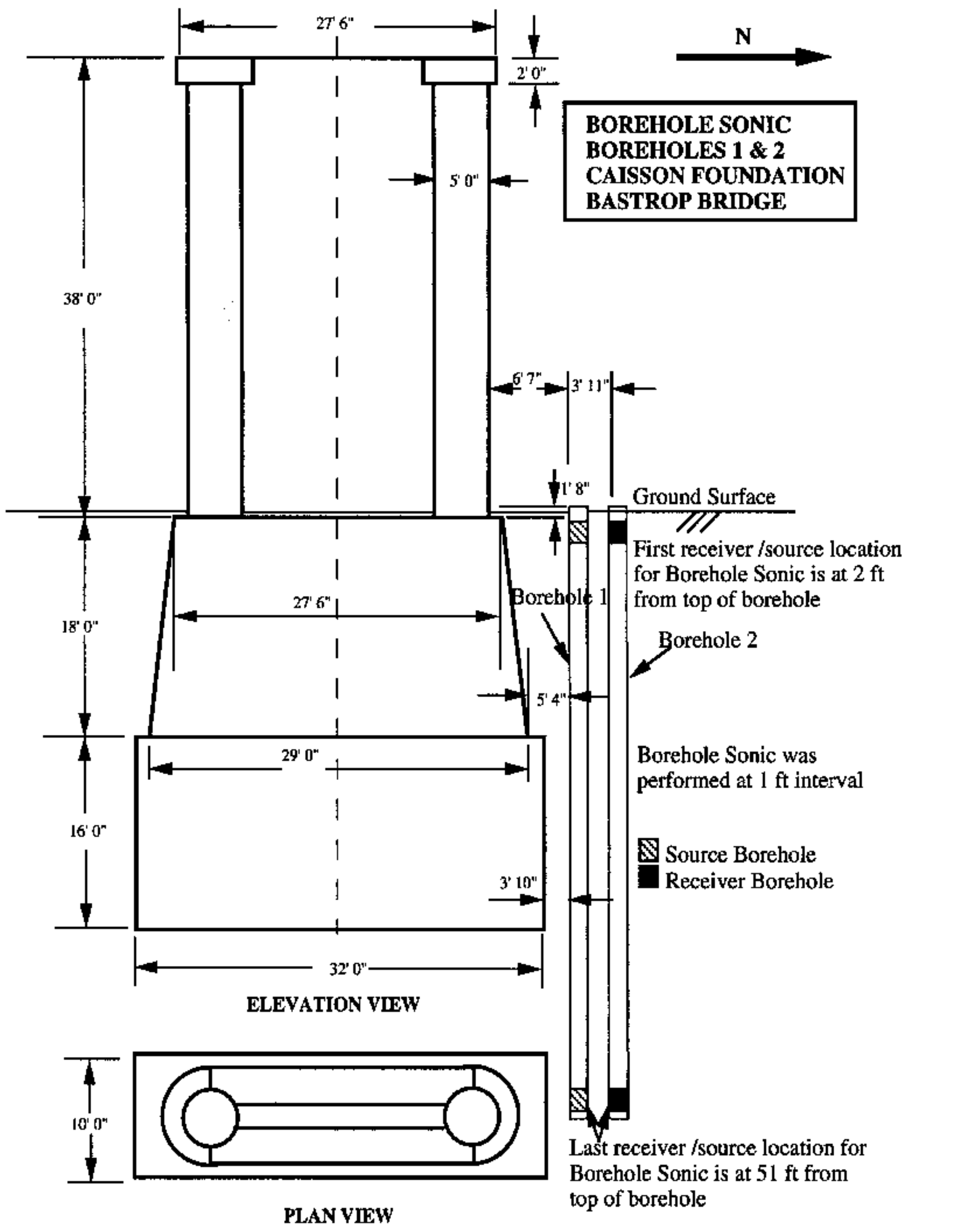

Figure 3- Field Layout of Borehole Sonic (BHS) Tests with the UT Austin System from the North Side of the Caisson Foundation at the Old Bastrop Bridge

