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SASW Testing in the Salt Lake Valley, UT Determine V_s Profiles

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Abstract

The purpose of this study is to determine intermediate (250 ft (75 m) to 750 ft (230 m)) to deep (≥ 750 ft (230 m)) shear-wave velocity (Vs) profiles in the Salt Lake Valley. The Spectral-Analysis-of-Surface-Waves (SASW) method was used in the field to profile 11 locations. Vs profiles from this work have been provided to the Utah Ground Shaking Working Group and added to the community velocity model (CVM). The CVM is the first research goal of a plan developed in 2004 by the Utah Ground Shaking Working Group to develop a ground-shaking map for the Salt Lake region. For the 11 locations tested, six deep and five intermediate-depth Vs profiles were evaluated. An unsuccessful attempt was made to profile "hard" rock (rock below the R2 boundary with Vs>4900 ft/s (1500 m/s)) at two sites. However, Vs profiling at the two rock sites was successful and found Vs values in the range of 260 ft/s (75 m/s) to 4000 ft/s (1200 m/s). All testing was performed using a low-frequency vibroseis called "Liquidator". Liquidator is specially designed to excite energy in the low-frequency range of 0.5 to 4

Hz. SASW testing at low frequencies allows Vs profiling to greater depths than any other active source. The Vs profiles at the sites were correlated with previous studies performed in the Salt Lake Valley. Most previous work involved Vs profiling at depths less than 150 ft (50 m). The primary focus of this study was to evaluate Vs profiles of the valley sediments at depths below 150 ft (50 m) and to determine the depth to the unconsolidated/semi-consolidated boundary (called the R1 boundary) in the Salt Lake Valley. Smoothed, Vs models are presented for the four types of unconsolidated sediments (called Q01, Q02, Q03, and Q05) in the Salt Lake Valley. Also, a smoothed Vs model for the semi-consolidated material below the R1 boundary is presented. These models are based on previous studies and the individual Vs profiles determined in this study.

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CHAPTER 1

INTRODUCTION

1.1. Overview

The Salt Lake Valley is a highly populated region in Northern Utah which is situated along the seismically active Wasatch Fault. This fault is an extremely important geologic feature and numerous studies have been completed and/or are underway to understand the consequences of a major earthquake along the Wasatch Fault. The Utah Ground Shaking Working Group (called Working Group (WG) hereafter) was formed in 2003 to develop a comprehensive earthquake preparedness program. One of the goals of this committee is to develop a ground-shaking map for the Salt Lake Valley region. To characterize the ground motions that would accompany a major earthquake, shear-wave velocity (Vs) profiles of the subsurface must be known. Therefore, one of the tasks of the WG is to develop a comprehensive set of Vs profiles for the Salt Lake Valley. This set of Vs profiles is referred to as the community velocity model (CVM).

The development of a CVM was the first research goal of a plan developed by the WG in 2004. Past studies have shown the effect of near-surface site amplification on ground motions due to soft near-surface sediments (Wong and Silva, 1993; Wong et al, 2002). Site-response mapping has been conducted using regional geology and available Vs profiles (Ashland and Rollins, 1999; Ashland and McDonald, 2003). Finite difference studies have demonstrated the potential for basin-effect amplification of ground motion in the Salt Lake Valley (Hill et al, 1990). Recent investigations have been performed to determine the shear wave velocities for shallow materials at depths less than 150 ft (50 m) (Bay, 2005). Very little information is known about shear wave velocities for depths greater than 150 ft (50

m). Vs profiles with depths greater than 150 ft (50 m) would add to the CVM and help in prediction of ground motions.

1.2 Purpose of This Study

The purpose of this study was to determine intermediate to deep shear wave velocities in the Salt Lake Valley region as well as attempting to obtain the Vs profiles at two hard rock sites by utilizing the Spectral-Analysis-of-Surface-Waves method (SASW). Profile depths in the range of 250 ft (75 m) to 750 ft (230 m) are defined as intermediate while depths equal to or greater than 750 ft (230 m) are defined as deep. A total of 11 sites was tested. Profiling depths ranged from 200 ft (60 m) to 350 ft (105 m) at the attempted hard rock sites and from 600 ft (180 m) to 1200 ft (365 m) at the soil sites. All 11 sites were tested using a low-frequency vibroseis called "Liquidator". The Vs profiles at the sites were correlated where possible with previous studies performed in the Salt Lake region. The primary focus of this study was to evaluate shear-wave velocities of the valley sediments at depths below 150 ft (50 m) and to determine the depth to the unconsolidated/semi-consolidated boundary (R1 boundary; Hill et al, 1990). A smoothed Vs model was determined for the four Quaternary Units and the semi-consolidated material beneath the R1 boundary. The smoothed models were based on the previous Vs profiles and the Vs profiles determined in this study.

1.3. Organization of Thesis

Chapter 2 presents a brief description of the geology in Salt Lake Valley as well as a brief discussion of the Wasatch Fault. Chapter 3 presents previous research work done in the Salt Lake Valley. Previous research work includes seismic reflection data, classification and site mapping based on grain size and surficial geology, geologic log reviews, and shear wave velocity analysis. Chapter 4 is a discussion of the SASW testing method and the procedures used in this study.

Chapter 5 presents the surficial geology of each site as well as the shear wave velocity profiles for all 11 sites. Chapter 6 combines the results of the field studies and compares the results with previous studies. Chapter 7 presents the smoothed Vs models for four Quaternary Units and the semi-consolidated material beneath the R1 boundary. Chapter 8 presents a summary, conclusions, and recommendations. The Appendix includes the "raw" data (wrapped phase plots versus frequency) for Sites 1 through 11.

CHAPTER 2

GEOLOGY OF THE SALT LAKE VALLEY

2.1. Overview

The Salt Lake Valley is a young Quaternary basin bounded by the Wasatch Mountains on the east, the Oquirrh Mountains on the west, and the Traverse Mountains on the south. Figure 2.1 shows the Salt Lake Valley area covered by this study.

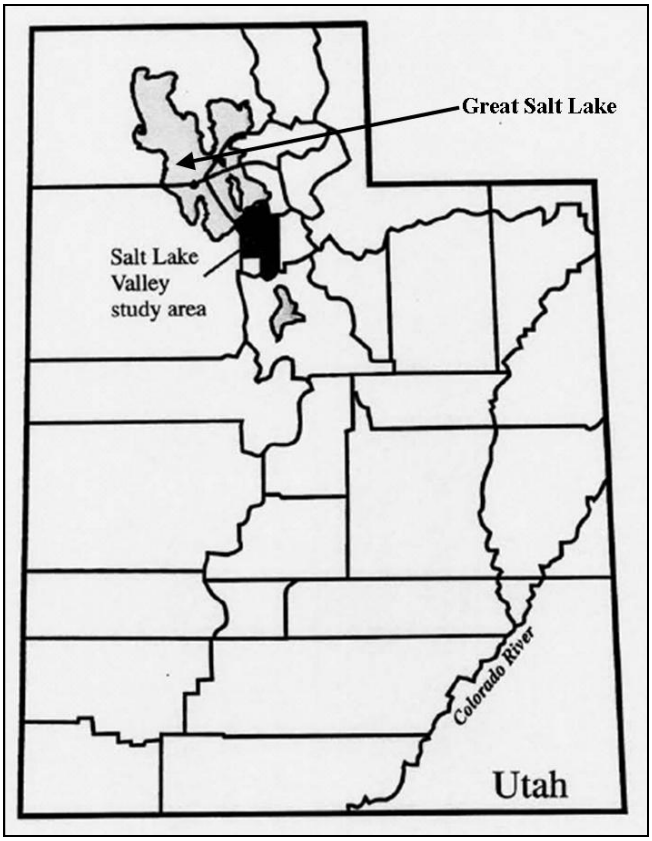

Figure 2.1 Salt Lake Valley Study Area (from Ashland and Rollins, 1999)

The near-surface geology of the study area consists of soft to stiff unconsolidated Quaternary sediments in Salt Lake Valley. The sediments have variable thicknesses ranging from shallow (less than 100 ft (30 m)) at locations along

the valley margins to more than 3300 ft (1000 m) in the central portion of the valley (Arnow and Mattick, 1968).

2.2. Mountains

The mountains surrounding the Salt Lake Valley are composed of a variety of rock types. Rock types in the Wasatch Range include Precambrian metamorphic rocks, Paleozoic and Mesozoic sedimentary rock, and Tertiary intrusive igneous rocks. Rock types in the Oquirrh Mountains include Paleozoic and Tertiary sedimentary rocks, and Tertiary intrusive and volcanic igneous rocks. The Traverse Mountains are composed of Paleozoic sedimentary rocks and Tertiary sedimentary and volcanic rocks. Figure 2.2 shows the mountains ranges in the Salt Lake Valley. Relatively thin Quaternary surficial deposits locally overlie rock units on mountain slopes and in canyons. These deposits consist of glacial soils, colluvium, and alluvium. The thicknesses of these surficial deposits in the mountain slopes and canyons locally exceed 10 feet (3 m) (Ashland and McDonald, 2003). In the eastern part of the Salt Lake Valley, Pleistocene glacial deposits exist locally in the Wasatch Range and along the valley margin at the mouths of glaciated canyons.

2.3. Salt Lake Valley Deposits

There are 3 main sedimentary deposits in the valley: (1) unconsolidated Quaternary sediments, (2) semi-consolidated Tertiary deposits, and (3) underlying consolidated rocks of several ages. The Salt Lake Valley has a combined thickness of unconsolidated Quaternary and semi-consolidated Tertiary basin-fill deposits that locally exceeds 3,300 feet (1000 m) Arnow and Mattick, 1968). Arnow and Mattick used water-well logs and geological and geophysical data to determine that the thickness of unconsolidated Quaternary basin-fill deposits exceeds 2,200 ft (670 m) in the northern part of the valley. Figure 2.3 is a reflection profile in the northern portion of Salt Lake Valley that shows the thicknesses of the unconsolidated

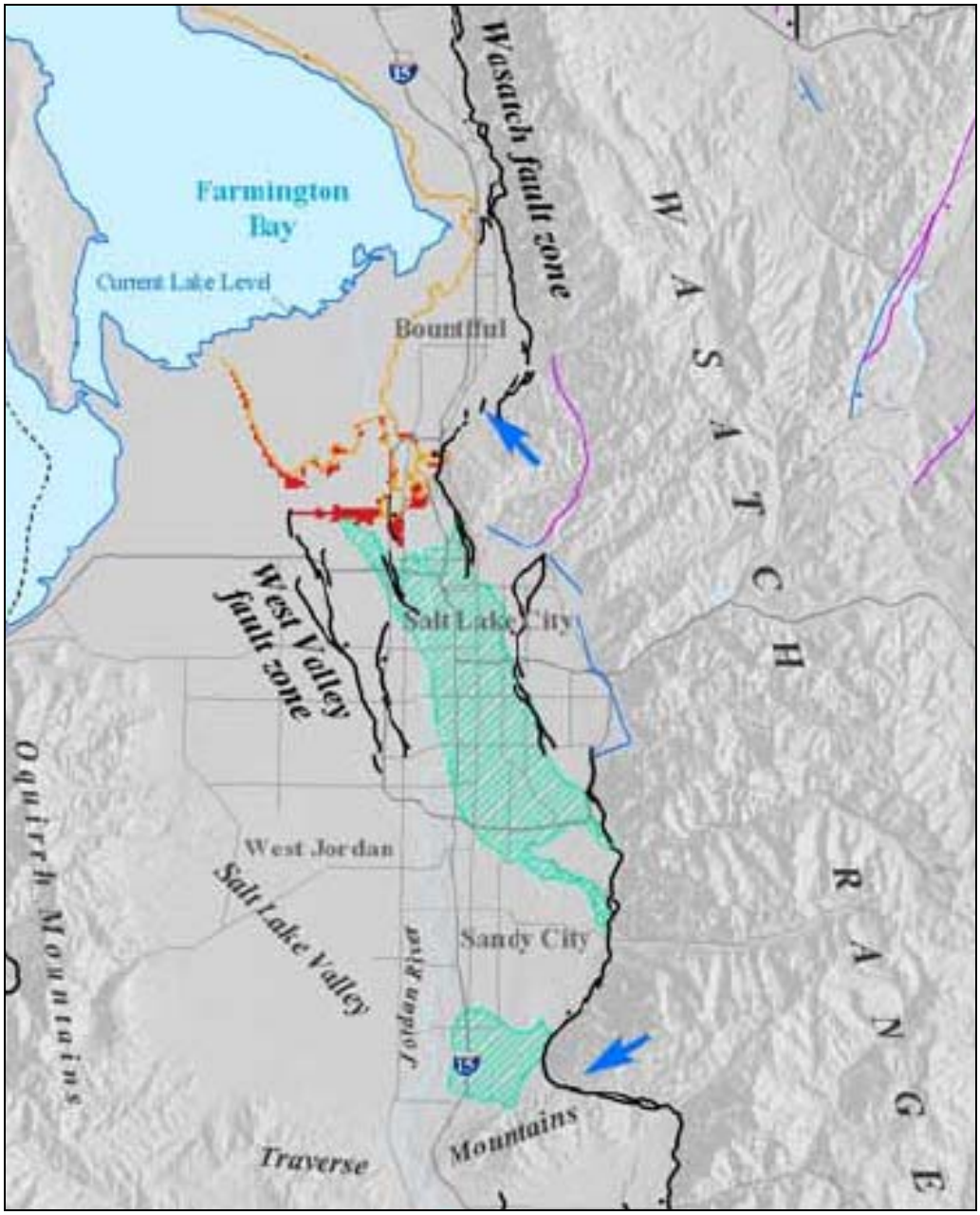

Figure 2.2 Mountain ranges and the Wasatch fault in the Salt Lake Valley (from Solomon et al, 2004)

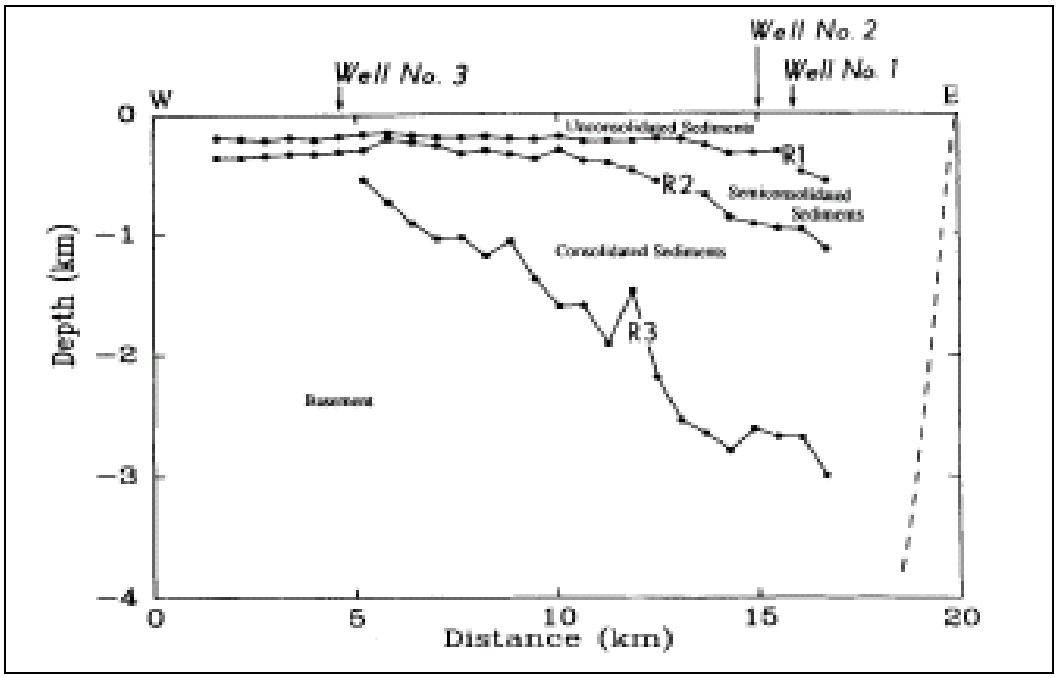

Figure 2.3 Interpreted reflection profile in the northern portion of the Salt Lake Valley (from Hill, et. al. 1990)

sediments, semi-consolidated sediments, consolidated sediments, and depth to basement rock. Unconsolidated Quaternary basin-fill deposits are less than 820 ft (250 m) thick in most of the valley (Wong et al, 2002). Figure 2.4 shows the depth of the unconsolidated sediments in the Salt Lake Valley. Lacustrian, fluvial, and deltaic deposits associated with Lake Bonneville comprise the predominate facies of the unconsolidated Quaternary sediments with lacustrian facies being the most prevalent (Miller, 1980; Davis, 1983). Coarse-grained Lake Bonneville shore facies which consist primarily of sand and gravel are present along the margins of the valley, whereas deep-water facies consisting of clay, silt, and fine sand dominate toward the center of the valley. Post-Bonneville sediments consist mostly of marsh, alluvial, and deltaic deposits associated with the Jordan River (seen in Figure 2.2) and its tributaries. These deposits are relatively thin, generally less than 16 ft (5 m) thick. The Salt Lake Formation which consists of Lacustrian calcareous silts and clays interspersed with volcanic ash and tuff composes the majority of the semi-

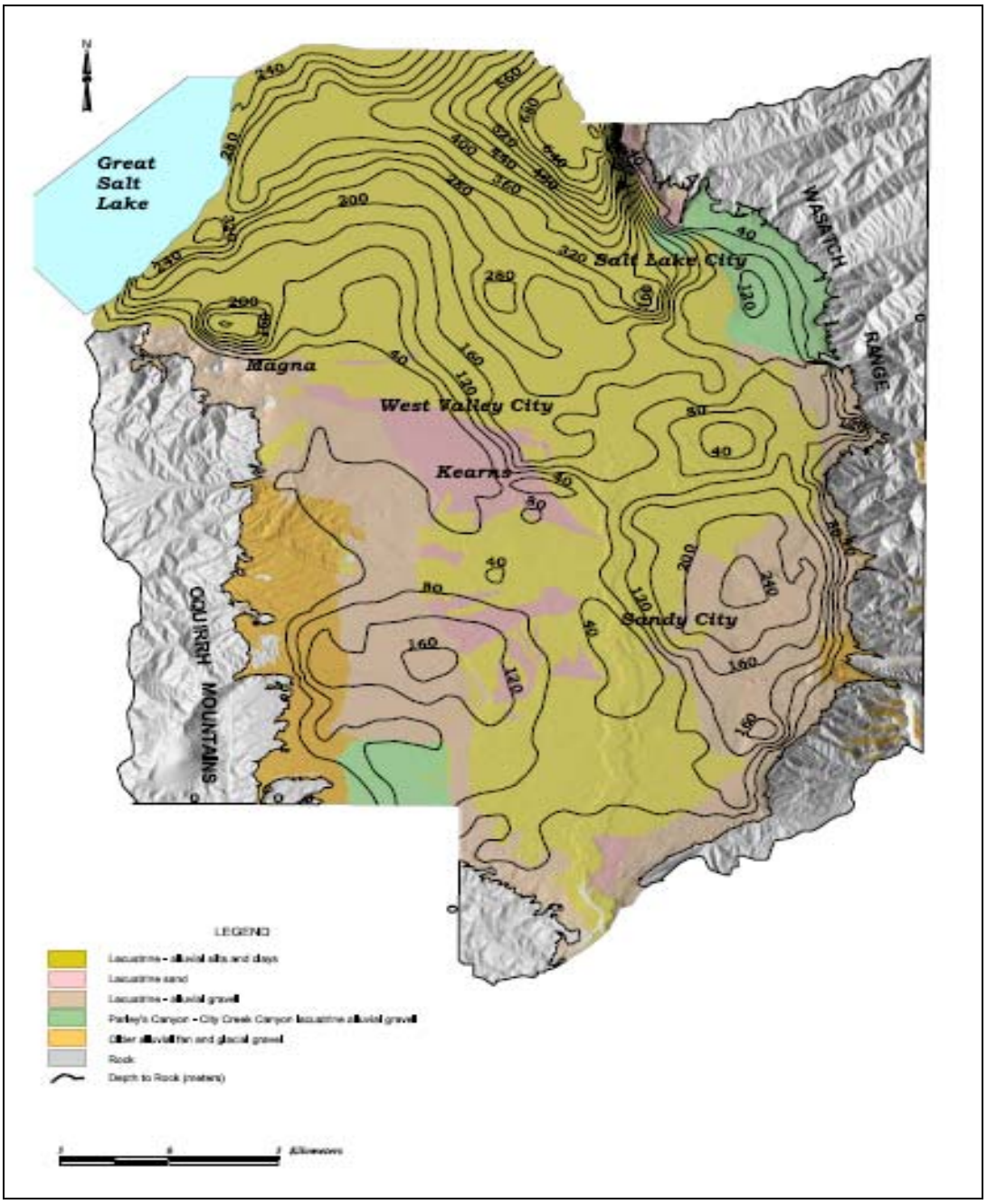

Figure 2.4 Estimated depth of unconsolidated sediments (from Wong et al., 2002)

consolidated sediments that are immediately beneath the unconsolidated sediments. Well data indicate that rock types in the consolidated layer include limestone, shale, andesite, quartzite, and conglomerate (Arnow and Mattick, 1968).

2.4. Wasatch Fault

The Wasatch Fault is a normal fault located primarily on the western edge of the Wasatch Mountains. Figure 2.2 shows the Salt Lake City segment of the Wasatch Fault. The Wasatch Fault is considered a major active zone and dozens of small earthquakes occur along it each year. The fault line is 240 miles long and is made up of several segments, each of which can independently produce earthquakes as powerful as magnitude 7.5. Paleoseismic trenches have indicated that the Salt Lake City segment of the Wasatch Fault, which extends along the eastern portion of the Salt Lake Valley, generated four surface-faulting earthquakes in the past 6000 years. These earthquakes recur on average about every 1350 $\pm$ 200 years, with the most recent surface-faulting earthquake occurring about 1300 years ago. Maximum expected earthquake magnitudes along the major segments range from **M** 7 to 7¼ (Wong et al, 2002).

CHAPTER 3

PREVIOUS STUDIES

3.1. Introduction

The response of the Salt Lake Valley sediments to an earthquake will be strongly influenced by the shear stiffness of the valley sediments as well as by basin effects resulting from the three-dimensional geometry of the Salt Lake Valley. The low-frequency (0.2 to 2 Hz) amplification of basin motions is primarily controlled by the unconsolidated and semi-consolidated lithographic units. The stiffness characteristics of the unconsolidated sediment/semi-consolidated sediment interface (termed R1 interface), the semi-consolidated/consolidated interface (termed R2 interface) and the consolidated/hard rock interface (termed R3 interface) will strongly influence the low-frequency amplifications (Hill et al, 1990). Figure 3.1 shows that the depth to the R1 boundary (away from the valley edges) varies from 120 to 2100 ft (35 to 640 m). Near the edge of the valley R1 and R2 appear closer to the surface. Previous studies have focused on the shear stiffness of valley sediments and the geometry of the valley. The Salt Lake Valley has been studied using geological information, seismic reflection and downhole testing, grain size, and shear-wave velocity measurements to categorize the valley. These previous studies are discussed below.

3.2. Reflection Data

Hill et al (1990) interpreted seismic reflection data as well as sonic and density logs to map an initial cross-section for the R1/R2/R3 boundaries. Figure 3.2 shows the location of the reflection profile and the three wells. As seen in Figure 3.2, these studies were performed in the northern portion of the valley. Figure 3.3 shows the well data for two of the three wells. As seen in Figure 3.3, the R1 boundary is readily seen in Well #2 and the R1 and R2 boundaries are very distinct in both wells.

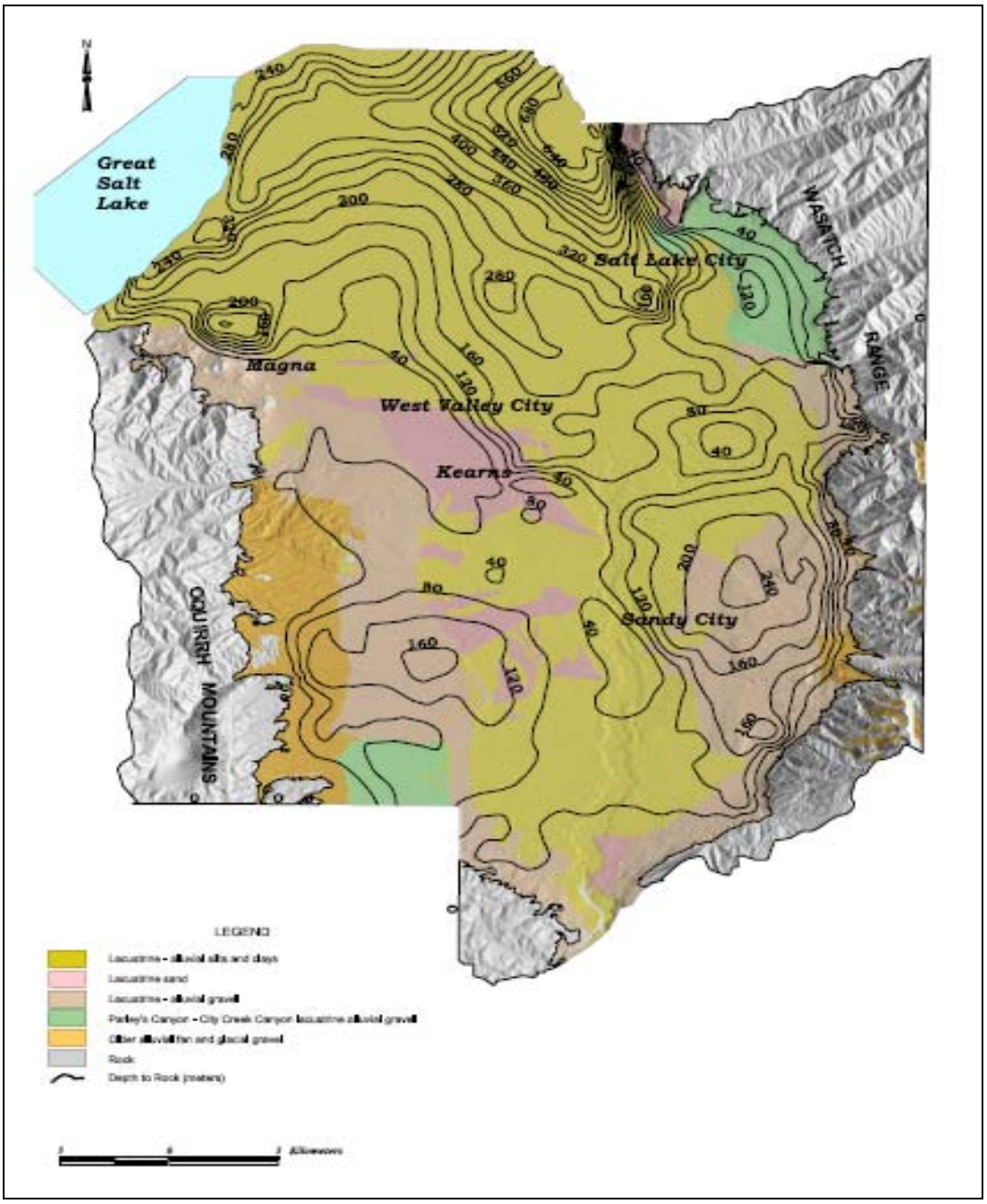

Figure 3.1 Estimated depth to the R1 Boundary (from Wong et al., 2002)

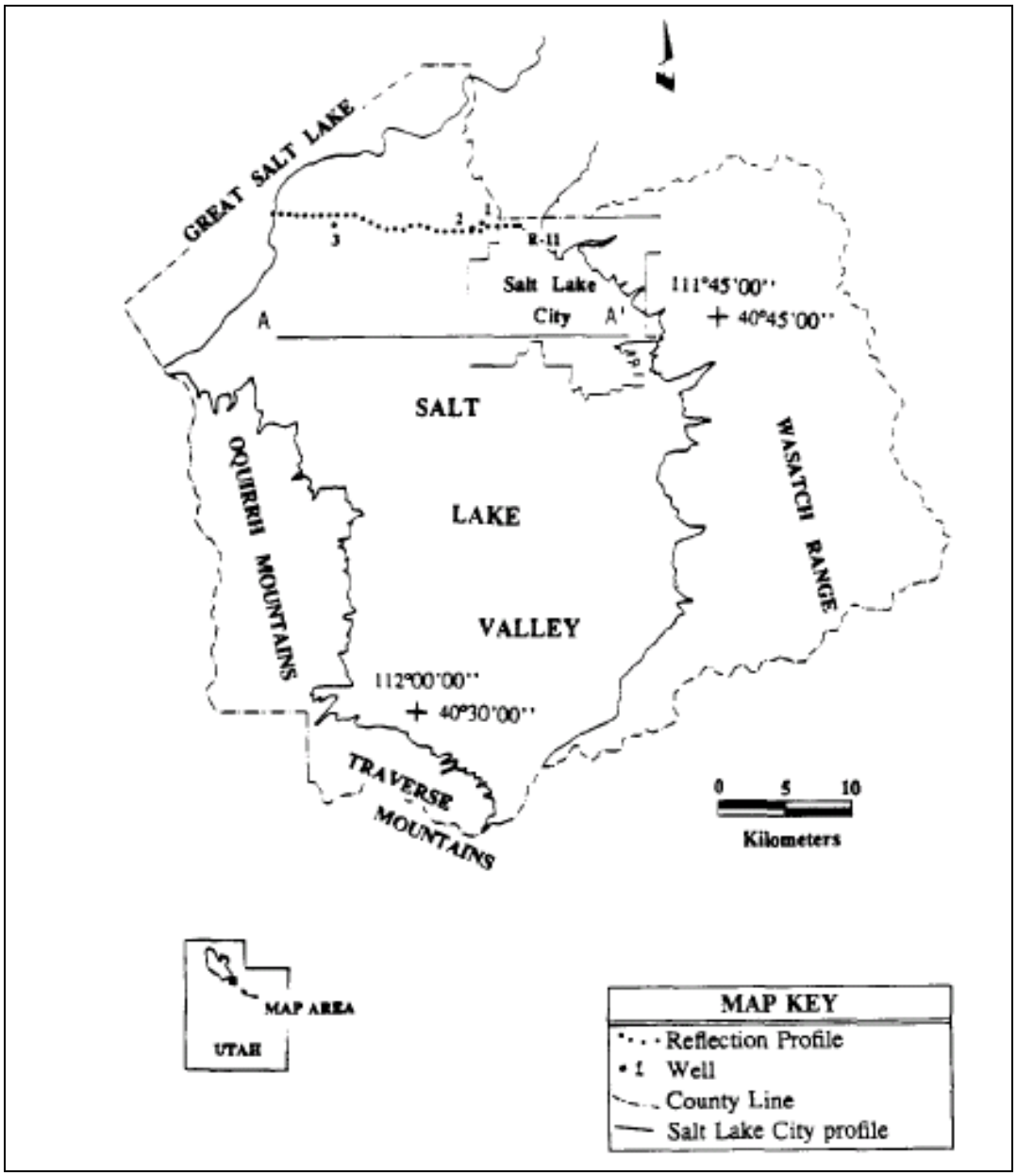

Figure 3.2 Map of reflection profile location (A-A') and location of three wells (#1, #2, and #3) used to determine depths to R1/R2/R3 interfaces (from Hill et al, 1990)

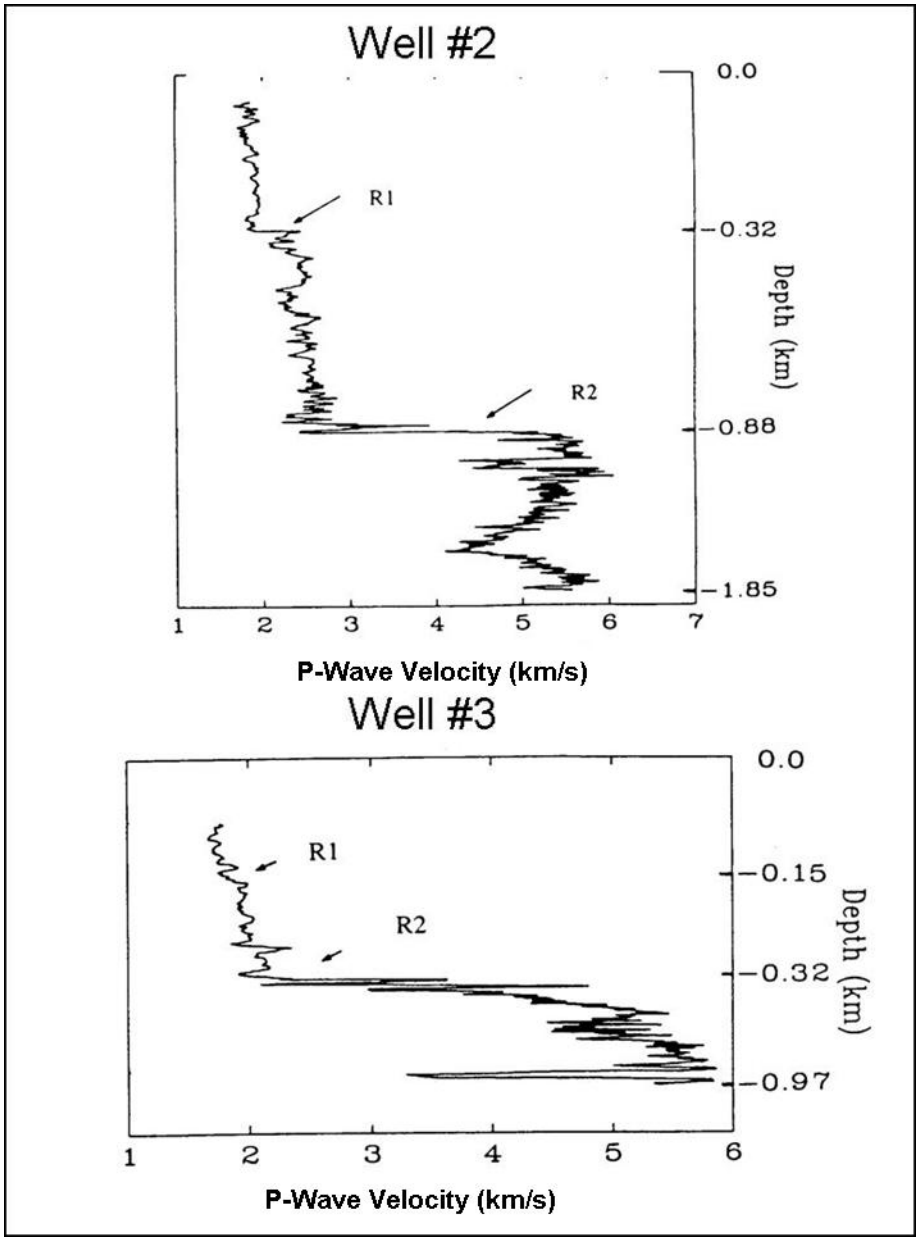

Figure 3.3 Sonic logs from wells #2 and #3 (from Hill, et. al. 1990)

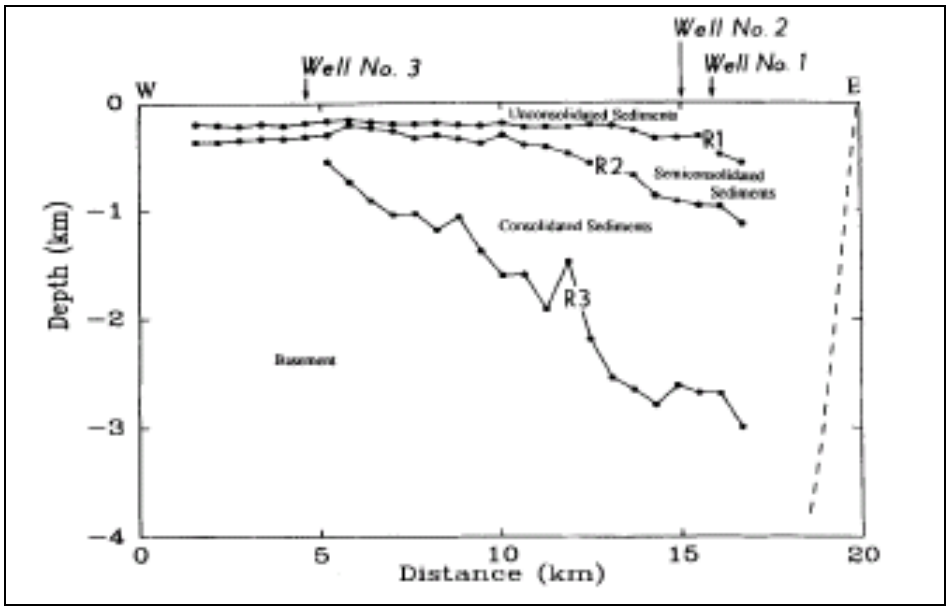

Figure 3.4 Interpreted reflection profile for the R1, R2, and R3 interfaces along reflection profile A-A' (from Hill, et. al. 1990)

Shear wave velocities were determined from the P-wave velocities by assuming Vp/Vs=1.72 (Hill et al, 1990). Figure 3.4 shows the interpreted reflection profile cross-section. As seen from the reflection profile in Figure 3.4, the depth to the R1 interface is greatest at Well #1 and is approximately 1300 ft (395m). As seen in Figure 3.1 this area is the deepest location of the R1 interface. The depth to the R1 interfaces decreases to the west of Wells #1 and #2 towards the Great Salt Lake and is approximately 500 ft (150m) at Well #3. In general, the depth to the R1 interface is greatest near the center of the valley and decreases towards the margins of the valley.

3.3. Mapping the Unconsolidated Sediments

Ashland and Rollins (1999) used the Unified Engineering Geology Mapping (UEGM) System, formerly referred to as the Genesis-Lithology-Qualifier (GLQ) System, to group traditional surficial geologic units. This system is based primarily on the basis of dominant grain size. Ashland (2001) added additional shallow shear wave velocity profiles to the existing database as well as assessed the distinctiveness of the units determined from Ashland and Rollins (1999). The shear wave velocity

data is discussed in Section 3.5. Ashland and Rollins identified five distinct Quaternary units and three bedrock units. The five Quaternary units are: lacustrine-alluvial silt, clay, and fine sand (Q01), lacustrine sand (Q02); lacustrine-alluvial gravel (Q03); Parley's Canyon - City Creek Canyon lacustrine-alluvial gravel (Q04); and older alluvial-fan/glacial gravel (Q05). The three bedrock units are: Tertiary sedimentary and volcanic rocks (T); Mesozoic sedimentary rocks (M); and Paleozoic and older rocks including Tertiary intrusives (P). Table 3.1 is a summary of the eight units. Figure 3.5 shows the surficial geologic classification based on the Ashland and Rollins (1999) and the Ashland (2001) studies.

Table 3.1 Explanation of Quaternary sediment units and bedrock units (from Ashland, 2001)

Unit	Vs30[1] (m/sec)	Description
Q01	199	Lacustine and alluvial silt and clay; alluvial or marsh deposits typically overlie lacustrine deposits.
Q02	301	Lacustrine sand, lacustrine silt and clay, latest Pleistocene to Holocene alluvial-fan deposits.
Q03	387	Lacustrine and alluvial gravel.
Q04	437	Pre-Bonneville alluvial-fan deposits.
Q05	486	Glacial deposits including till and outwash.
T	1023	Tertiary sedimentary and volcanic rocks, and tufa-cemented soils (near Midway); excludes Tertiary intrusive rocks.
M	1449	Mesozoic sedimentary rocks.
P	2197	Paleozoic and older sedimentary, igneous, and metamorphic rocks; and Tertiary intrusive (igneous) rocks.

[1] Logarithmic mean

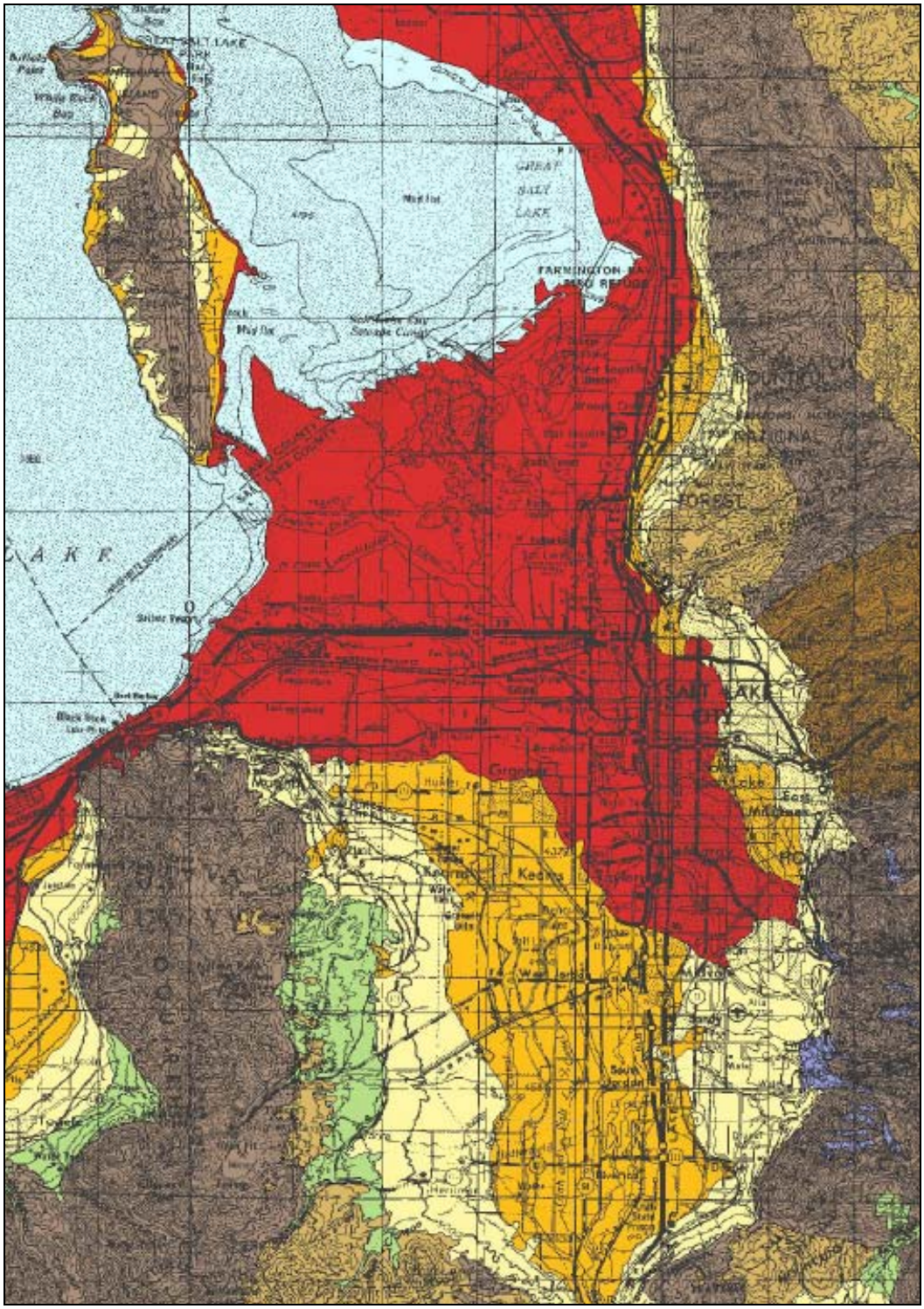

Figure 3.5 Surficial geologic classifications (from Ashland, 2001)

3.4. Site Response Units

Wong et al (2002) defined the site response of soil and unconsolidated sediments in terms of the shear wave velocity profile, depth to the R1 interface, and dynamic nonlinear curves (shear modulus and damping). Based largely on the classification put forth by Ashland and Rollins (1999), Wong et al defined five distinct site-response units: lacustrine-alluvial silt and clay, lacustrine sand, lacustrine-alluvial gravel, Parley's Canyon - City Creek Canyon lacustrine-alluvial gravel, and older alluvial-fan/glacial gravel. Figure 3.6 shows the shear wave profiles used by Wong et al in their report for three of the five units. The velocity profiles used in their report give the average profiles for the lacustrine-alluvial silt and clay, lacustrine sand, and lacustrine-alluvial gravel units. No Vs data was available for the other two units.

Table 3.2 shows a summary of the average shear-wave velocity in the upper 100 ft (30m; termed Vs30) estimates and the corresponding International Building Code (IBC) classification that were presented in Ashland and McDonald (2003). Table 3.3 shows the IBC site class definitions as defined by average shear wave velocity.

Ashland and McDonald (2003) used additional shear wave velocities and field mapping to further characterize the Salt Lake Valley. Figure 3.7 is a map of the eight units as determined by Ashland and McDonald (2003). This map was used to determine the locations for this study (Q01E and Q01D are considered one unit for the purposes of this study, Qafo is unit Q04, and Qg is unit Q05). It was considered important to test in units Q01, Q02, and Q03 as these 3 units cover a majority of the valley. Also, by spreading the testing locations throughout different units it was possible to sample the widest range of materials and shear wave velocities.

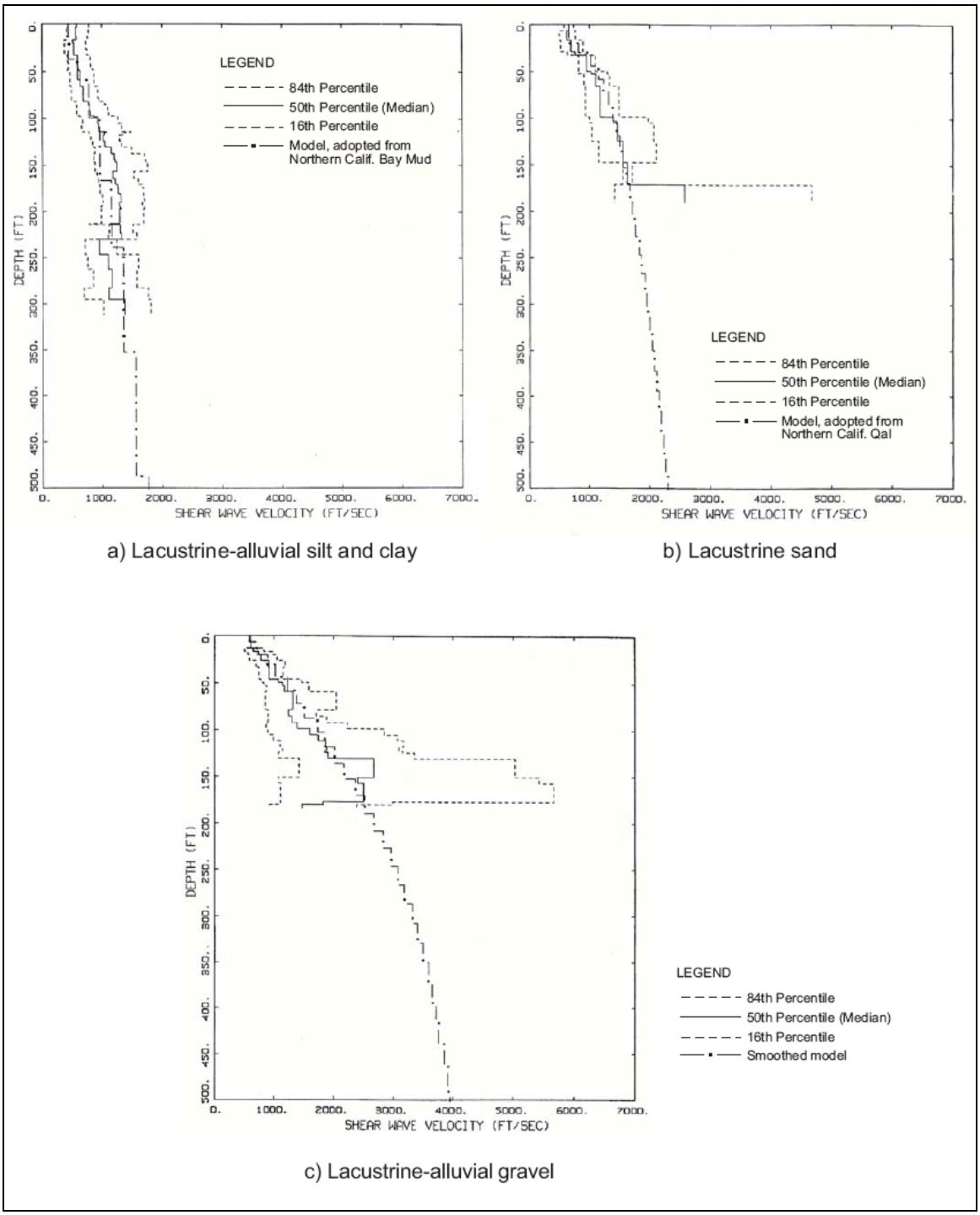

Figure 3.6 Shear-wave velocity profiles for the lacustrine-alluvial silt and clay, lacustrine sand, and lacustrine-alluvial gravel units (from Wong, et. al. 2002)

Table 3.2 Summary of Vs30 for Quaternary sediment units and bedrock units (from Ashland and McDonald, 2003)

Summary of Vs30 Estimates

Unit	Vs30[1,2,3] (m/sec)			IBC Site Class		
	Mean	Maximum	Minimum	Mean	Maximum	Minimum
Q01	199	325	151	D	D	E
Q02	298	469	212	D	C	D
Q03	389	590	260	C	C	D
Q04	437	---	---	C	---	---
Q05	486	---	---	C	---	---
T	1010	1230	837	B	B	B
M	1459	1782	1067	B	A	B
P[4]	2197	---	---	A	---	---

[1] Logarithmic mean
[2] Vs30 for units Q04, Q05, and P estimated from published Vs values for similar soils or rocks
[3] Vs30 for units T and M estimated based on Vs measurements of "buried rock" in Salt Lake Valley
[4] Includes older basement rocks and Tertiary intrusives

Table 3.3 IBC Site Class Definitions (2003 IBC, Table 1615.1.1)

SITE CLASS	Soil Profile Name	Shear Wave Velocity, Vs30 (ft/s)	Shear Wave Velocity, Vs30 (m/s)
A	Hard Rock	Vs30>5000	Vs30>1515
B	Rock	2500<Vs30<5000	760<Vs30<1515
C	Very dense soil and soft rock	1200<Vs30<2500	365<Vs30<760
D	Stiff soil profile	600<Vs30<1200	180<Vs30<365
E	Soft soil profile	Vs30<600	Vs30<180

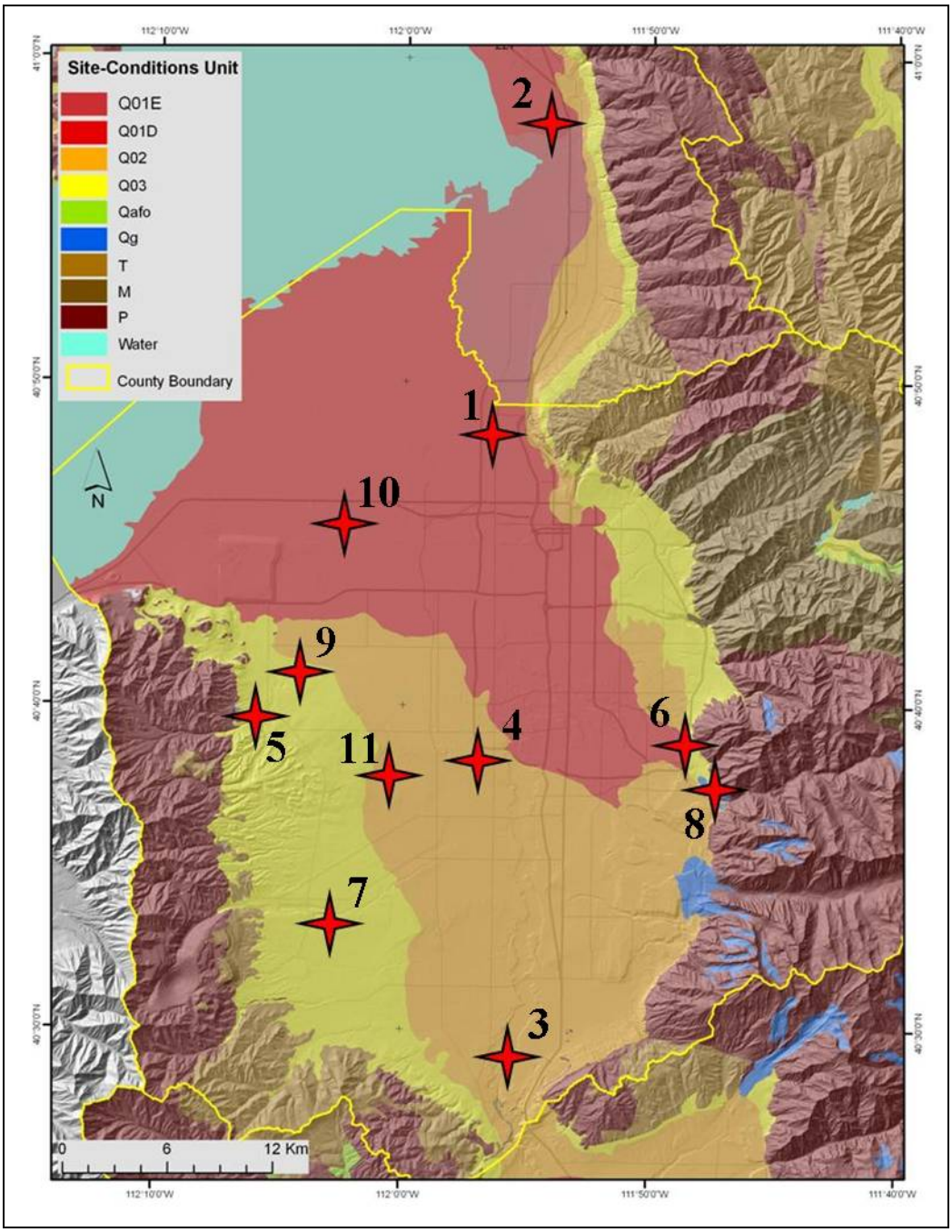

Figure 3.7 Map of the five Quaternary and three bedrock units (from Ashland and McDonald, 2003)

3.5. Shear-Wave Velocity

Almost all of the shear wave velocity information about the Salt Lake Valley is confined to the upper 100 to 150 ft (30 to 45 m). Deeper velocity profiles used in previous basin effect studies are based primarily on reflection surveys and two sonic logs, all of which measured P-wave velocities. Shear wave velocities greater than 2500 ft/s (760 m/s) indicate a position below the R1 interface while velocities greater than 4900 ft/s (1500 m/s) indicate a position below the R2 interface (personal communication with Mr. Gary Christenson, 2007).

Bay et al (2005) performed shallow surface wave studies in the Salt Lake Valley and surrounding areas (Weber, Davis, Utah, and Cedar Valley Basins). They collected a total of 89 shallow shear wave profiles using the SASW method and also supplemented the data with P-wave refraction testing. This data is the most extensive profiling to date in the Salt Lake region. It should be noted that all of the shear wave velocity profiles are shallow. No profile extends deeper than 300 feet (90 m) and a majority of the profiles are less than 150 feet (45 m).

Figure 3.8 shows the location of all the shallow shear wave testing performed in the Salt Lake County and southern Davis County, the general area covered in this study. A total of 139 shallow shear wave velocity profiles have been compiled for the Salt Lake Valley; 70 profiles in unit Q01; 43 in unit Q02; 20 in unit Q03; and six in Q04. A total of 16 shallow shear wave velocity profiles have been compiled for Davis County; 7 in unit Q01 and 9 in unit Q02. Figures 3.9 through 3.12 show the shear wave profiles for units Q01, Q02, Q03, and Q05 in the Salt Lake Valley.

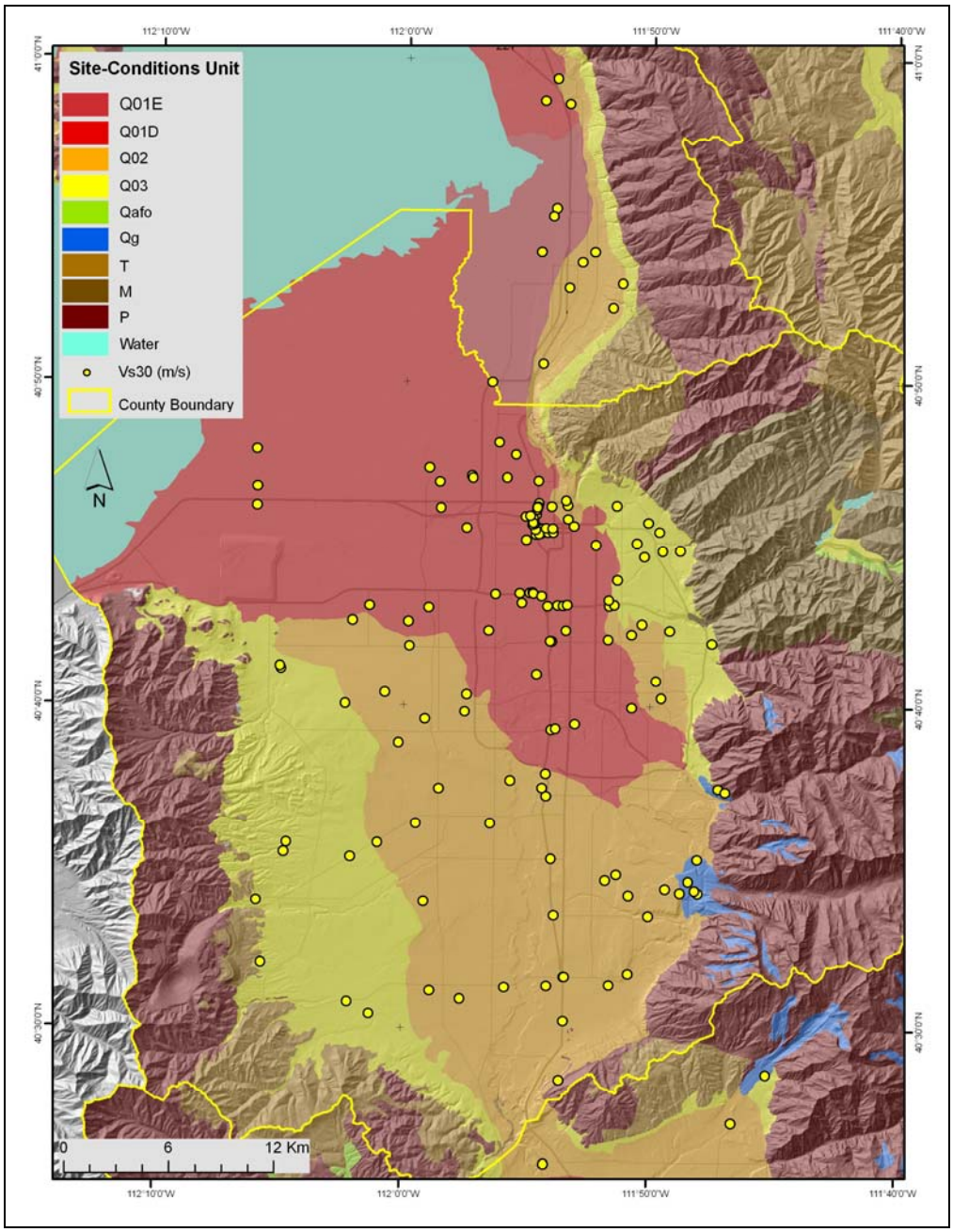

Figure 3.8 Location of all shallow shear wave profiles in Salt Lake Valley and Southern Davis County (provided by Greg McDonald, Utah Geological Survey)

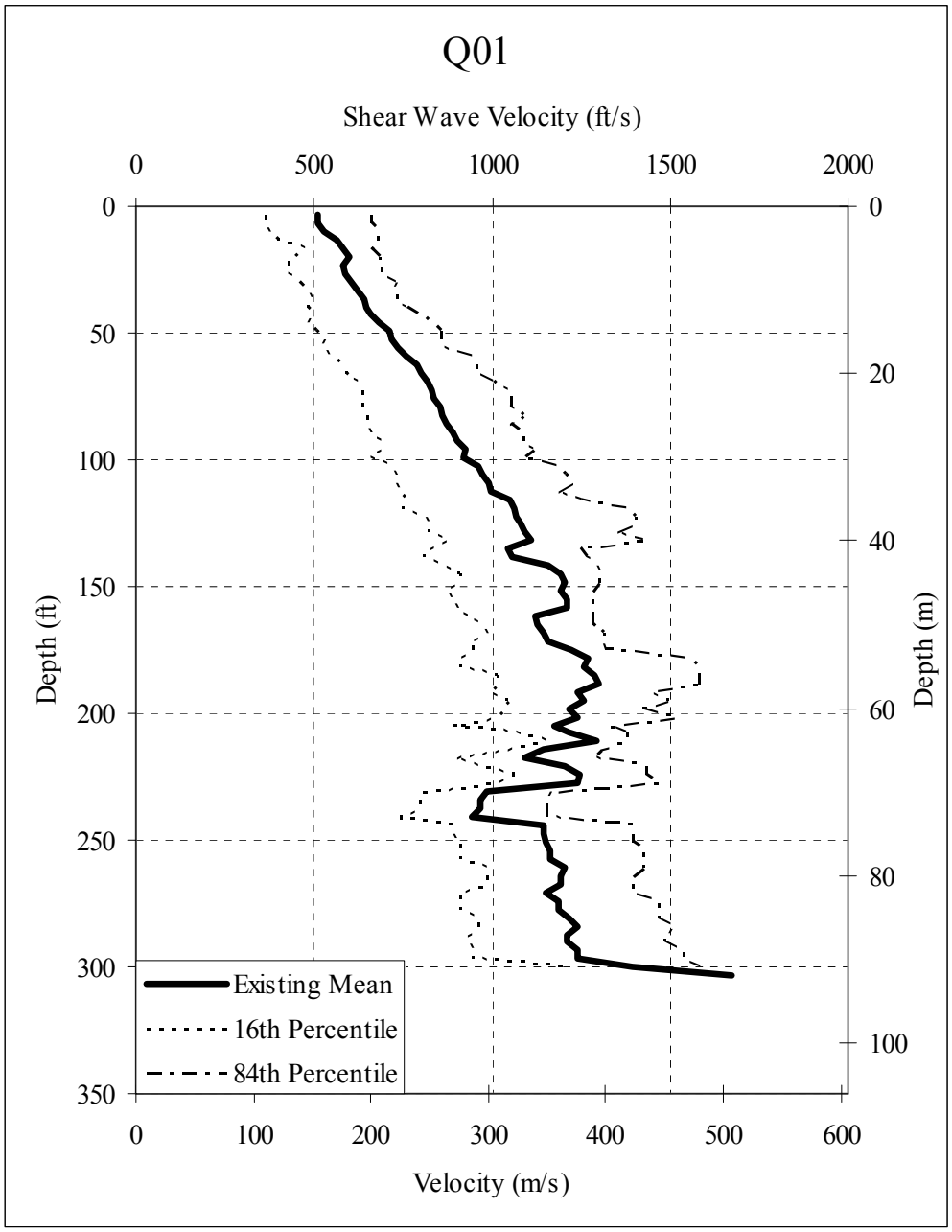

Figure 3.9 Shear wave velocity profile for Q01 unit in Salt Lake Valley. (Provided by Greg McDonald, Utah Geological Survey; 70 Profiles in total)

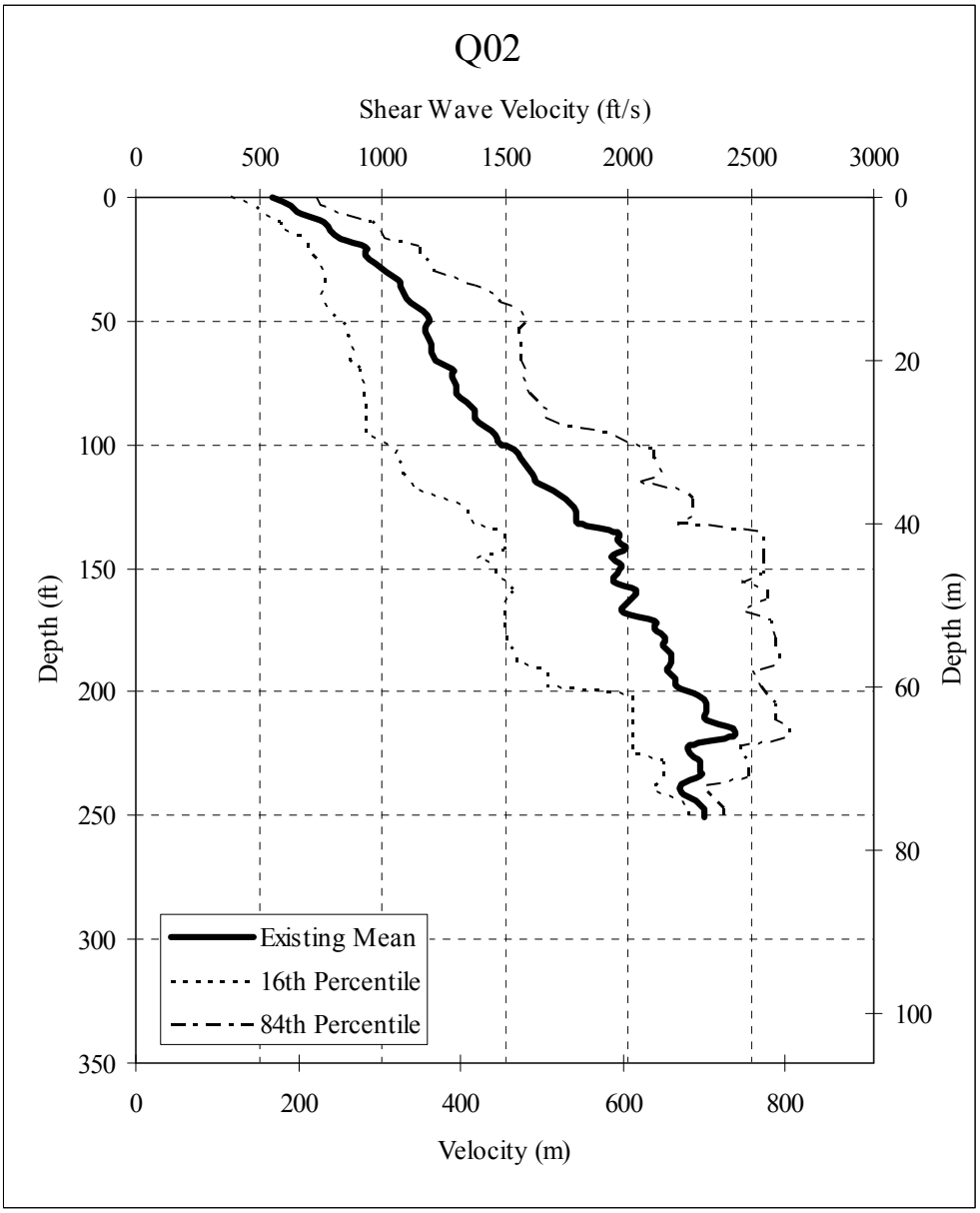

Figure 3.10 Shear wave velocity profile for Q02 unit in Salt Lake Valley. (Provided by Greg McDonald, Utah Geological Survey; 42 Profiles in total)

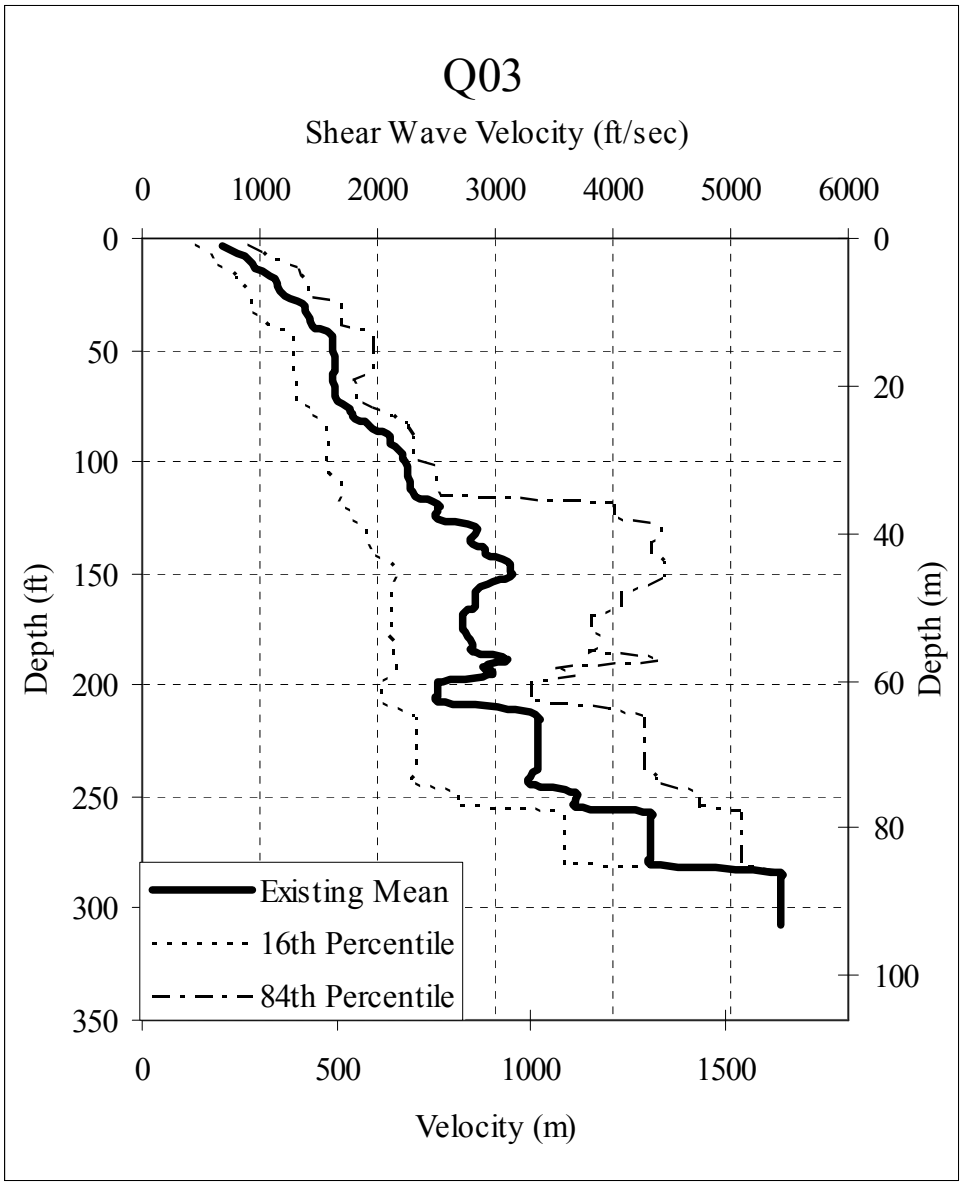

Figure 3.11 Shear wave velocity profile for Q03 unit in Salt Lake Valley. (Provided by Greg McDonald, Utah Geological Survey; 20 Profiles in total)

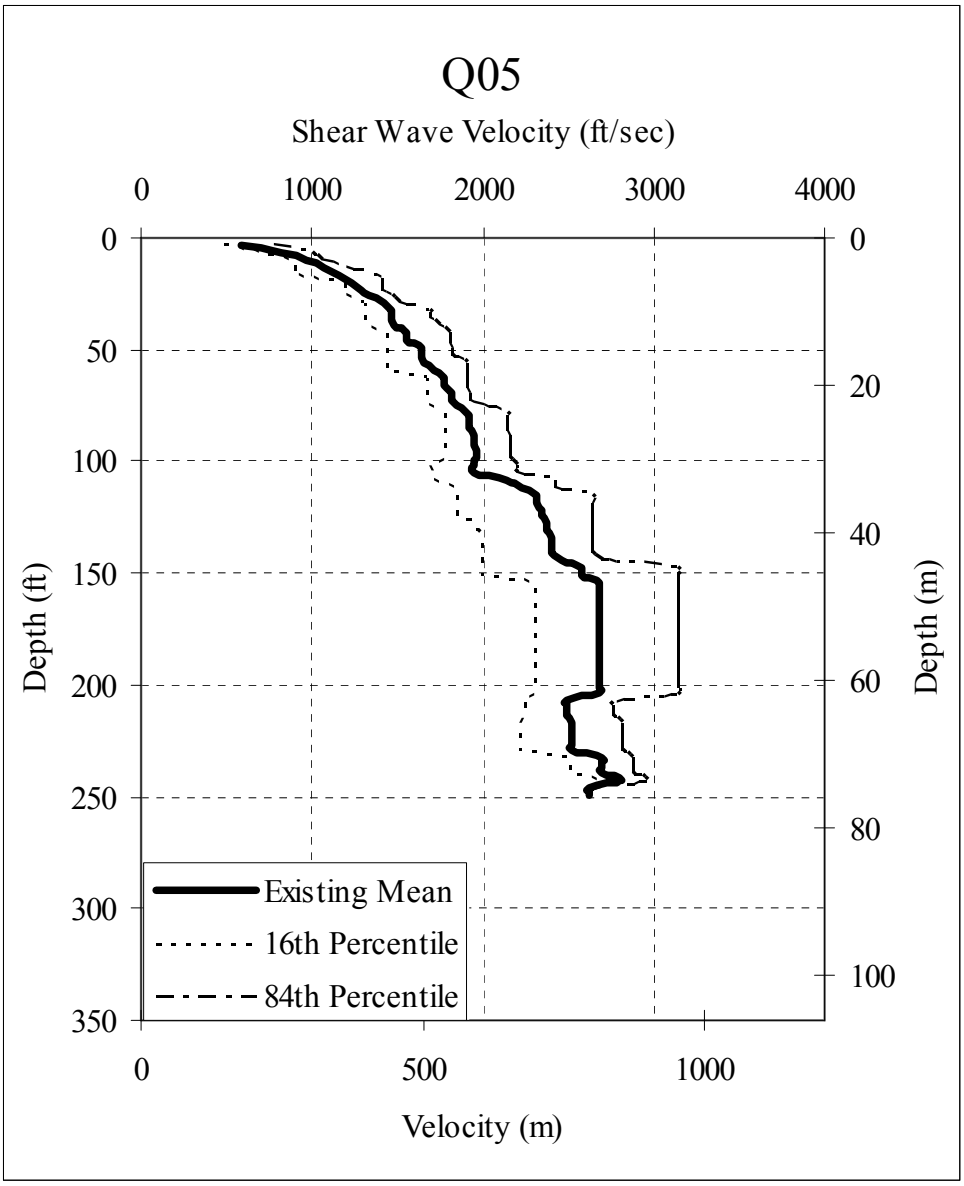

Figure 3.12 Shear wave velocity profile for Q05 unit in Salt Lake Valley. (Provided by Greg McDonald, Utah Geological Survey; 7 Profiles in total)

3.6 Summary

Previous studies have been done to better determine the response of the Salt Lake Valley sediments to an earthquake. The Salt Lake Valley has been studied using geological information, seismic reflection and downhole testing, grain size, and shear wave velocity measurements to determine the site response. Seismic reflection and downhole sonic logs were used to measure depths to the R1/R2/R3 interfaces. The surficial geology was mapped according to grain size and shear wave velocity and site response units were then determined. Numerous shallow shear wave velocity profiles have been collected from around the Salt Lake Valley. These shear wave velocity profiles have been used to further define the mapped units.

CHAPTER 4

SASW TESTING METHOD

4.1. Introduction

The Spectral-Analysis-of-Surface-Waves (SASW) method is a nonintrusive seismic method which utilizes Rayleigh waves to determine shear wave velocity profiles. The SASW method uses many and varying receiver spacings which allows testing over a wide range in Raleigh wavelengths. Raleigh waves are produced at the surface using a vertical source and their propagation is measured by two or more vertical receivers arranged in a linear array. The basis for the SASW method is the dispersive characteristic of Rayleigh waves when they are propagating in a (horizontally) layered system. The velocity of a surface wave depends on the frequency (or wavelength) of the wave. Dispersion is the variation of velocity with frequency and it arises because waves of different wavelengths travel through different layers of the subsurface. High-frequency (short wavelength) waves propagate only through near-surface materials. Lower-frequency waves with longer wavelengths propagate through the near-surface as well as deeper soils. By producing Rayleigh waves with a wide range of wavelengths (frequencies) it is possible to sample different portions of the subsurface as illustrated in Figure 4.1.

SASW testing involves generating surface waves with a vertical excitation and then measuring the vertical surface motions. Receivers are arranged in a straight line which stretches outward from the source. Three receiver locations were used in the testing in the Salt Lake Valley. Various spacings between the receivers and between the first receiver and source are used. The varying spacings makes it possible to measure varying wavelengths. The general testing configuration for one source/receiver set-up is illustrated in Figure 4.2. In this example, a source and two receivers are used whereas in this study 3 receivers were used to increase productivity

in the field. Testing is performed with several sets of source-receiver spacings, and the entire combination of source-receiver spacings is called an SASW array.

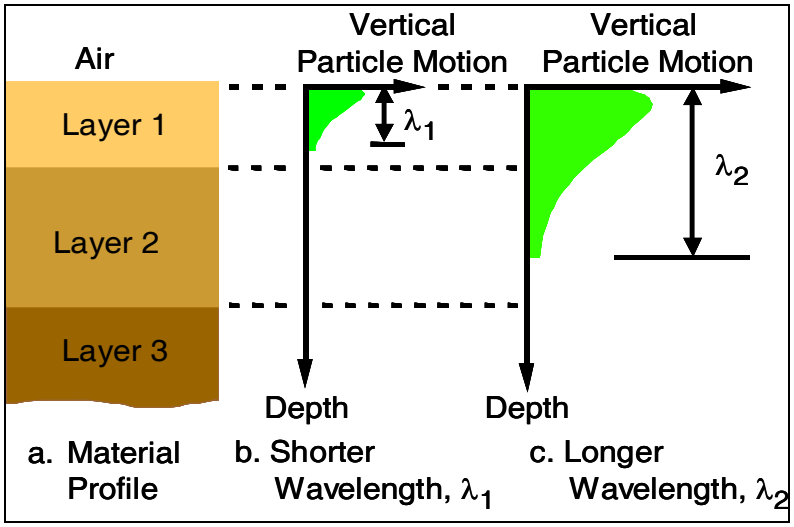

Figure 4.1 Illustration of surface waves with different wavelengths sampling different materials in a layered system (from Stokoe et al, 2005)

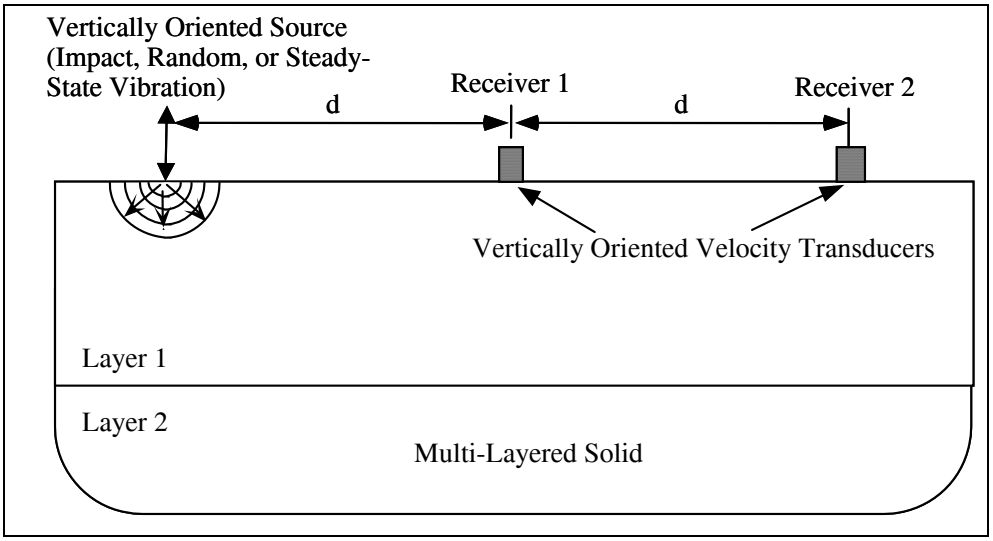

Figure 4.2 Schematic diagram of the generalized equipment arrangement used in SASW testing (from Stokoe et al, 2005)

The variation in phase shift with frequency for surface waves propagating between adjacent receivers is recorded for each receiver spacing. From each receiver pair, the phase velocity of the surface wave can be calculated at each frequency from:

$$V_R = f \bullet \frac{360}{\phi} \bullet d \qquad (1)$$

where V_R is the phase velocity in ft/sec or m/s, f is the frequency in Hertz (cycles per sec), ϕ is the phase angle in degrees (at frequency f), and d is the distance between the receivers in the same length units as used to represent V_R. The phase velocity, V_R, depends primarily on the material properties (shear wave velocity, mass density, and Poisson's ratio or compression wave velocity) over a depth of approximately one wavelength. From this calculation, a plot of phase velocity versus frequency, called a dispersion curve, is generated. This procedure is repeated for all source-receiver spacings used at the site and usually involves significant overlapping in the dispersion data between adjacent receiver sets. The individual dispersion curves from all receiver spacings are combined into a single composite dispersion curve called the experimental or field dispersion curve. A forward - modeling procedure is then used to match the field dispersion curve with a one-dimensional layered system of varying layer stiffnesses and thicknesses. The shear wave velocity profile that generates a dispersion curve that most closely matches the field dispersion curve is then presented as the shear wave velocity profile for the site (Stokoe, et al 2005).

4.2 Summary of SASW Procedures Used in the Salt Lake Valley

Eleven SASW test arrays were evaluated at locations in Salt Lake County and Davis County, UT. The approximate locations of the eleven SASW arrays are shown in Figure 4.3.

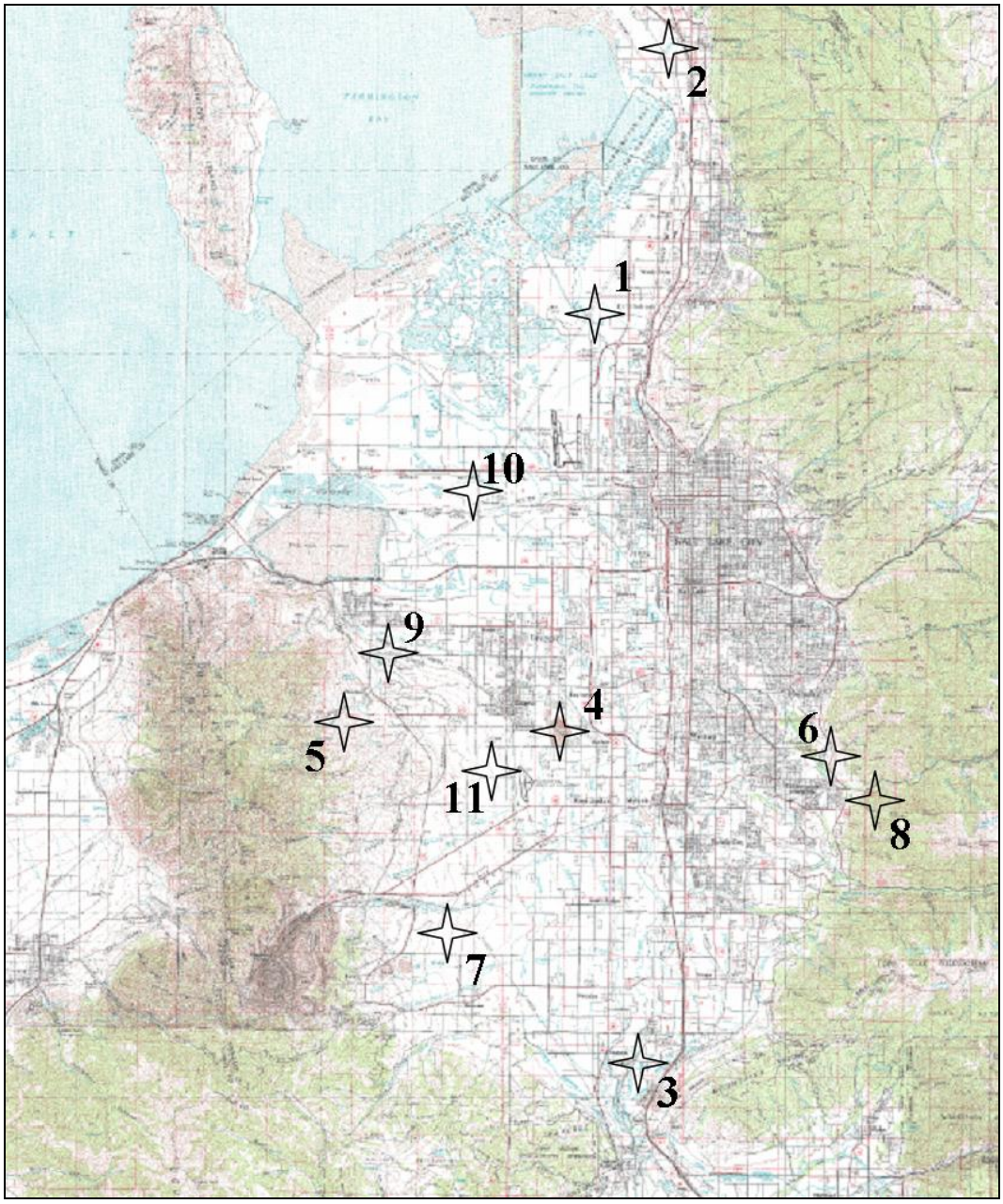

Figure 4.3 Map of SASW test locations in Salt Lake Valley, UT

Three receivers were used at each source/receiver set-up. This arrangement allowed two sets of SASW test results to be obtained simultaneously, which cut testing time in half as compared to using only two receivers. The middle receiver was usually located at the center line of the test array unless space limitations required a shift of the center line. For the shorter wavelengths, source-to-receiver spacings of 3, 6, 12.5, and 25 ft, tests were performed in both the forward and reverse directions using a sledge hammer for an impact source. For the longer wavelengths, source-to-receiver spacings of 25 ft and greater, testing was performed only in the forward direction using a large vibroseis truck ("Liquidator") as the source.

In general, distances between receivers of 3, 6, 12.5, 25, 50, 100, 200, 400, 500, 800 and 1000 ft were used. These receiver spacings resulted in extensive overlapping of the individual dispersion curves used to develop the composite field curve which adds reliability to the composite dispersion curve. In order to avoid near-field effects no wavelengths were used which were longer than twice the distance from source to receiver one. To measure the longest spacing distances, a total station was used to survey distances as shown in Figure 4.4.

Vertical velocity transducers were used as receivers. All tests were conducted with Mark Products Model L-4C transducers (I.D. Numbers of 3773, 3774 and 3775) which have a natural frequency of 1 Hz. Figure 4.5 shows one L-4C receiver being placed in the field with a hand level. The key points for the receivers are that: (1) they have significant output over the measurement frequency range, (2) they are matched so that any differences in phase are negligible over the measurement frequency range, (3) they are coupled well to the soil, (4) the coupling is similar for each receiver, and (5) ambient temperatures were low enough (below 85°F) so as not to impact geophone performance. Figure 4.6 shows blue-ice jackets that were used to maintain temperatures below 85°F. Figure 4.7 shows the geophone covers that were placed over the blue-ice jackets to insulate (somewhat) the jackets.

Figure 4.4 Photograph of total station survey equipment used to measure distances at Site 7

Figure 4.5 Photograph of 1-Hz geophone and a hand-level

Figure 4.6 Photograph of 1-Hz geophone and blue-ice used for cooling

Figure 4.7 Photograph of 1-Hz geophone and insulating cover

The two types of seismic sources that were used in this study to generate energy over the required frequency ranges were a sledge hammer and Liquidator. At the shorter receiver spacings (3, 6, 12.5, 25 ft), a sledge hammer was used as shown in Figure 4.8.

Figure 4.8 Photograph of Mr. Bohyung Lee using sledge hammer source at Site 11 (Municipal Airport #2)

For receiver spacings equal to and greater than 25 ft, Liquidator, a vibroseis that is owned and operated by The University of Texas at Austin (UT), was used. Figure 4.9 is a photograph of Liquidator in use in Salt Lake Valley. Liquidator can excite energy in the low-frequency range of 0.5 to 4 Hz, which allows V_s profiling to greater depths than can be obtained by any other active source.

Figure 4.9 Photograph of Liquidator at Site 7 (Kennecott)

The recording device used in these tests was a Hewlett-Packard (HP) 35670A Dynamic Signal Analyzer, a four-channel analyzer. The dynamic signal analyzer was used to record the geophone output and to perform calculations in the frequency domain so that the relative phase of the cross-power spectrum could be reviewed in the field during data collection. Additionally, the source output of the analyzer was used to control the vibration frequency and amplitude of Liquidator. SASW tests with Liquidator were performed in a stepped-sine mode (from high to low frequencies at most sites), where the source signal was swept over the frequencies of interest and the relative phase and coherence were determined at each frequency. This process allowed the operator to evaluate subjectively the data being collected in the field to assure consistency with the expected Rayleigh wave propagation in a layered halfspace. Figure 4.10 shows the data recording equipment in operation in Salt Lake Valley.

Figure 4.10 Photograph of Mr. Brad Wilder Operating the Hewlett Packard Signal Analyzer at Site 10 (5600W and 640S)

4.3. Spectral Calculations

The dynamic signal analyzer was used to measure time-domain records (x(t) and y(t)) from the three receivers. These time records were then transformed into the frequency domain (X (f) and Y (f)) and used to calculate the power spectra (G_{XX} and G_{YY}), the cross spectrum (G_{XY}) and the coherence function (γ^2). Expressions for these quantities are:

$$G_{XX} = X^*(f) \bullet X(f) \tag{2}$$

$$G_{YY} = Y^*(f) \bullet Y(f) \tag{3}$$

$$G_{XY} = X^*(f) \bullet Y(f) \tag{4}$$

$$\phi(f) = \arctan \bullet \frac{\mathrm{Im}(G_{XY})}{\mathrm{Re}(G_{XY})} \tag{5}$$

$$\gamma^2(f) = \frac{\left|G_{XY}(f)\right|^2}{G_{XX}(f) \bullet G_{YY}(f)} \tag{6}$$

where $G_{XY}(f) = \frac{1}{N}\sum_{i=1}^{N} X^{'}(f) \bullet Y_i(f)$ is the cross power spectrum from coherent signal averaging, (*) represents the complex conjugate of the quantity, Im signifies the imaginary part of the expression, Re signifies the real part of the expression, and $\phi(f)$ is the relative phase between two receivers of the cross power spectrum (Stokoe et al, 1994).

The relative phase of the cross spectrum $\phi(f)$ is the key spectral quantity in SASW testing. The spectral functions were determined one frequency at a time in a stepped-sine fashion. The number of averages and integration time was adjusted in the field to control how long the source remained at each frequency. The phase represents the phase difference of the motion at the two receivers. One set of spectral functions was measured for each receiver spacing and testing direction.

As an example, Figure 4.11a shows the wrapped phase spectrum and Figure 4.11b shows coherence the function from one receiver spacing. These data were collected with the 200-ft receiver spacing at Site 4. The "saw tooth" pattern in the wrapped phase is the pattern that the operator is expecting in the field. The decrease in the values of the coherence function below 4Hz are also common in these measurements. However, in this case, the drop in the coherence values occurs at a phase of about 180° which fall in the range of data deleted from the analysis; that is, no data with wavelengths longer than twice the source-to-first-receiver are used as discussed below.

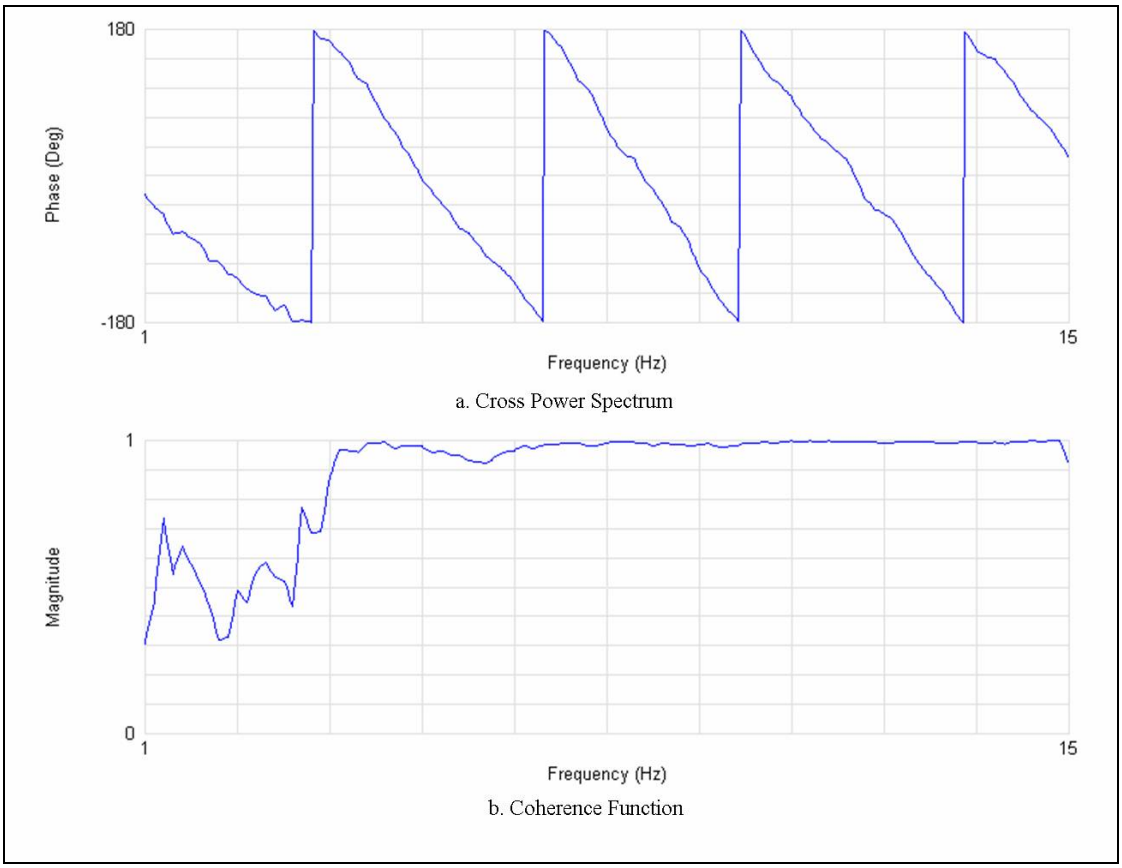

Figure 4.11 Phase of the cross power spectrum and coherence function measured at Site 4 with a 200-ft receiver spacing

4.4. Data Reduction and Forward Modeling Procedures

The data collected in the field are in the form of phase plots and coherence functions as shown in Figure 4.11. These data were saved on data disks and subsequently saved to desktop and laptop computers. The data were then reduced and interpreted using the program WinSASW, developed by Prof. Sung Ho Joh at the University of Texas at Austin.

For each receiver spacing, the phase plot and coherence function were loaded into WinSASW. A masking procedure was then performed to manually eliminate portions of the data with poor signal quality or portions of the data contaminated by

the near-field waveform components. Figure 4.12 shows the masking applied to the phase plot collected with 200-ft spacing at Site 4 that is shown in Figure 4.11.

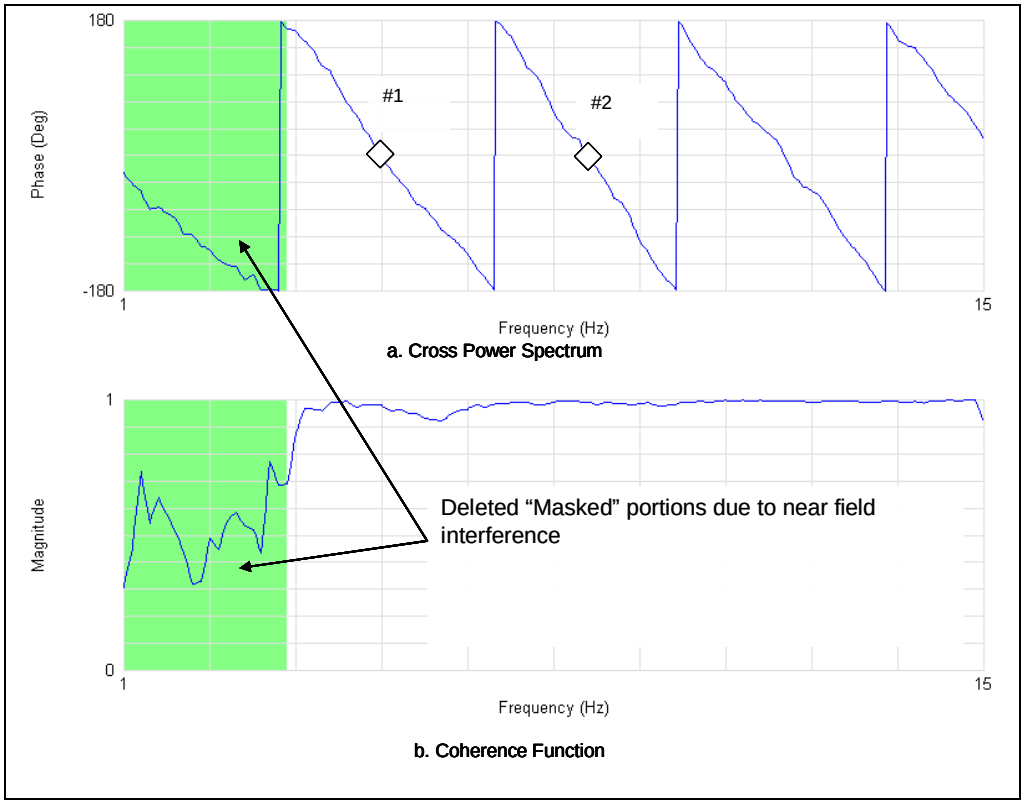

Figure 4.12 Phase of the cross power spectrum and coherence function measured at Site 4 with 200-ft receiver spacing showing the masking applied to the near-field region

The program uses the masking information and "360° jumps" in the wrapped phase to unwrap the phase plot, and then calculate the individual dispersion curve using the relationship presented in Equation 1. For instance, points #1 and #2 in Figure 4.12a represent one and two wavelengths, respectively, between the receiver pair. Hence, the unwrapped phase angles are 360° and 720°, resulting in phase velocities of 1040 and 860 ft/s (315 and 260 m/s), respectively. The complete individual dispersion curve calculated from the unmasked portion of the wrapped phase record in Figure 4.12a is shown in Figure 4.13.

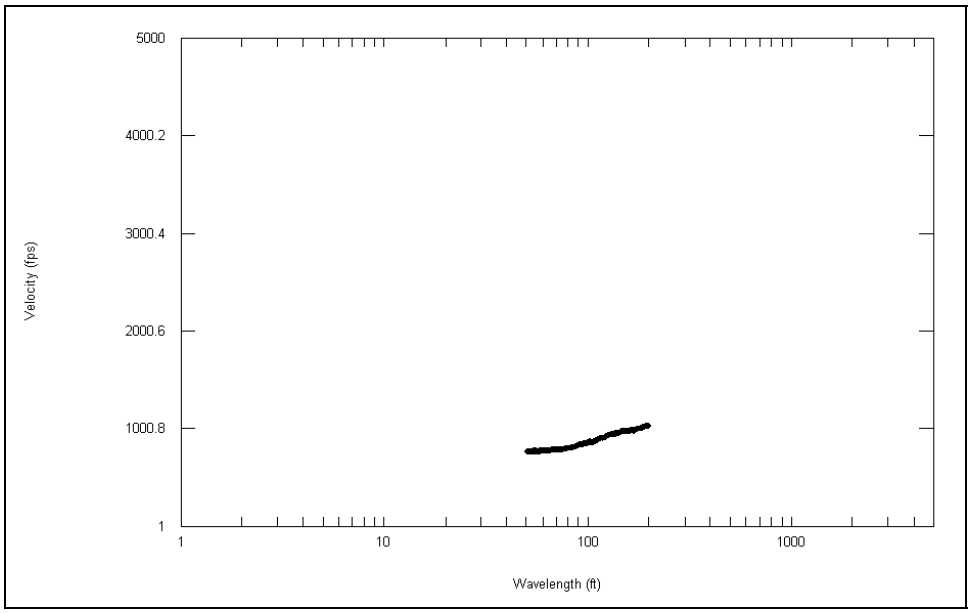

Figure 4.13 Individual dispersion curve from unwrapped phase record in Figure 4.12a measured at Site 4 with 200-ft spacing

This process was repeated for all receiver spacings resulting in a composite experimental dispersion curve that covers a wide range of wavelengths. Figure 4.14 shows the composite experimental dispersion curve created at Site 4.

The maximum wavelength, λ_{max}, measured at Site 4 was about 2500 ft (760 m). This wavelength was measured with S-R2 = 1500 ft (455 m) and R2-R3=500 ft (150 m). The maximum depth to which the V_s profile is reported is λ_{max} /2 or about 1250 ft (380 m).