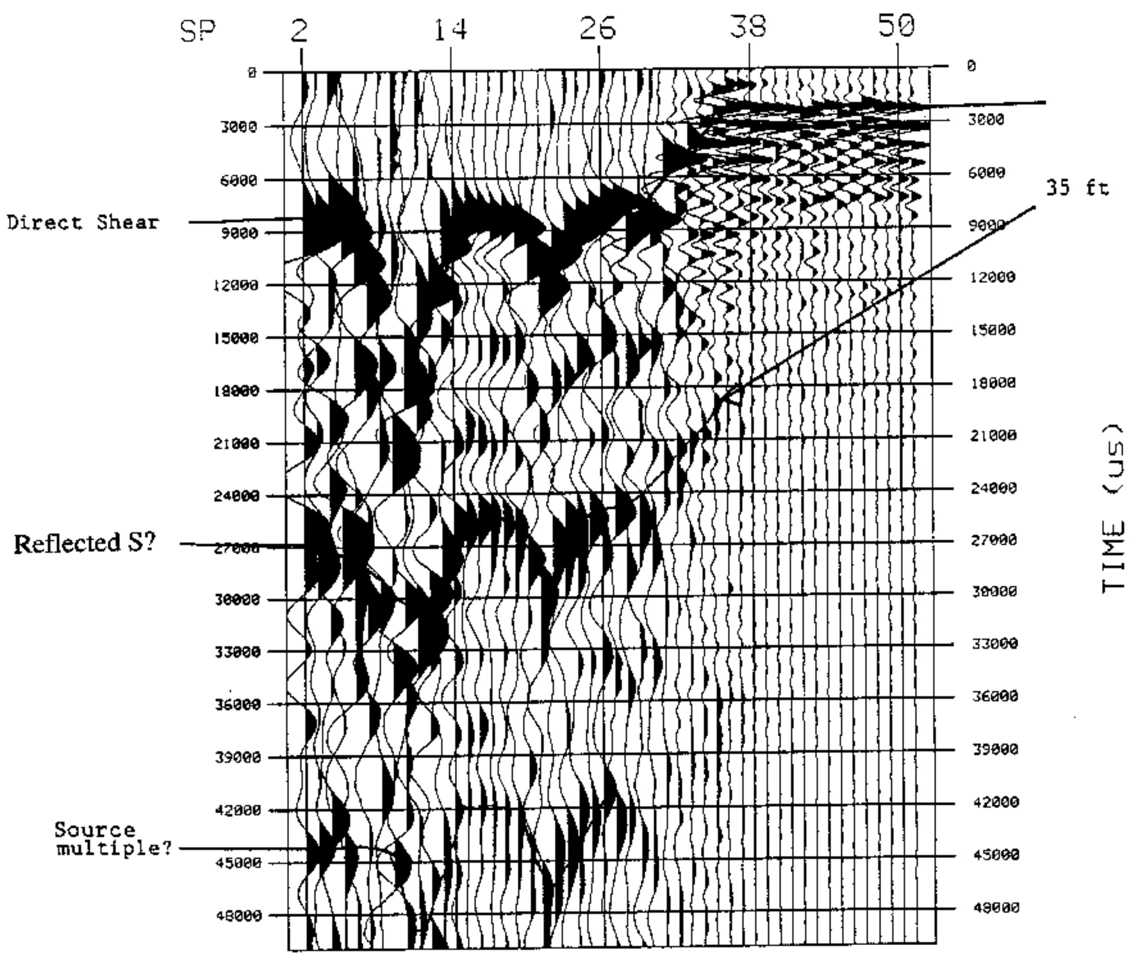

Figure 4- Borehole Sonic (BHS) Field Records from the Caisson Foundation with the UT Austin System at the Old Bastrop Bridge

SPECTRAL ANALYSIS OF SURFACE WAVES (SASW) METHOD AND TEST RESULTS

The SASW method was initiated at the University of Texas at Austin in the early 1980's with funding from the Texas Department of Transportation (Heisey at al, 1982; Nazarian, 1984). Active research has been performed in the past 15 years to improve the theoretical and practical aspects of the method (Aouad, 1993). One advantage of the SASW method is that measurements are performed using a source and two receivers placed on the exposed portion of a bridge abutment. In case of bridge abutments, the SASW method can determine the thickness or depth of abutments provided certain physical conditions are met.