The next step in the data reduction process is the creation of the theoretical dispersion curve. The software program WinSASW uses an algorithm developed by Dr. Jose Roesset using a stiffness matrix approach to generate a theoretical dispersion curve for a given shear wave velocity profile. The theoretical dispersion curve was generated using a complete solution that includes all modes and both surface and body waves (3D approach). An initial shear wave velocity profile is assumed based on the characteristics of the measured experimental dispersion curve. The theoretical

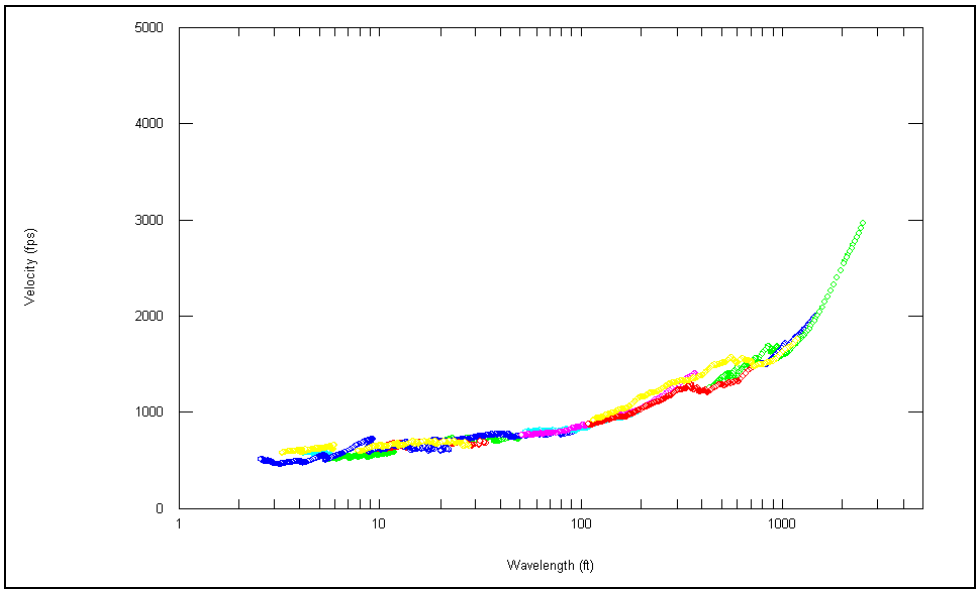

Figure 4.14 Composite experimental dispersion curve created from phase measurements performed at all receiver spacings at Site 4

dispersion curve is generated and then compared to the experimental curve. The features of Vs profile (shear wave velocities and layer thicknesses) are iteratively changed until an acceptable fit to the experimental curve is achieved. Figure 4.15 shows the final fit to the composite experimental dispersion curve for Site 4, and Figure 4.16 shows the final shear wave velocity profile.

4.5. Assumptions

For the theoretical analysis, some assumptions have to be made. First, the unit weight and Poisson's ratio of the material must be assumed. Poisson's ratio was assumed to be 0.30 for all materials above the water table. This value of Poisson's ratio is a reasonable assumption for soil when the soil is not saturated (assumed to be approximated by soil above the water table) in the profiling depth. When no water table is present, the value of Poisson's ratio has only a minor influence on the calculated dispersion curve (Stokoe, et al, 1994). The unit weight of the soil was assumed to be 120 pcf. Relative changes in unit weight with depth affect the dispersion curve, but the effect on the final shear wave velocity profile is also minor.

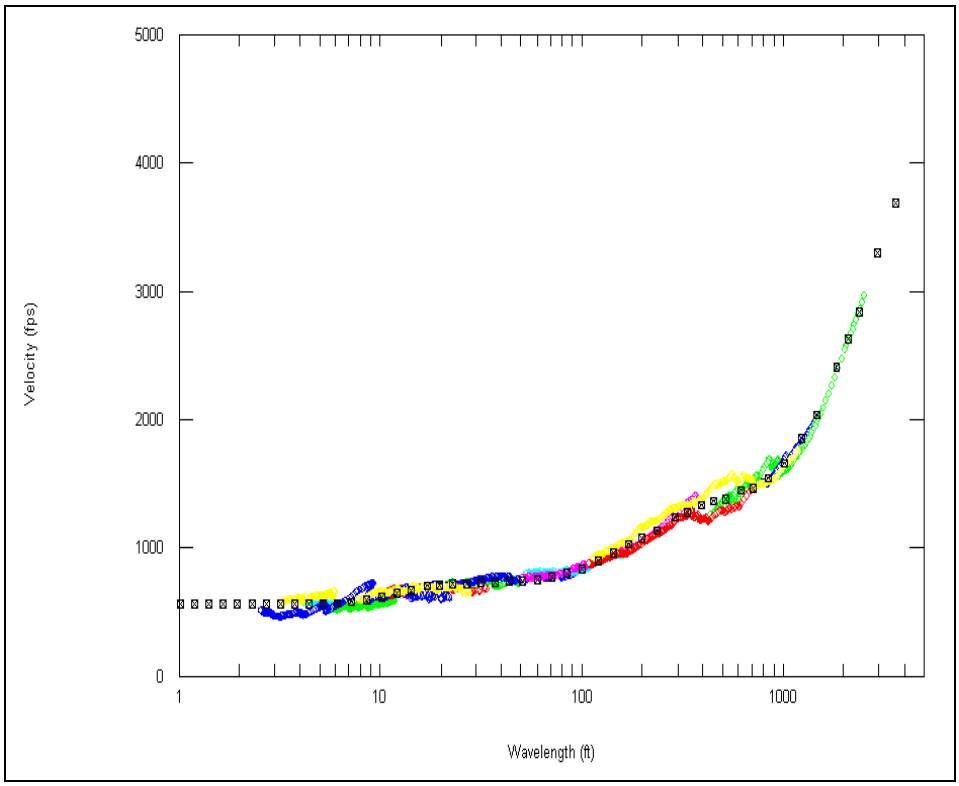

Figure 4.15 Comparison of the fit of the theoretical dispersion curve to the experimental dispersion curve at Site 4

Therefore, precise knowledge of the unit weights at all depths is not required. (Stokoe et al, 2005).

The values of Poisson's ratio of the unconsolidated soil layers under the water table were calculated by WinSASW. The P-wave velocities of soil layers beneath the water table were assumed to be 5200 ft/s (1585 m/s) and values of Poisson's ratio were calculated from the assumed P-wave and S-wave velocities. For the semi-consolidated layers (below the R1 interface, Vs >2500 ft/s or >760 m/s), Poisson's ratio was assumed to be 0.30 and the unit weight was assumed to be 130 pcf. Below the R1 interface WinSASW calculated the values of the P-wave velocities from the assumed values of Poisson's ratio and S-wave velocities.

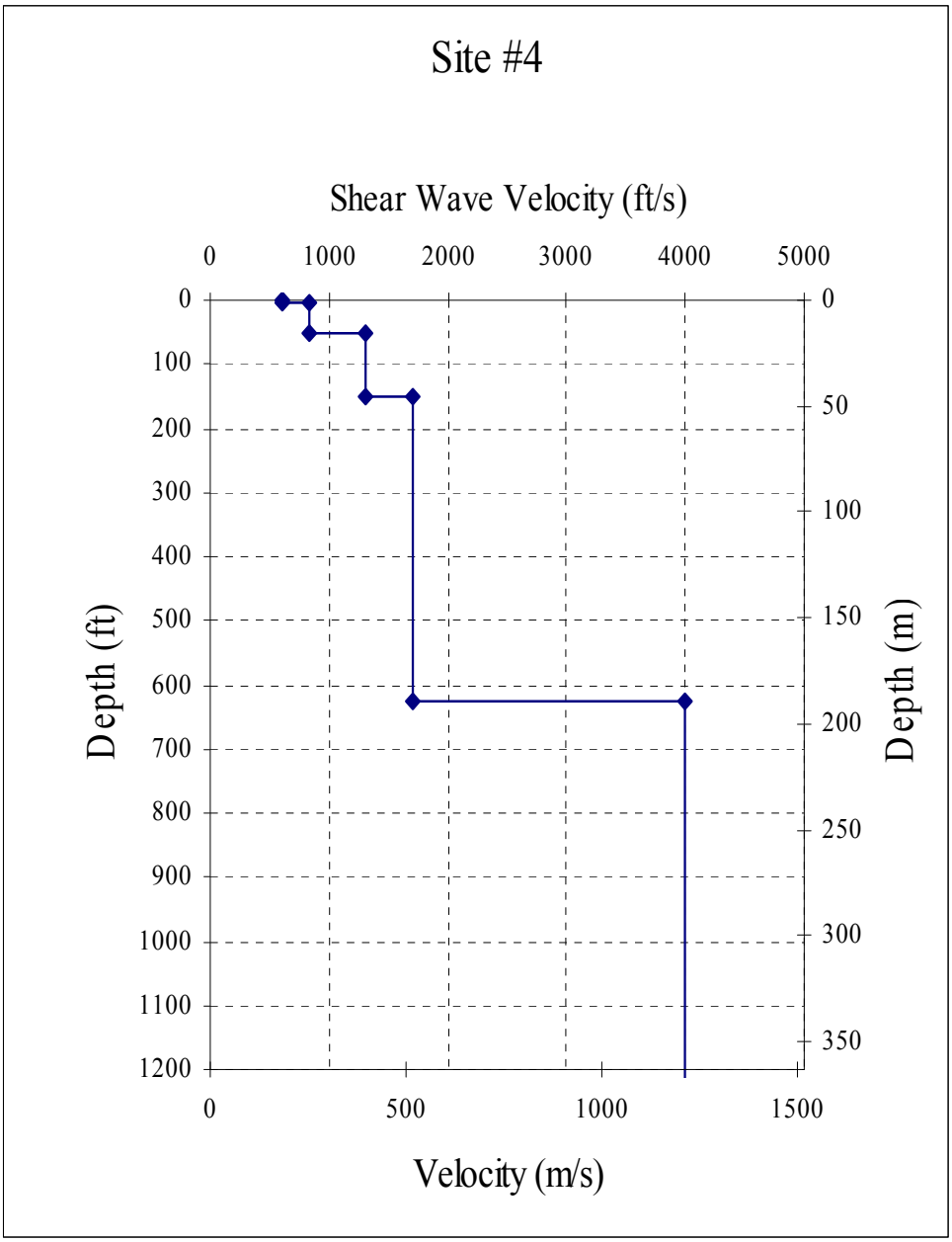

Figure 4.16 Shear wave velocity profile determined at Site 4

The final shear wave velocity profile is presented to a depth of approximately 0.5 times the maximum wavelength (λ_{max} /2) in the experimental dispersion curve. This cutoff depth is based on the fact that most of the particle motion occurs at depths less than one-half of the wavelength, as shown in Figure 4.1. Past experience has shown this to be an acceptable cut-off depth for most shear wave velocity profiles (Stokoe, et al, 1994).

4.6. Summary

The SASW testing procedure is a nonintrusive seismic method. The test method involves creating Rayleigh waves with a vertical excitation and measuring the vertical surface motion at various distances away from the source. A plot of phase velocity versus frequency (dispersion curve) is generated from the field testing. The field testing includes numerous source to receiver spacings and all the individual dispersion curves are combined to create the field dispersion curve. A forward-modeling procedure is then used to match the field dispersion curve with a one-dimensional layered system of varying layer stiffnesses and thicknesses. Eleven SASW test arrays were evaluated for this study. The two sources for this study were a sledge hammer for the shorter wavelengths and a large vibroseis truck, "Liquidator", for the longer wavelengths. Liquidator can excite energy in the low-frequency range of 0.5 to 4 Hz, which allows V_s profiling to greater depths than any other active source. The final Vs profile is presented to a depth of 0.5 times the maximum wavelength in the experimental dispersion curve.

CHAPTER 5

FIELD STUDIES

5.1. Introduction

Eleven SASW arrays were evaluated in the Salt Lake Valley. Figure 5.1 shows the location of the 11 sites. Ten sites are located in Salt Lake County and one site is located in Davis County (Site 2). Figure 5.2 shows the location of the eleven sites on the most recent Quaternary site class map. Table 5.1 lists the Quaternary unit associated with each SASW site. A brief overview of each site is presented below. The Vs profile determined at each site and a list of parameters used to determine the profile are presented along with the site description.

5.2. SITE 1: Legacy Parkway South (Center Street)

Site 1 is located in the northern portion of the Salt Lake Valley along the proposed Legacy Parkway Highway, to the north of Center Street and west of Highway 68 (Centerline Location: Latitude: 40°50'54.00"N; Longitude: 111°55'36.00"W). The test line has a north-south trendline and is located on a gravel road which has a compacted, stiff layer approximately 3 to 4 feet (1m) thick. Figure 5.3 shows the location of Site 1. The star designates the approximate location of the centerline of the array.

As shown in Figure 5.2, this site was mapped in the Q01 Unit by Ashland and McDonald (2003). The surficial geology is classified as lacustrine and alluvial silt, clay, and fine sand. Also, in the Q01 Unit, alluvial or marsh deposits typically overlie lacustrine deposits. The Q01 unit has a Vs30 value of 653 ft/s (196 m/s)(Ashland and McDonald, 2003). An estimated depth to the unconsolidated/semi-consolidated R1 interface is 1300 to 1650 feet (395 m to 500 m) as presented in Wong et al, 2002.

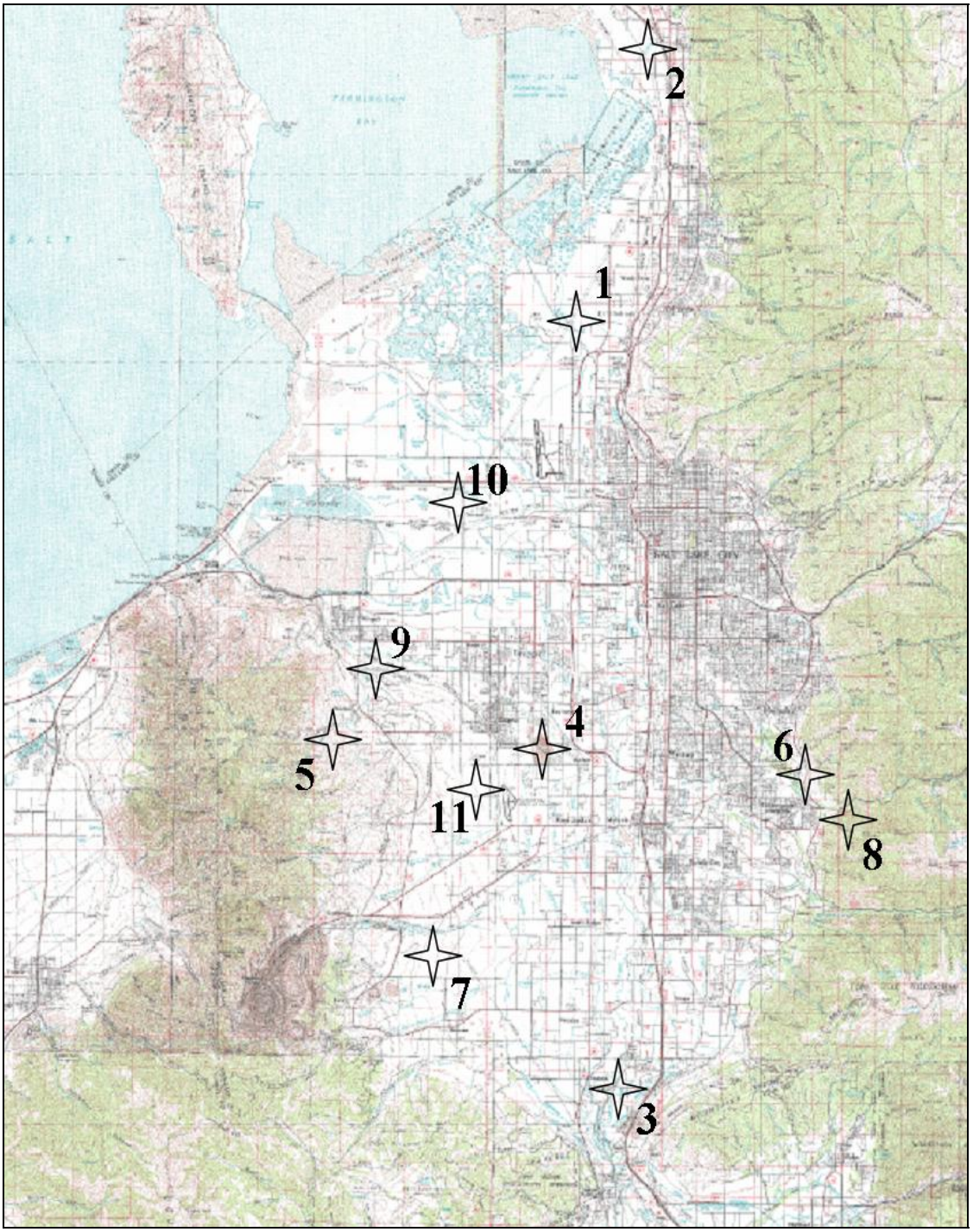

Figure 5.1 Map of SASW test locations in Salt Lake Valley, UT

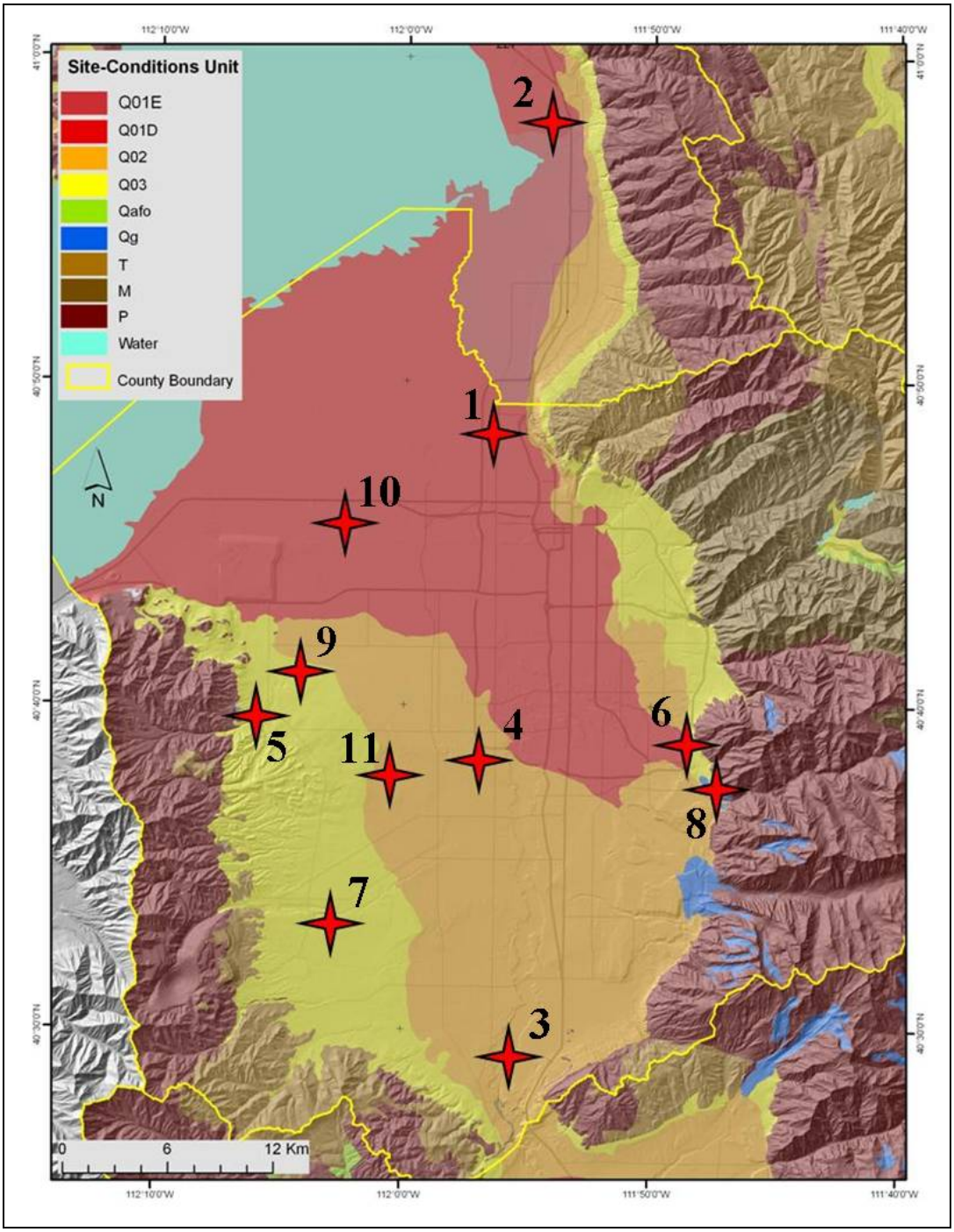

Figure 5.2 Quaternary units map with location of 11 SASW test locations in Salt Lake Valley, UT (from Ashland and McDonald, 2003)

Table 5.1 List of SASW sites and the associated Quaternary unit

SITE #	Name	Quaternary Unit
1	Legacy Parkway South (Center St.)	Q01
2	Legacy Parkway North (Farmington)	Q01
3	Mt Jordan Sod Farm	Q02
4	6200 S. & Bangeter Hwy	Q02
5	Coon Canyon	Q03
6	I-215 Onramp at 6200 S	Q03
7	Kennecott	Q03
8	Holladay Gun Club	Q05
9	Fire Training Tower	Q03
10	5600 W & 640 S.	Q01
11	Muni Airport #2	Q02

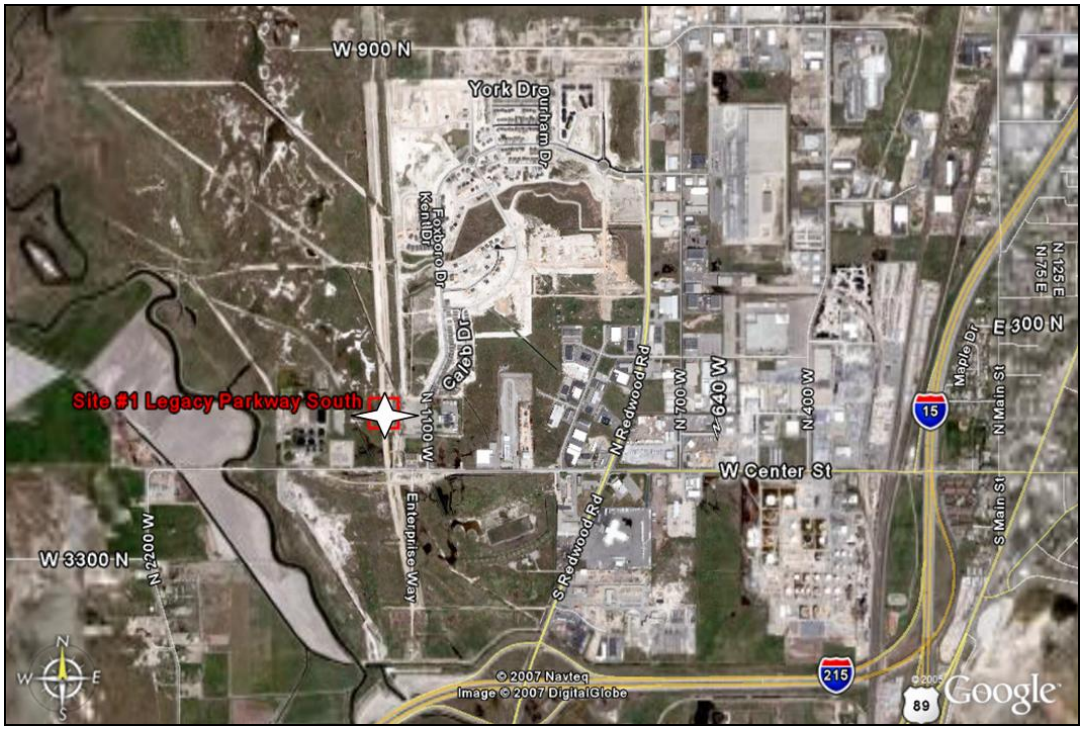

Figure 5.3 Map of Site 1 (Legacy Parkway South); from earth.google.com

Site 1 is also located near two of the wells which have a sonic log, Well #2 and #3 in Figure 3.2. The approximate depth to the R1 interface between unconsolidated and semi-consolidated sediments at Well #2 is interpreted to be 1000 to 1200 feet (300 to 365 m). The depths to the R1 interface from Well #2 and from Wong et al (2002) are not an exact match due to the sloping nature of the R1 interface as seen in Figure 3.1.

Figure 5.4 shows the Vs profile determined from the SASW test at Site 1. The values of the parameters used to determine the Vs profile are listed in Table 5.2. V_{S30} at Site 1 is 586 ft/s (178 m/s) and the depth to R1 is 665 ft (200 m). These values will be compared with the other measurements in Chapter 6.

5.3. SITE 2: Legacy Parkway North (Farmington)

Site 2 is located north of the Salt Lake Valley in Farmington (Davis County) and is on the southwest corner of the intersection of Interstate 15 and West State Street (Centerline Location: Latitude: 40°58'43.00"N; Longitude: 111°53'56.00"W). The test line was located along a dirt road which had approximately 0.5 to 1 (0.3 m) feet of native soil that had been compacted due to occasional off-road traffic. Figure 5.5 shows the location of Site 2. The star designates the approximate location of the centerline of the array.

As shown in Figure 5.2, this site is located in Davis County. The surficial geologic setting is mapped in the Q01 unit; lacustrine and alluvial silt, clay, and fine sand with alluvial or marsh deposits typically overlying the lacustrine deposits.

Figure 5.6 shows the Vs profile determined from the SASW test at Site 2. The values of the parameters used to determine the Vs profile are listed in Table 5.3. V_{S30} at Site 2 is 615 ft/s (185 m/s) and the depth to R1 is 400 ft (120 m). These values will be compared with other measurements in Chapter 6. The Vs profile

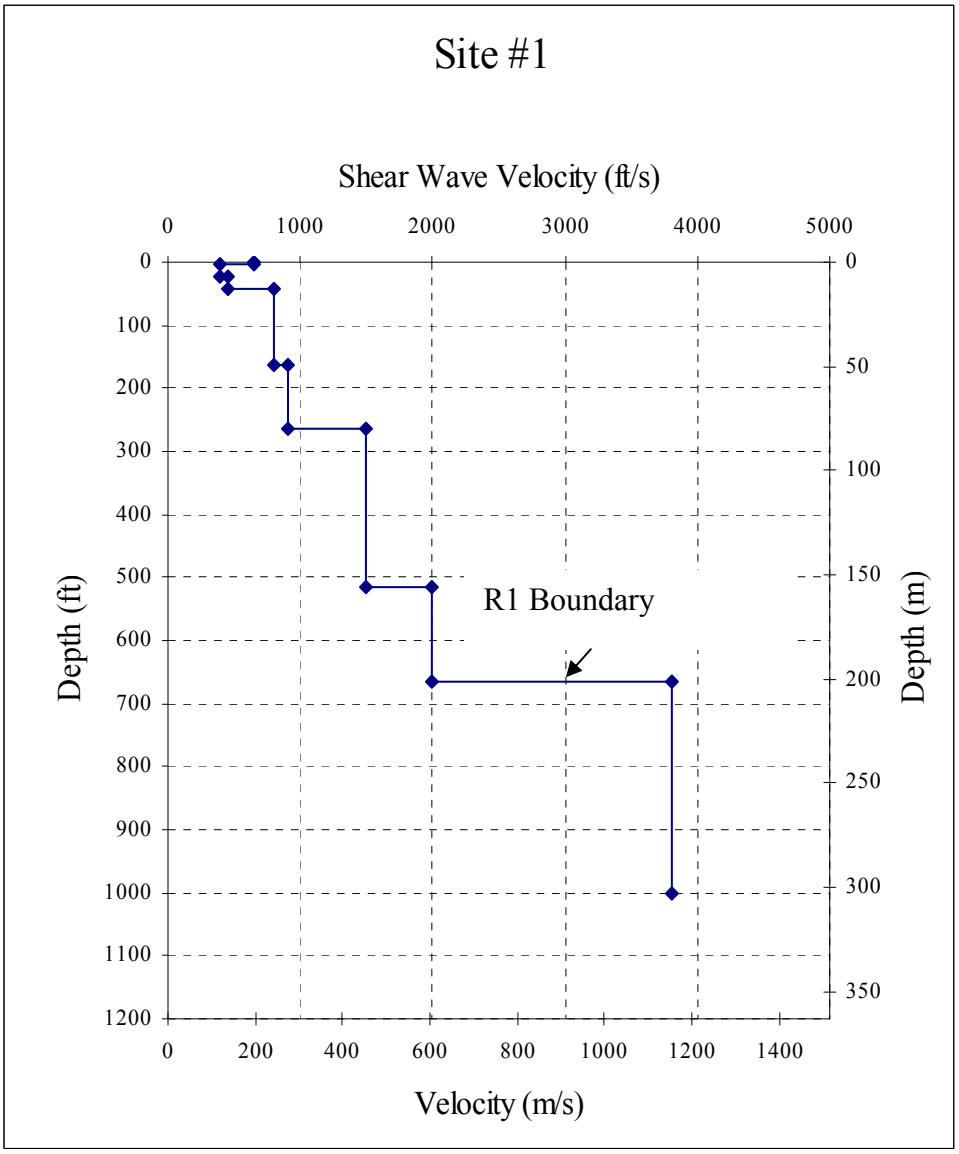

Figure 5.4 Shear wave velocity profile determined at Site 1 (Legacy Parkway South)

Table 5.2 Profile Parameters Used to Develop Theoretical Dispersion Curve at Site 1

Layer No.	Thickness, ft	P-Wave Velocity, ft/s	S-Wave Velocity, ft/s	Assumed Poisson's Ratio	Assumed Total Density, pcf
1	4	1216	650	0.30	120
2	20	5200*	400	0.497	120
3	20	5200	450	0.496	120
4	120	5200	800	0.488	120
5	100	5200	900	0.485	120
6	250	5200	1500	0.4555	120
7	150	5200	2000	0.413	120
8	∞	7109	3800	0.30	130

* Depth of Water Table is 4 ft.

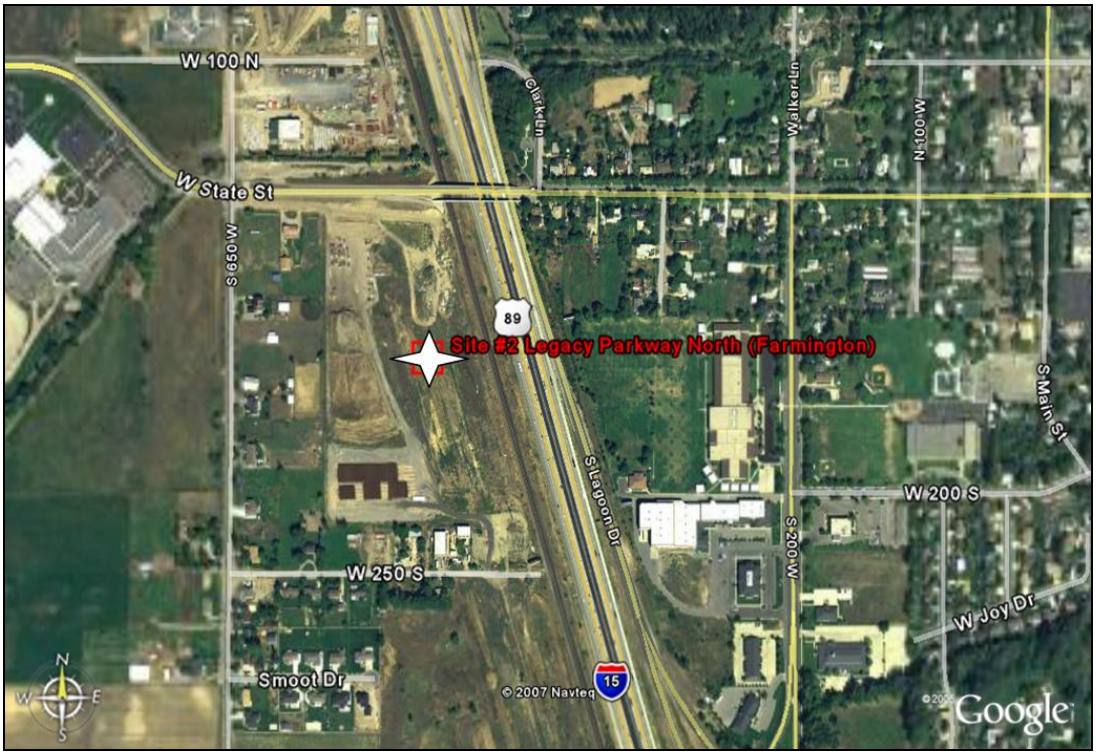

Figure 5.5 Map of Site 2 (Legacy Parkway North); from earth.google.com

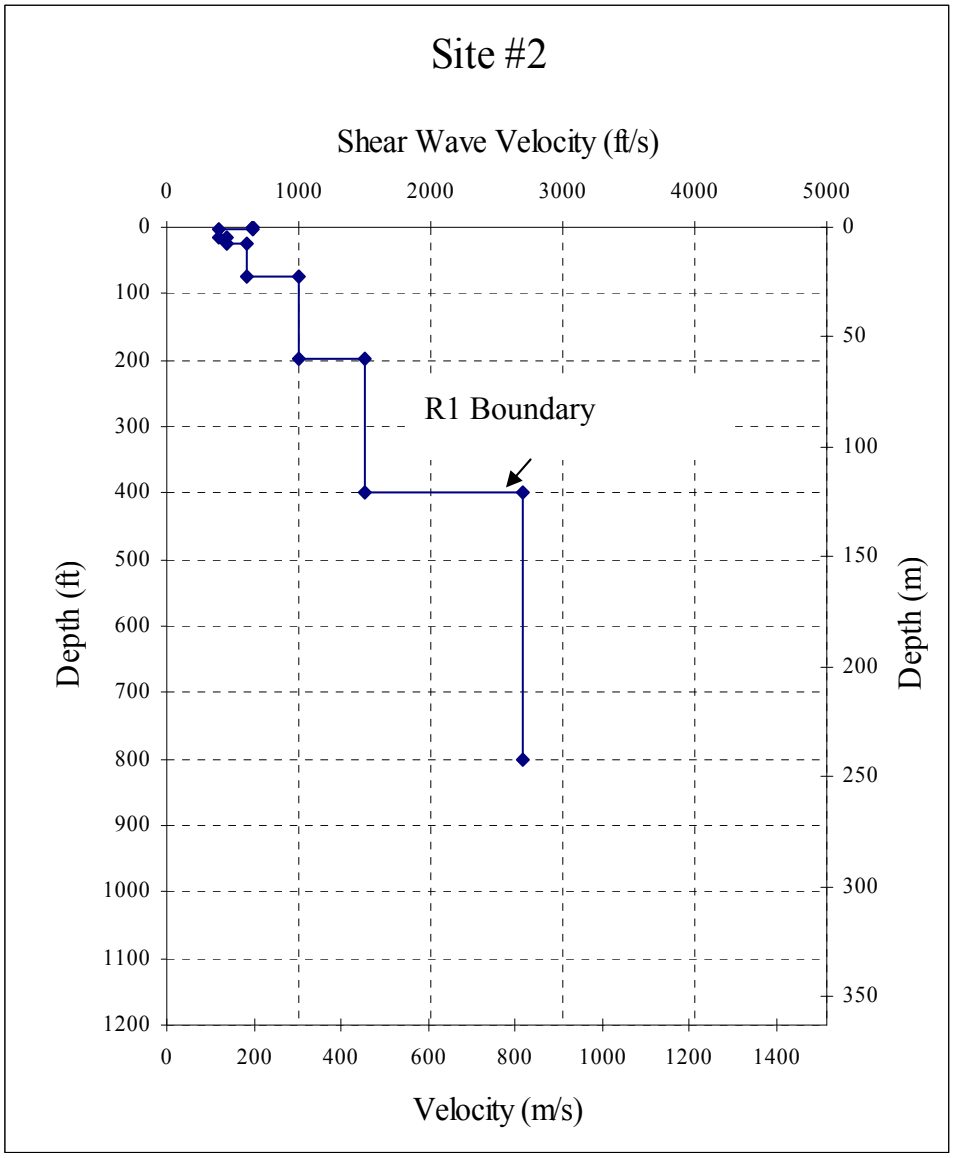

Figure 5.6 Shear wave velocity profile determined at Site 2 (Legacy Parkway North)

Table 5.3 Profile Parameters Used to Develop Theoretical Dispersion Curve at Site 2

Layer No.	Thickness, ft	P-Wave Velocity, ft/s	S-Wave Velocity, ft/s	Assumed Poisson's Ratio	P-Wave Velocity, ft/s
1	4	1216	650	0.30	120
2	10	5200*	400	0.497	120
3	10	5200	450	0.496	120
4	50	5200	600	0.495	120
5	125	5200	1000	0.481	120
6	200	5200	1500	0.455	120
7	∞	5200	2700	0.315	130

* Depth of Water Table is 4 ft

extends to a depth of 800 ft (240 m). The profile is not deeper due to the geographical boundaries at Site 2 which limited the maximum receiver spacing distances.

5.4. SITE 3: Mt. Jordan Sod Farm

Site 3 is located in the southern portion of the Salt Lake Valley just west of Interstate I-15 and south of 14600 S (Centerline Location: Latitude: 40°28'38.00"N; Longitude: 111°55'6.00"W). Testing was conducted at the Mt. Jordan Sod Farm. The test line had an east-west trendline and was located along a gravel road which has a compacted, stiff layer approximately 1-2 feet thick (0.5 m). Figure 5.7 shows the location of Site 3. The star designates the approximate location of the centerline of the array.

As shown in Figure 5.2, this site was mapped in the Q02 unit by Ashland and McDonald (2003). The surficial geology is characterized as lacustrine sand, with interbedded lacustrine silt and clay; as well as the latest Pleistocene to Holocene alluvial-fan deposits. This site is close to the Q02/Q03 boundary; where the Q03 unit is identified as having a higher gravel content. The Q02 unit has a mean V_{S30} value of 977 ft/s (298 m/s), whereas the Q03 unit has a mean V_{S30} value of 1276 ft/s (389 m/s)(Ashland and McDonald, 2003). An estimated depth to the unconsolidated/semi-

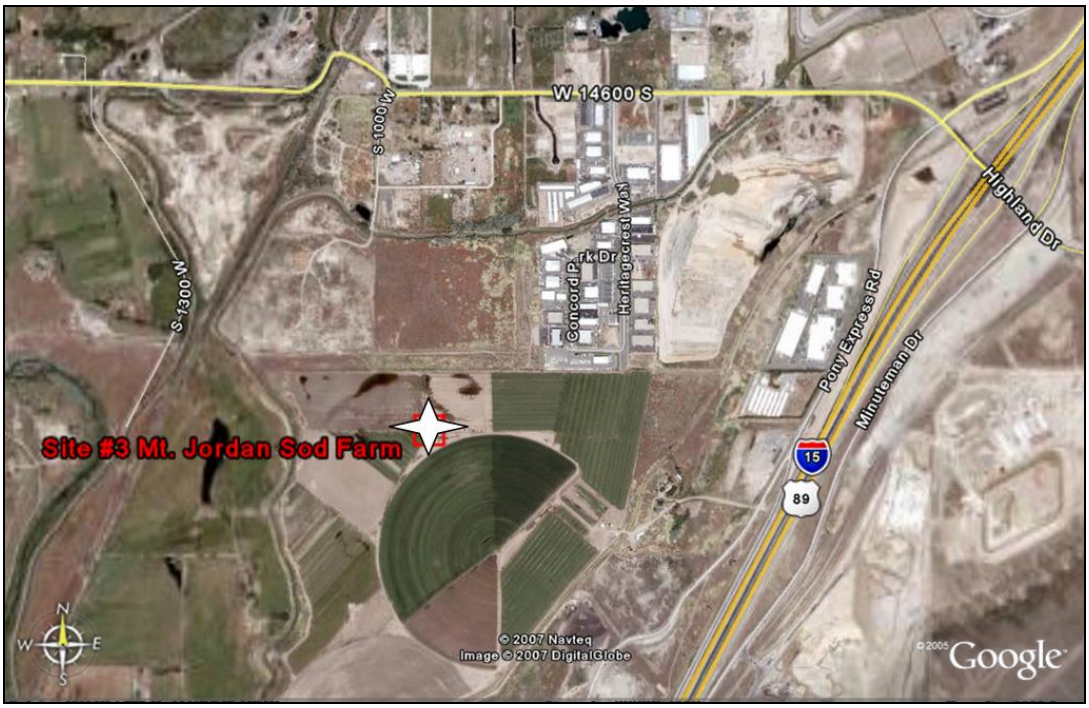

Figure 5.7 Map of Site 3 (Mt. Jordan Sod Farm); from earth.google.com

consolidated R1 interface is less than 150 feet (45 m) as presented in Wong et al, 2002.

Figure 5.8 shows the Vs profile determined from the SASW test at Site 3. The values of the parameters used to determine the Vs profile are listed in Table 5.4. V_{S30} at Site 2 is 668 ft/s (204 m/s) and the depth to R1 is 315 ft (95 m). These values will be compared with the other measurements in Chapter 6.

5.5. SITE 4: UDOT (6200 South and Bangeter Highway)

Site 4 is located in the central portion of the Salt Lake Valley at the northeast corner of the intersection of 6200 S and Bangerter Highway (Centerline Location: Latitude: 40°38'31.40"N; Longitude: 111°58'19.60"W). This site is currently owned by the Utah Department of Transportation (UDOT). The test line has a north-south trendline and is situated on loose, native, silty sand/sandy silt. Figure 5.9 shows the

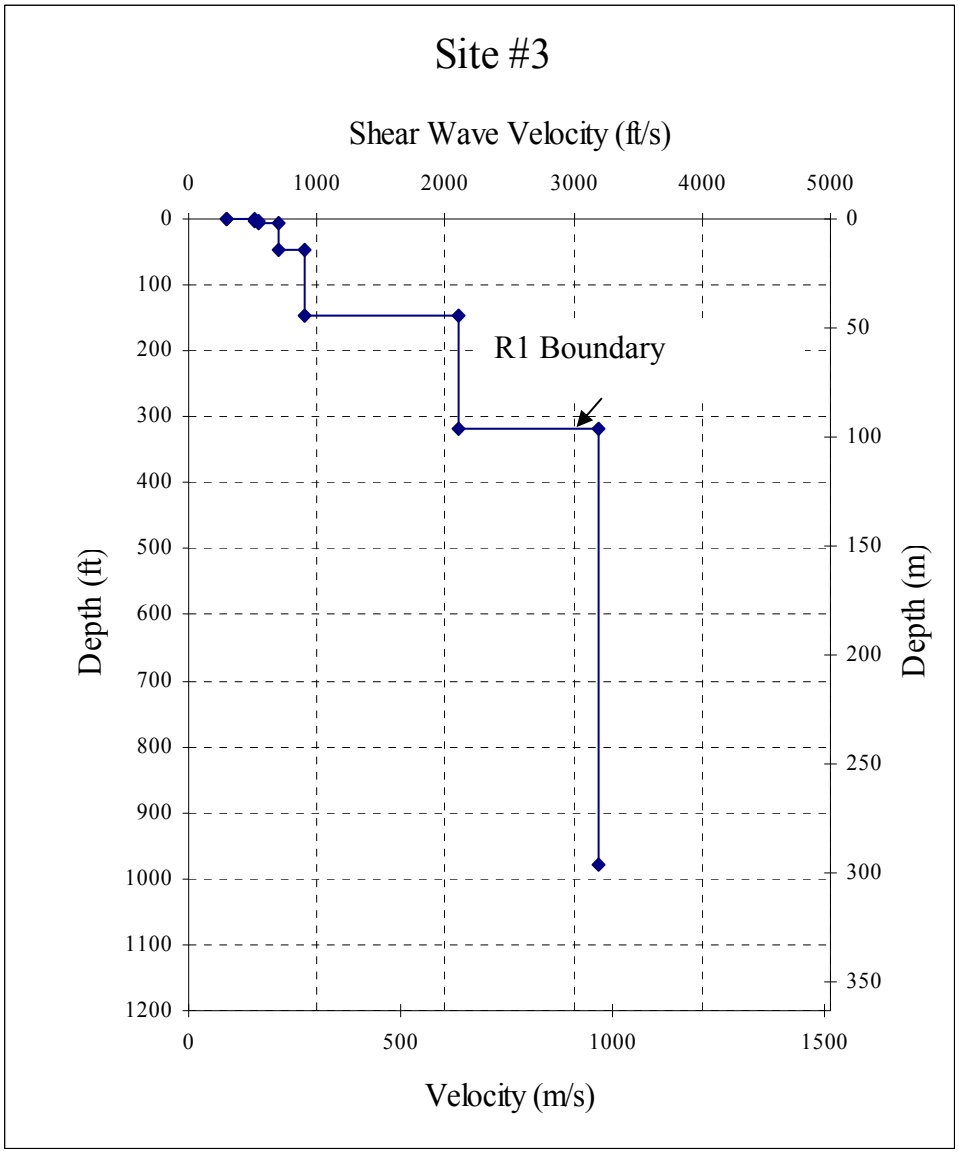

Figure 5.8 Shear wave velocity profile determined at Site 3 (Mt. Jordan Sod Farm)

Table 5.4 Profile Parameters Used to Develop Theoretical Dispersion Curve at Site 3

Layer No.	Thickness, ft	P-Wave Velocity, ft/s	S-Wave Velocity, ft/s	Assumed Poisson's Ratio	Assumed Total Density, pcf
1	0.8	561.3	300	0.30	120
2	1	954.1	510	0.30	120
3	5	1010.3	540	0.30	120
4	40	5200*	700	0.491	120
5	100	5200	900	0.485	120
6	170	5200	2100	0.403	120
7	∞	5986.7	3200	0.30	130

* Depth of Water Table is 6.8 ft

location of Site 4. The star designates the approximate location of the centerline of the array.

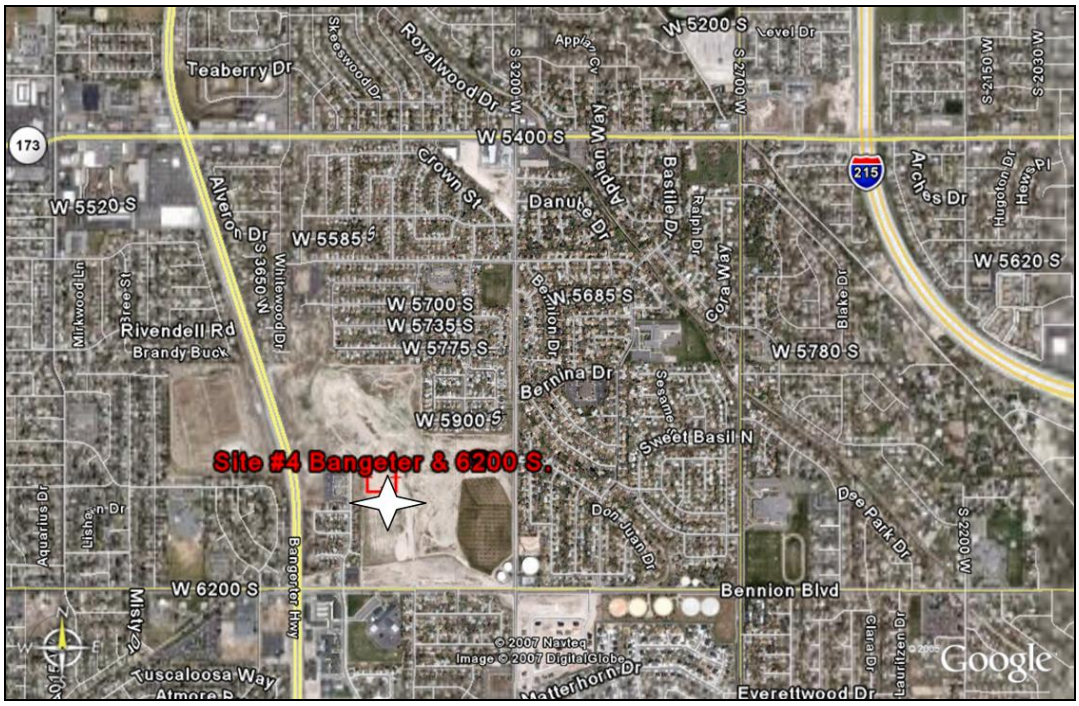

Figure 5.9 Map of Site 4 (Bangerter and 6200 S); from earth.google.com

As shown in Figure 5.2, this site was mapped in the Q02 unit by Ashland and McDonald (2003). The surficial geology is characterized as lacustrine sand, with

interbedded lacustrine silt and clay; as well as the latest Pleistocene to Holocene alluvial-fan deposits. Site 4 is also near the mapped boundary between the Q01/Q02 units where the Q01 unit is identified as having more fine-grained sand than the Q02 unit. The Q02 unit has a mean V_{S30} value of 977 ft/s (298 m/s) whereas the Q01 unit has a mean V_{S30} value of 653 ft/s (199 m/s). An estimated depth to the unconsolidated/semi-consolidated R1 interface is 100 to 250 feet (30 to 75 m) as presented in Wong et al, 2002.

Figure 5.10 shows the Vs profile determined from the SASW test at Site 4. The values of the parameters used to determine the Vs profile are listed in Table 5.5. V_{S30} at Site 4 is 987 ft/s (300 m/s) and the depth to R1 is 625 ft (190 m). These values will be compared with the other measurements in Chapter 6.

5.6. SITE 5: Coon Canyon

Site 5 is located on the western side of the Salt Lake Valley in Coon Canyon. The test line was in a field which was adjacent to a gravel road running along Coon Canyon which leads to the North Oquirrh (NOQ) ANSS strong motion site (Centerline Location: Latitude: 40°39'17.00"N; Longitude: 112° 6'34.00"W). An attempt was made to test adjacent to the strong motion site but it is believed that the reflections from the sloping bedrock canyon led to poor data. The actual test site is located to the east of the strong motion site and is on a field of undisturbed, native sand and gravel. Site 5 is approximately one mile to the east of the strong motion site. Figure 5.11 shows the location of Site 5. The star designates the approximate location of the centerline of the array.

As shown in Figure 5.2, this site was mapped in the Q03 unit by Ashland and McDonald (2003). The surficial geology is characterized as lacustrine and alluvial gravel and sand. Site 5 is also near the mapped boundary between the Q03/Q04 units where the Q04 unit is identified as a pre-Bonneville alluvial-fan deposit. Site 5 is also near the mapped boundary between the Q03/Q02 units where the Q02 unit is

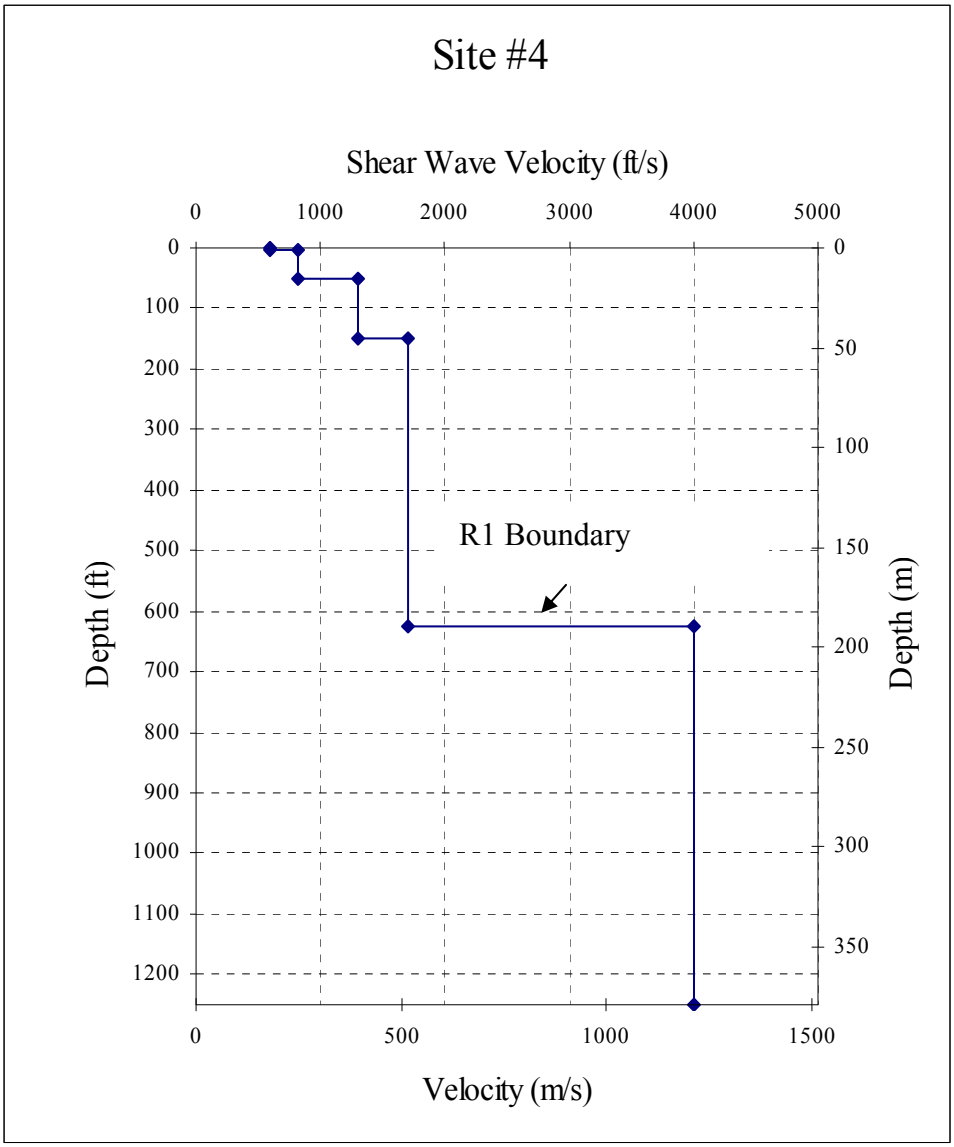

Figure 5.10 Shear wave velocity profile determined at Site 4 (6200 S and Bangerter Hwy.)

Table 5.5 Profile Parameters Used to Develop Theoretical Dispersion Curve at Site 4

Layer No.	Thickness, ft	P-Wave Velocity, ft/s	S-Wave Velocity, ft/s	Assumed Poisson's Ratio	P-Wave Velocity, ft/s
1	5	1122.5	600	0.30	120
2	45	1543.4	825	0.30	120
3	100	2432.1	1300	0.30	120
4	475	5200*	1700	0.440	120
5	∞	7483.3	4000	0.30	130

* Depth to Water Table is 150 ft

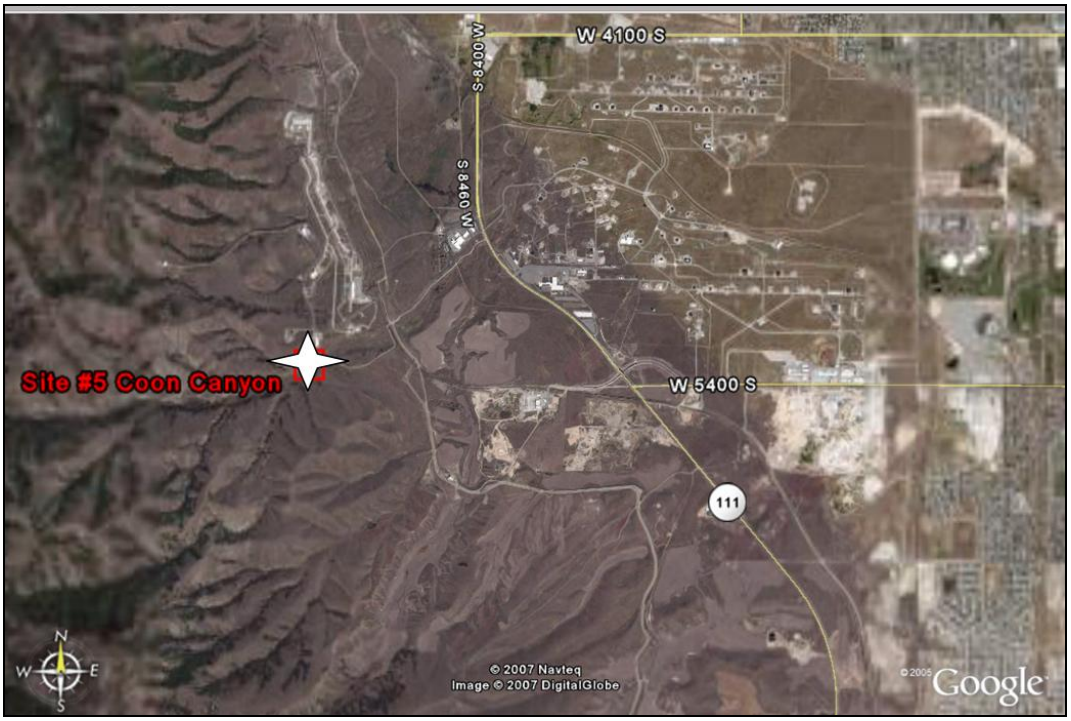

Figure 5.11 Map of Site 5 (Coon Canyon); from earth.google.com

identified as having more silt and clay. Site 5 is also near the "P" unit which is classified as Paleozoic and older sedimentary, igneous, and metamorphic rocks; and Tertiary intrusive rocks. This location may also be further subdivided into a "possible subunit" Coon Canyon-Barneys Creek (CCBC). This "subunit" has values of Vs30 that are in the upper half of the ranges in Vs30 for site class C and this high Vs30 value may reflect the presence of rock or rock-like material at a depth of

approximately 90 ft (25 m) (Ashland and McDonald, 2003). Ashland and Rollins (1999) believed that in this area there was potential for the lacustrine gravels to be underlain by higher shear wave velocity pre-Bonneville alluvial fan gravels (similar to Q04). Figure 5.12 shows the locations of the four sites in this study (5, 6, 7 and 9) which are in these "possible subunits". The Q03 unit has a mean V_{S30} value of 1276 ft/s (389 m/s) whereas the Q02 unit has a mean V_{S30} value of 977 ft/s (298 m/s)and the Q04 unit has a mean V_{S30} value of 1433 ft/s (437 m/s) (Ashland and McDonald, 2003). An estimated depth to the unconsolidated/semi-consolidated R1 interface is less than 150 feet (45 m) according to Wong, et al, 2002.

Figure 5.13 shows the Vs profile determined from the SASW test at Site 5. The values of the parameters used to determine the Vs profile are listed in Table 5.6. V_{S30} at Site 5 is 1385 ft/s (422 m/s) and the depth to R1 is 150 ft (45 m). These values will be compared with other measurements in Chapter 6. The Vs profile extends to a depth of 360 ft (110 m). The profile is not deeper due to the geographical boundaries at Site 5 which limited the maximum receiver spacing distances.

5.7. SITE 6: I-215 Onramp

Site 6 is located on the east side of the Salt Lake Valley along the northbound on-ramp for I-215 at 6200 S (Centerline Location: Latitude: 40°38'19.00"N; Longitude: 111°48'27.00"W). This site is located adjacent to the Old Mill Golf Course. The test line was located on the fill used to construct the onramp although it is unclear the actual depth of fill beneath the test line. Figure 5.14 shows the location of Site 6. The star designates the approximate location of the centerline of the array.

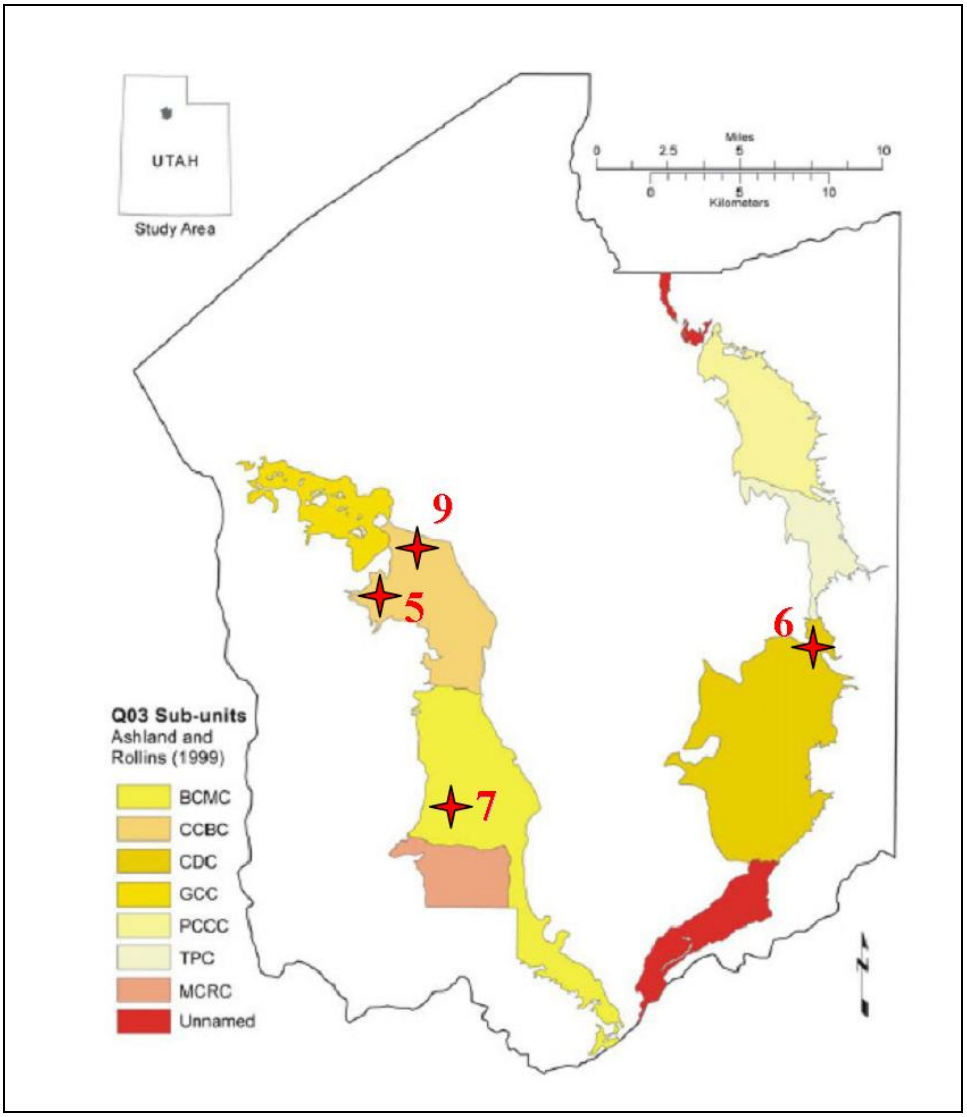

Figure 5.12 Possible Q03 subunits with location of four SASW test locations in the Salt Lake Valley, UT (from Ashland and McDonald, 2003)

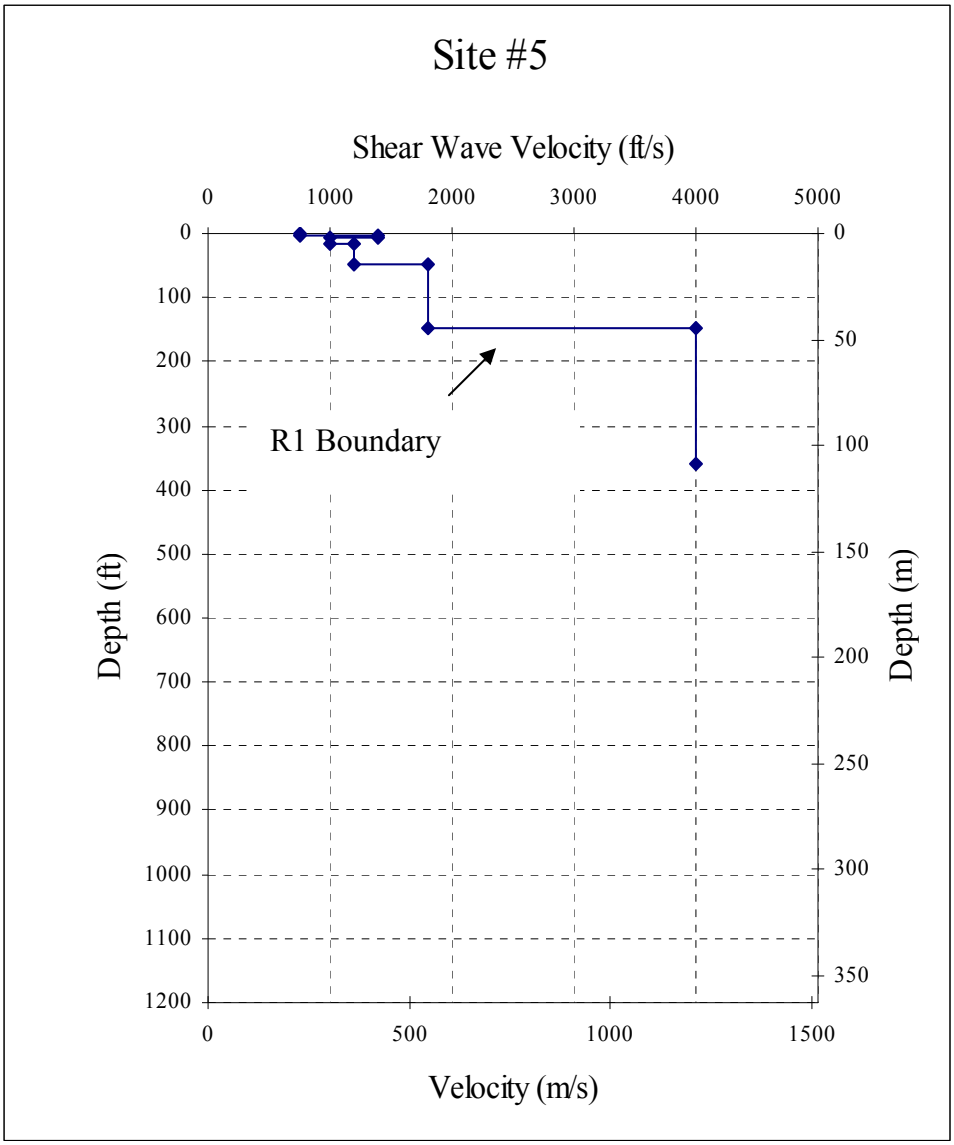

Figure 5.13 Shear wave velocity profile determined at Site 5 (Coon Canyon)

Table 5.6 Profile Parameters Used to Develop Theoretical Dispersion Curve at Site 5

Layer No.	Thickness, ft	P-Wave Velocity, ft/s	S-Wave Velocity, ft/s	Assumed Poisson's Ratio	Assumed Total Density, pcf
1	4.5	1421.8	760	0.30	120
2	3	2619.2	1400	0.30	120
3	10	1683.8	1000	0.30	120
4	30	2245	1200	0.30	120
5	100	3367.5	1800	0.30	120
6	∞	7483.3	4000	0.30	130

Figure 5.14 Map of Site 6 (I-215 Onramp); from earth.google.com

As shown in Figure 5.2, this site was mapped in the Q03 unit by Ashland and McDonald (2003). The surficial geology is characterized as lacustrine and alluvial gravel and sand. Site 6 is also close to the mapped boundary between the Q01/Q03 units where the Q01 unit is identified with more fine grained silt, clay, and sand. Site

6 is also near the mapped boundary between the Q03/Q02 units where the Q02 unit is identified as having more silt and clay. Site 6 is also near very close to the "P" unit which is classified as Paleozoic and older sedimentary, igneous, and metamorphic rocks; and Tertiary intrusive rocks. As seen in Figure 5.12, this site may also be further subdivided into "possible subunit" Cottonwood Delta Complex (CDC). The two previous Vs30 values in this "subunit" are the lower bound of the Vs30 data for unit Q03. The Q03 unit has a mean V_{S30} value of 1276 ft/s (389 m/s) whereas the Q02 unit has a mean V_{S30} value of 977 ft/s (298 m/s); and the Q01 unit has a mean V_{S30} value of 653 ft/s (199 m/s) (Ashland and McDonald, 2003). An estimated depth to the unconsolidated/semi-consolidated R1 interface ranges from 200 to 400 feet (60 to 120 m) as presented in Wong et al, 2002.

Figure 5.15 shows the Vs profile determined from the SASW test at Site 6. The values of the parameters used to determine the Vs profile are listed in Table 5.7. V_{S30} at Site 6 is 1223 ft/s (370 m/s) and the depth to R1 is 245 ft (75 m). These values will be compared with the other measurements in Chapter 6. The Vs profile at Site 6 extends to 750 ft (230 m). The profile is not deeper due to significant noise interference from the adjacent interstate and also due to geographical limitations.

5.8. SITE 7: Kennecott (11800 South)

Site 7 is located in the southwestern portion of the Salt Lake Valley to the north of 11800 South and east of Highway 111 and is located on Kennecott Land Company property (Centerline Location: Latitude: 40°33'4.00"N; Longitude: 112° 3'5.00"W). The test line has an east-west trendline and is located on native, loose sand and gravel. Figure 5.16 shows the location of Site 7. The star designates the approximate location of the centerline of the array.

As shown in Figure 5.2, this site was mapped in the Q03 unit by Ashland and McDonald (2003) The surficial geology is characterized as lacustrine and alluvial gravel and sand. This location may also be further subdivided into "possible subunit"

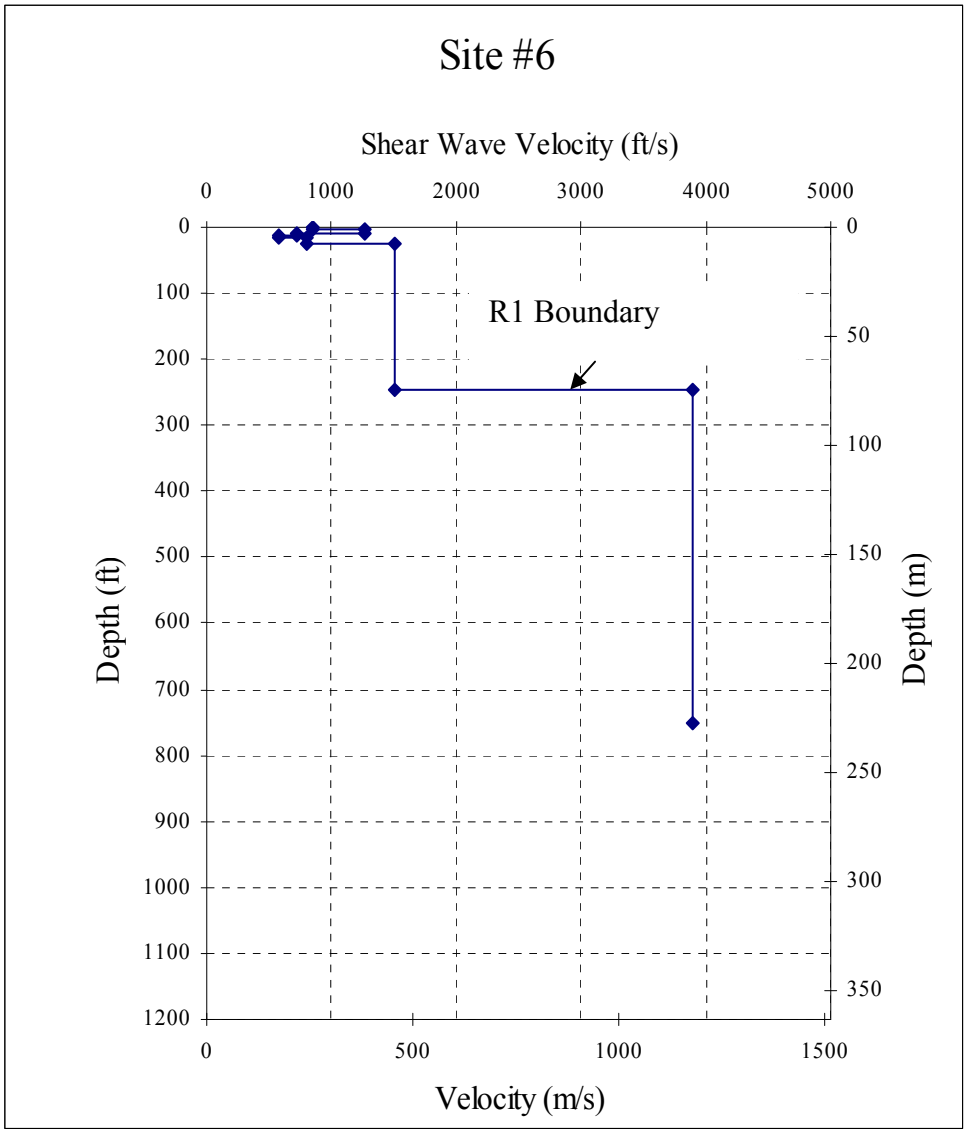

Figure 5.15 Shear wave velocity profile determined at Site 6 (I-215 Onramp)

Table 5.7 Profile Parameters Used to Develop Theoretical Dispersion Curve at Site 6

Layer No.	Thickness, ft	P-Wave Velocity, ft/s	S-Wave Velocity, ft/s	Assumed Poisson's Ratio	Assumed Total Density, pcf
1	2	1590.2	850	0.30	120
2	6	2376	1270	0.30	120
3	3	1356.4	725	0.30	120
4	5	1075.7	575	0.30	120
5	10	1496.7	800	0.30	120
6	220	5200*	1500	0.455	120
7	∞	7296.2	3900	0.30	130

* Depth to Water Table is 26 ft

Figure 5.16 Map of Site 7 (Kennecott); from earth.google.com

Barneys Creek-Midas Creek (BCMC) as shown in Figure 5.12. The BCMC "possible subunit" was identified based on estimated variations in geological characteristics and engineering properties (Ashland and McDonald, 2003). The Q03 unit has a mean

V_{S30} value of 1276 ft/s (389 m/s) (Ashland and McDonald, 2003). An estimated depth to the unconsolidated/semi-consolidated R1 interface is 200 to 400 feet (60 to 120 m) as presented in Wong et al, 2002.

Figure 5.17 shows the Vs profile determined from the SASW test at Site 7. The values of the parameters used to determine the Vs profile are listed in Table 5.8. V_{S30} at Site 7 is 994 ft/s (303 m/s) and the depth to R1 is 300 ft (90 m). These values will be compared with the other measurements in Chapter 6. The Vs profile extends to 600 ft (180 m) at Site 7. The shallow depth is most likely due to the high amount of mining equipment traffic on the Kennecott property.

5.9. SITE 8: Holladay Gun Club

Site 8 is located in the eastern portion of the Salt Lake Valley at the Holladay Gun Club (Centerline Location: Latitude: 40°37'19.00"N; Longitude: 111°47'13.00"W). An attempt was made to test rock near this site but it is believed that the reflections from the sloping bedrock led to poor data. The test line has an east-west trendline and is located on the eastern shooting range. Figure 5.18 shows the location of Site 8. The star designates the approximate location of the centerline of the array.

As shown in Figure 5.2, this site was mapped in the Q05 unit by Ashland and McDonald (2003). The surficial geology is characterized as glacial deposits including till and outwash. The Q05 unit has a mean V_{S30} value of 1594 ft/s (486 m/s) (Ashland and McDonald, 2003). An estimated depth to the unconsolidated/semi-consolidated R1 interface is less than 150 feet (45 m) as presented in Wong et al, 2002.

Figure 5.19 shows the Vs profile determined from the SASW test for Site 8. The values of the parameters used to determine the Vs profile are listed in Table 5.9. V_{S30} at Site 8 is 994 ft/s (303 m/s) and the depth to R1 is 200 ft (60 m). These values

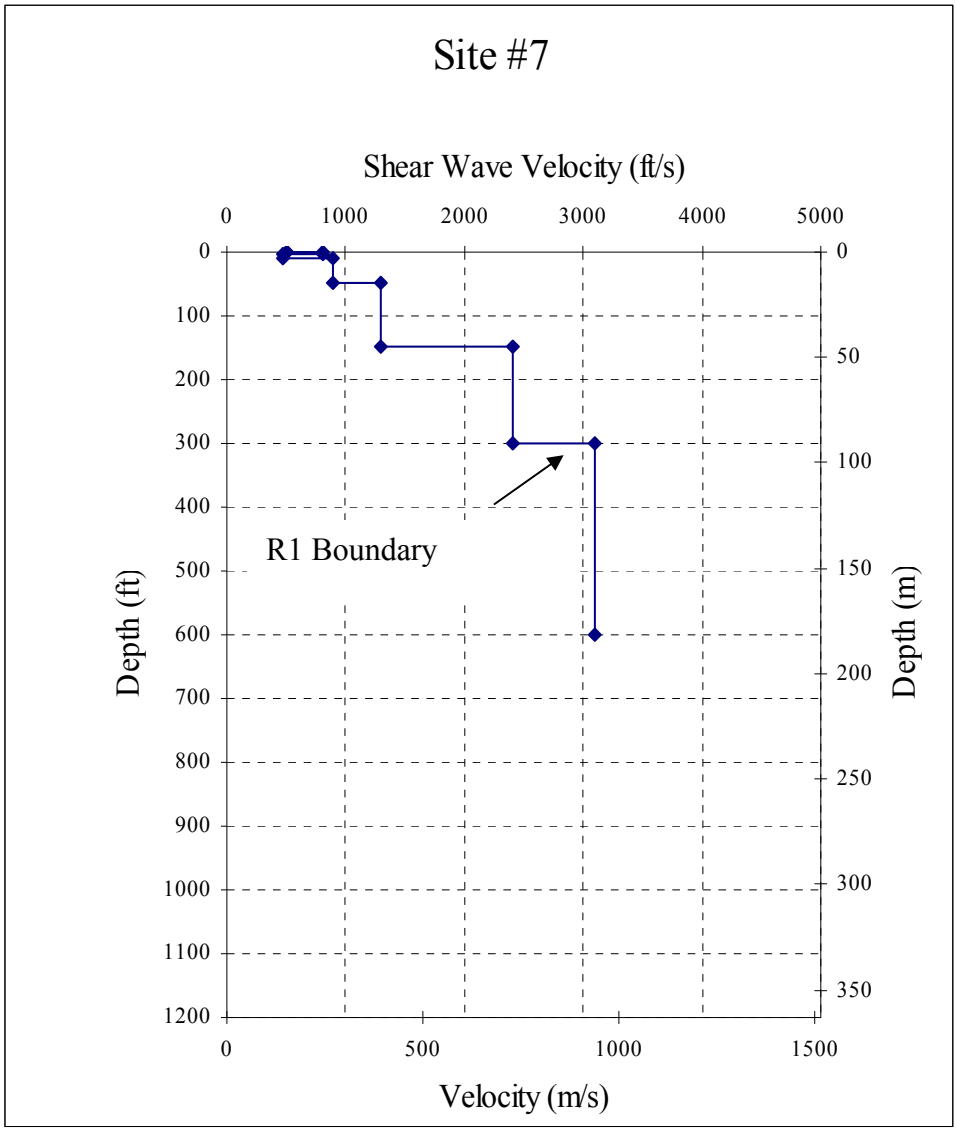

Figure 5.17 Shear wave velocity profile determined at Site 7 (Kennecott)

Table 5.8 Profile Parameters Used to Develop Theoretical Dispersion Curve at Site 7

Layer No.	Thickness, ft	P-Wave Velocity, ft/s	S-Wave Velocity, ft/s	Assumed Poisson's Ratio	Assumed Total Density, pcf
1	1.5	1122.5	500	0.30	120
2	3	1496.7	800	0.30	120
3	5	888.6	475	0.30	120
4	40	1216	900	0.30	120
5	100	2806.2	1300	0.30	120
6	150	5200*	2400	0.365	120
7	∞	5799.6	3100	0.30	130

* Depth to Water Table is 150 ft

will be compared with the other measurements in Chapter 6. Due to very limited space the Vs profile only extends to a depth of 250 ft (75 m).

Figure 5.18 Map of Site 8 (Holladay Gun Club); from earth.google.com

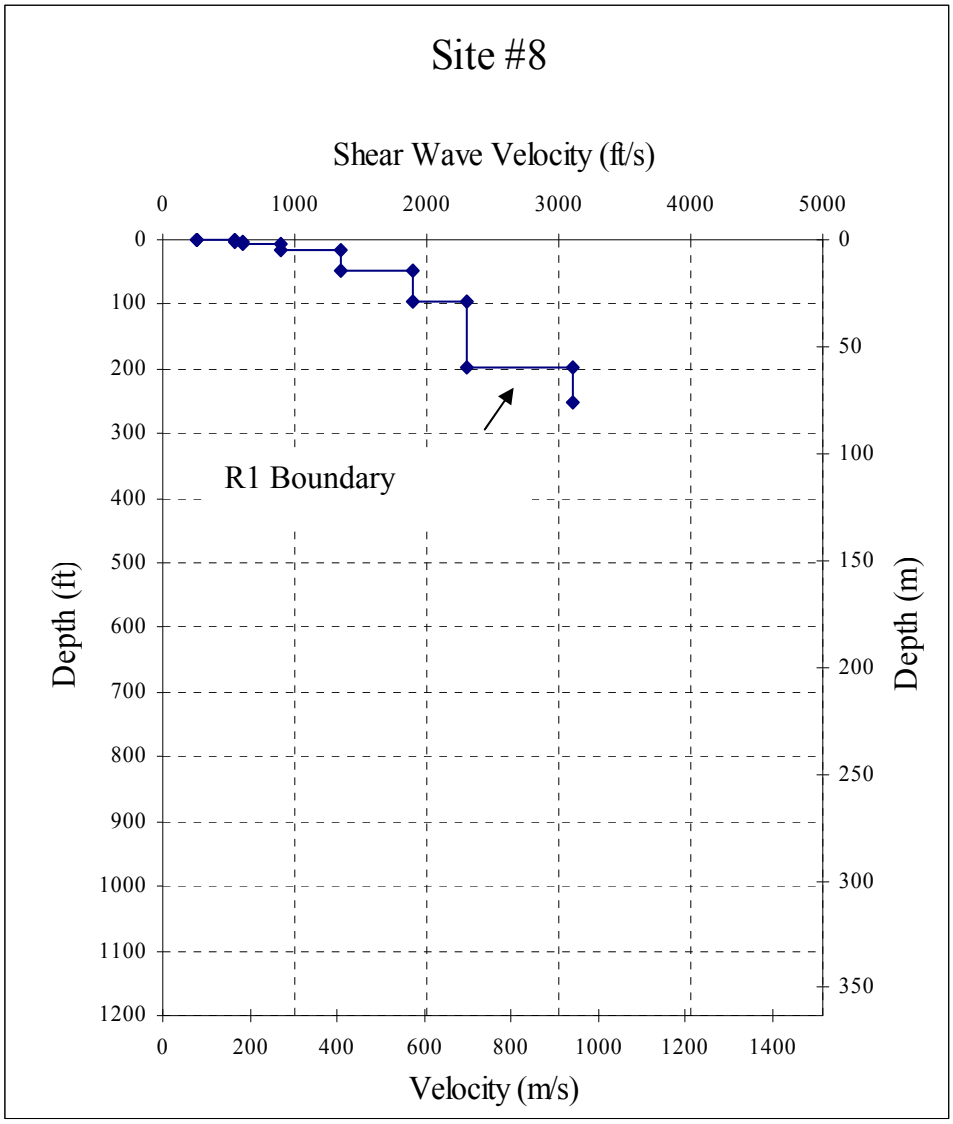

Figure 5.19 Shear wave velocity profile determined at Site 8 (Holladay Gun Club)

Table 5.9 Profile Parameters Used to Develop Theoretical Dispersion Curve at Site 8

Layer No.	Thickness, ft	P-Wave Velocity, ft/s	S-Wave Velocity, ft/s	Assumed Poisson's Ratio	Assumed Total Density, pcf
1	0.6	467.7	250	0.30	120
2	1	1029	550	0.30	120
3	5	1122.5	600	0.30	120
4	10	1683.8	900	0.30	120
5	30	2525.6	1350	0.30	120
6	50	3554.6	1900	0.30	120
7	100	4302.9	2300	0.30	120
8	∞	5799.6	3100	0.30	130

5.10. SITE 9: Fire Training Tower

The Salt Lake County Fire Training Tower is located in the northwest corner of the Salt Lake Valley, northwest of the intersection of 4100S and 8000W (Centerline Location: Latitude: 40°41'11.00"N; Longitude: 112° 5'7.00"W). The test line has an east-west trendline and is located on a gravel road. Figure 5.20 shows the location of Site 9. The star designates the approximate location of the centerline of the array.

As shown in Figure 5.2, this site was mapped in the Q03 unit by Ashland and McDonald (2003). The surficial geology is characterized as lacustrine and alluvial gravel and sand. Site 9 may also be further subdivided into "possible subunit" Coon Canyon-Barneys Creek (CCBC) as shown in Figure 5.12. This "subunit" is in the upper half of the range in Vs30 for site class C and this high Vs30 value reflects the presence of rock or rock-like material at a depth of approximately 90 ft (25 m) (Ashland and McDonald, 2003). Ashland and Rollins (1999) believed that in this area there was potential for the lacustrine gravels to be underlain by higher shear wave velocity pre-Bonneville alluvial fan gravels (similar to Q04). The Q03 unit has a mean V_{S30} value of 1276 ft/s (389 m/s) (Ashland and McDonald, 2003). An

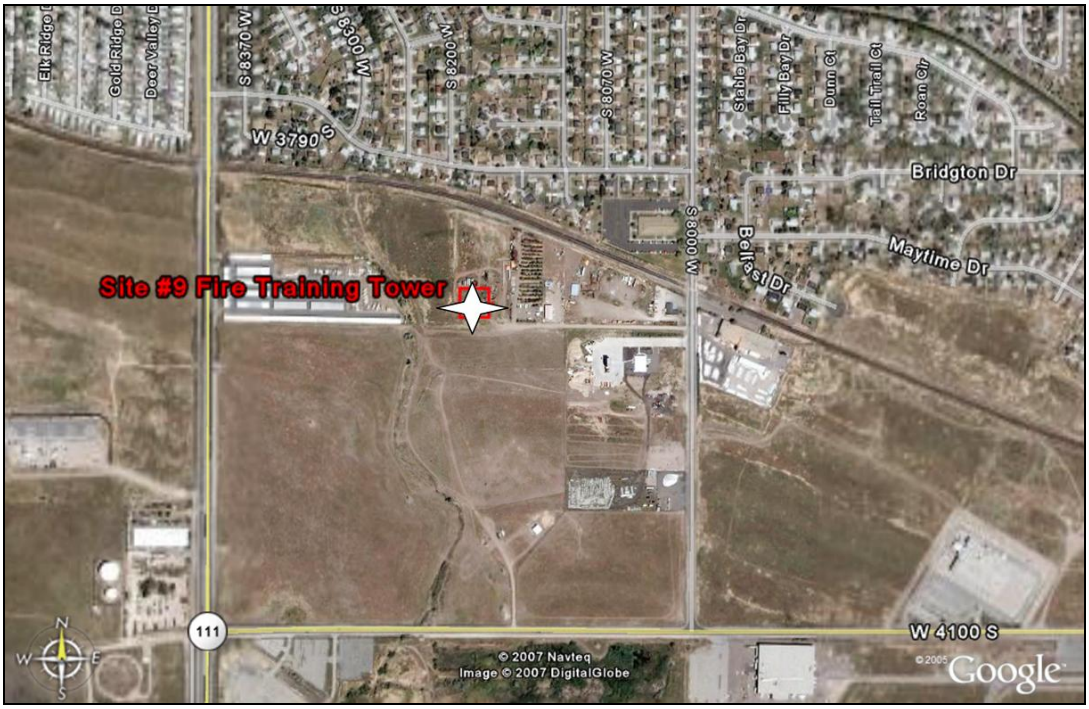

Figure 5.20 Map of Site 9 (Fire Training Tower); from earth.google.com

estimated depth to the unconsolidated/semi-consolidated R1 interface is 50 to 150 feet (15 to 45 m) as presented in Wong et al, 2002.

Figure 5.21 shows the Vs profile determined from the SASW test at Site 9. The values of the parameters used to determine the Vs profile are listed in Table 5.10. V_{S30} at Site 9 is 1357 ft/s (414 m/s) and the depth to R1 is 120 ft (35 m). These values will be compared with the other measurements in Chapter 6. The Vs profile at Site 9 extends to a depth of 500 ft (150 m) due to geographical limitations which limited receiver spacings and the possible presence of igneous intrusions on the western portion of the array.

5.11. SITE 10: 5600W and 640S

Site 10 is located in the northwest portion of the Salt Lake Valley northwest of the intersection of 5600W and 640S (Centerline Location: Latitude: 40°45'26.00"N;

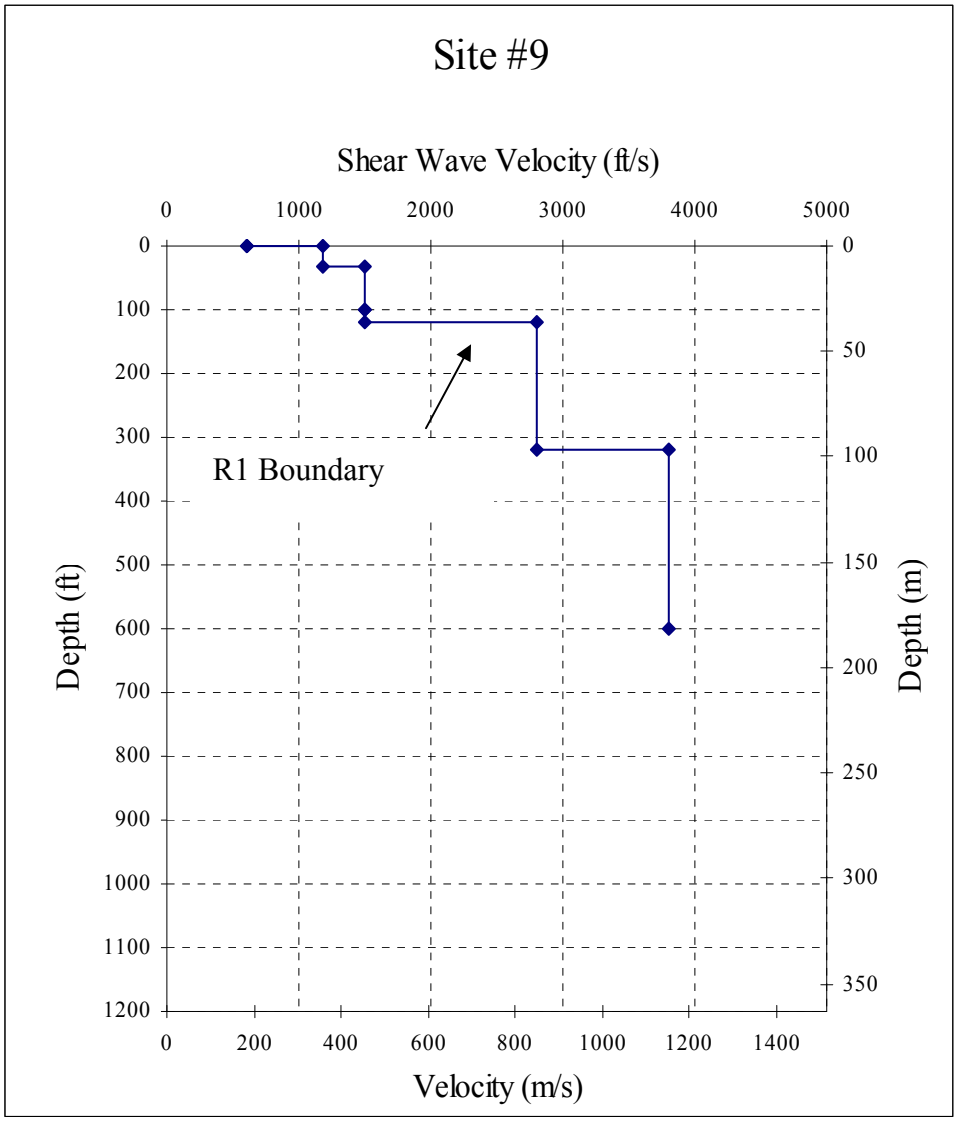

Figure 5.21 Shear wave velocity profile determined at Site 9 (Fire Training Tower)

Table 5.10 Profile Parameters Used to Develop Theoretical Dispersion Curve at Site 9

Layer No.	Thickness, ft	P-Wave Velocity, ft/s	S-Wave Velocity, ft/s	Assumed Poisson's Ratio	Assumed Total Density, pcf
1	1.5	1122.5	600	0.30	120
2	30	2198.2	1175	0.30	120
3	68	2806.2	1500	0.30	120
4	20	5200*	1500	0.455	120
5	200	5238.3	2800	0.30	120
6	∞	7109.2	3800	0.30	130

* Depth to Water Table is 99.5 ft

Longitude: 112° 1'38.00"W). The test line has a north-south trendline and is located on native, loose, silty sand/sandy silt. Figure 5.22 shows the location of Site 10. The star designates the approximate location of the centerline of the array.

As shown in Figure 5.2, this site was mapped in the Q01 Unit by Ashland and McDonald (2003). The surficial geology can be classified as lacustrine and alluvial silt, clay, and fine sand. Also, in the Q01 Unit alluvial or marsh deposits typically overlie lacustrine deposits. The Q01 unit has a Vs30 value of 653 ft/s (199 m/s) (Ashland and McDonald, 2003). An estimated depth to the unconsolidated/semi-consolidated R1 interface is 400 to 600 feet (120 to 180 m) as presented in Wong, et al, 2002.

Site 10 is also located near to one well which has a sonic log, Well #3 in Figure 3.2. The approximate depth to the R1 interface between unconsolidated and semi-consolidated sediments at Well #3 is interpreted to be 500 feet (150 m). This value matches with the value presented in Wong et al, 2002.

Figure 5.23 shows the Vs profile determined from the SASW test at Site 10. The values of the parameters used to determine the Vs profile are listed in Table 5.11.

Figure 5.22 Map of Site 10 (5600W and 640S); from earth.google.com

V_{S30} at Site 1 is 663 ft/s (202 m/s) and the depth to R1 is 535 ft (165 m). These values will be compared with the other measurements in Chapter 6. The profile at Site 10 may only extend to a depth of 650 ft (200 m) due to difficulty in propagating the longer wavelengths through the silts and clays that are present at this site or due to lateral inhomogeneity beneath the SASW array.

5.12. SITE 11: Municipal Airport #2

Site 11 is located in the west-central portion of the Salt Lake Valley adjacent to Municipal Airport #2 (Centerline Location: Latitude: 40°37'55.00"N; Longitude: 111°59'58.00"W). The test line has a north-south trendline and is located on compacted silty sand fill alongside Airport Road. Figure 5.24 shows the location of Site 11. The star designates the approximate location of the centerline of the array.

As shown in Figure 5.2, this site was mapped in the Q02 unit by Ashland and McDonald (2003). The surficial geology is characterized as lacustrine sand, with

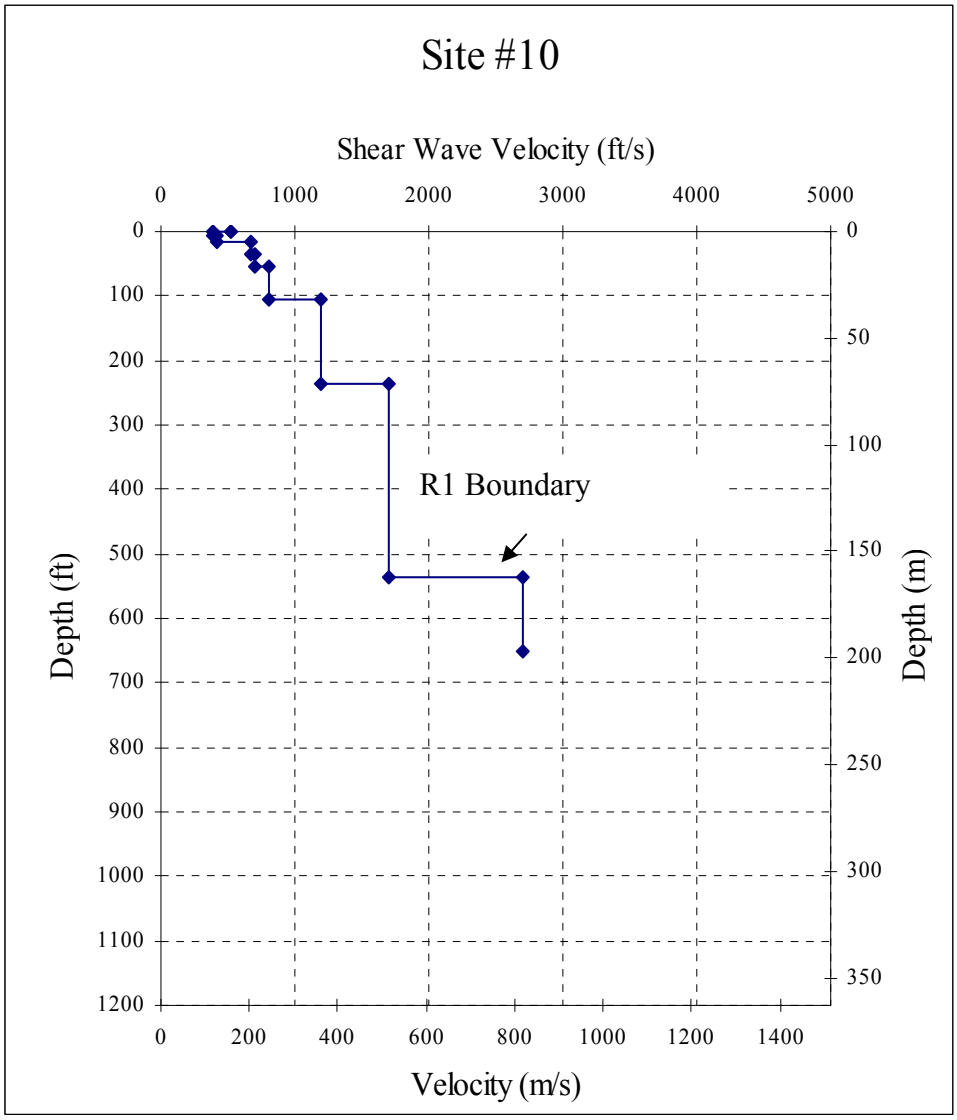

Figure 5.23 Shear wave velocity profile determined at Site 10 (5600W and 640S)

Table 5.11 Profile Parameters Used to Develop Theoretical Dispersion Curve at Site 10

Layer No.	Thickness, ft	P-Wave Velocity, ft/s	S-Wave Velocity, ft/s	Assumed Poisson's Ratio	Assumed Total Density, pcf
1	1.5	982.2	525	0.30	120
2	4	739	395	0.30	120
3	10	5200*	415	0.497	120
4	20	5200	675	0.491	120
5	20	5200	700	0.491	120
6	50	5200	800	0.488	120
7	130	5200	1200	0.472	120
8	300	5200	1700	0.440	120
9	∞	5200	2700	0.315	130

* Depth to Water Table is 5.5 ft

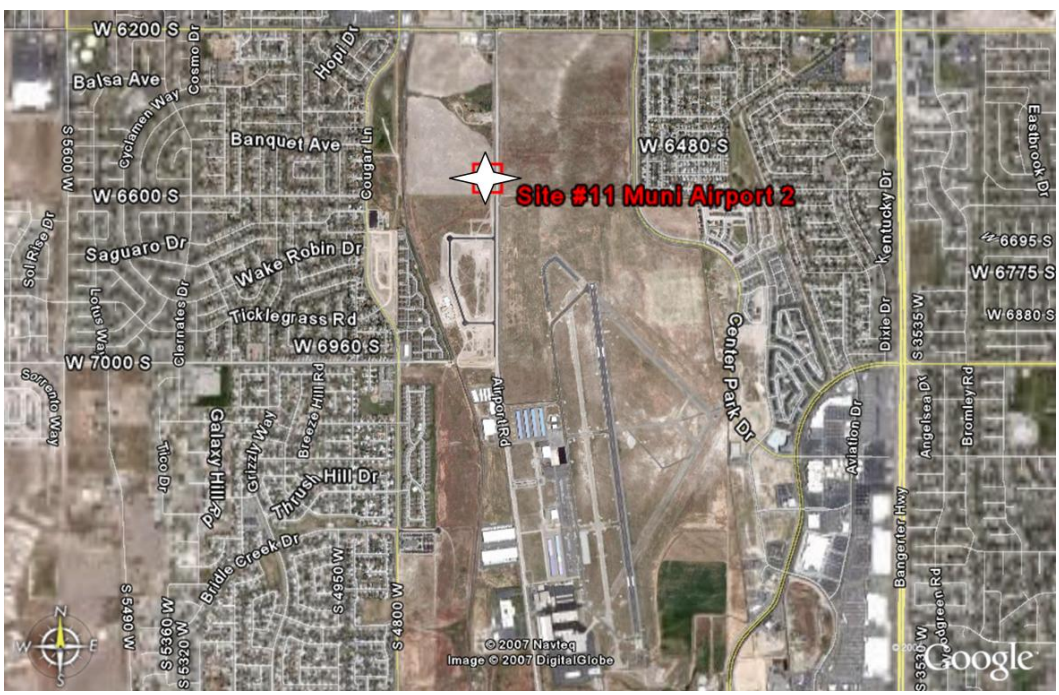

Figure 5.24 Map of Site 11 (Municipal Airport #2); from earth.google.com

interbedded lacustrine silt and clay; as well as the latest Pleistocene to Holocene alluvial-fan deposits. This site is close to the Q02/Q03 boundary; where the Q03 unit is identified as having a higher gravel content than the Q02 unit. The Q02 unit has a mean V_{S30} value of 977 ft/s (298 m/s) whereas the Q03 unit has a mean V_{S30} value of

1276 ft/s (389 m/s) (Ashland and McDonald, 2003). An estimated depth to the unconsolidated/semi-consolidated R1 interface is 100 to 200 feet (30 to 60 m) as presented in Wong et al, 2002.