In SASW tests, two receivers are placed on the ground/structural member surface to monitor the passage of surface waves due to an impact from a source placed at distance from Receiver 1 equal to the distance between the two receivers. A digital analyzer is used to record the receiver outputs for spectral (frequency) analyses. The result of the analysis is a plot of the phase difference between the two receivers versus frequency. A dispersion curve (surface wave velocity versus wavelength) is calculated from the phase plot using the following equations:

$$t = N/360 \qquad (1)$$

$$V_R = X/t \qquad (2)$$

$$8_R = V_R/f \qquad (3)$$

where t = Time, V_R = Surface Wave Velocity, X = distance between receivers, 8_R = Wavelength, f = Frequency. The final process in SASW testing is the Forward Modeling process to determine the shear wave velocity profile. The forward modeling process is an iterative process, and involves comparing the actual dispersion curve with a theoretical dispersion curve calculated from an assumed shear wave velocity profile.

The SASW test array for the west abutment of the Hamden Bridge is shown in Fig. 5. Three receiver spacings of 1, 2 and 4 m (3, 6 and 12 ft) were used. The composite dispersion curve from the three receiver spacings is shown in Fig. 6. The dispersion curve shows a two layer system with two different velocities. The first part, up to a wavelength of 3 m (9 ft), shows a surface wave velocity of 2,350 m/sec (7,700 ft/sec) which is indicative of concrete velocities. The second part shows velocities of approximately 1,200 m/sec (4,000 ft/sec) for wavelengths greater than 3 m (9 ft) which are indicative of velocities of medium-hard rock. Therefore, it is inferred from the SASW measurements that the depth of the abutment is approximately equal to 3 m (9 ft).

CONCLUSIONS

The results of this research indicate that the Parallel Seismic method has the broadest application for determining the depth of the unknown foundation. When piles are encountered below massive pilecaps, none of the surface methods can predict the existence or the depth of the piles. For determining the depth of the unknown foundation down to the pilecap, the Ultraseismic method proved to be the best surface method. The Sonic Echo/Impulse Response (SE/IR) and Bending Waves (BW) methods proved to be applicable for columnar types of foundations. Reflections from the foundation/soil boundary and boundaries of the structural elements of the superstructure and the substructure complicate the interpretation of the SE/IR and BW data. Limited research with the