Figure 5.25 shows the Vs profile determined from the SASW test at Site 3. The values of the parameters used to determine the Vs profile are listed in Table 5.12. V_{S30} at Site 2 is 1116 ft/s (340 m/s) and the depth to R1 is 390 ft (120 m). These values will be compared with the other measurements in Chapter 6.

5.13 Summary

Eleven SASW arrays were evaluated in the Salt Lake Valley. These locations were spread across the valley to test as many Quaternary units as possible and to attempt to obtain a good sample of the entire valley. The location of each site was presented as well as the respective Quaternary unit in which each site was located. A Vs profile was provided for each site as well as a table which lists the parameters used to determine the Vs profile. The Vs_{30} for each site as well as the depth to R1 was also presented.

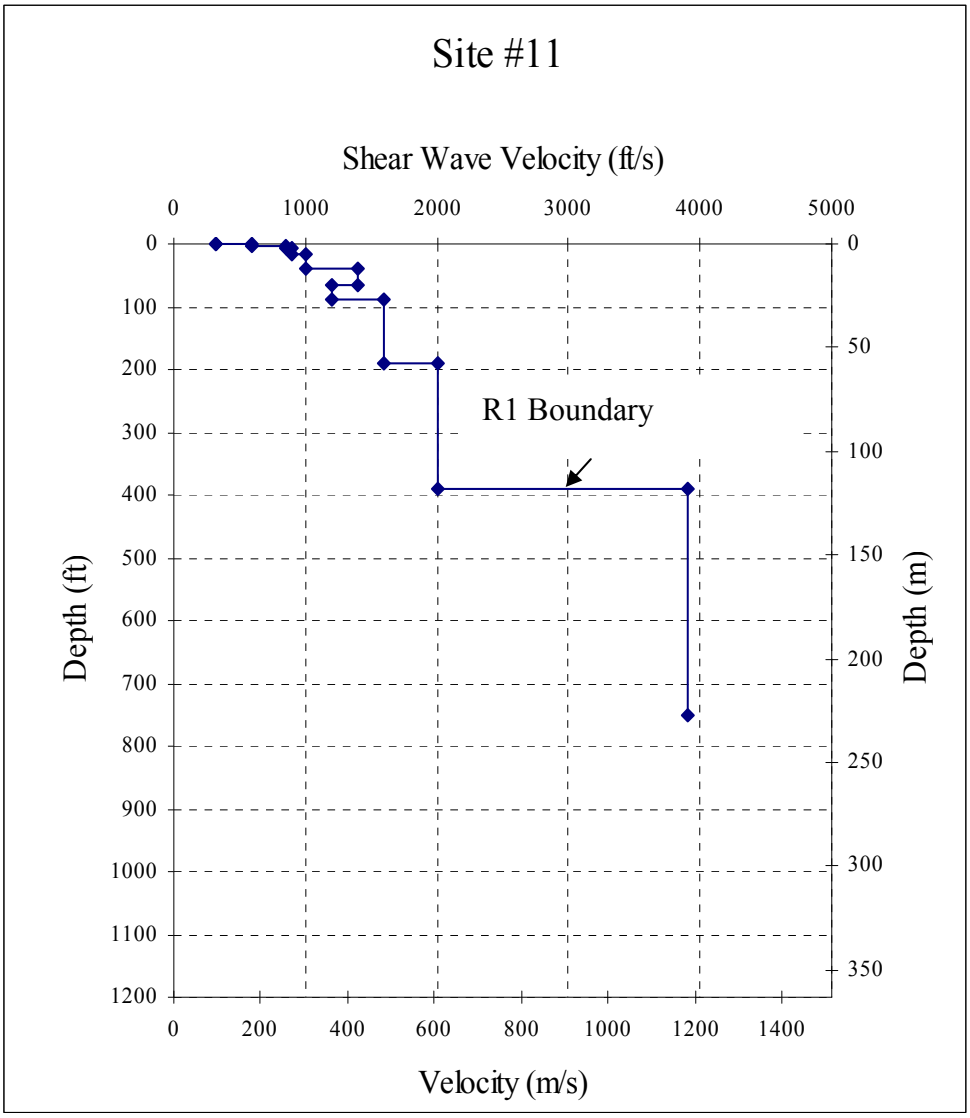

Figure 5.25 Shear wave velocity profile determined at Site 11 (Municipal Airport #2)

Table 5.12 Profile Parameters Used to Develop Theoretical Dispersion Curve at Site 11

Layer No.	Thickness, ft	P-Wave Velocity, ft/s	S-Wave Velocity, ft/s	Assumed Poisson's Ratio	Assumed Total Density, pcf
1	1	598.7	320	0.3	120
2	1.5	1122.5	600	0.3	120
3	2.5	1590.2	850	0.3	120
4	10	1683.8	900	0.3	120
5	25	1870.8	1000	0.3	120
6	25	2619.2	1400	0.3	120
7	25	5200*	1200	0.4719	120
8	100	5200	1600	0.4477	120
9	200	5720.2	2000	0.4304	120
10	∞	7296.2	3900	0.3	130

* Depth to Water Table is 65 ft

CHAPTER 6

ANALYSIS OF Vs PROFILES MEASURED IN THE SALT LAKE VALLEY

6.1. Overview

To develop the CVM, six deep (≥ 750 ft (230 m)) and five intermediate-depth (250 ft (75 m) to 750 ft (230 m)) sites were tested. An unsuccessful attempt was made to test rock at Sites 5 and 8 in Figure 5.1. Testing was unsuccessful because of insufficient lateral extent to permit profiling through surficial sediments. The purpose of the analysis is to investigate the eleven Vs profiles: (1) to try to develop sets of Vs profiles that fit the different material types, (2) to determine the depths to the R1 and R2 boundaries based on Vs>2500 ft/s (760 m/s) for the R1 boundary and Vs>4900 ft/s (1500 m/s) for the R2 boundary, (3) to compare the Vs profiles with measurements from other studies, and (4) to compare the Vs profiles with empirical data.

6.2. Profiling Depths and Depths to the R1 Boundary

The total depth of the Vs profile at each site and the depth to the R1 boundary are presented in Table 6.1. The site locations are shown in Figure 5.1. The R1 boundary was found in all eleven Vs profiles while the R2 boundary was not seen in any of the Vs profiles.

In Table 6.2, the R1 boundary determined by the SASW test method and from Wong et al, 2002 are compared. Five of the eleven sites have depths to the R1 boundary that match (Sites 5, 6, 7, 9, and 10). A "match" was considered to occur when the depths were within 10% of each other. Site 2 is outside the mapped area so no comparison can be made. The depth to the R1 boundary determined by the SASW test method at Site 1 (665 ft (200m)) is approximately half of the mapped value (1400 ft to 2000 ft (425 to 610 m)). The depth to the R1 boundary at Site 3 determined by

Table 6.1 Depth of Each Vs Profile and Depth to the R1 Boundary in the Profile

SITE #	Name	Profile Depth ft (m)	Depth to R1 ft (m)
1	Legacy Parkway South (Center St.)	1000 (305)	665 (205)
2	Legacy Parkway North (Farmington)	800 (245)	400 (120)
3	Mt Jordan Sod Farm	980 (300)	315 (95)
4	6200 S. & Bangeter Hwy	1250 (380)	625 (190)
5	Coon Canyon	360 (110)	150 (45)
6	I-215 Onramp at 6200 S	750 (230)	245 (75)
7	Kennecott	600 (180)	300 (90)
8	Holladay Gun Club	250 (75)	200 (60)
9	Fire Training Tower	500 (150)	120 (35)
10	5600 W & 640 S.	650 (200)	535 (165)
11	Municipal Airport #2	750 (230)	390 (120)

Table 6.2 Comparison R1 Depths from Wong et al (2002) and from the SASW Vs Profiles

	Depth to R1 Boundary ft (m)	
SITE #	Wong et al (2002)	SASW
1	1400-2000 (425-610)	665 (200)
2	xx *	400 (120)
3	150 (45)	315 (95)
4	120-360 (35-110)	625 (190)
5	<150 (<45)	150 (45)
6	200-400 (60-120)	245 (75)
7	200-400 (60-120)	300 (90)
8	<150 (<45)	195 (60)
9	50-150 (15-45)	120 (37)
10	400-600 (120-180)	535 (165)
11	100-200 (30-60)	390 (120)

* Site 2 is outside the mapped area in Wong et al, 2002

the SASW method (315 ft (95 m)) is approximately double the mapped value (150 ft (45 m)). The depth to the R1 boundary at Site 4 determined by the SASW method (625 ft (190 m)) is approximately double the mapped value (120 to 360 ft (35 to 110 m)).

In addition to the comparison of depths to the R1 boundary from the map (Wong et al, 2002), Site 1 is located near Well #2 (Figures 3.2 and 3.3). Well #2 indicates a depth to R1 of approximately 1000 ft (300 m) which is deeper than the depth to R1 determined by the SASW test method at Site 1 (665 ft (200 m)). Site 10 is located near Well #3 (Figures 3.2 and 3.3). Well #3 indicates a depth to R1 of approximately 500 ft (150 m) which is close (within 10%) to the depth to R1 determined by the SASW test method at Site 10 (535 ft (160 m)).

6.3. Vs Profiles

Figure 6.1 shows a comparison of all 11 SASW shear wave velocity profiles determined in this study. As seen in the figure, a similarity between all the sites is that Vs increases with depth. After that similarity, there are significant differences between the sites. Therefore, they do not fall into one group but need to be subdivided into groups as discussed below.

6.3.1. Groupings of Vs Profiles

The 11 sites have been grouped according to the surficial geology at the site and the location of each site in the Salt Lake Valley. The sites were divided into three groups as follows: Group 1 - silt, clay and fine sand in the northern portion of the valley (Sites 1, 2, and 10); Group 2 - sand with interbedded clay and silt in the central and south-central portions of the valley (Sites 3, 4, 11); and Group 3 - sand and gravel in the east and west margins of the valley (Sites 5, 6, 7, 8, and 9). Figures 6.2 through 6.4 show the profiles for these three classifications. As seen in these figures, the Vs profiles within each group are similar in terms of shear wave velocities and depths to the R1 boundary.

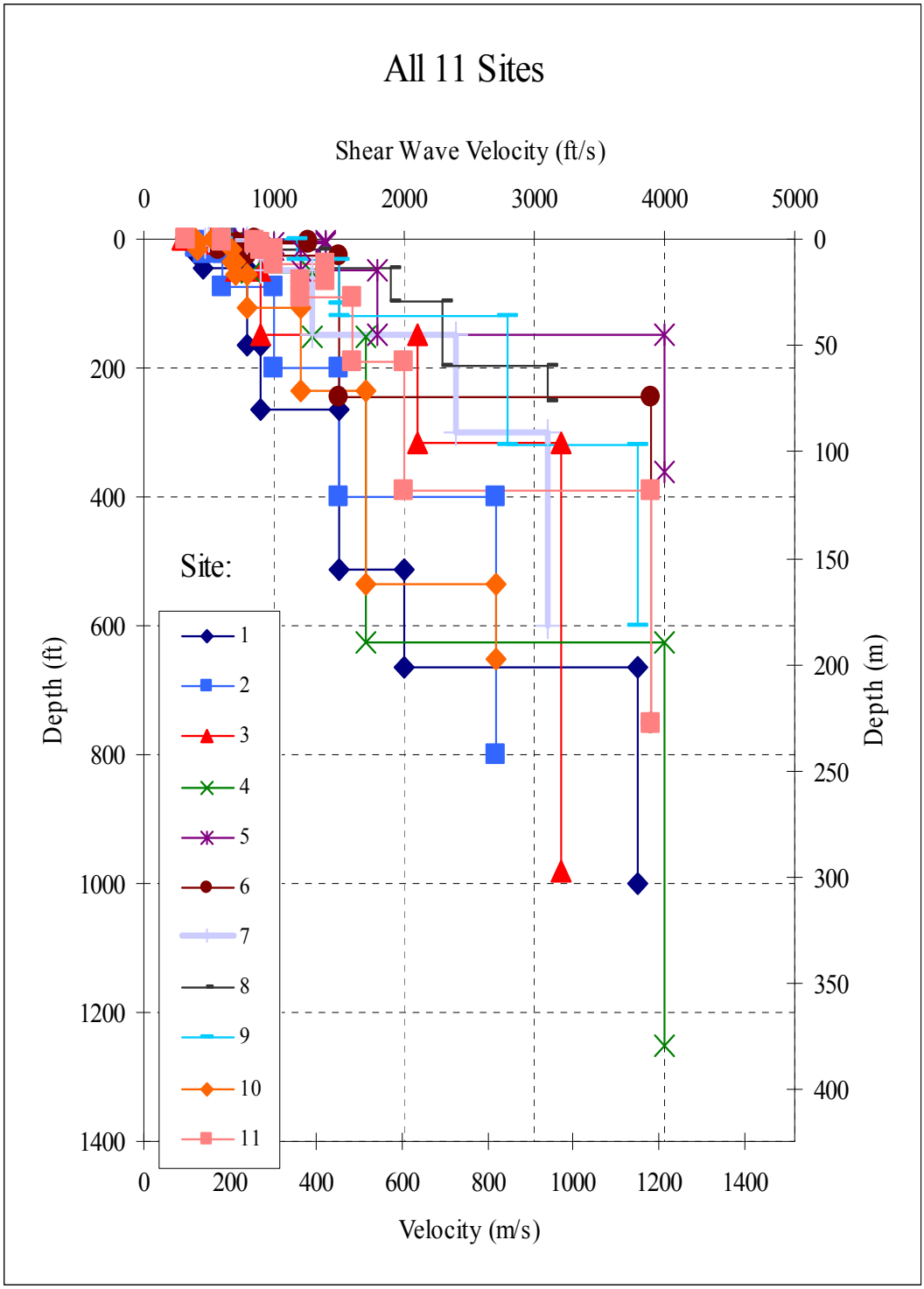

Figure 6.1 Shear wave velocity profiles for all 11 Sites

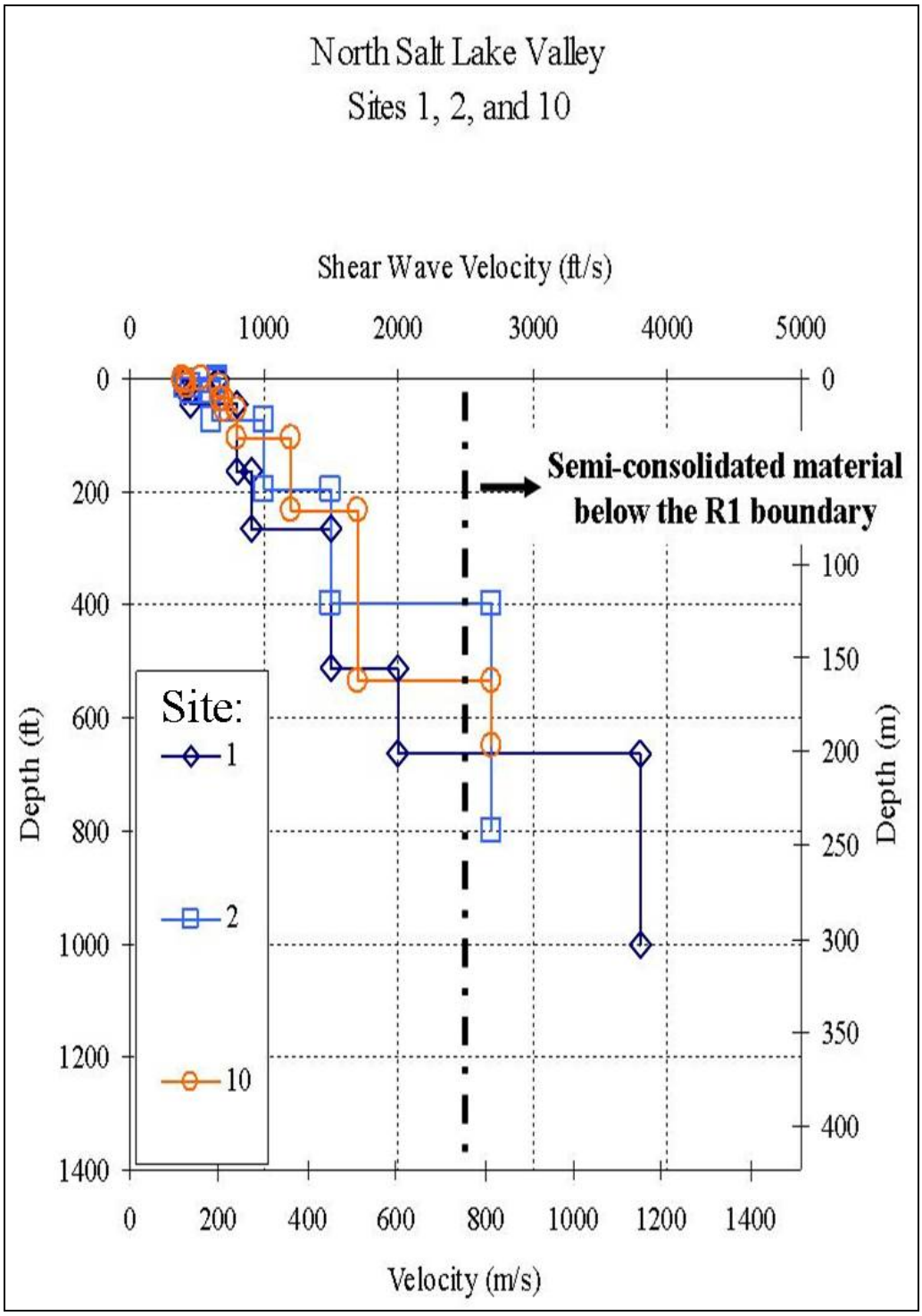

Figure 6.2 Shear wave velocity profiles for Group 1 - clay, silt, and fine sand in the northern portion of the Salt Lake Valley

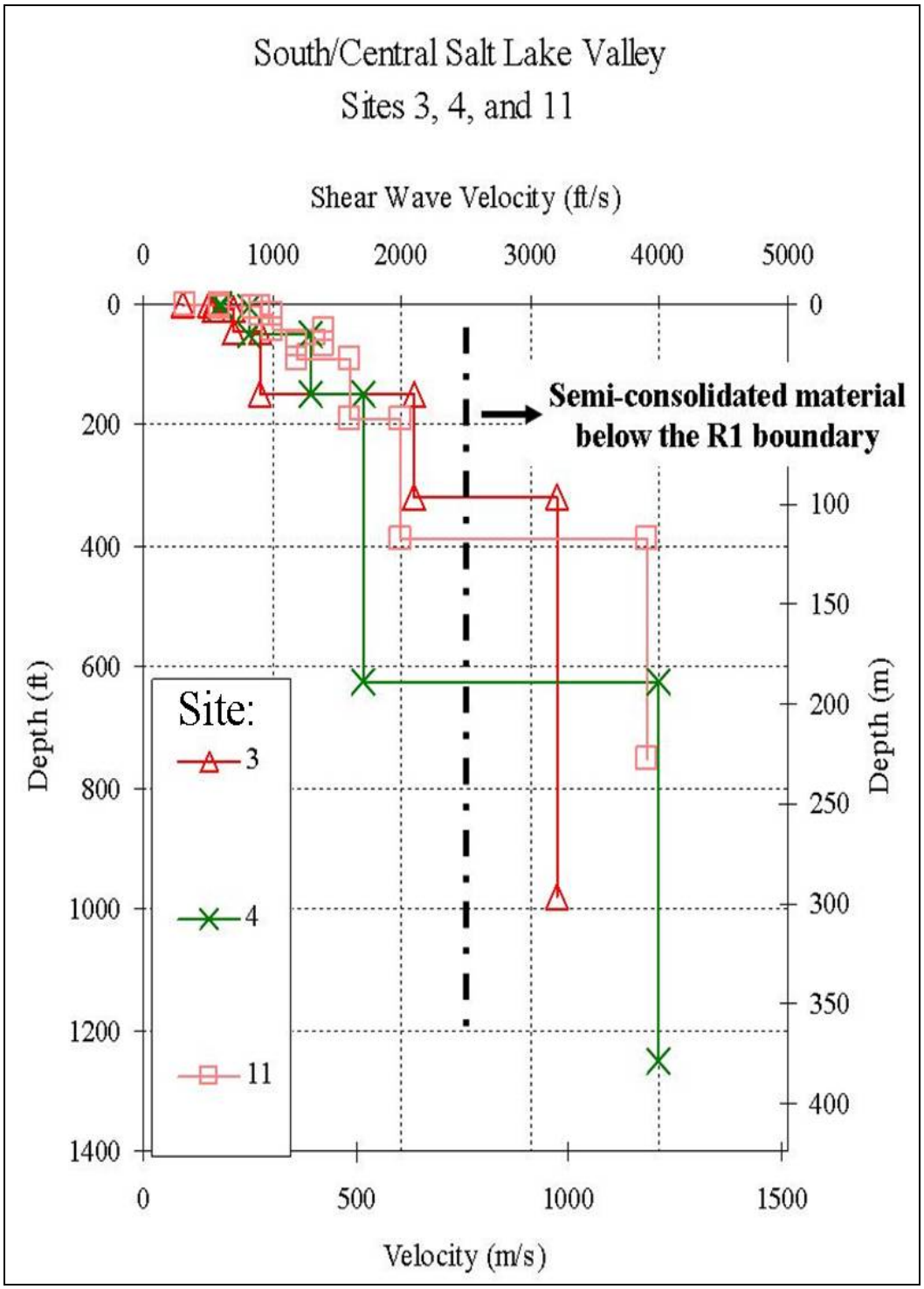

Figure 6.3 Shear wave velocity profiles for Group 2 - sand with interbedded clay and silt in the south/central portion of the Salt Lake Valley

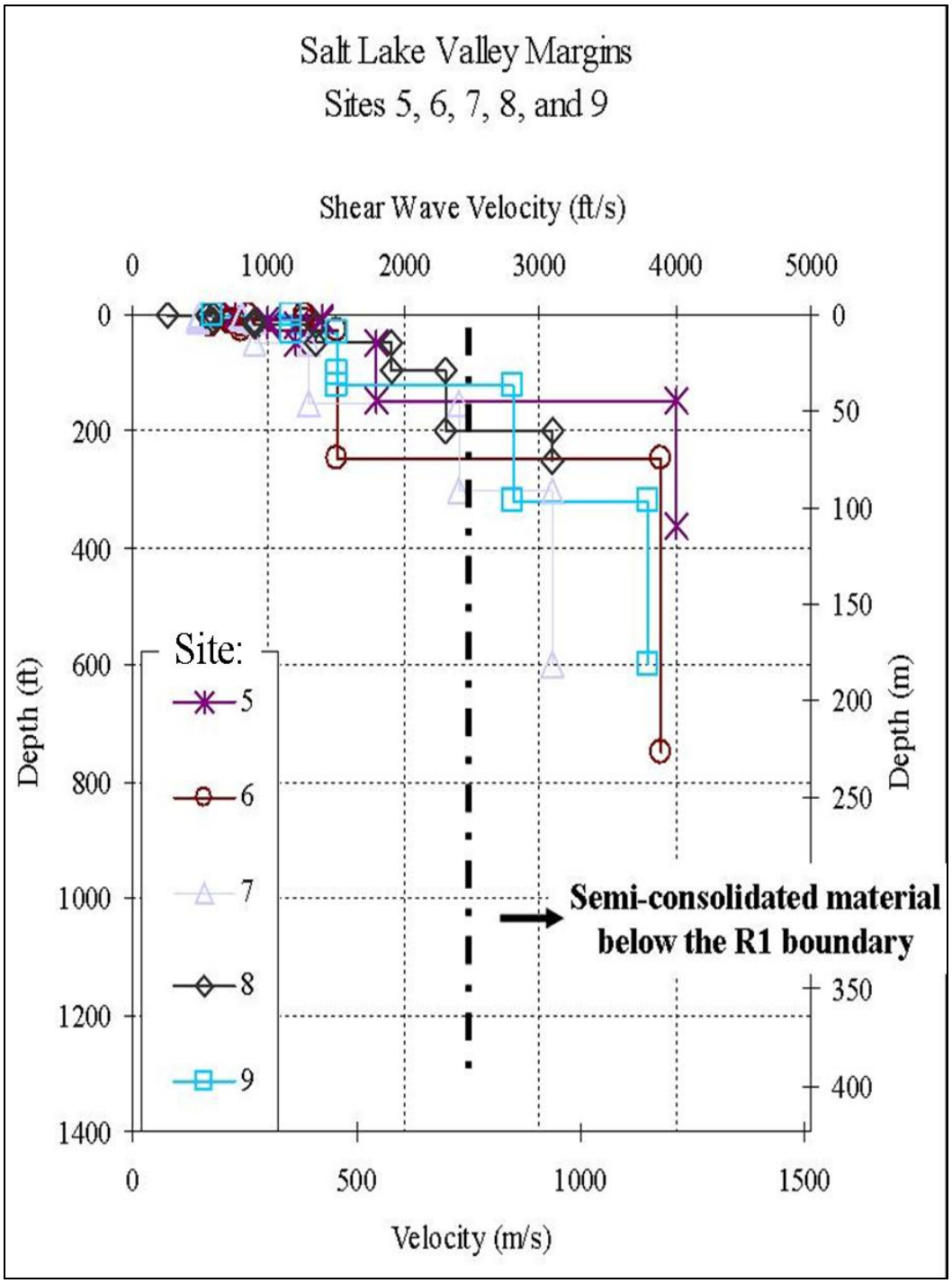

Figure 6.4 Shear wave velocity profiles for Group 3 - sand and gravel in the margins of the Salt Lake Valley

6.3.2. Grouping of Unconsolidated Sediments

To better visualize the three groupings, only the material above the R1 boundary (unconsolidated sediments) is shown in Figures 6.5 through 6.7. A "best-fit" curve is also shown in these figures. The "best-fit" curves were simply determined by eye.

As seen in Figures 6.5 through 6.7, Group 1 has the lowest Vs values above the R1 boundary while Group 3 has the highest Vs values above the R1 boundary. This relative difference is more easily seen by comparing the "by eye" curves in Figure 6.8. The depths to the R1 boundary are greatest in Group 1 and least in Group 3. Also, Group 3 exhibits the greatest range in Vs in the unconsolidated sediments.

6.3.3. Groupings of Semi-Consolidated Sediments (Material below the R1 Boundary)

To study only the material between the R1 and R2 boundary (semi-consolidated sediments below the R1 boundary), the Vs profiles below the R1 boundary are shown in Figures 6.9 through 6.11 for the material below Groups 1, 2 and 3, respectively. None of the profiles reach the depth of the R2 boundary. As seen in the figures, all of these Groups have semi-consolidated Vs values less than 4000 ft/s (1200 m). Groups 2 and 3 have higher Vs values in the semi-consolidated layer than Group 1. However, this may be the result of the limited number of profiles that were measured in any group. In Group 3, Site 9 is the only site that has a Vs "jump" after the R1 boundary. Below the R1 boundary at Site 9, the Vs increases from 2800 ft/s (840 m/s) to 3800 ft/s (1140 m/s) at a depth of 320 ft (95 m). The depth to the R1 boundary at Site 9 is 120 ft (35 m).

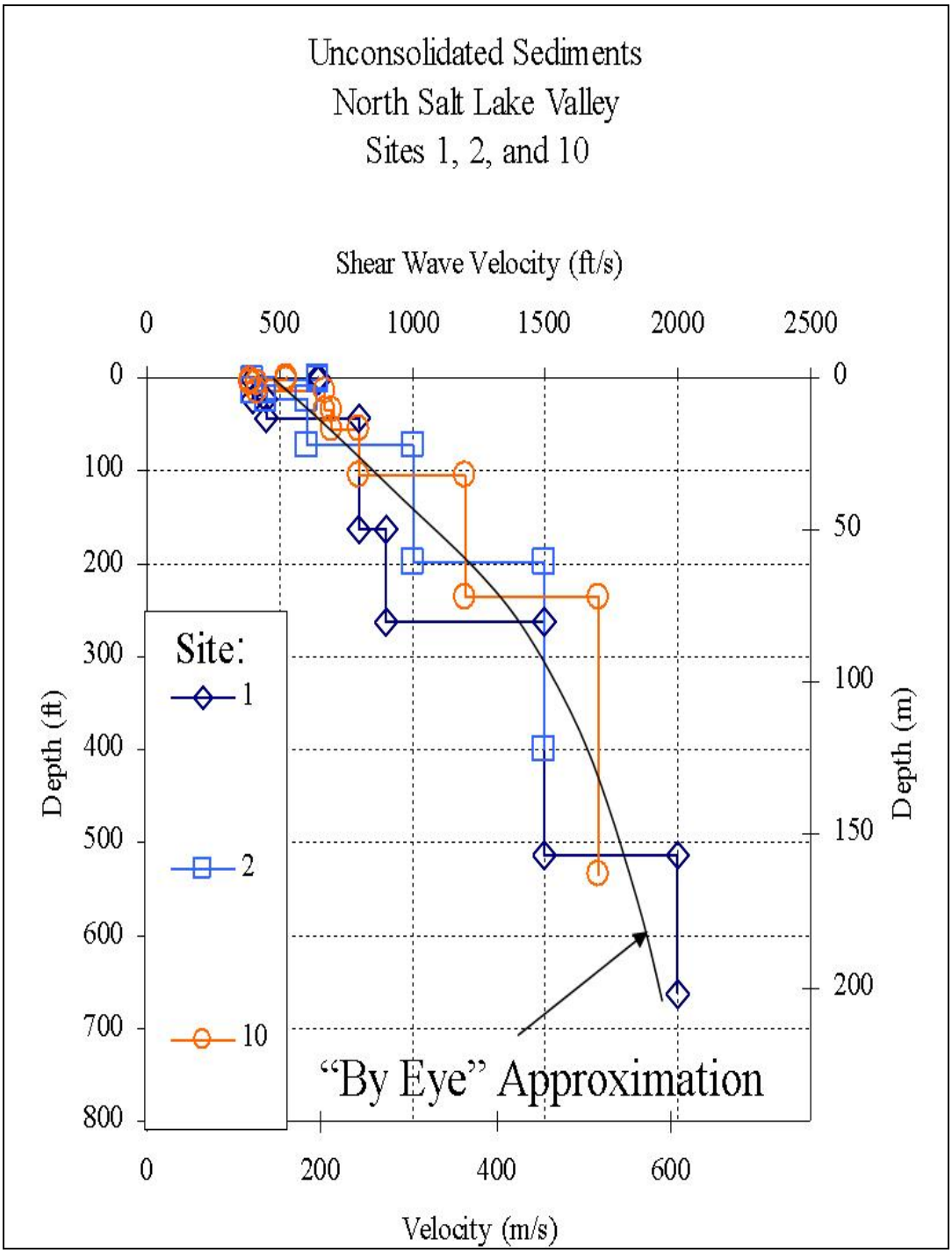

Figure 6.5 Shear wave velocity profiles for unconsolidated sediments in Group 1-clay, silt, and fine sand in the northern portion of the Salt Lake Valley

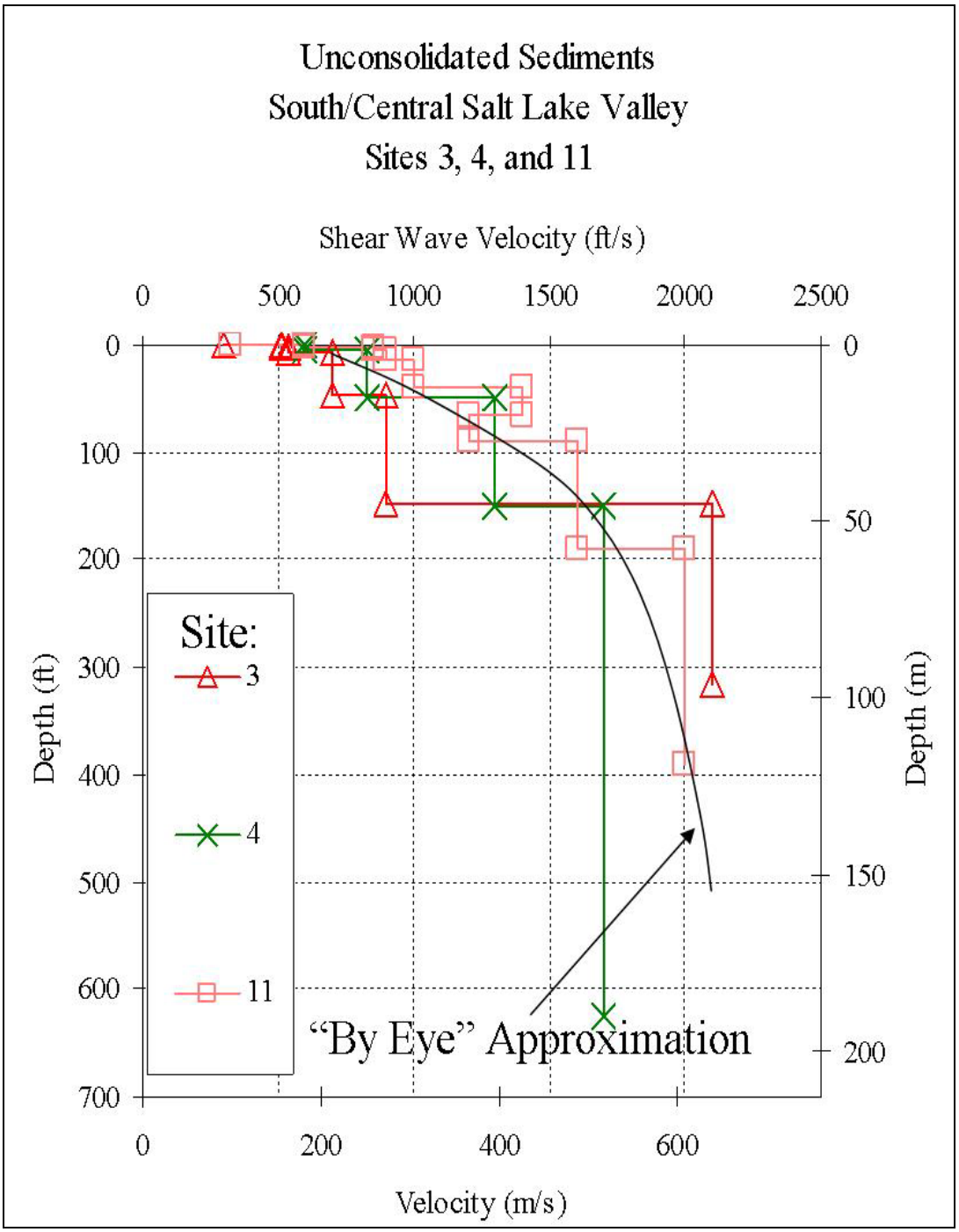

Figure 6.6 Shear wave velocity profiles for unconsolidated sediments in Group 2-sand with interbedded clay and silt in the south/central portion of the Salt Lake Valley

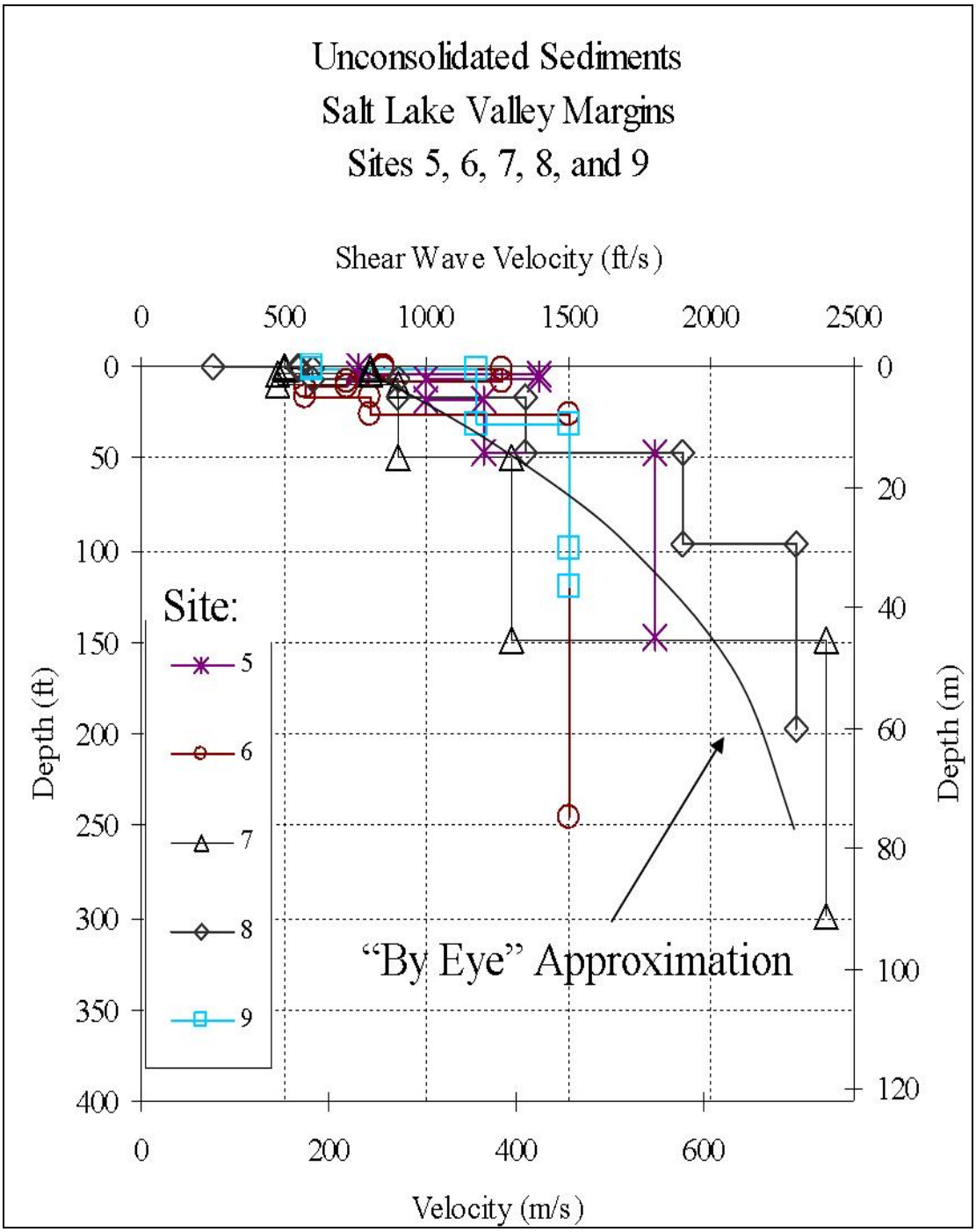

Figure 6.7 Shear wave velocity profiles for unconsolidated sediments in Group 3-sand and gravel in the margins of the Salt Lake Valley

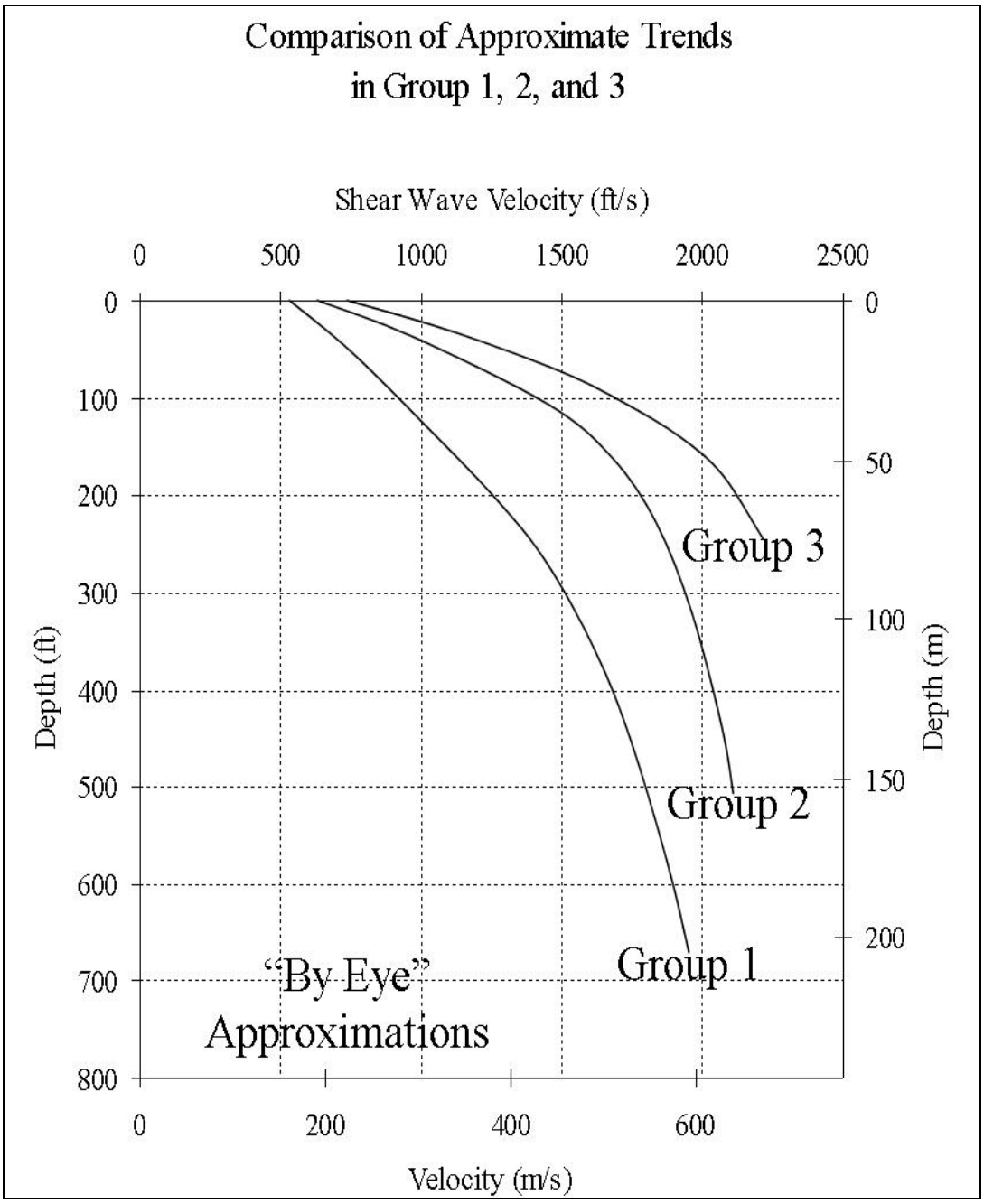

Figure 6.8 Comparison of the approximate trends in the Vs profiles in Groups 1, 2 and 3 that were fit by eye

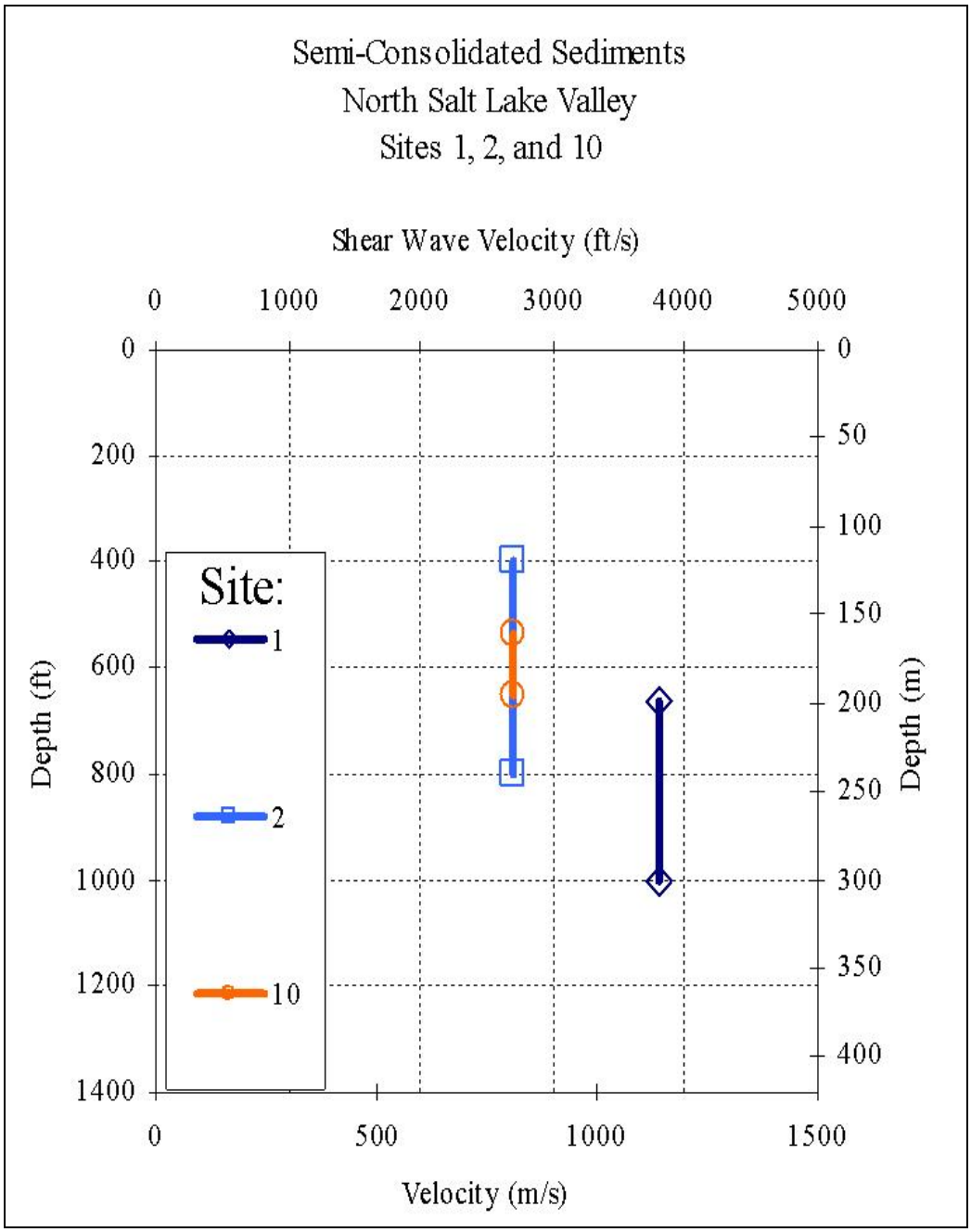

Figure 6.9 Shear wave velocity profiles for semi-consolidated sediments below Group 1-clay, silt, and fine sand in the northern portion of the Salt Lake Valley

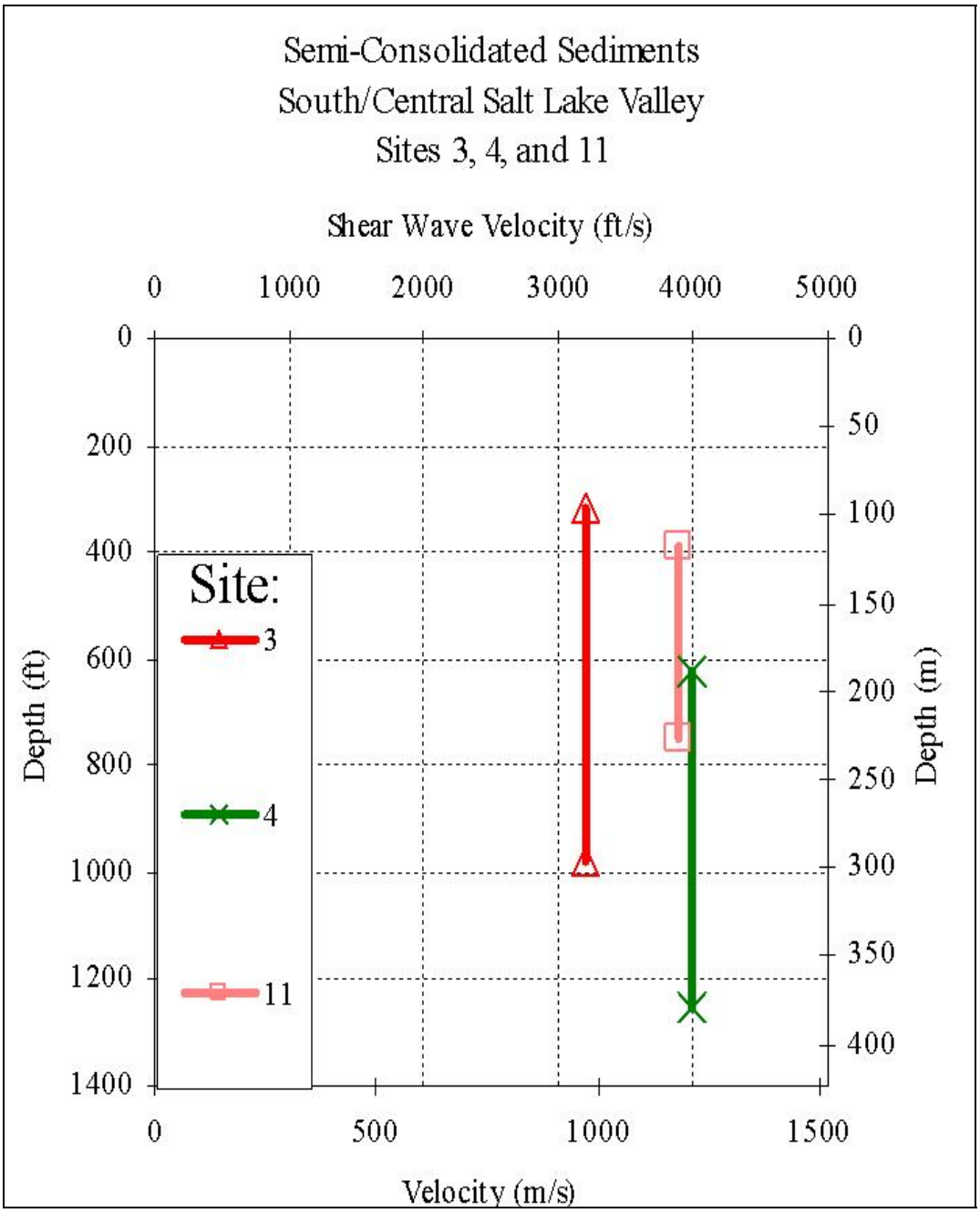

Figure 6.10 Shear wave velocity profiles for semi-consolidated sediments below Group 2-sand with interbedded clay and silt in the south/central portion of the Salt Lake Valley

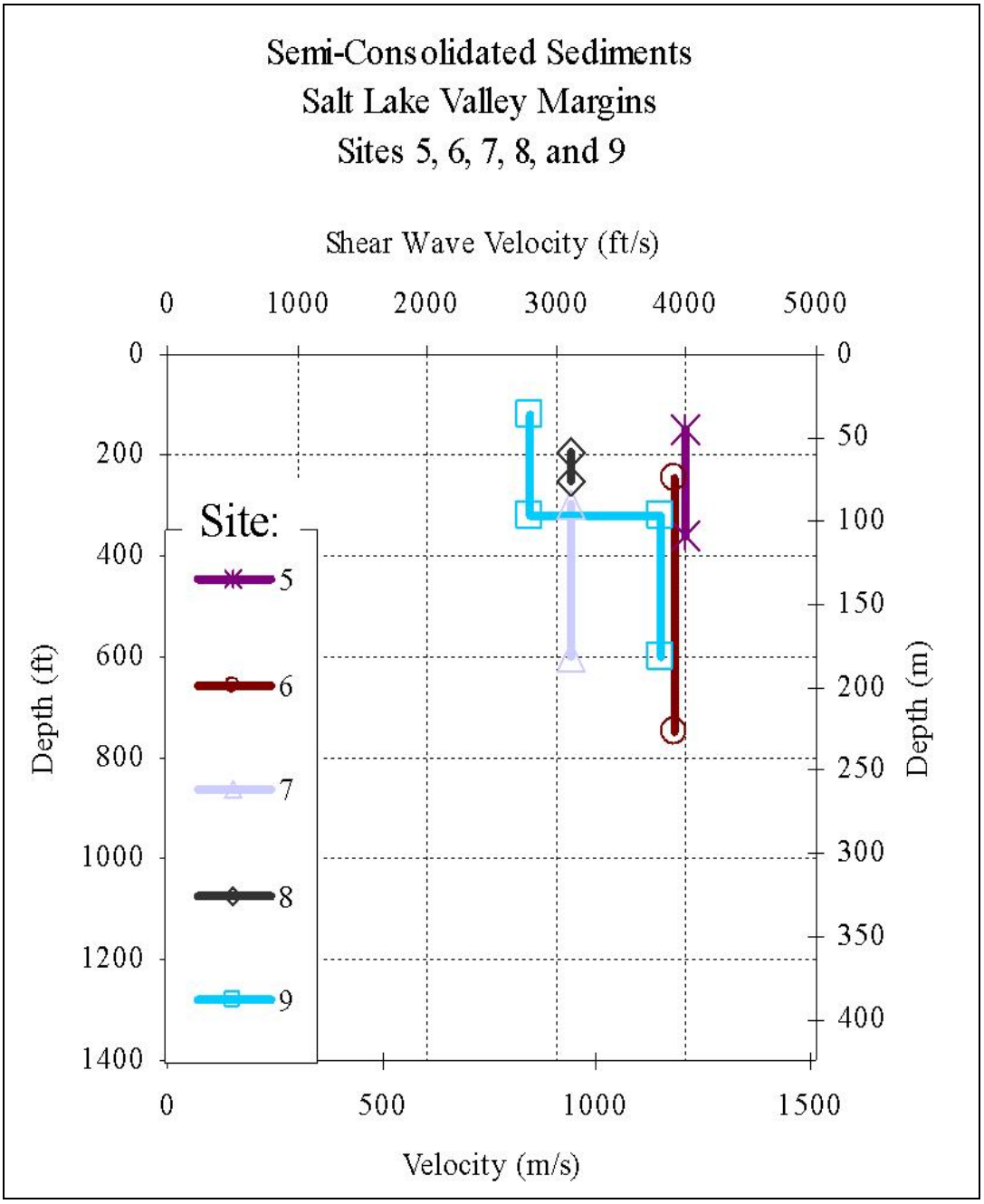

Figure 6.11 Shear wave velocity profiles for semi-consolidated sediments below Group 3-sand and gravel in the margins of the Salt Lake Valley

It is interesting to note that Vs profiles in the semi-consolidated sediments as thick as 650 ft (200 m) were measured. To determine a median profile and the 16th and 84th percentile of the semi-consolidated material, all profiles with thicknesses of about 300 ft (90 m) and greater have been plotted in Figure 6.12 (the sites are Sites 1, 2, 3, 4, 5, 6, 7, 9 and 11). In this figure, the top of each Vs profile is located at a "zero" depth. As seen, the median Vs increases slightly with depth below the R1 boundary although there is a slight decrease in the median Vs before the overall increase.

6.4. Comparison with Existing Vs Profiles

A comparison of existing Vs profiles and Vs profiles measured in this study was performed. Existing Vs profiles for the Salt Lake Valley were provided by Greg McDonald of the UGS (McDonald, 2007). These profiles are classified according to the Quaternary Units shown in Figure 3.6. This study performed SASW testing in the Q01, Q02, Q03, and Q05 units. Only the unconsolidated sediments are included in the SASW Vs profiles.

Figure 6.13 illustrates the Vs profiles in the Q01 unit, which is classified as silt, clay, and fine-grained sand. The Group 1 profiles presented in Figure 6.5 fall into this Q01 unit. Prior to this study, there were 70 velocity profiles in the Q01 unit, with the deepest profile reaching a depth of 300 ft (90 m). The three SASW tests that were performed in the Q01 unit in this study are Sites 1, 2, and 10, with the deepest profile of unconsolidated sediments reaching a depth of 665 ft (200 m) at Site 1. As seen in Figure 6.13, there is a good comparison between the two median Vs profiles to a depth of 300 ft (90 m). There is also a continuous increasing trend in the Vs profile below 300 ft (90 m) as expected for soil.

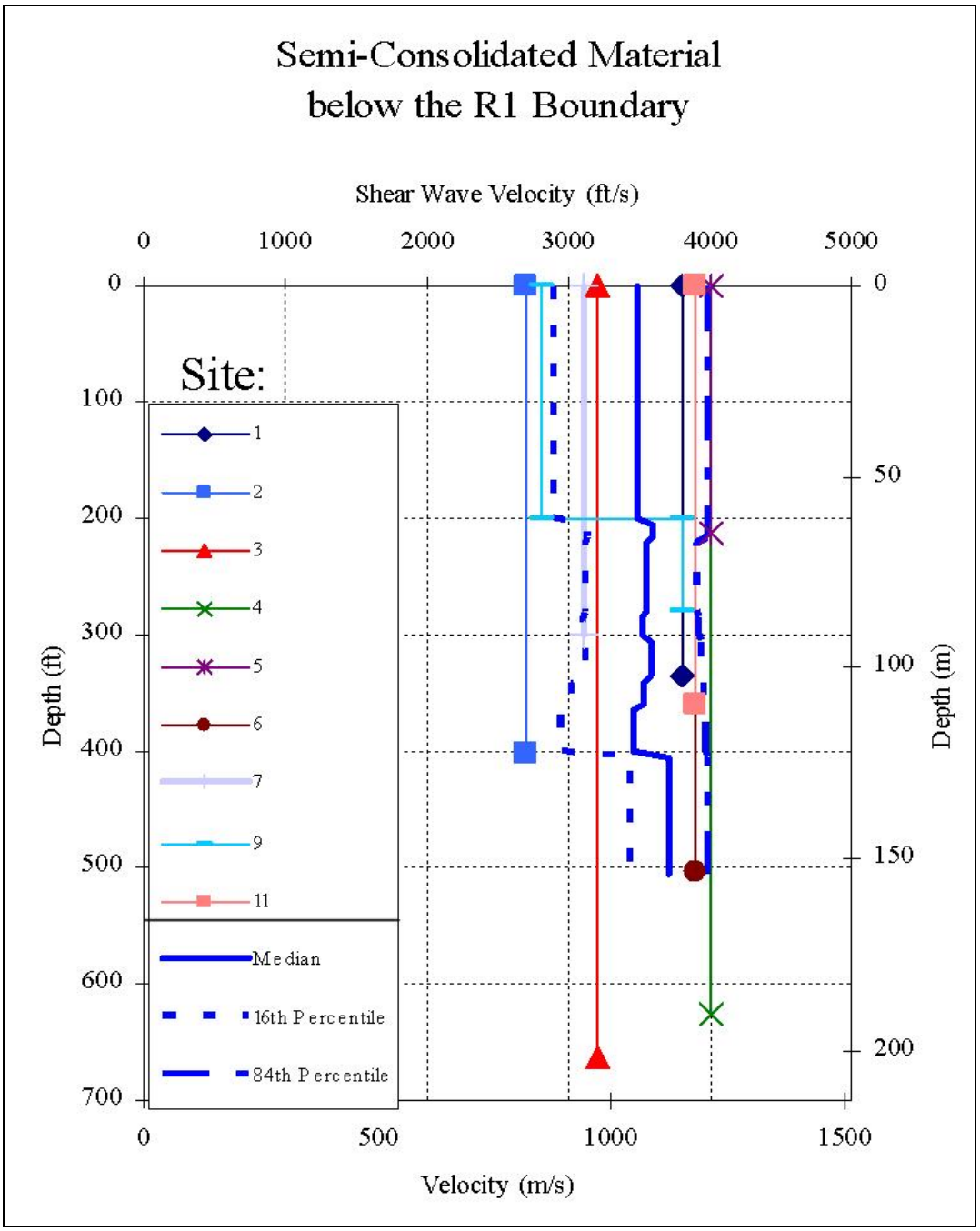

Figure 6.12 Shear wave velocity profiles measured below the R1 boundary with the SASW tests

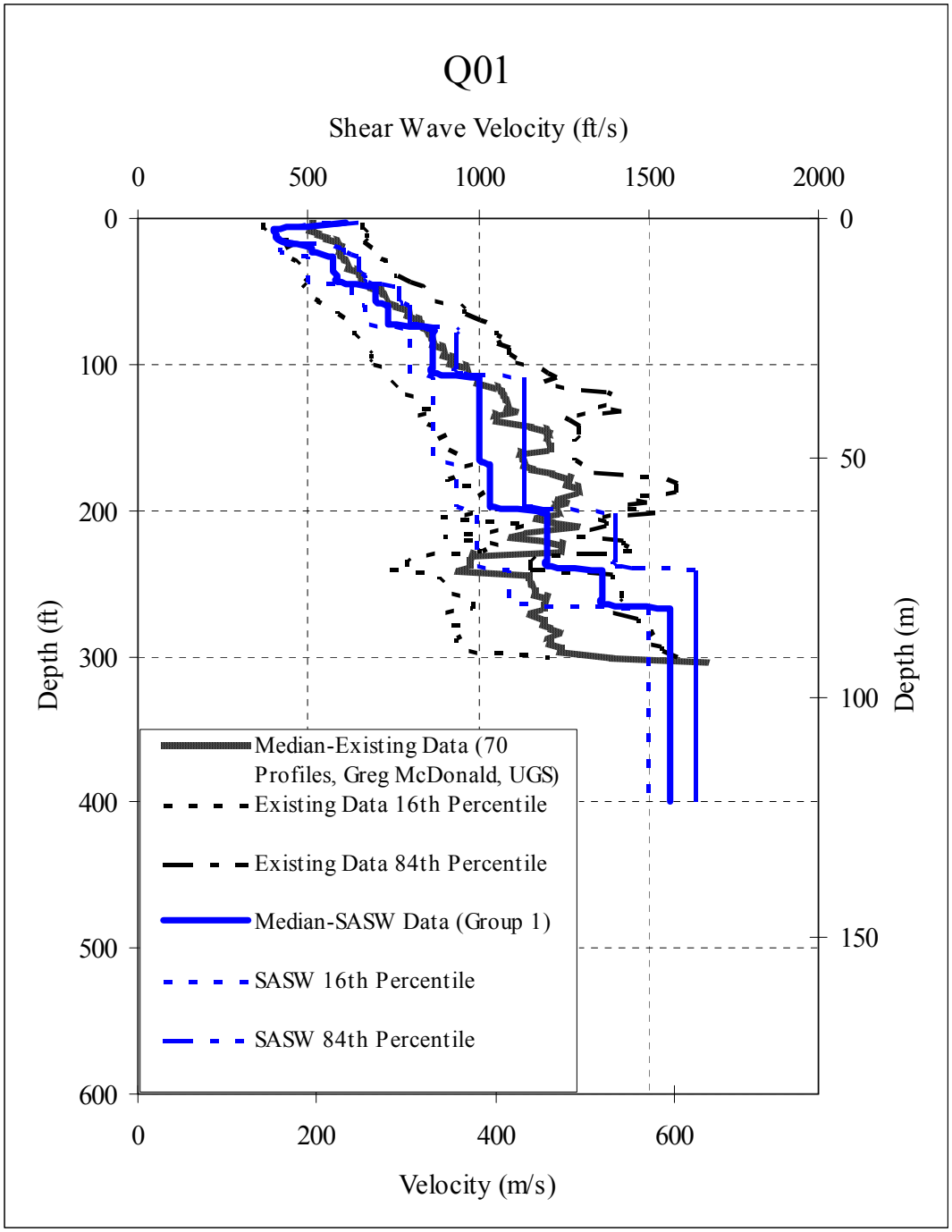

Figure 6.13 Shear wave velocity profiles for the Q01 Unit; existing data (70 Profiles) and SASW data from this study (Group 1)

Figure 6.14 illustrates the Vs profiles in the Q02 unit, which is classified as sand with interbedded silt and clay. The Group 2 profiles presented in Figure 6.6 fall into this Q02 unit. Prior to this study, there were 43 velocity profiles in the Q02 unit, with the deepest profile reaching a depth of 250 ft (75 m). The three SASW tests that were performed in the Q02 unit in this study are Sites 3, 4, and 11, with the deepest profile of the unconsolidated sediments reaching a depth of 625 ft. (190 ft). As seen in Figure 6.14, there is a good comparison between the two median Vs profiles to a depth of approximately 200 ft (60 m). Below 200 ft (60 m), the SASW Vs profile shows a nearly constant Vs profile.

Figure 6.15 illustrates the Vs profiles in the Q03 unit, which is classified as sand and gravel. Prior to this study, there were 20 velocity profiles in the Q03 unit, with the deepest profile reaching a depth of 300 ft (90 m). The four SASW tests that were performed in the Q03 unit in this study are Sites 5, 6, 7, and 9, with the deepest profile reaching a depth of 300 ft (90 m). There is a good comparison between the two median Vs profiles to a depth of 75 ft (25 m). Below this depth, the data provided by the UGS increases in shear wave velocity faster than the SASW data. The data provided by the UGS did not distinguish between materials which are above or below the R1 boundary and it is clear that the higher Vs values in the UGS profile contain a significant amount of material below the R1 boundary simply by the values of Vs > 2500 ft/s (760 m/s). There is also a continuous increasing trend in the Vs as expected for soil.

Figure 6.16 illustrates the Vs profiles in the Q05 unit, which is classified as glacial deposits including till and outwash. Prior to this study, there were 7 velocity profiles in the Q05 unit, with the deepest profile reaching a depth of 250 ft (75 m). The one SASW test that was performed in the Q05 unit in this study is Site 8. The unconsolidated sediments at Site 8 extend to a depth of 200 ft (60 m). The data

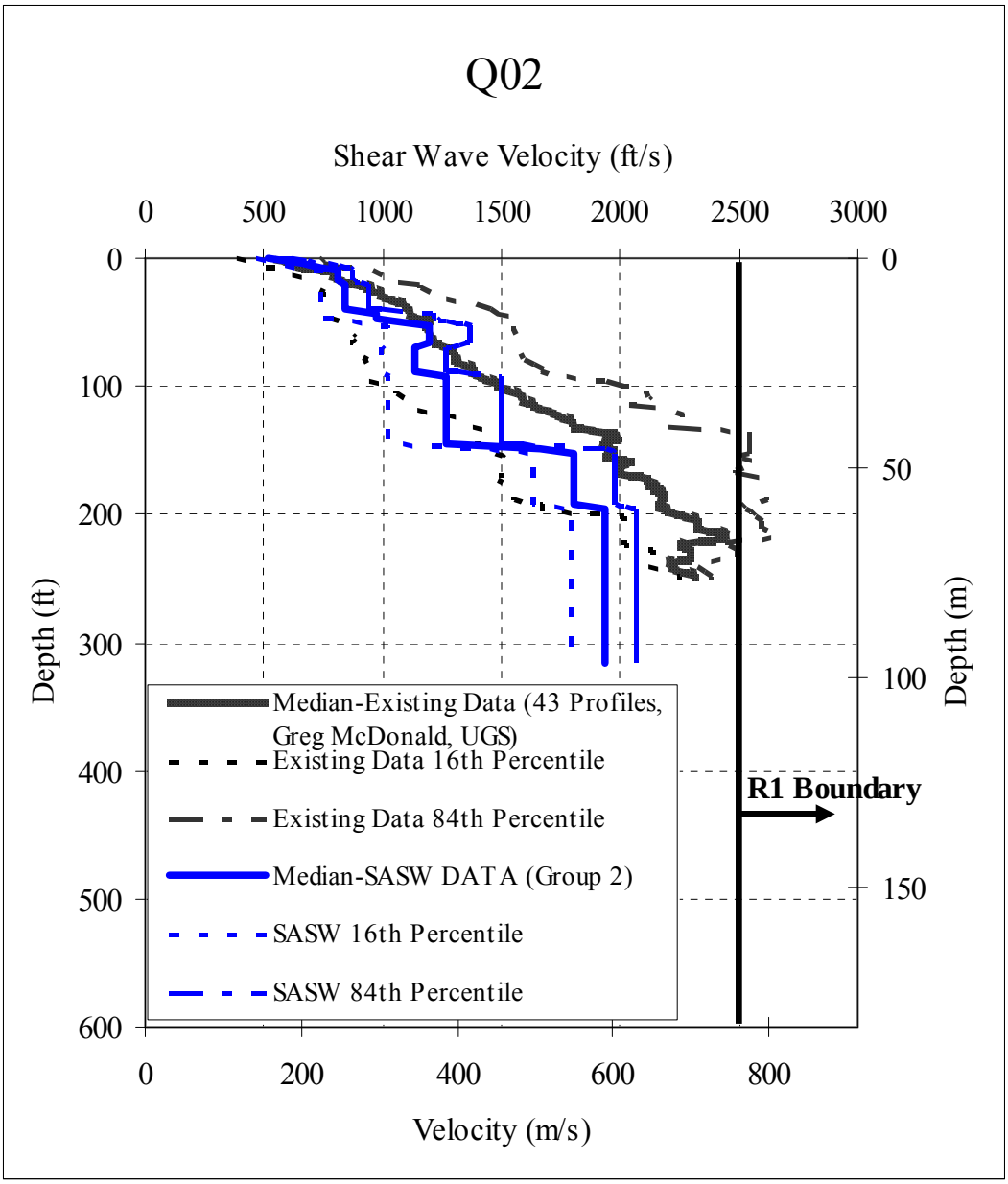

Figure 6.14 Shear wave velocity profiles for the Q02 Unit; existing data (42 Profiles) and SASW data from this study (Group 2)

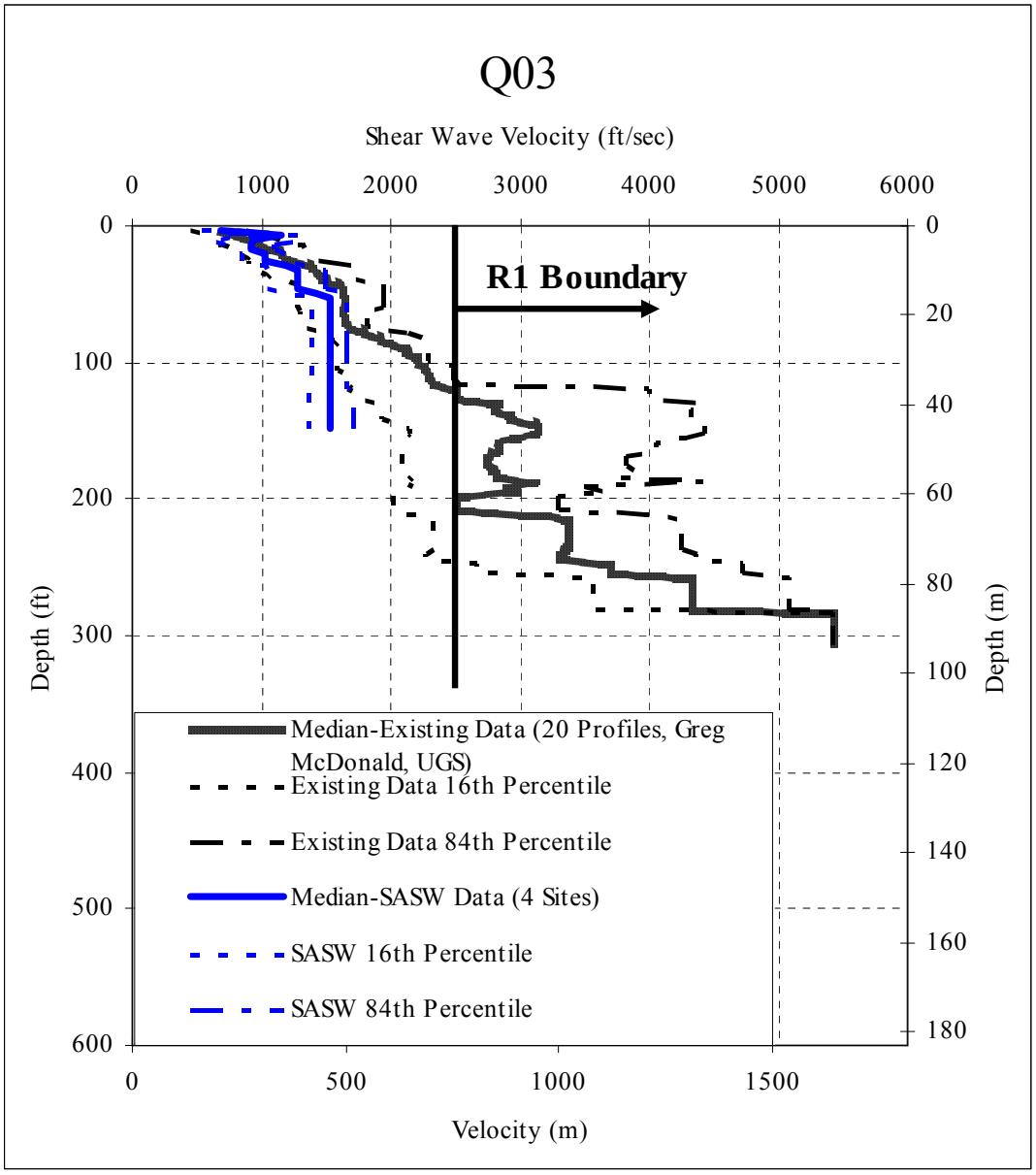

Figure 6.15 Shear wave velocity profiles for the Q03 Unit; existing data (20 Profiles) and SASW data from this study (Sites 5, 6, 7, and 9)

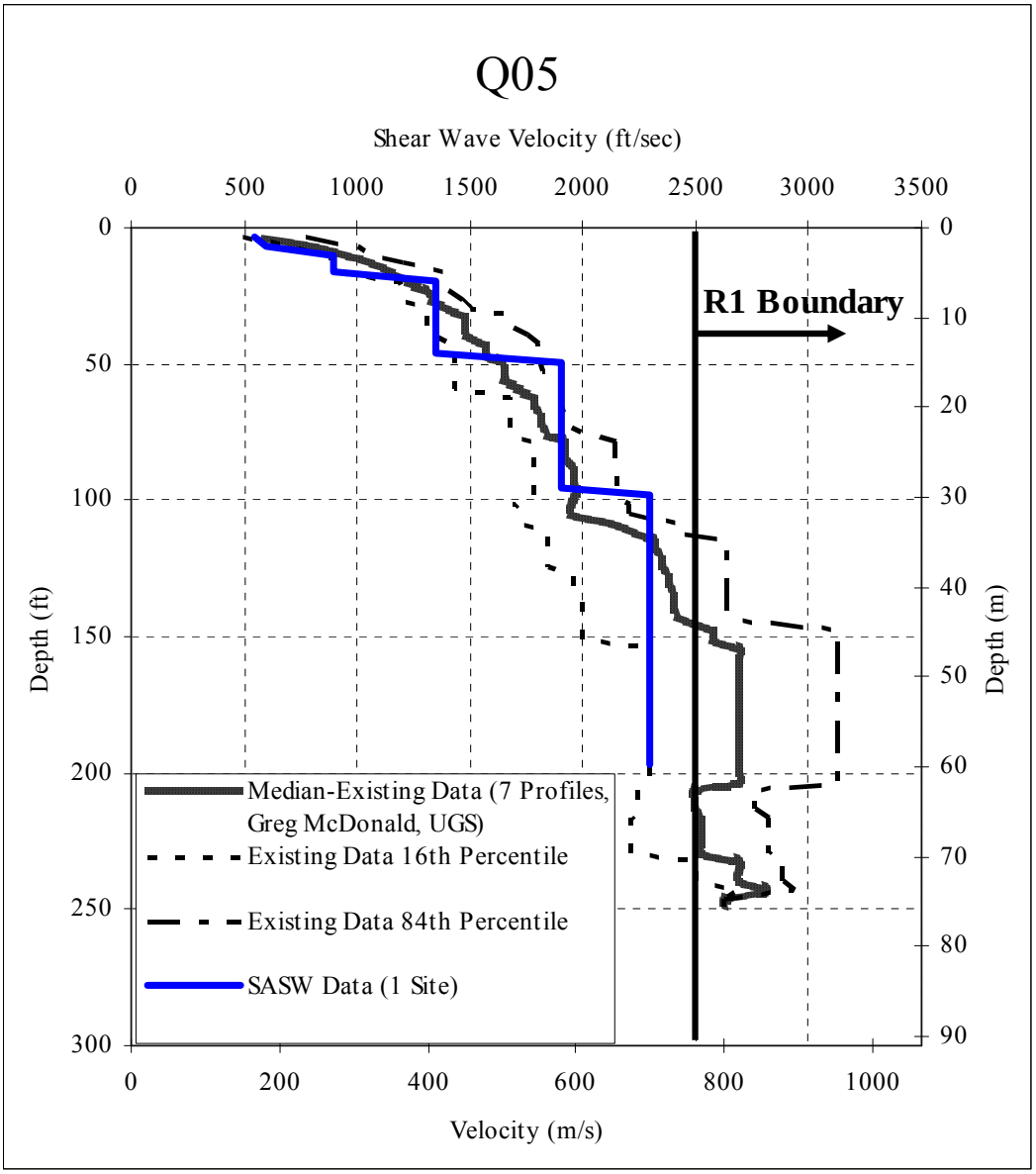

Figure 6.16 Shear wave velocity profiles for the Q05 Unit; existing data (7 Profiles) and SASW data from this study (Site 8)

provided by the UGS did not distinguish between materials which are above or below the R1 boundary. As seen in Figure 6.16, there is a very good comparison between the two Vs profiles to a depth of 150 ft (45 m). There is also a continuous increasing trend in the Vs below as expected for soil. However, below this depth, the UGS profile clearly contains material below the R1 boundary.

6.5. Summary

To help develop the CVM, six deep (≥ 750 ft (230 m)) and five intermediate-depth (250 ft (75 m) to 750 ft (230 m)) Vs profiles were measured. These profiles were analyzed: (1) to try to develop sets of Vs profiles that fit the different material types, (2) to determine the depths to the R1 and R2 boundaries based on Vs, (3) to compare the Vs profiles with other studies, and (4) to compare the Vs profiles with empirical data. The depth to the R1 boundary was compared with existing data. The 11 Vs profiles were placed into three groups based on the surficial geology. These three groups were then analyzed in terms of: (1) the overall Vs profile, (2) the unconsolidated sediment Vs profile, and (3) the semi-consolidated Vs profile. The SASW profiles were also organized by Quaternary Unit (Q01, Q02, Q03, and Q05) and compared with existing Vs profiles. In general, the comparison between existing Vs profiles and SASW Vs profiles is good.

CHAPTER 7

DEVELOPMENT OF SMOOTHED Vs PROFILES FOR THE COMMUNITY VELOCITY MODEL

7.1. Introduction

To develop the CVM, generalized Vs profiles for the different materials in the Salt Lake Valley are needed. The eleven Vs profiles determined in this study are grouped according to the surficial geology. Smoothed Vs models for the four Quaternary Units are presented in this chapter. The models are based on current and previous shear-wave testing. Previous testing in the Salt Lake Valley includes downhole, seismic cone penetration, and surface wave testing. A smoothed Vs model is also presented for the semi-consolidated material below the R1 boundary.

7.2. Development of Smoothed Vs Model Profiles

To develop the Vs models, all Vs profiles determined to date in the Salt Lake Valley (139 total profiles) were used. Models were developed for the unconsolidated sediments and the semi-consolidated material. The UGS data that were provided for soils above the R1 boundary were revised, and all Vs values $\geq$2500 ft/s (760 m/s) were removed. The revised lognormal medians from the previous data are compared to the individual Vs profiles for each surficial unit (Q01, Q02, Q03 and Q05) measured in this study. All Vs profiles for a given Quaternary unit were grouped together and the lognormal median, 16th and 84th percentiles of the lognormal median, and the coefficient of variation (COV) were calculated. The smoothed Vs model for each unit was determined from the revised median from the previous studies and individual Vs profiles from this study. The upper 5 ft (1.5 m) was not included in the smoothed Vs models.

To determine the model for the semi-consolidated materials, only profiles that extend below the R1 boundary by more than 300 ft (90 m) were analyzed. Nine of the eleven Vs profiles from this study were used to determine the semi-consolidated Vs model.

7.2.1. Smoothed Vs Model for the Q01 Unit

Figure 7.1 presents the 70 revised Vs profiles (only Vs values<2500 ft/s (760 m/s) were used) determined in the Q01 Unit prior to this study. Figure 7.2 presents the lognormal median and the 16th and 84th percentiles for the revised UGS data in the Q01 unit. Figure 7.3 presents the three Vs profiles determined in the Q01 unit for this study (Sites 1, 2, and 10) as well as the revised lognormal median from the 70 profiles provided by the UGS. Good agreement is shown between the median and the three profiles in this study in the top 200 ft (60 m). The revised UGS data is presented in Figure 7.4. Figure 7.4a presents the lognormal median and 16th and 84th percentiles for the previous 70 Vs profiles. Figure 7.4b presents the profiles of the coefficient of variation (COV) and number of measurements. Figure 7.5 presents the original median, the revised median, and the "new" revised median from all 73 profiles. No statistical analysis was performed when there were less than three profiles.

The recommended smoothed Vs model for the Q01 Unit is presented in Figure 7.6. The smoothed profile was simply constructed by eye as a best-fit profile. Below 300 ft (90 m), the "by eye" fit was used because of the lack of data. Below 200 ft (60 m), the general trend shown by the deep SASW measurements was followed due to the increasing velocity with depth shown by the deeper SASW measurements. Table 7.1 presents the smoothed curve discritized at 5 ft (1.5 m), 10 ft (3 m), and then in 20-ft (6 m) intervals. The discritized data in Table 7.1 are compared with the smoothed curve in Figure 7.6.

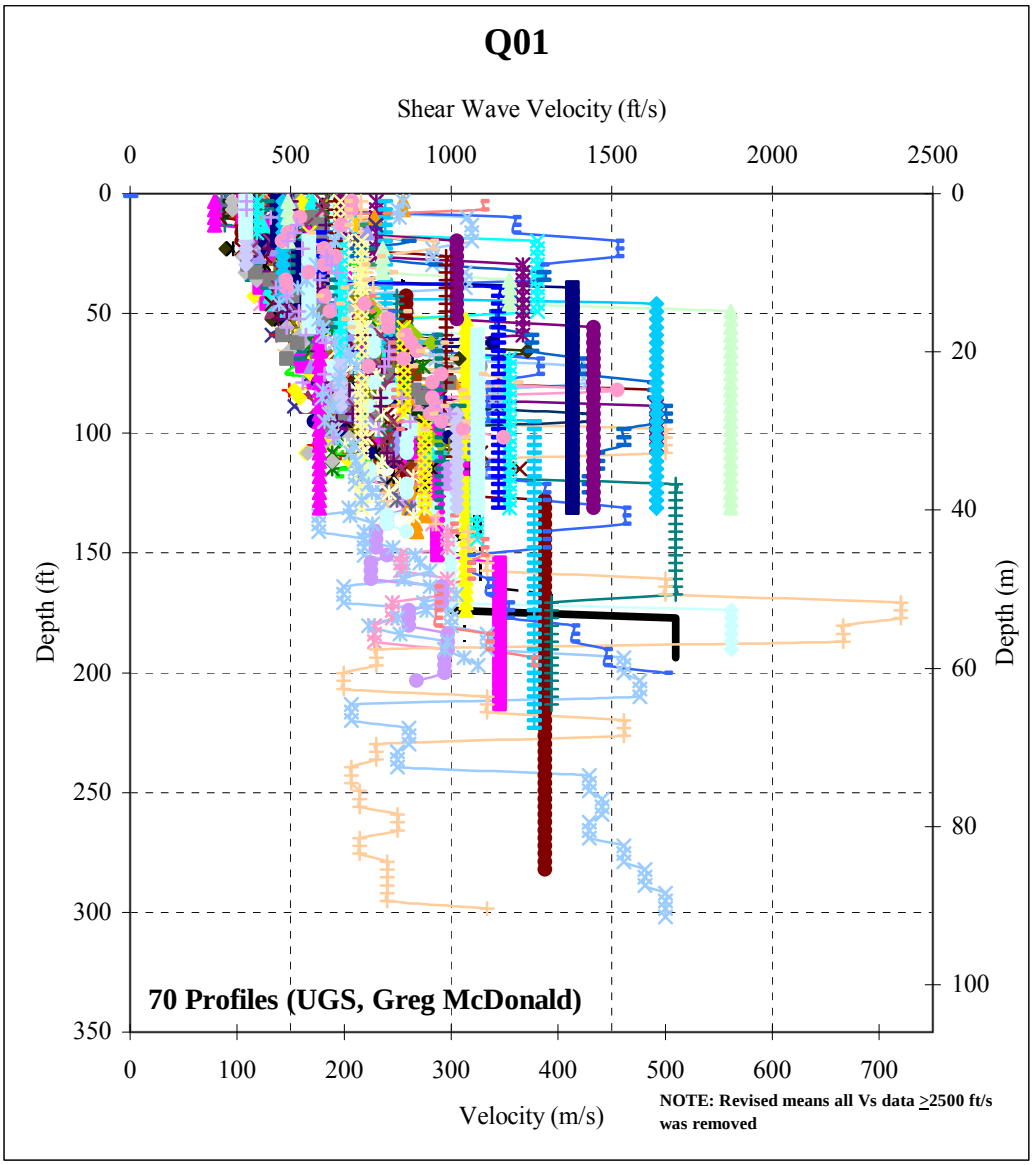

Figure 7.1 Revised Vs profiles for 70 sites in the Q01 Unit

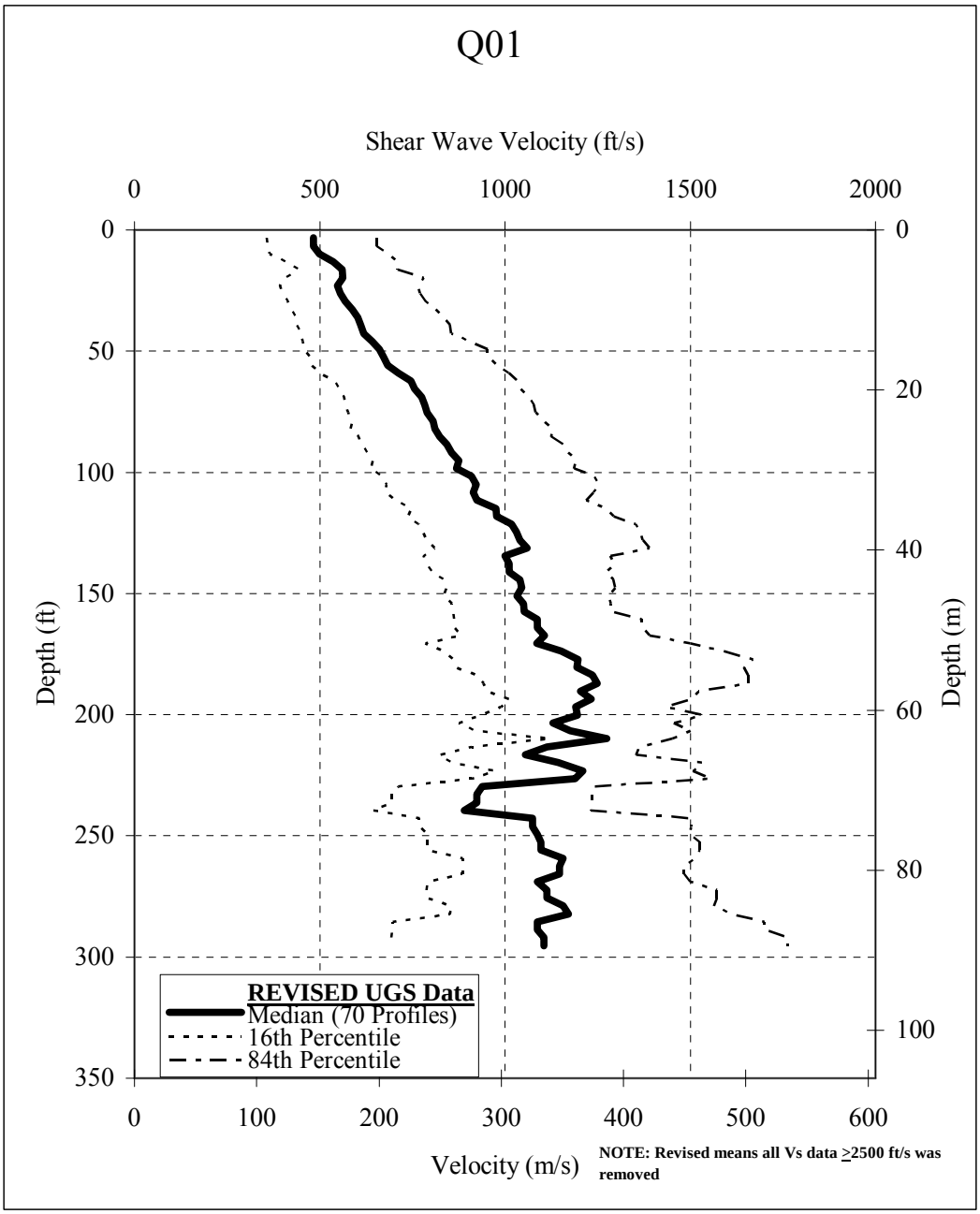

Figure 7.2 Revised UGS median (70 profiles) for the Q01 Unit

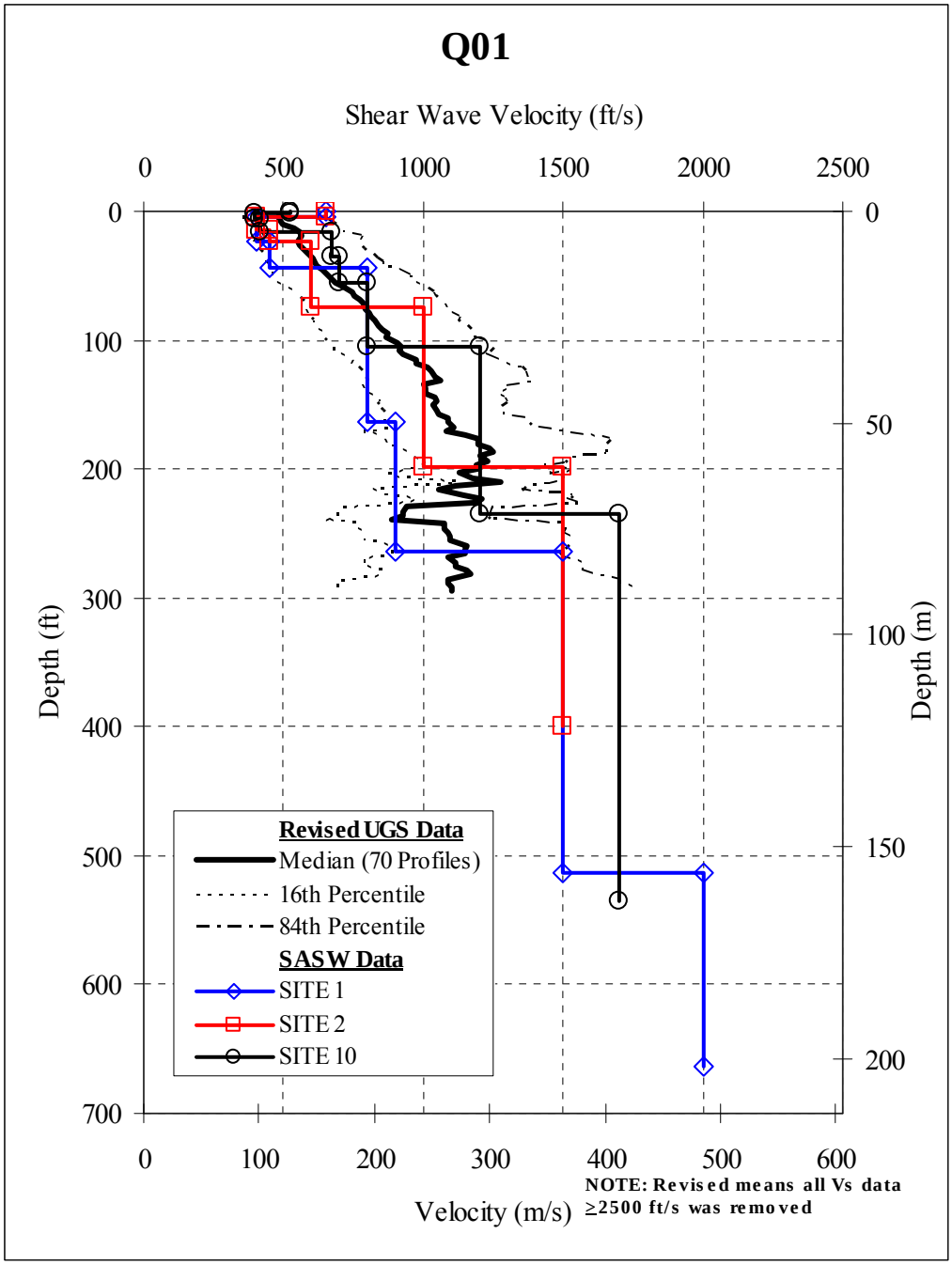

Figure 7.3 Three SASW Vs profiles determined in this study along with the revised median for the Q01 Unit from prior studies

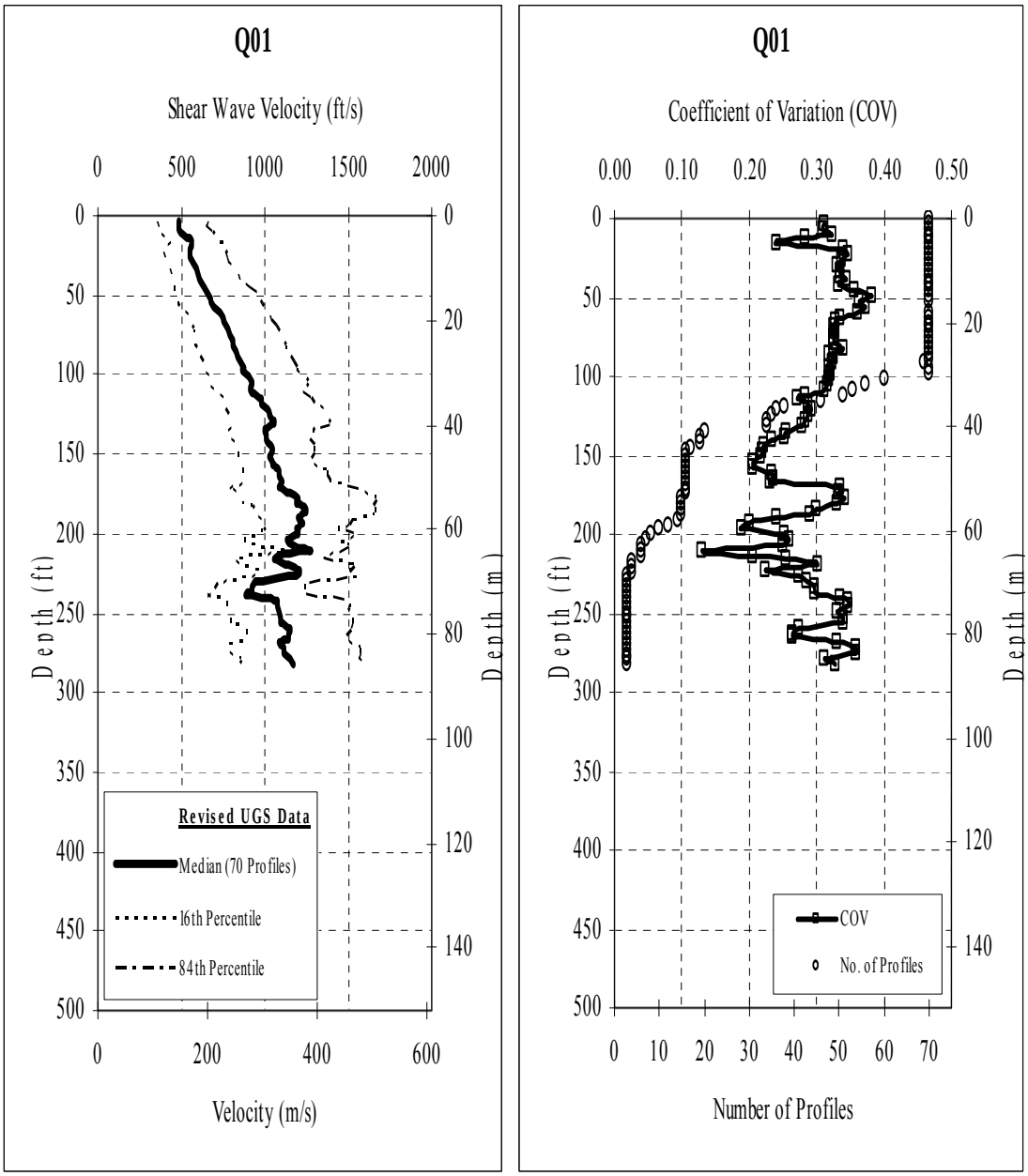

Figure 7.4 a) Median Vs profile for the 70 previous sites, and b) COV and number of Profiles

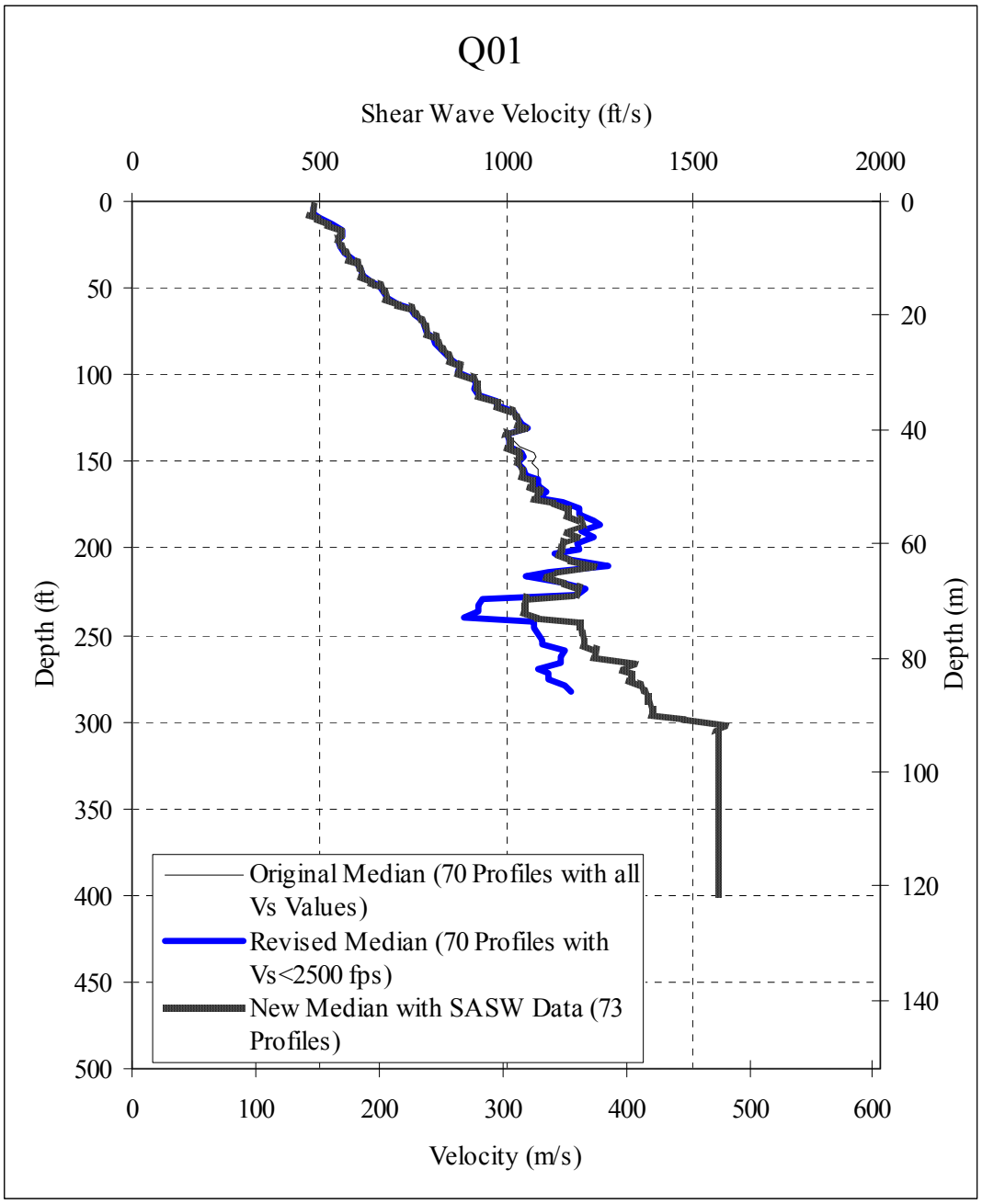

Figure 7.5 Statistical analysis of all Vs measurements in the Q01 Unit

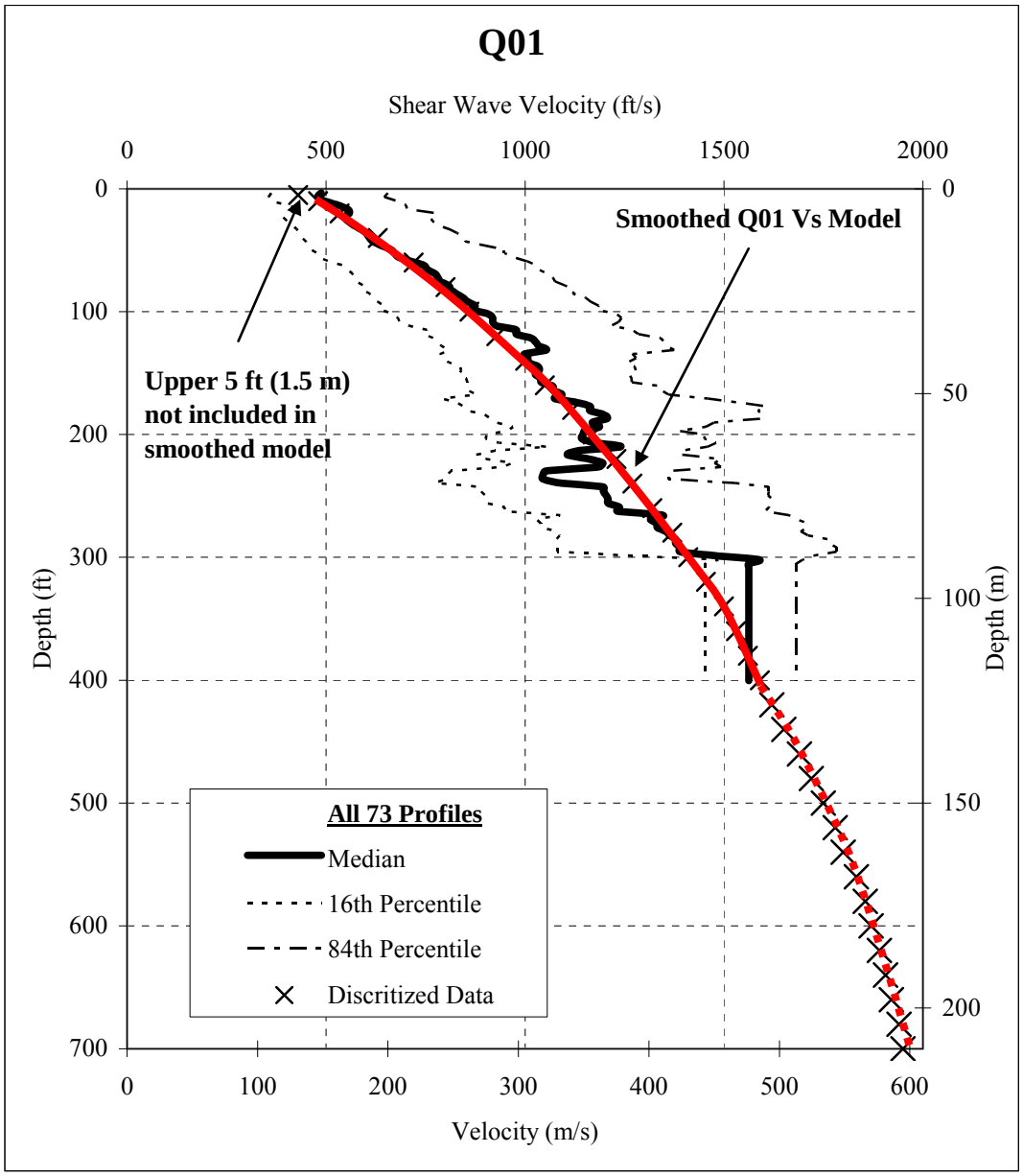

Figure 7.6 Smoothed Vs model recommended for the Q01 Unit

Table 7.1 Tabulated values for the smoothed Vs model in the Q01 Unit

	Velocity			Velocity			Velocity	
Depth ft (m)	ft/s	m/s	Depth ft (m)	ft/s	m/s	Depth	ft/s	m/s
5 (1.5)	430	131	260 (78)	1320	402	540 (162)	1800	549
10 (3)	480	146	280 (84)	1370	418	560 (168)	1833	559
20 (6)	534	163	300 (90)	1410	430	580 (174)	1855	565
40 (12)	630	192	320 (96)	1455	443	600 (180)	1870	570
60 (18)	720	219	340 (102)	1500	457	620 (186)	1891	576
80 (24)	800	244	360 (108)	1530	466	640 (192)	1906	581
100 (30)	860	262	380 (114)	1560	475	660 (198)	1921	586
120 (36)	928	283	400 (120)	1590	485	680 (204)	1940	591
140 (42)	1000	305	420 (126)	1620	494	700 (210)	1950	594
160 (48)	1050	320	440 (132)	1650	503			
180 (54)	1118	341	460 (138)	1690	515			
200 (60)	1170	357	480 (144)	1720	524			
220 (66)	1230	375	500 (150)	1750	533			
240 (72)	1270	387	520 (156)	1780	543			

7.2.2. Smoothed Vs Model for the Q02 Unit

Figure 7.7 presents the 42 revised Vs profiles determined in the Q02 Unit prior to this study. Figure 7.8 presents the lognormal median and the 16th and 84th percentiles for the revised UGS data in the Q02 Unit. Figure 7.9 presents the three Vs profiles determined in the Q02 Unit for this study (Sites 3, 4, and 11) and the revised lognormal median from the 42 profiles provided by the UGS. The revised UGS data is presented in Figure 7.10. Figure 7.10a presents the median and 16th and 84th percentiles and Figure 7.10b presents the profiles of the coefficient of variation (COV) and number of profiles. Figure 7.11 presents the original median, the revised median, and the "new" revised median from all 45 profiles. No statistical analysis was performed when there were less than three profiles.