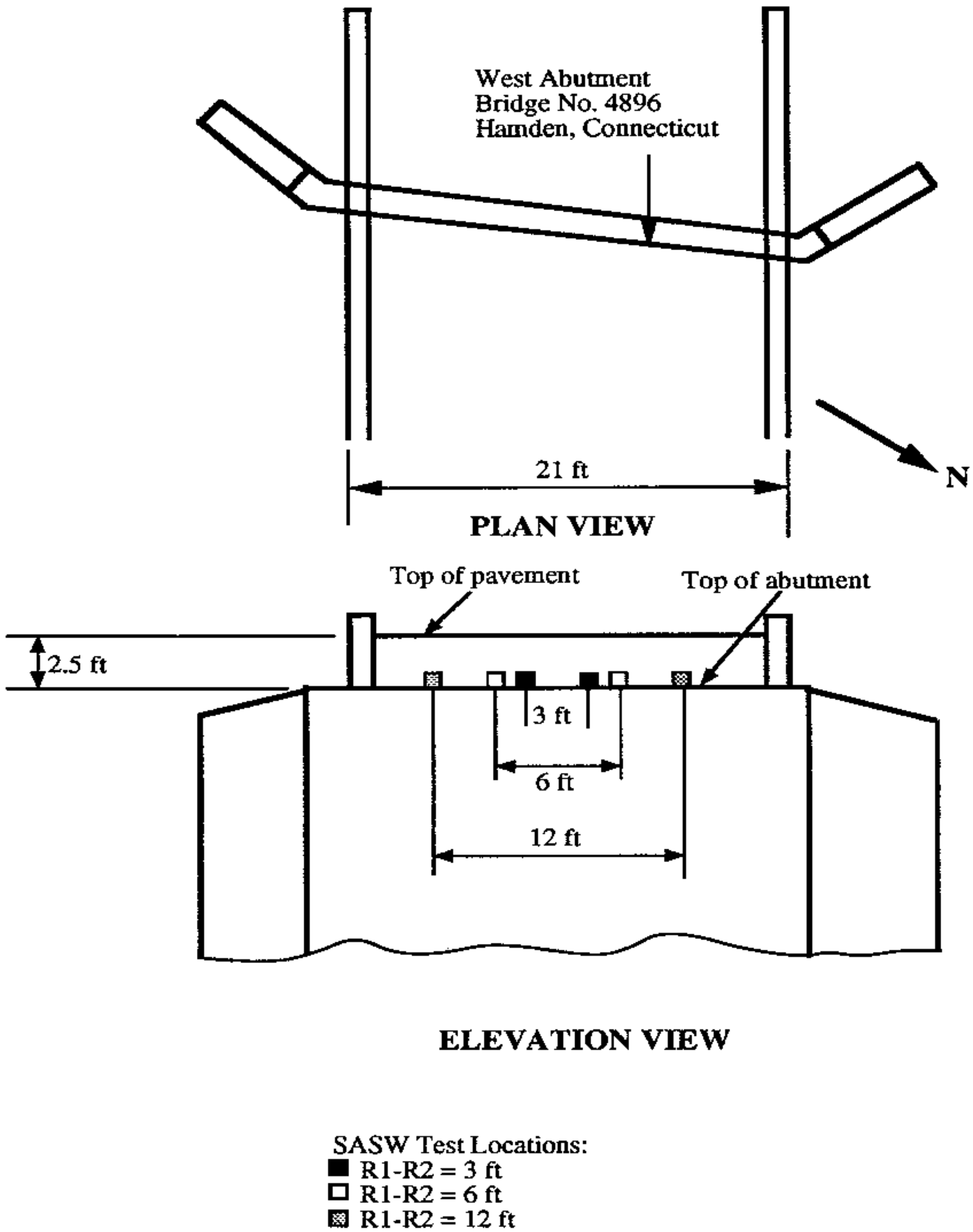

Figure 5- Spectral Analysis of Surface Waves (SASW) Test Array, Bridge No. 4896 West Abutment, Hamden, Connecticut

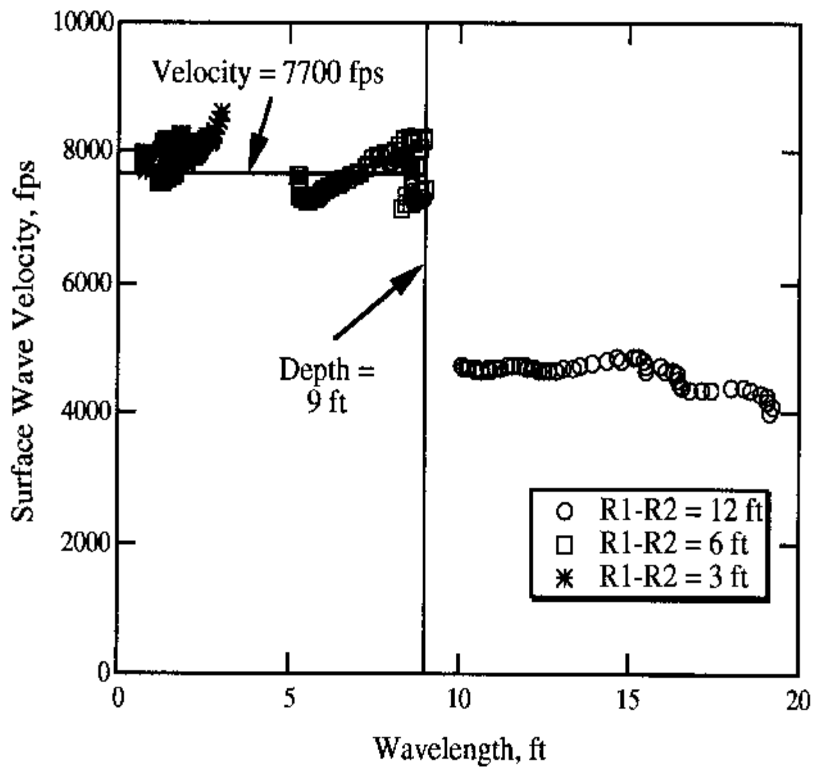

Figure 6- Experimental Dispersion Curve Determined from SASW Measurements West Abutment, Hamden, Connecticut

induction field method showed promise of the method. However, the method is only applicable to foundations with continuous steel reinforcement (par of the rebar should be exposed) and exposed steel piles.

Two potential methods for determining the depth of wall shaped foundations are the SASW and BHS methods. Case studies were presented herein to show the use of each of these methods. The applicability of the SASW method is limited by the lateral extent of the foundation. Therefore, for deep wall shaped foundations, the SASW method is capable of predicting that the foundation is deeper than a certain depth but cannot determine the actual depth. The BHS method requires large extent to be able to identify reflections from that boundary.

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