The recommended smoothed Vs model for the Q02 Unit is presented in Figure 7.12. The smoothed profile was simply constructed by eye as a best-fit profile. Below 300 ft (90 m), the "by eye" fit was used because of the lack of data. Below 200 ft (60 m), the general trend shown by the deep SASW measurements was

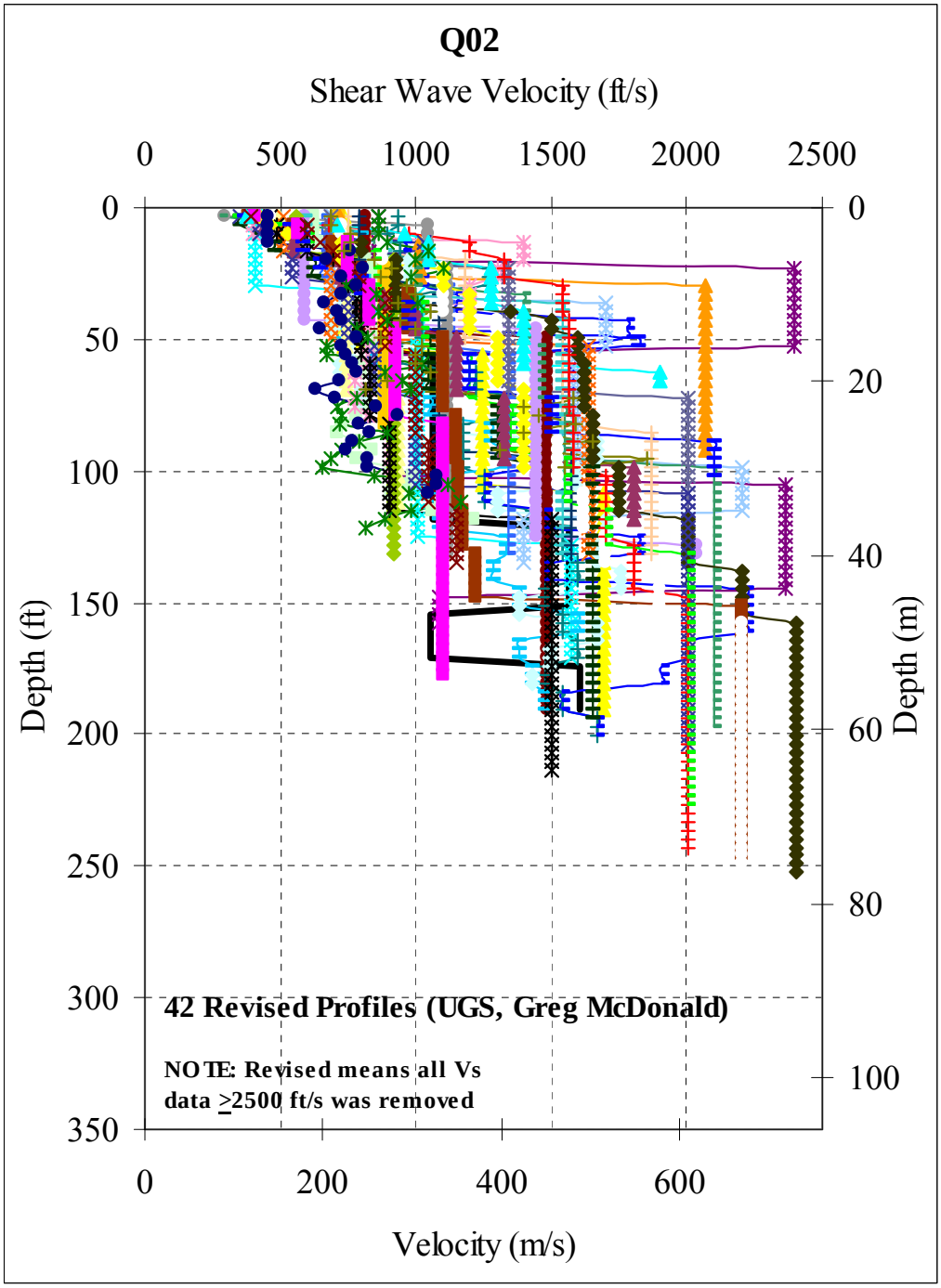

Figure 7.7 Revised Vs profiles for 42 sites in the Q02 Unit

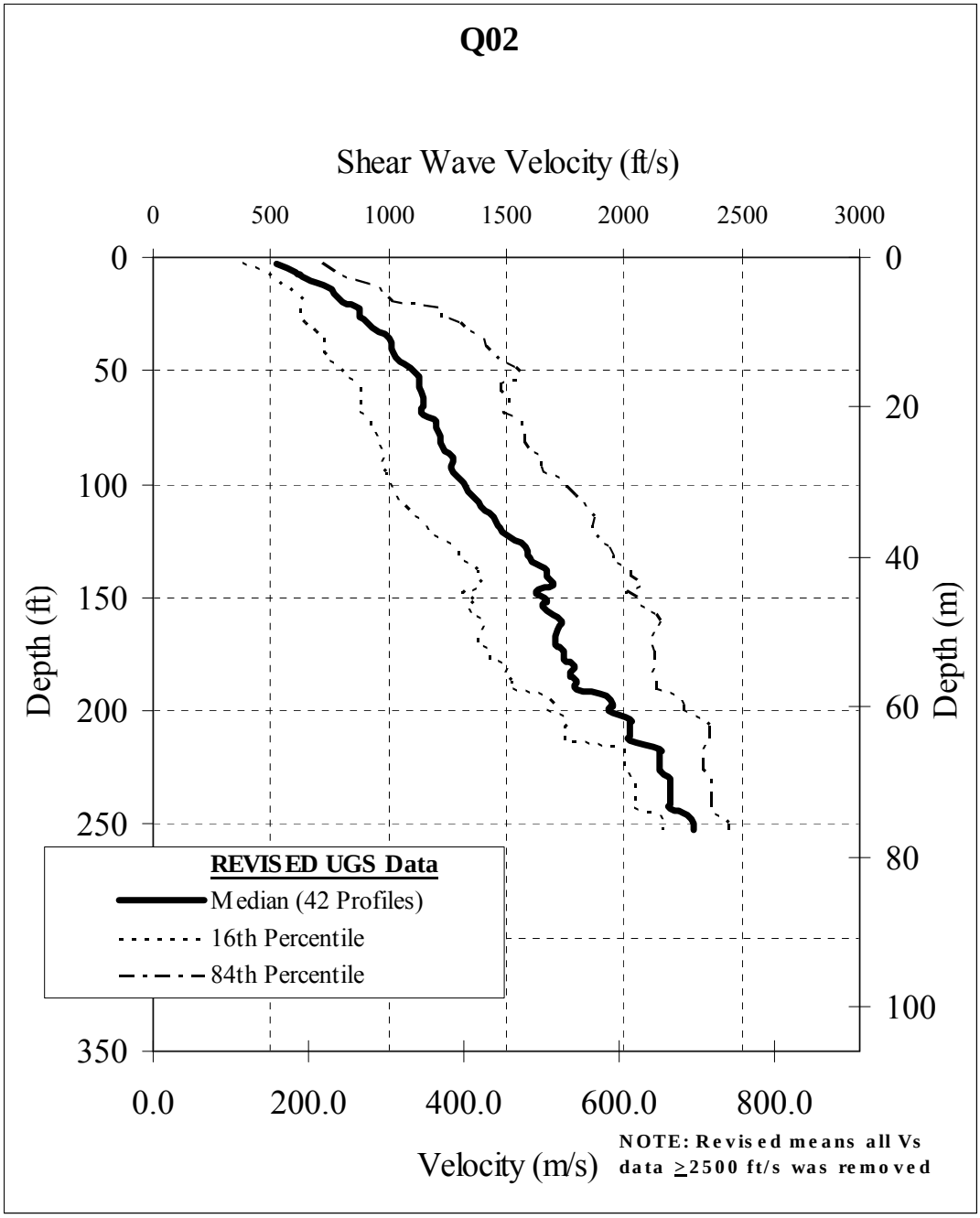

Figure 7.8 Revised UGS median (42 profiles) for the Q02 Unit

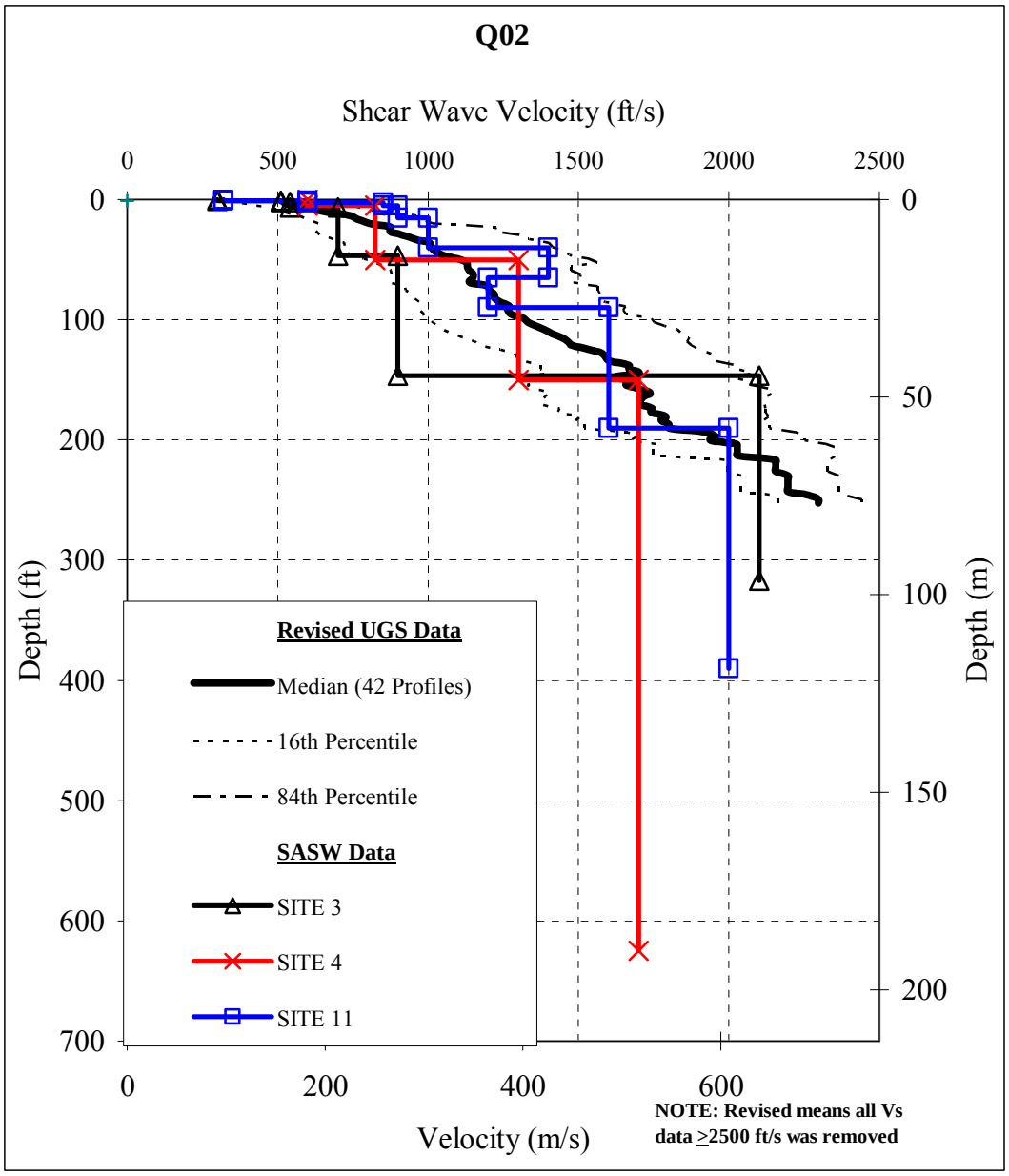

Figure 7.9 Three SASW Vs profiles determined in this study along with the revised median for the Q02 Unit from prior studies

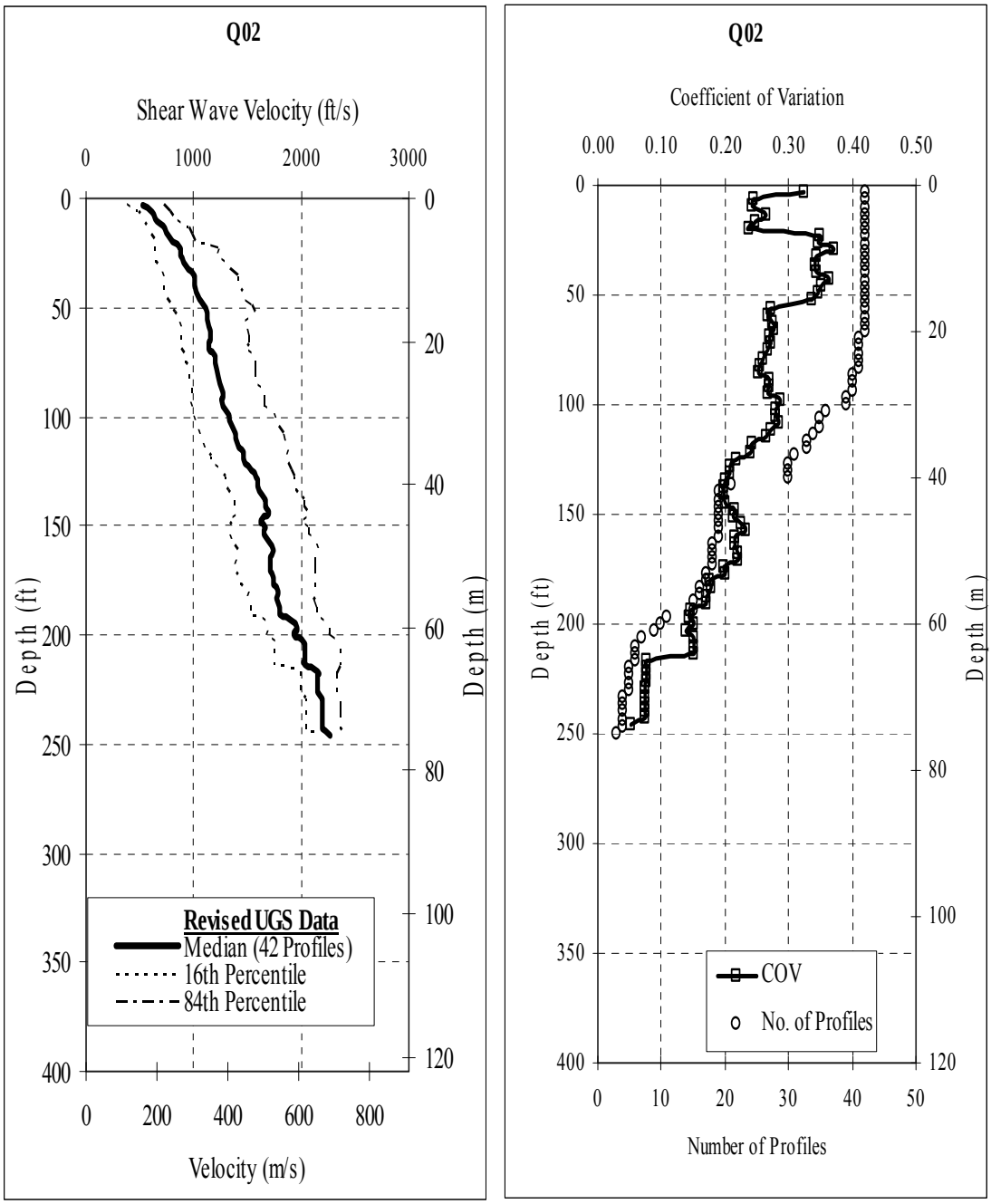

Figure 7.10 a) Median Vs profile for the previous 42 sites, and b) COV and number of profiles

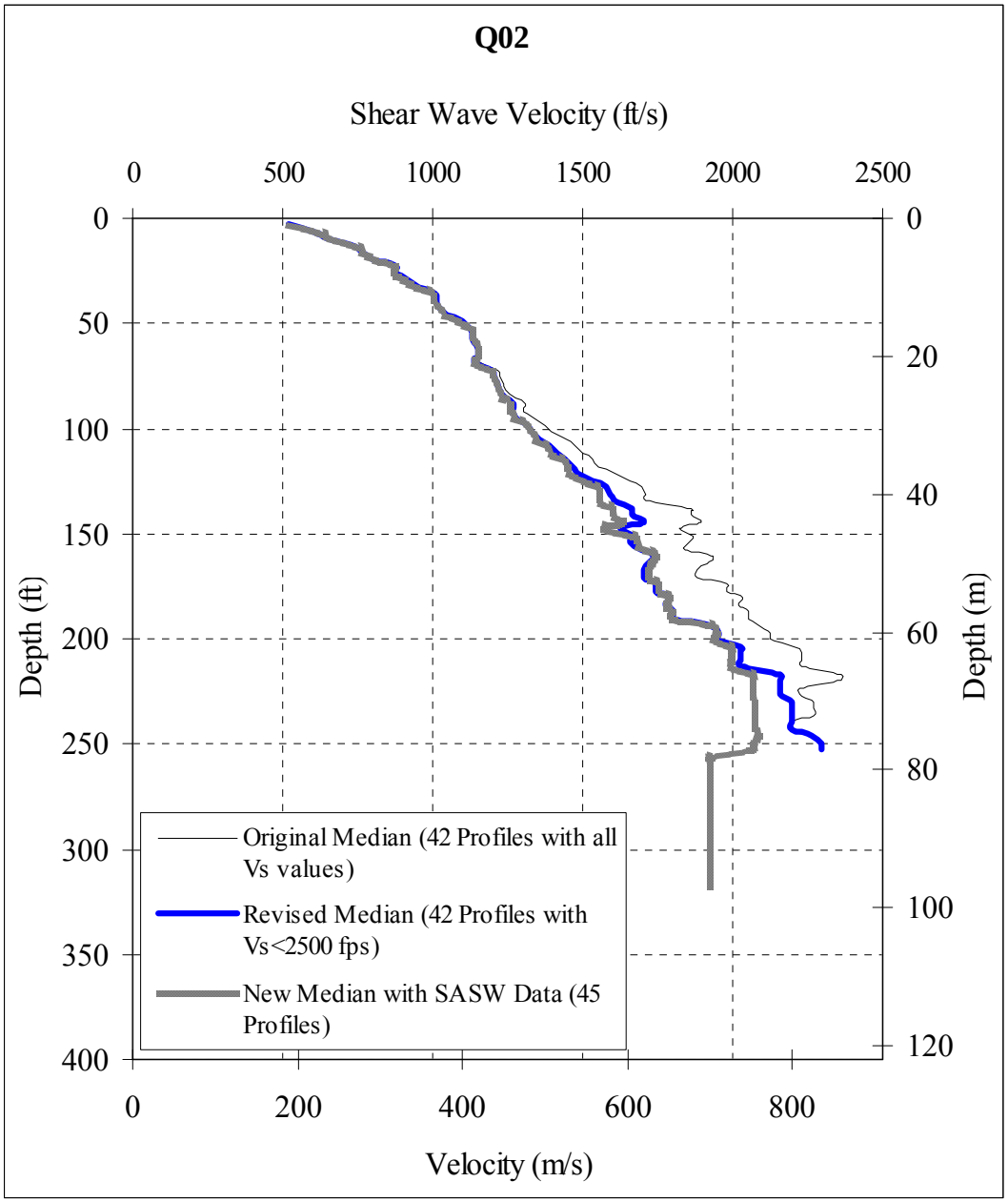

Figure 7.11 Statistical analysis of all Vs measurements in the Q02 Unit

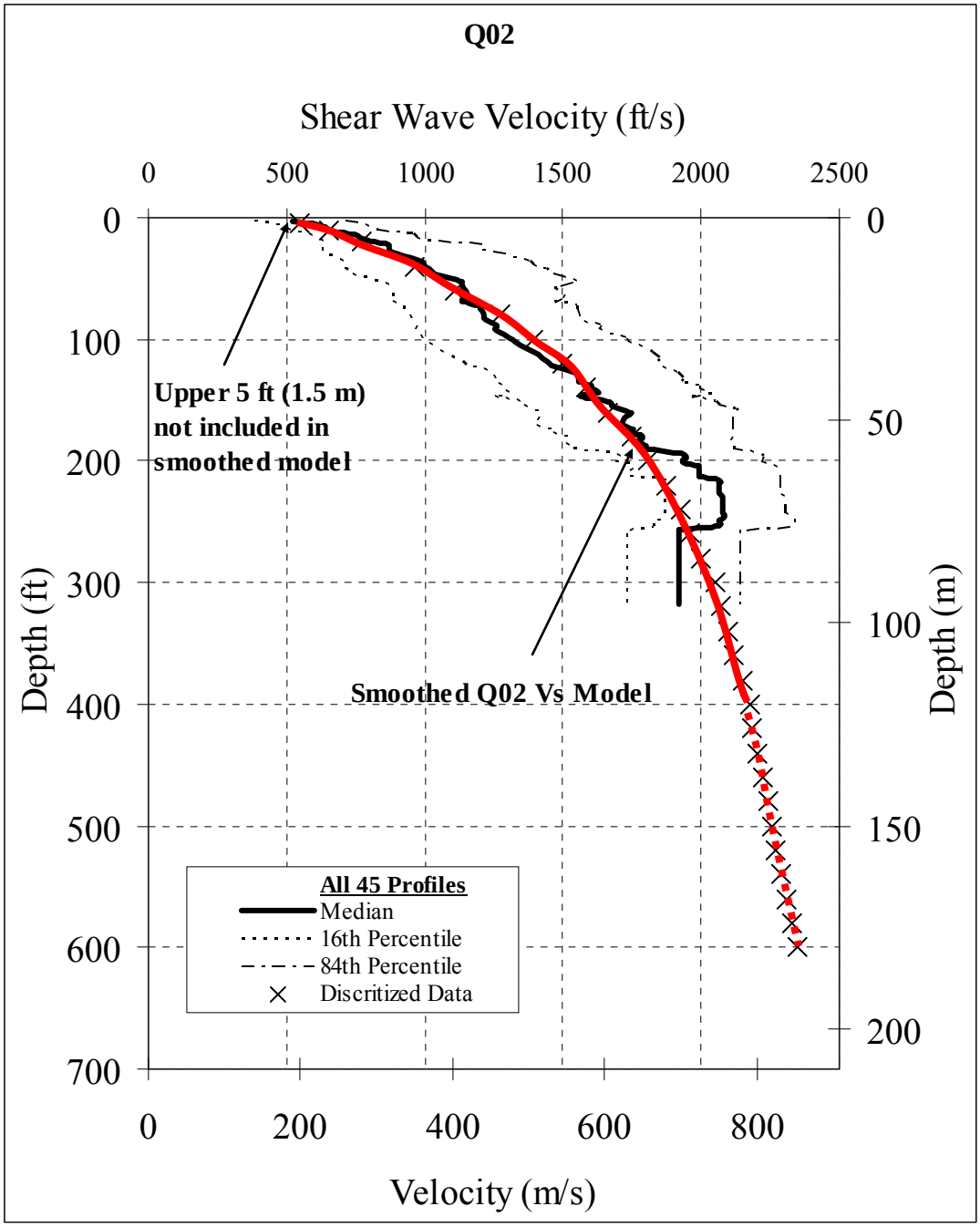

Figure 7.12 Smoothed Vs model recommended for the Q02 Unit

followed due to the increasing velocity with depth shown by the deeper SASW measurements. Table 7.2 presents the smoothed curve discritized at 5 ft (1.5 m), 10 ft (3 m), and then in 20-ft (6 m) intervals. The discritized data in Table 7.2 are compared with the smoothed curve in Figure 7.12.

Table 7.2 Tabulated values for the smoothed Vs model in the Q02 Unit

	Velocity			Velocity			Velocity	
Depth ft (m)	ft/s	m/s	Depth ft (m)	ft/s	m/s	Depth	ft/s	m/s
5 (1.5)	550	168	260 (78)	1960	597	540 (162)	2305	703
10 (3)	650	198	280 (84)	2000	610	560 (168)	2321	707
20 (6)	770	235	300 (90)	2050	625	580 (174)	2330	710
40 (12)	960	293	320 (96)	2070	631	600 (180)	2350	716
60 (18)	1110	338	340 (102)	2100	640			
80 (24)	1270	387	360 (108)	2120	646			
100 (30)	1390	424	380 (114)	2150	655			
120 (36)	1500	457	400 (120)	2175	663			
140 (42)	1604	489	420 (126)	2185	666			
160 (48)	1690	515	440 (132)	2212	674			
180 (54)	1750	533	460 (138)	2225	678			
200 (60)	1810	552	480 (144)	2240	683			
220 (66)	1871	570	500 (150)	2274	693			
240 (72)	1925	587	520 (156)	2282	696			

7.2.3. Development of the Smoothed Vs Model for the Q03 Unit

Figure 7.13 presents the 20 revised Vs profiles determined in the Q03 Unit prior to this study. Figure 7.14 presents the lognormal median and the 16th and 84th percentiles for the revised UGS data in the Q03 unit. Figure 7.15 presents the four Vs profiles determined in the Q03 Unit for this study (Sites 5, 6, 7, and 9) and the revised lognormal median from the 20 profiles provided by the UGS. The revised UGS data is presented in Figure 7.16. Figure 7.16a presents the median and 16th and 84th percentiles and Figure 7.16b presents the profiles of the coefficient of variation (COV) and number of profiles. Figure 7.17 presents the original median (20 profiles with all Vs values), the revised median (20 profiles with Vs<2500 ft/s (760 m/s)), and the "new" revised median (24 profiles with Vs<2500 ft/s (760 m/s)). No statistical analysis was performed when there were less than three profiles.

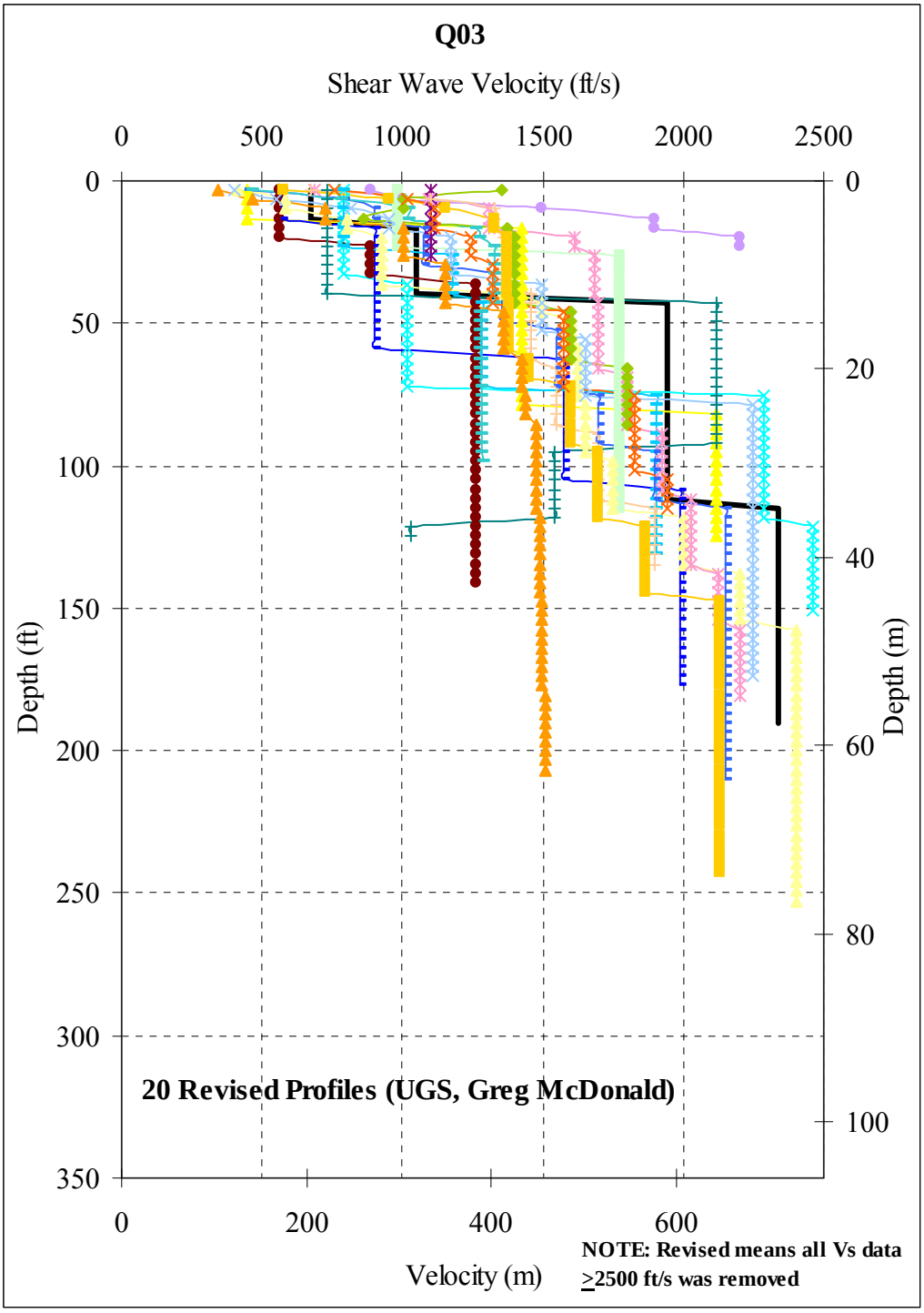

Figure 7.13 Revised Vs profiles for 20 sites in the Q03 Unit

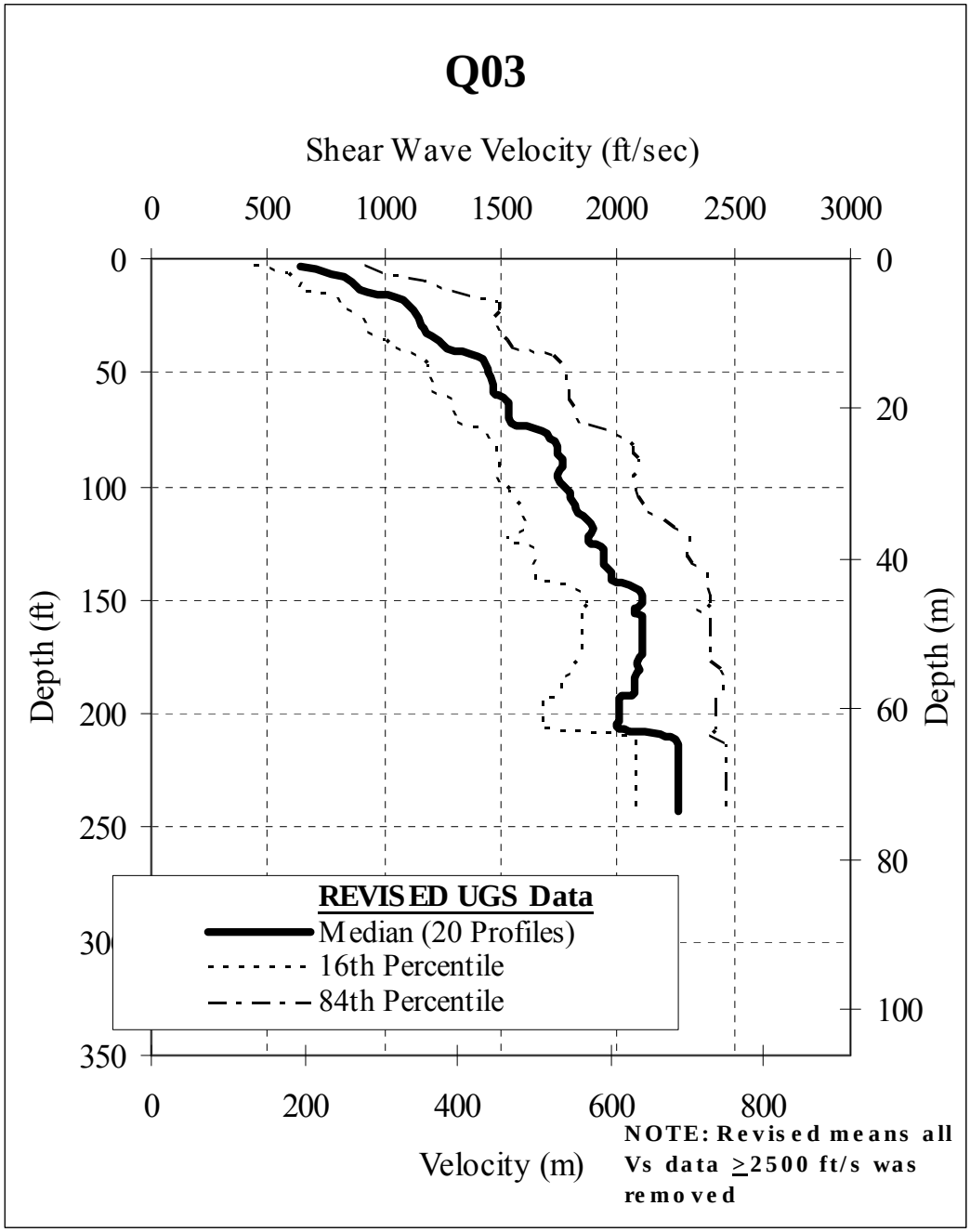

Figure 7.14 Revised UGS median (20 profiles) for the Q03 Unit

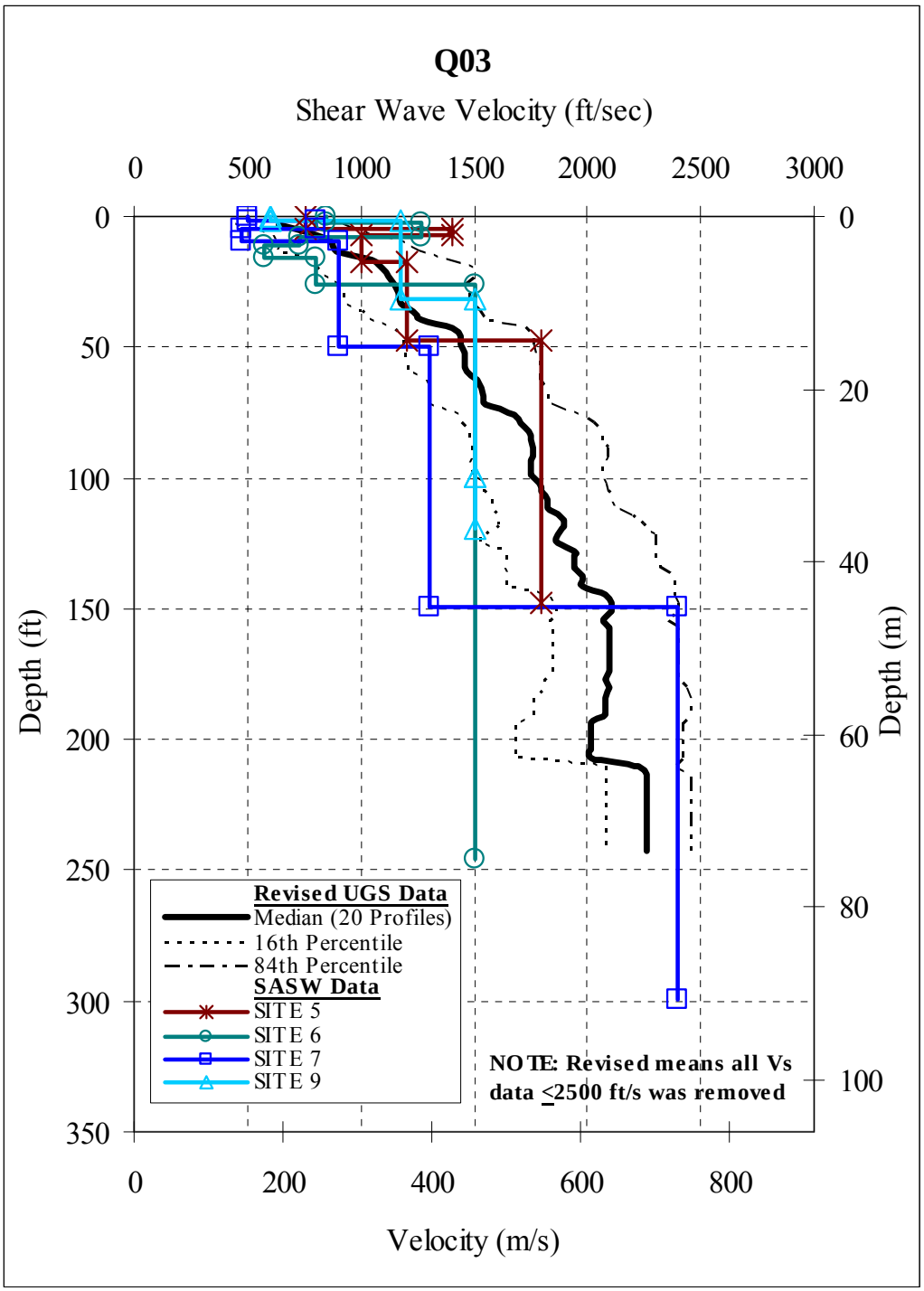

Figure 7.15 Four SASW Vs profiles determined in this study along with the revised median for the Q03 Unit from prior studies

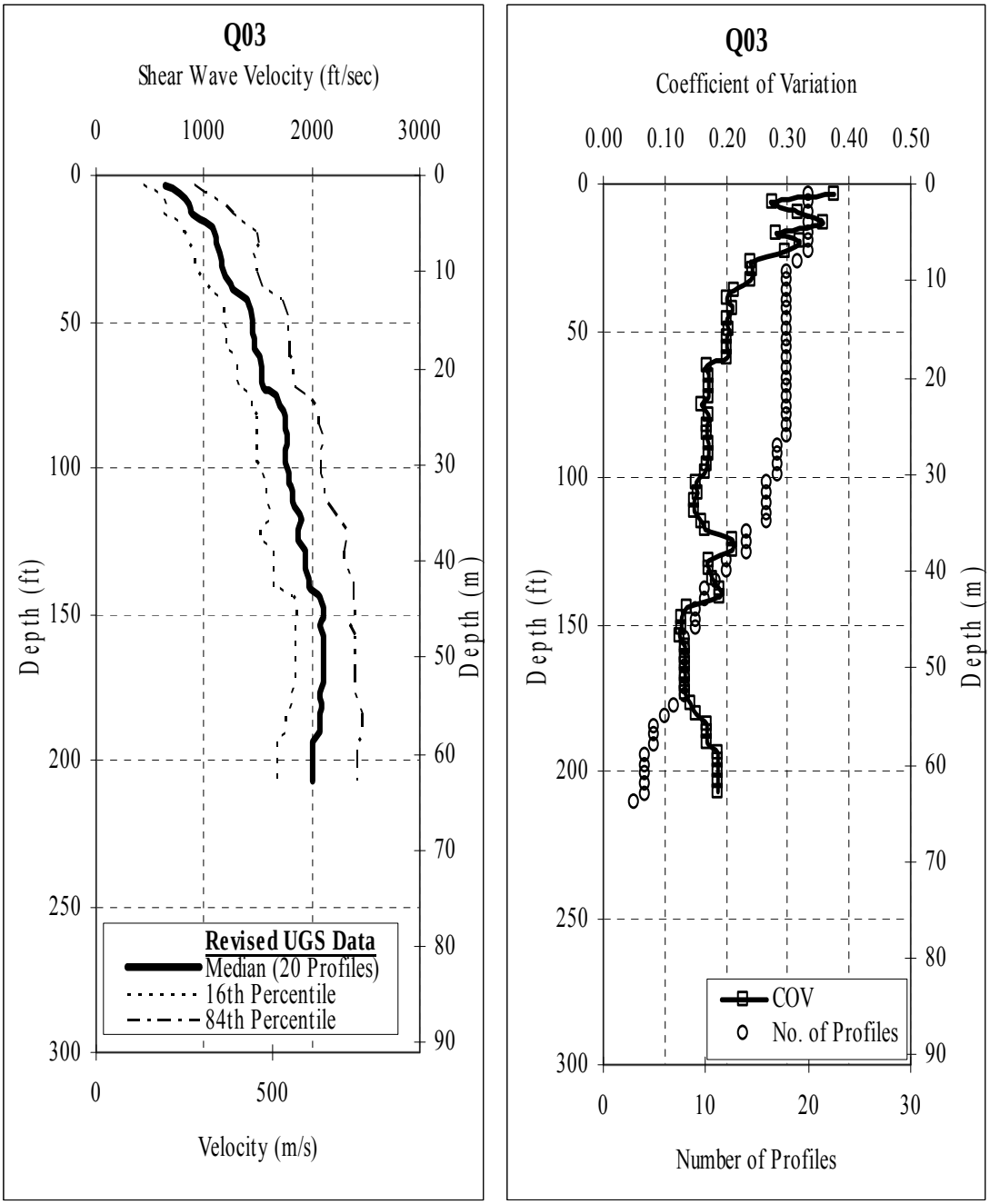

Figure 7.16 a) Median Vs Profile for the 20 previous sites, and b) COV and number of Profiles

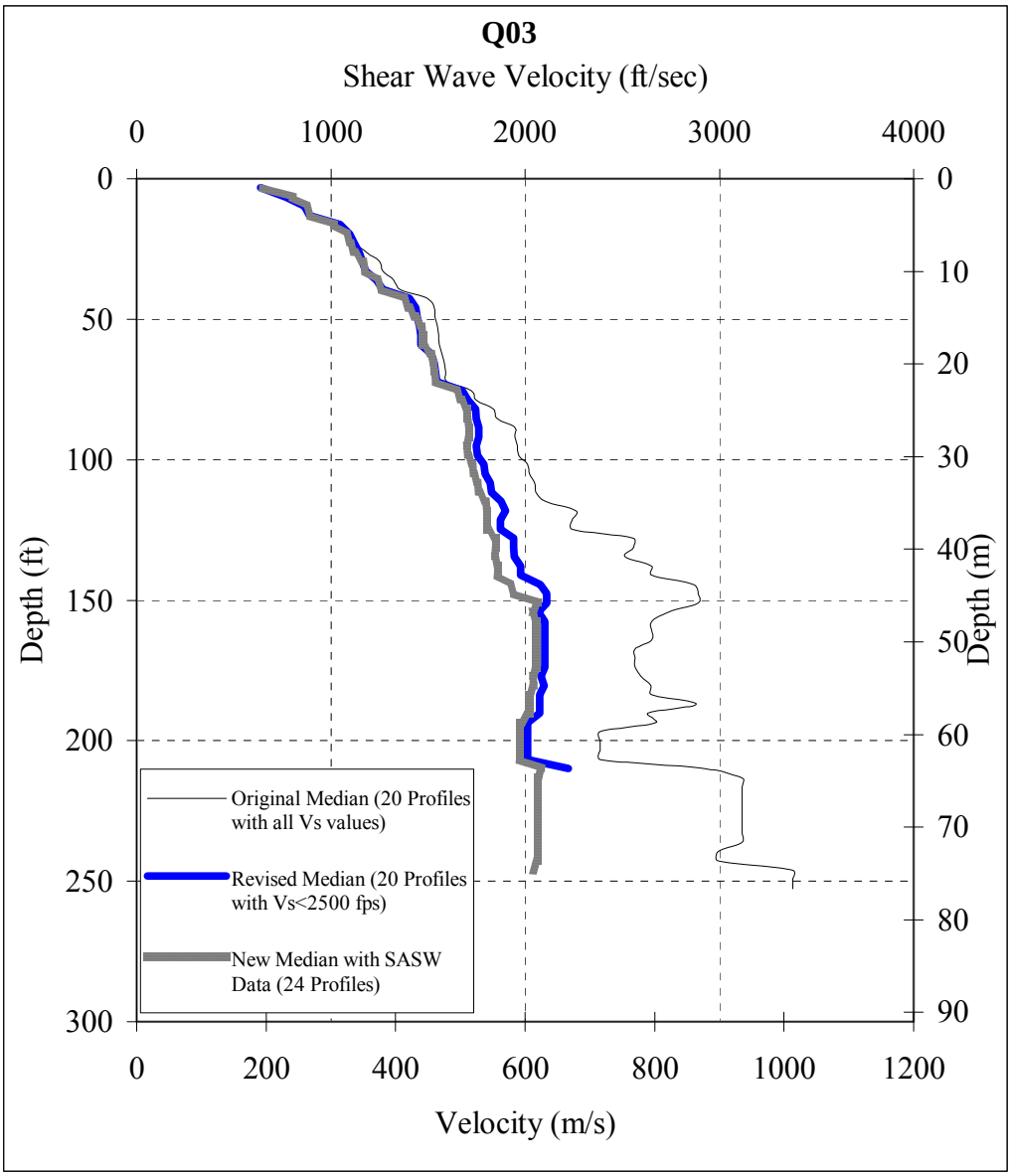

Figure 7.17 Statistical analysis of all Vs measurements in the Q03 Unit

The recommended smoothed Vs model for the Q03 Unit is presented in Figure 7.18. The smoothed profile was simply constructed by eye as a best-fit profile. Below 250 ft (75 m), the "by eye" fit was used because of the lack of data. Table 7.3 presents the smoothed curve discritized at 5 ft (1.5 m) and then in 10-ft (3 m) intervals. The discritized data in Table 7.3 are compared with the smoothed curve in Figure 7.18.

Table 7.3 Tabulated values for the smoothed Vs model in the Q03 Unit

	Velocity			Velocity			Velocity	
Depth ft (m)	ft/s	m/s	Depth ft (m)	ft/s	m/s	Depth	ft/s	m/s
5 (1.5)	750	229	140 (42)	1890	576	280 (84)	2118	646
10 (3)	850	259	150 (45)	1920	585	290 (87)	2126	648
20 (6)	1010	308	160 (48)	1950	594	300 (90)	2135	651
30 (9)	1150	351	170 (51)	1971	601			
40 (12)	1270	387	180 (54)	1990	607			
50 (15)	1390	424	190 (57)	2010	613			
60 (18)	1480	451	200 (60)	2020	616			
70 (21)	1550	472	210 (63)	2040	622			
80 (24)	1640	500	220 (66)	2060	628			
90 (27)	1700	518	230 (69)	2075	632			
100 (30)	1740	530	240 (72)	2085	636			
110 (33)	1790	546	250 (75)	2090	637			
120 (36)	1820	555	260 (78)	2100	640			
130 (39)	1850	564	270 (81)	2110	643			

7.2.4. Development of the Smoothed Vs Model for the Q05 Unit

Figure 7.19 presents the seven revised Vs profiles determined in the Q05 Unit prior to this study. Figure 7.20 presents the lognormal median and the 16th and 84th percentiles for the revised UGS data in the Q05 Unit. Figure 7.21 presents the one SASW Vs profile determined in the Q05 Unit for this study (Site 8) and the revised median from the seven profiles provided by the UGS. The revised UGS data is presented in Figure 7.22. Figure 7.22a presents the median and 16th and 84th percentiles and Figure 7.22b presents the profiles of the coefficient of variation

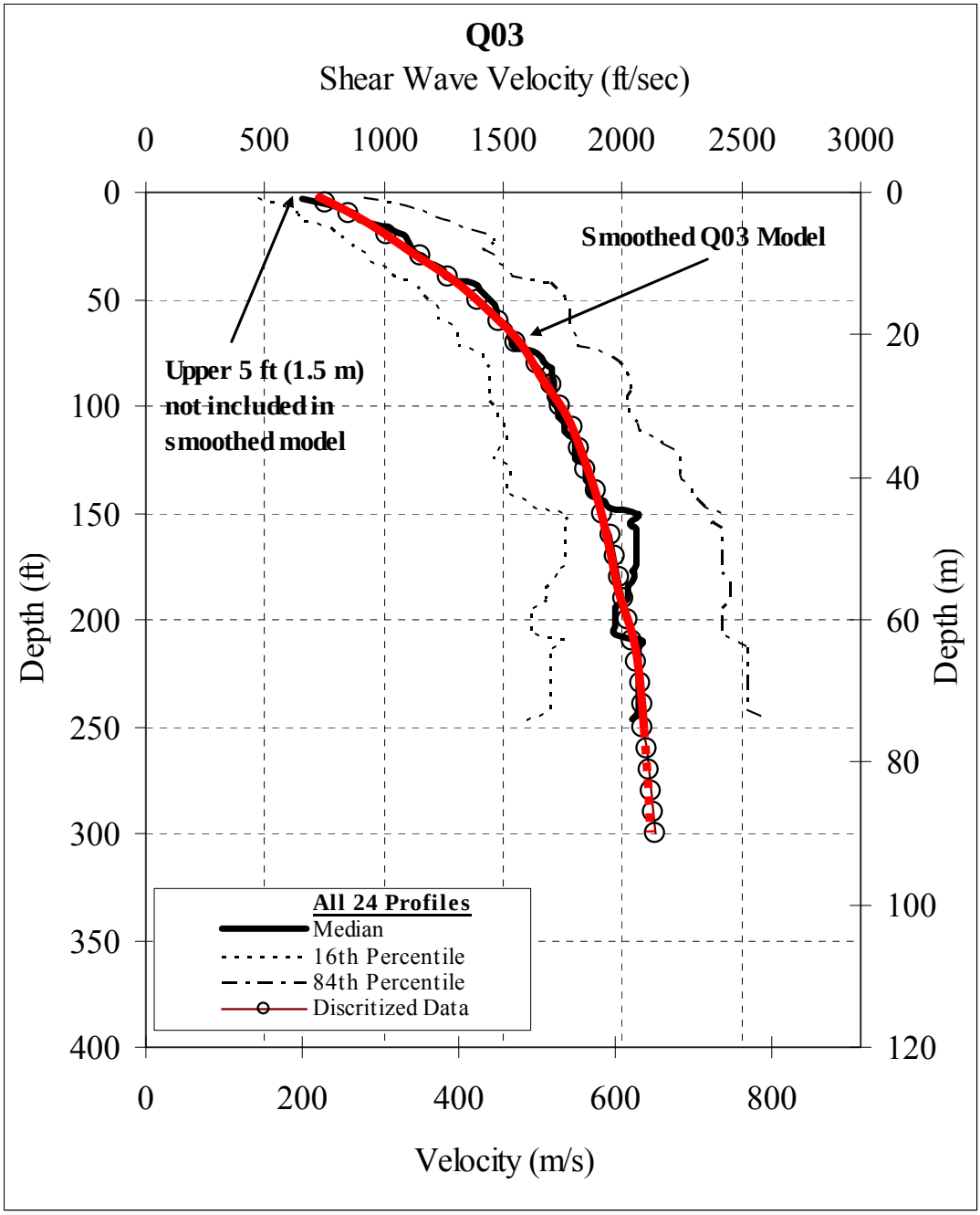

Figure 7.18 Smoothed Vs model recommended for the Q03 Unit

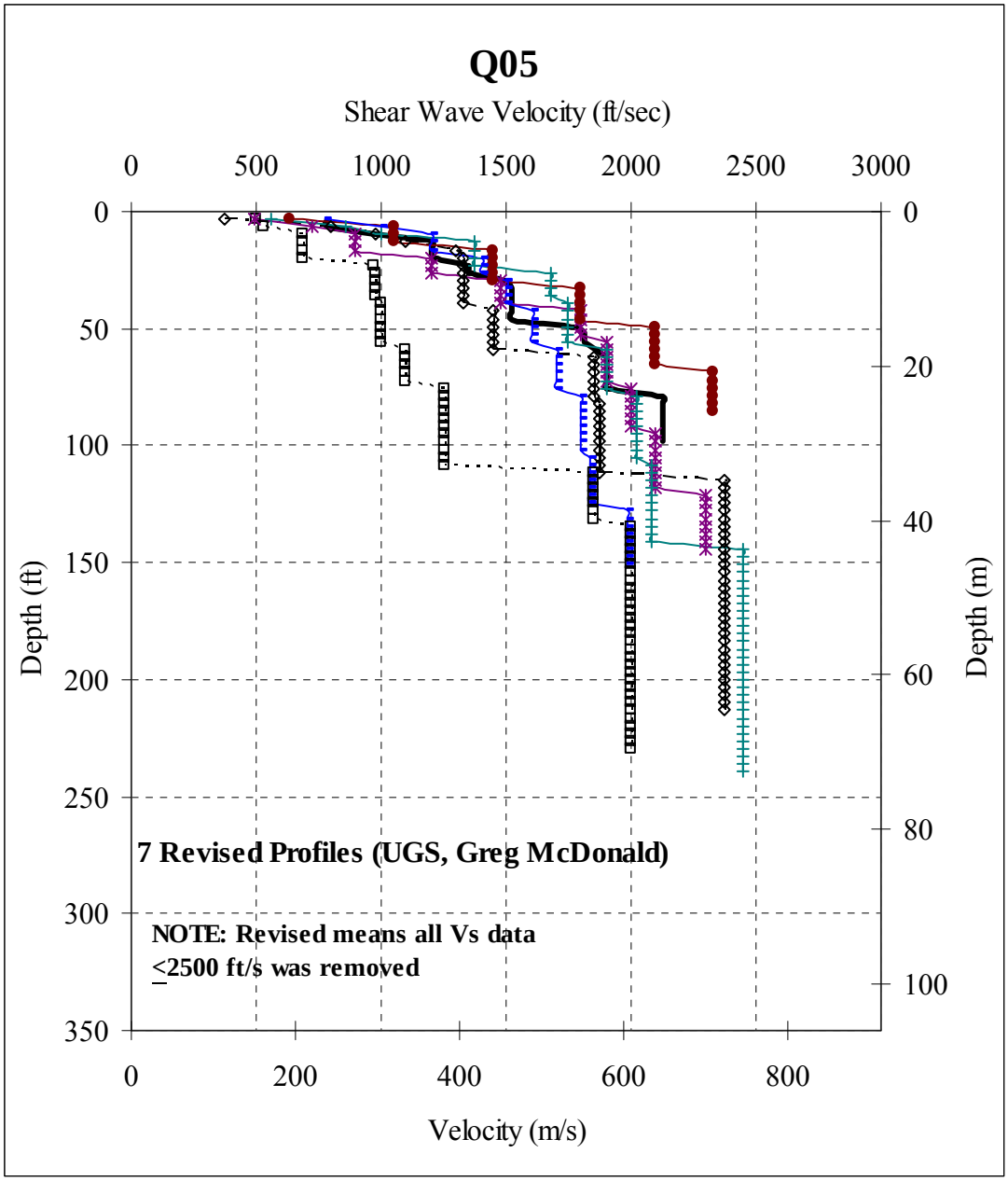

Figure 7.19 Revised Vs profiles for 7 sites in the Q05 Unit

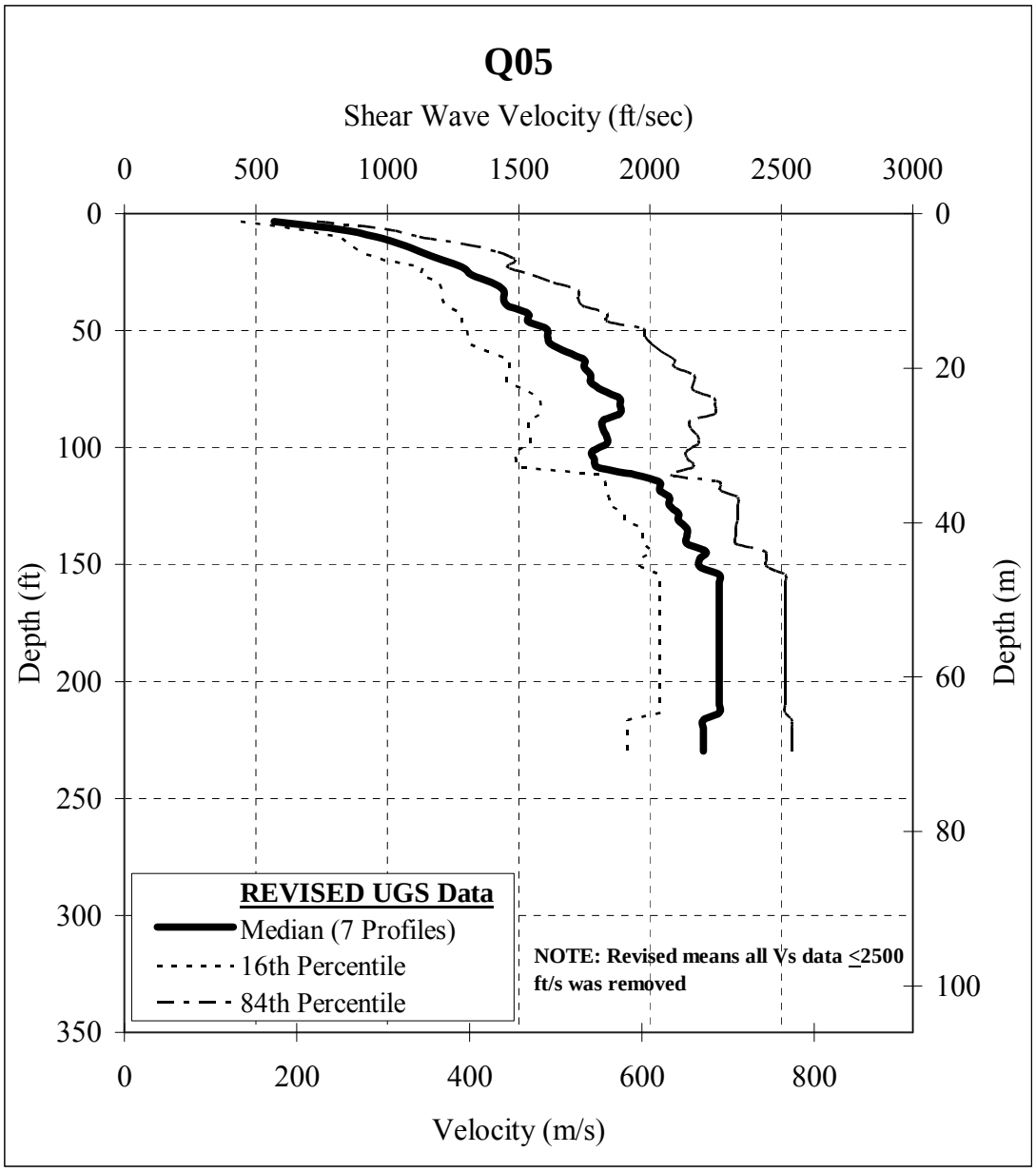

Figure 7.20 Revised UGS median (7 profiles) for the Q05 Unit

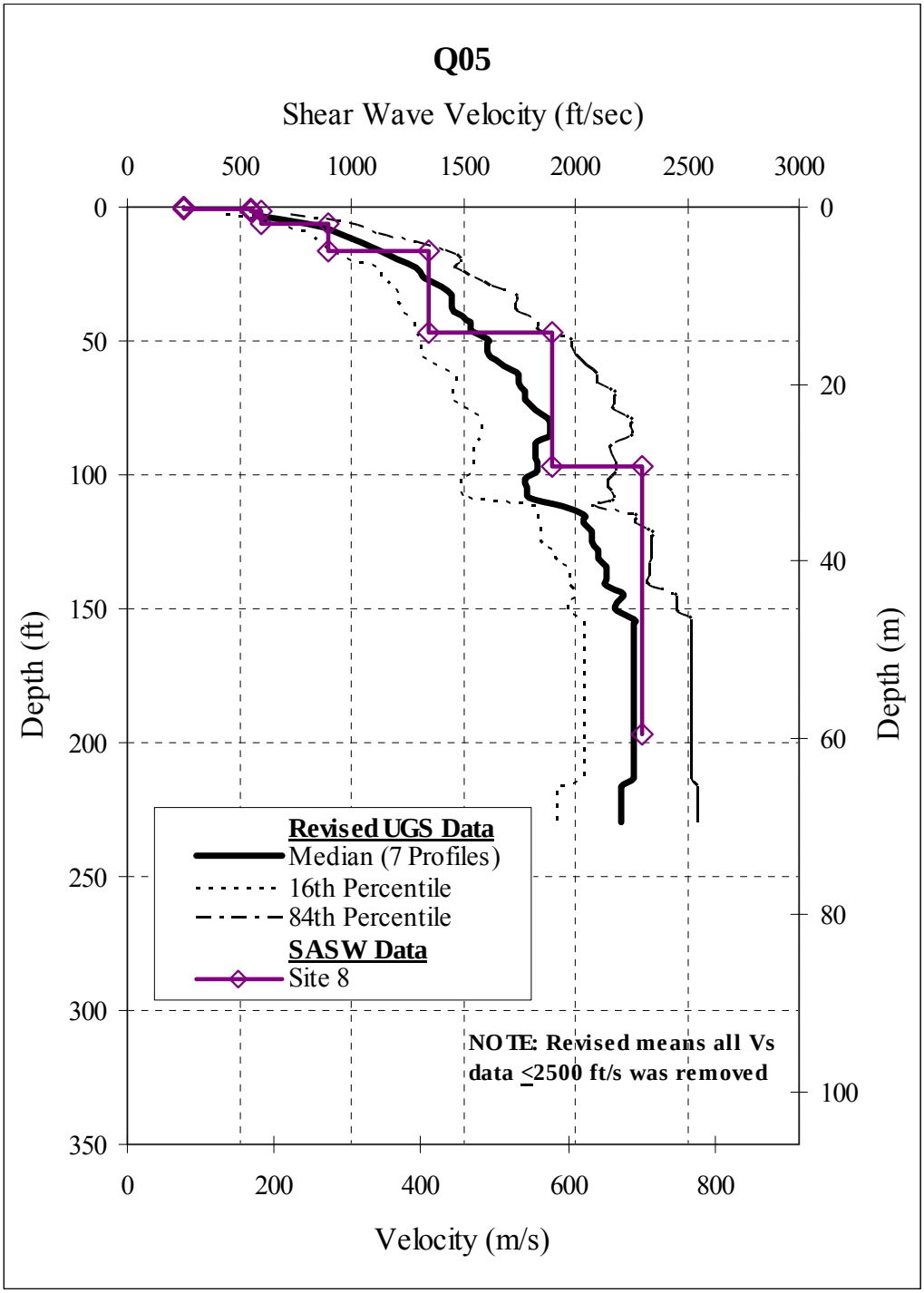

Figure 7.21 One SASW Vs profile determined in this study along with the revised median for the Q05 Unit from prior studies

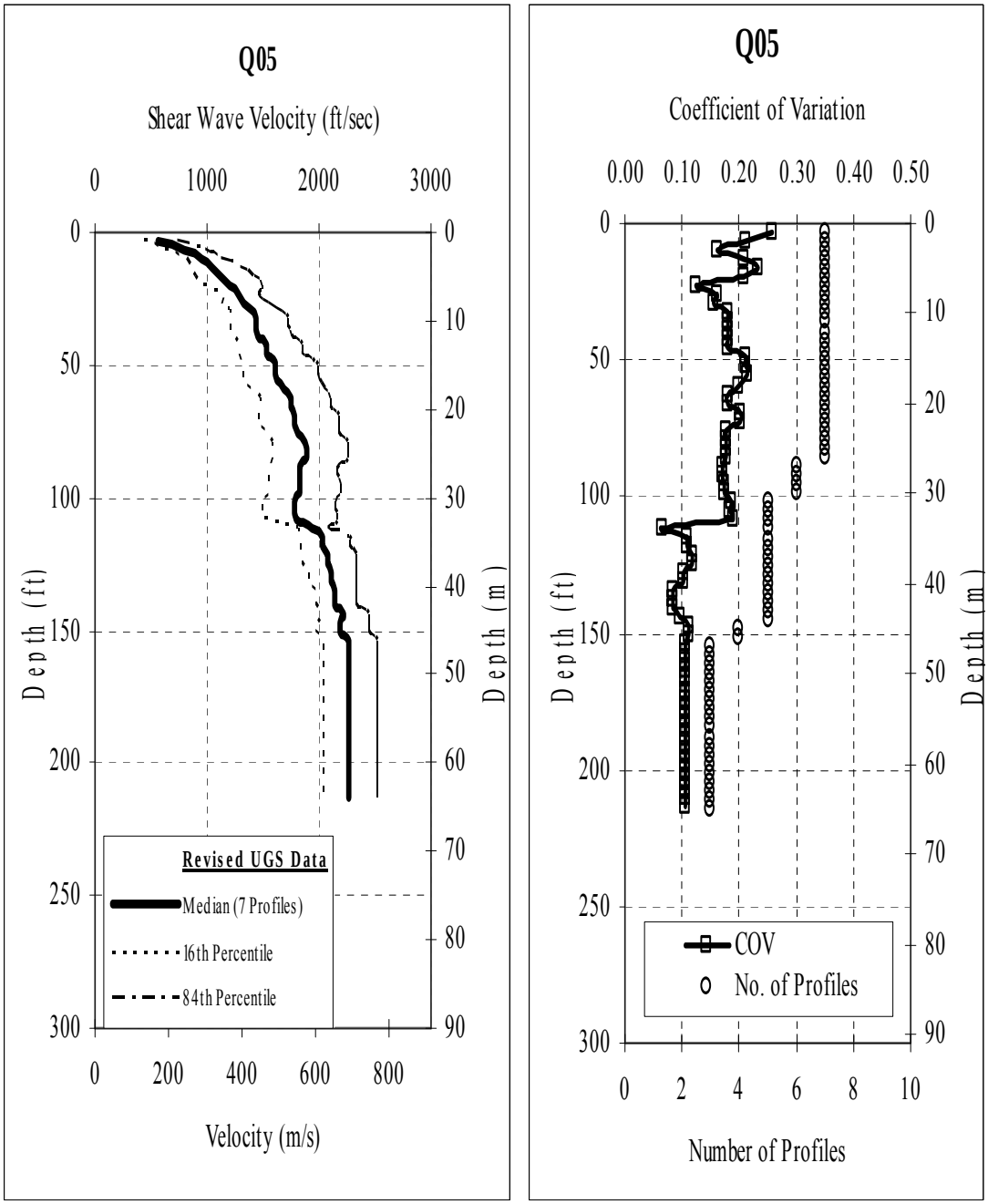

Figure 7.22 a) Median Vs profiles for 8 previous sites, and b) COV and number of profiles

(COV) and number of profiles. Figure 7.23 presents the original median (seven profiles with all Vs values), the revised median (seven profiles with Vs<2500 ft/s (760 m/s)), and the "new" revised median (eight profiles with Vs<2500 ft/s (760 m/s)). No statistical analysis was performed when there were less than three profiles.

The recommended smoothed Vs model for the Q05 Unit is presented in Figure 7.24. The smoothed profile was simply constructed by eye as a best-fit profile. Below 200 ft (60 m), the "by eye" fit was used because of the lack of data. Table 7.4 presents the smoothed curve discritized at 5 ft (1.5 m) and then in 10-ft (3 m) intervals. The discritized data in Table 7.4 are compared with the smoothed curve in Figure 7.24.

Table 7.4 Tabulated values for the smoothed Vs model in the Q05 Unit

	Velocity			Velocity			Velocity	
Depth ft (m)	ft/s	m/s	Depth ft (m)	ft/s	m/s	Depth	ft/s	m/s
5 (1.5)	750	229	140 (42)	2200	671	280 (84)	2485	757
10 (3)	980	299	150 (45)	2240	683	290 (87)	2495	760
20 (6)	1200	366	160 (48)	2270	692	300 (90)	2500	762
30 (9)	1360	415	170 (51)	2300	701			
40 (12)	1500	457	180 (54)	2330	710			
50 (15)	1600	488	190 (57)	2350	716			
60 (18)	1700	518	200 (60)	2375	724			
70 (21)	1790	546	210 (63)	2395	730			
80 (24)	1870	570	220 (66)	2410	735			
90 (27)	1940	591	230 (69)	2425	739			
100 (30)	2000	610	240 (72)	2440	744			
110 (33)	2056	627	250 (75)	2455	748			
120 (36)	2100	640	260 (78)	2465	751			
130 (39)	2167	661	270 (81)	2475	754			

7.2.5. Development of the Vs Model Beneath the R1 Boundary

A lognormal median was presented in Section 6.3.3 for the semi-consolidated material beneath the R1 boundary. It was assumed that all the semi-consolidated material in the Salt Lake Valley is similar and only one model was determined. To determine the model for the semi-consolidated materials, only profiles that extend

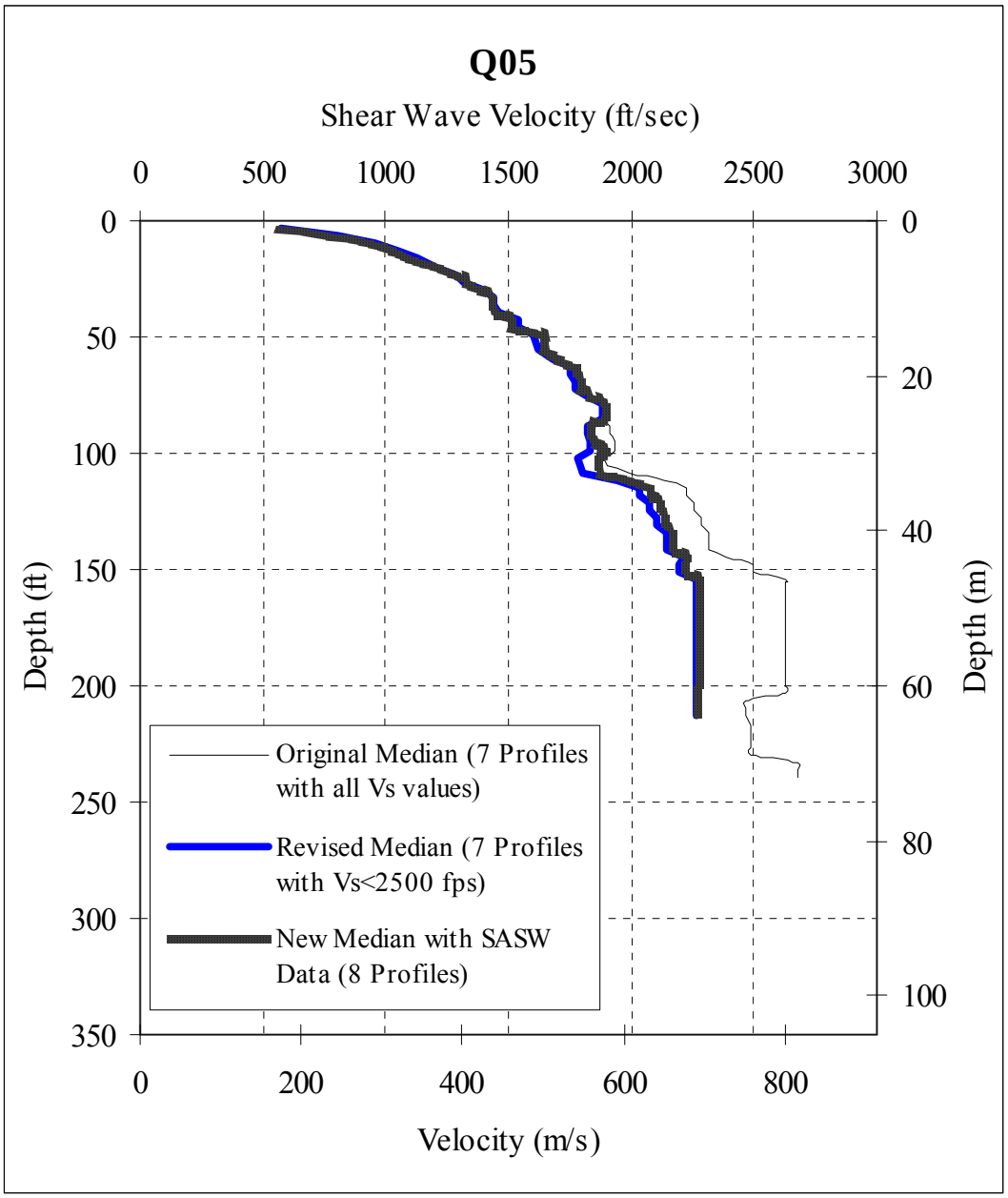

Figure 7.23 Statistical analysis of all Vs measurements in the Q05 Unit

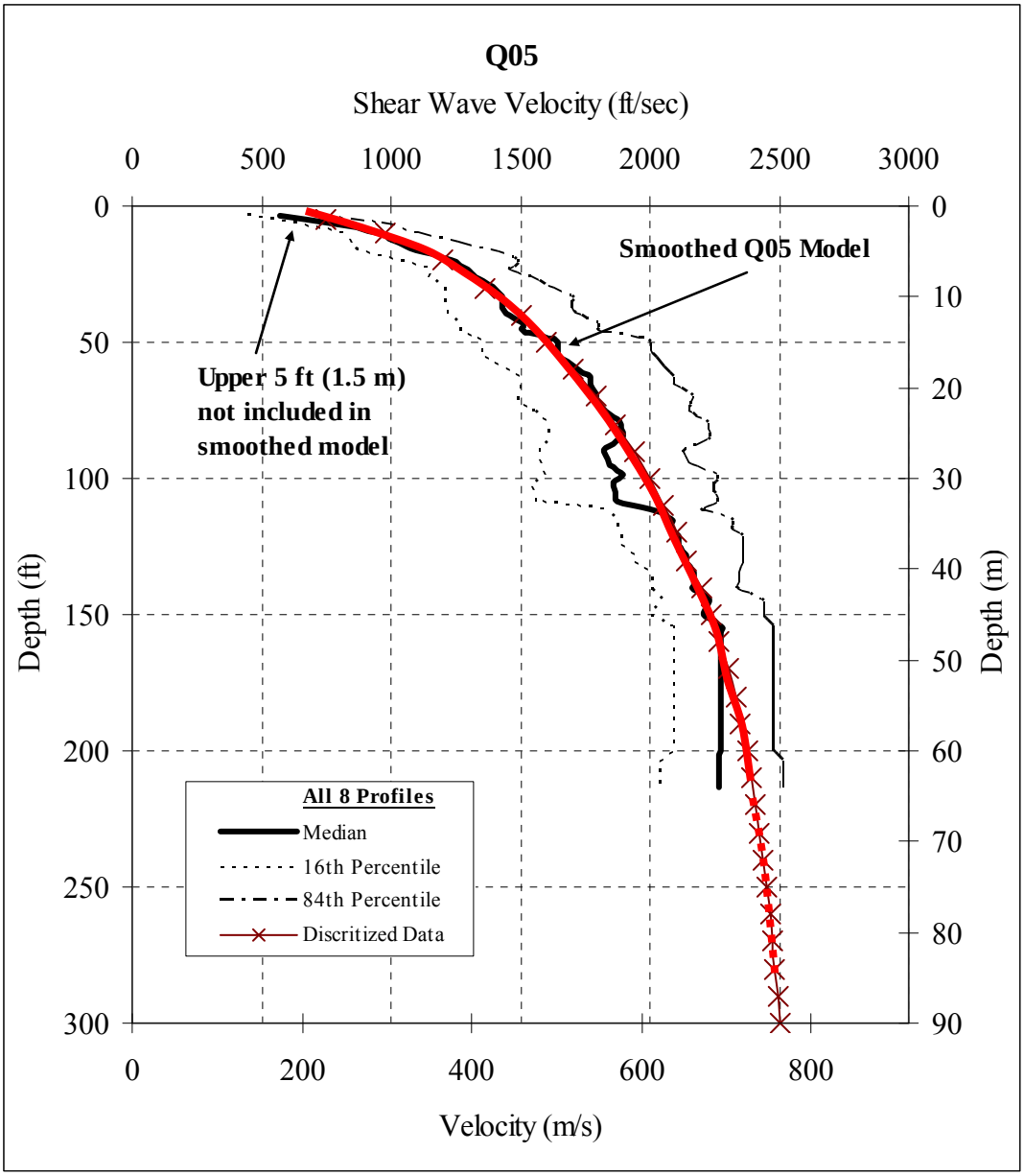

Figure 7.24 Smoothed Vs model recommended for Q05 Unit

below the R1 boundary greater then 300 ft (90 m) were analyzed. Nine of the eleven Vs profiles from this study were used to determine the semi-consolidated Vs model (Sites 1, 2, 3, 4, 5, 6, 7, 9 and 11). Figure 7.25 shows the semi-consolidated material that has a thickness greater than 300 ft (90 m) where the top of each Vs profile is located at a "zero" depth. Figure 7.26 presents a statistical analysis for the semi-consolidated material beneath the R1 boundary. Figure 7.26a presents the median and 16th and 84th percentiles and Figure 7.26b presents the profiles of the coefficient of variation (COV) and number of profiles. The recommended smoothed Vs profile for the semi-consolidated material is presented in Figure 7.27.

7.3. Comparison of the Proposed Smoothed Vs Models for the Unconsolidated Sediments with Prior Models

The smoothed models proposed for the unconsolidated sediments in Section 7.2 are compared to the three models presented in Wong et al (2002). The three models presented by Wong et al (2002) are: 1) lacustrine-alluvial silt and clay, 2) lacustrine sand, and 3) lacustrine-alluvial gravel. Figure 3.6 illustrates the three Wong et al (2002) models.

7.3.1. Q01-Unit and Silt and Clay Models

Figure 7.28 compares the smoothed Vs model for the Q01 Unit with the previous lacustrine-alluvial silt and clay model. The smoothed Vs model for the Q01 Unit is in good agreement with the lacustrine-alluvial silt and clay model proposed by Wong et al (2002).

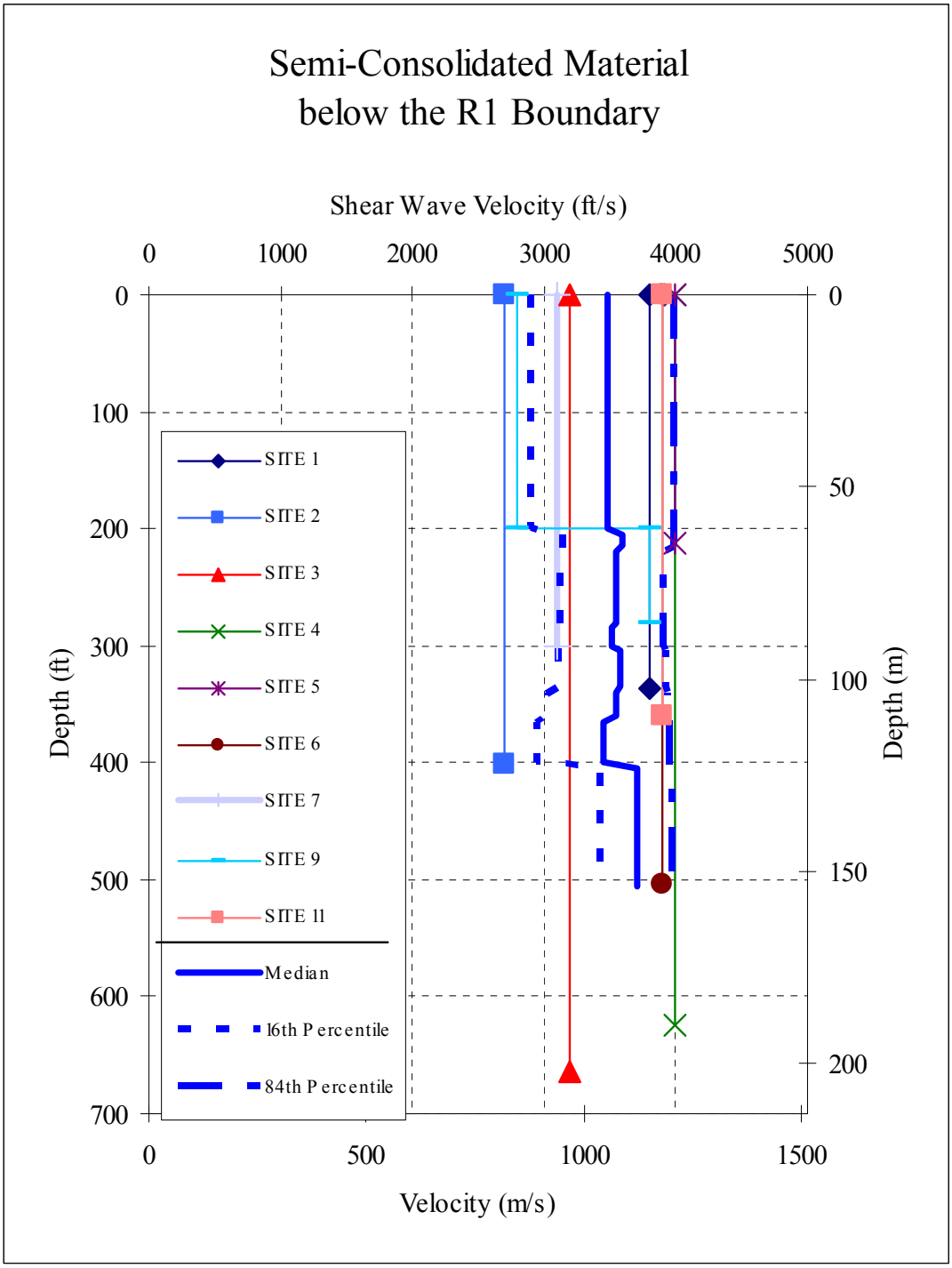

Figure 7.25 Shear wave velocity profiles measured below the R1 boundary with the SASW tests (R1 Boundary taken as depth equal to "zero")

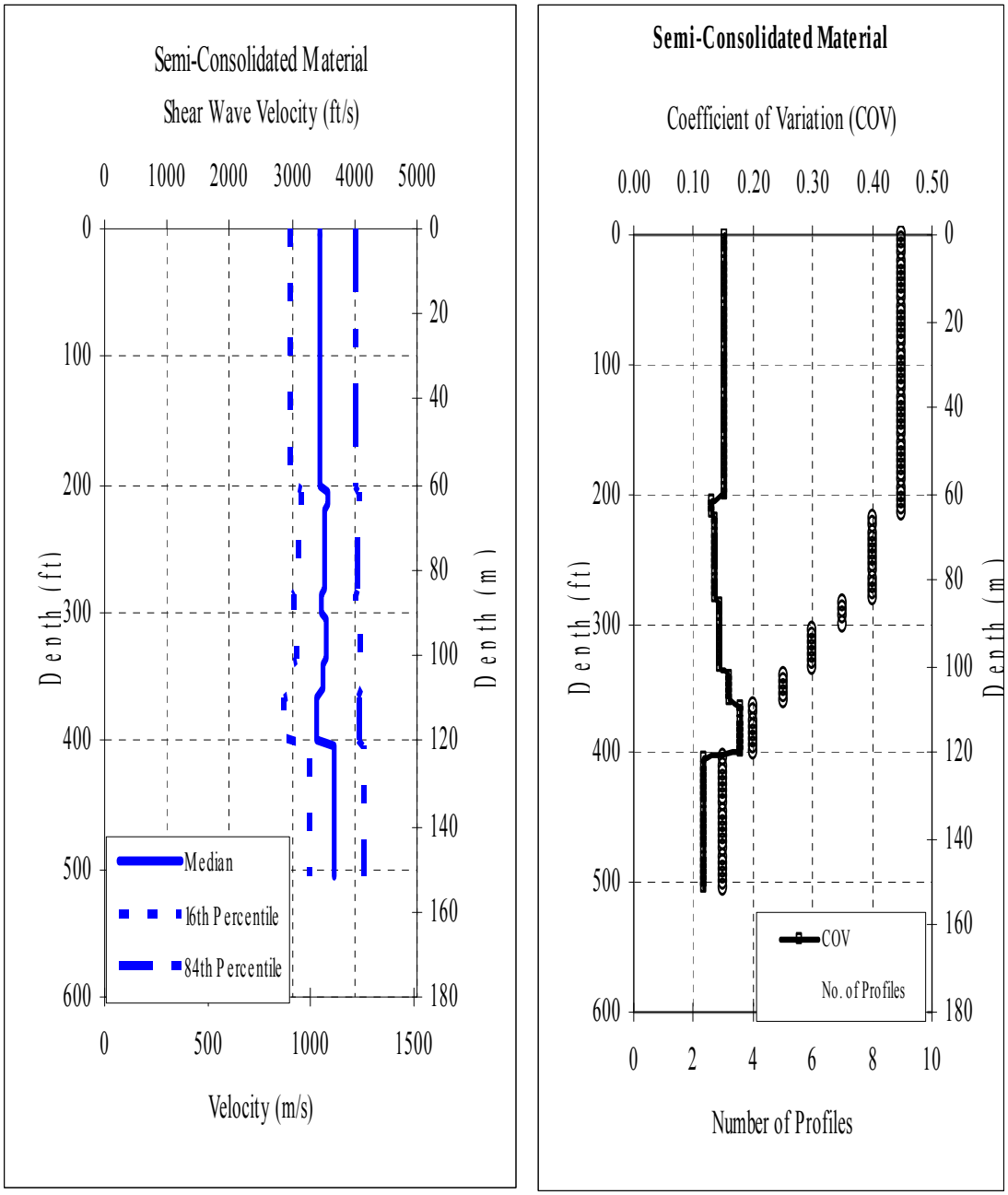

Figure 7.26 a) Median Vs profiles for 9 sites, and b) COV and number of profiles

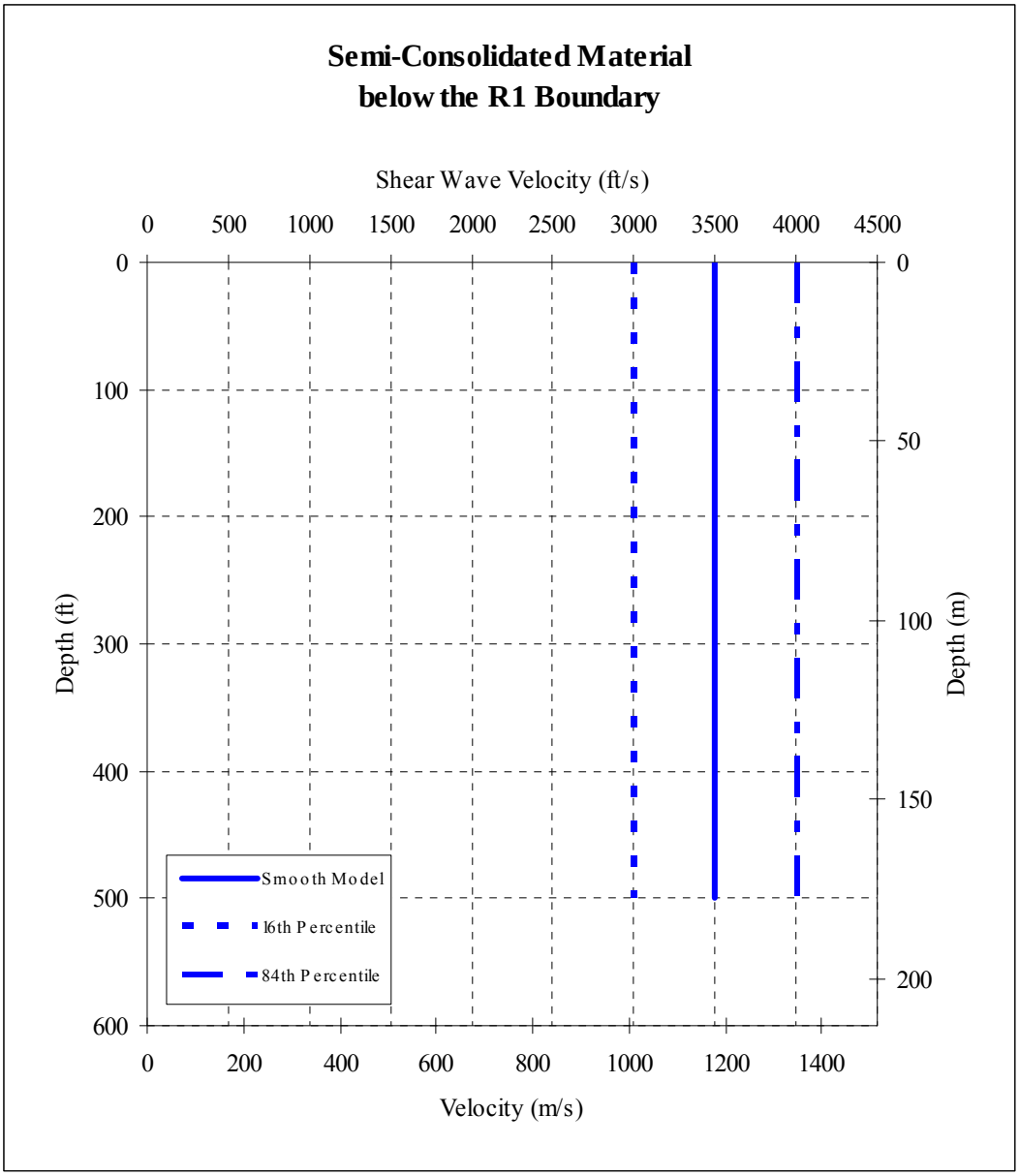

Figure 7.27 Smooth model for semi-consolidated material beneath the R1 boundary

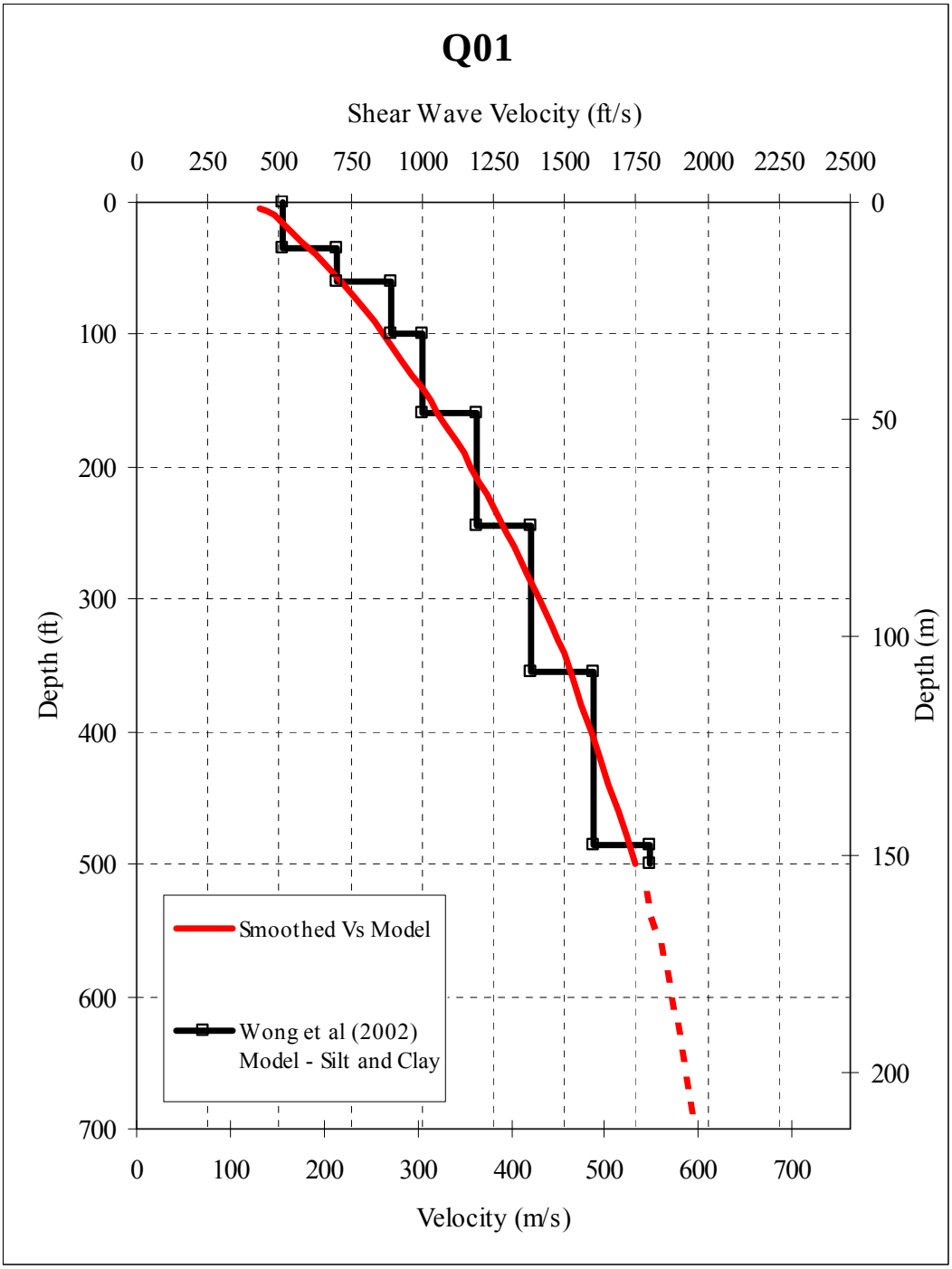

Figure 7.28 Comparison of smoothed Vs model for the Q01 Unit model and the Vs model from Wong et al (2002) for lacustrine-alluvial silt and clay

7.3.2. Q02-Unit and Sand Models

The smoothed Vs model for the Q02 Unit is compared with the lacustrine sand model proposed by Wong et al (2002) in Figure 7.29. The proposed smoothed Q02 Unit Vs model has slightly lower Vs values than the Wong et al (2002) model over the depth range of approximately 20 ft (6 m) to 180 ft (55 m). However, below 180 ft (55 m), excellent agreement exists between the two models.

7.3.3. Q03 Unit and Q05 Unit Models and the Gravel Model

The smoothed Vs model for the Q03 Unit is compared with the previous lacustrine-alluvial gravel model in Figure 7.30. Good agreement exists between the two models at depths less than about 75 ft (23 m). At depth below 75 ft (23 m), the smoothed Vs model exhibits somewhat lower Vs values.

The smoothed Vs model for the Q05 Unit is compared with the previous lacustrine-alluvial gravel model in Figure 7.31. Note that Figures 7.30 and 7.31 compare two different Vs models (Q03 and Q05) models with the same Wong et al (2002) model, lacustrine-alluvial gravel. The Q03 Vs model has lower Vs values than the previous gravel model while the Q05 Vs model has higher Vs values in general than the previous gravel model.

7.4. Example Profiles Using the Smoothed Curves

Figure 7.32 presents the four smoothed models for a side-by-side comparison. The smoothed models for the unconsolidated sediments and semi-consolidated materials are combined to provide examples for estimating the CVM for different parts of the Salt Lake Valley with different sediments above the R1 boundary.

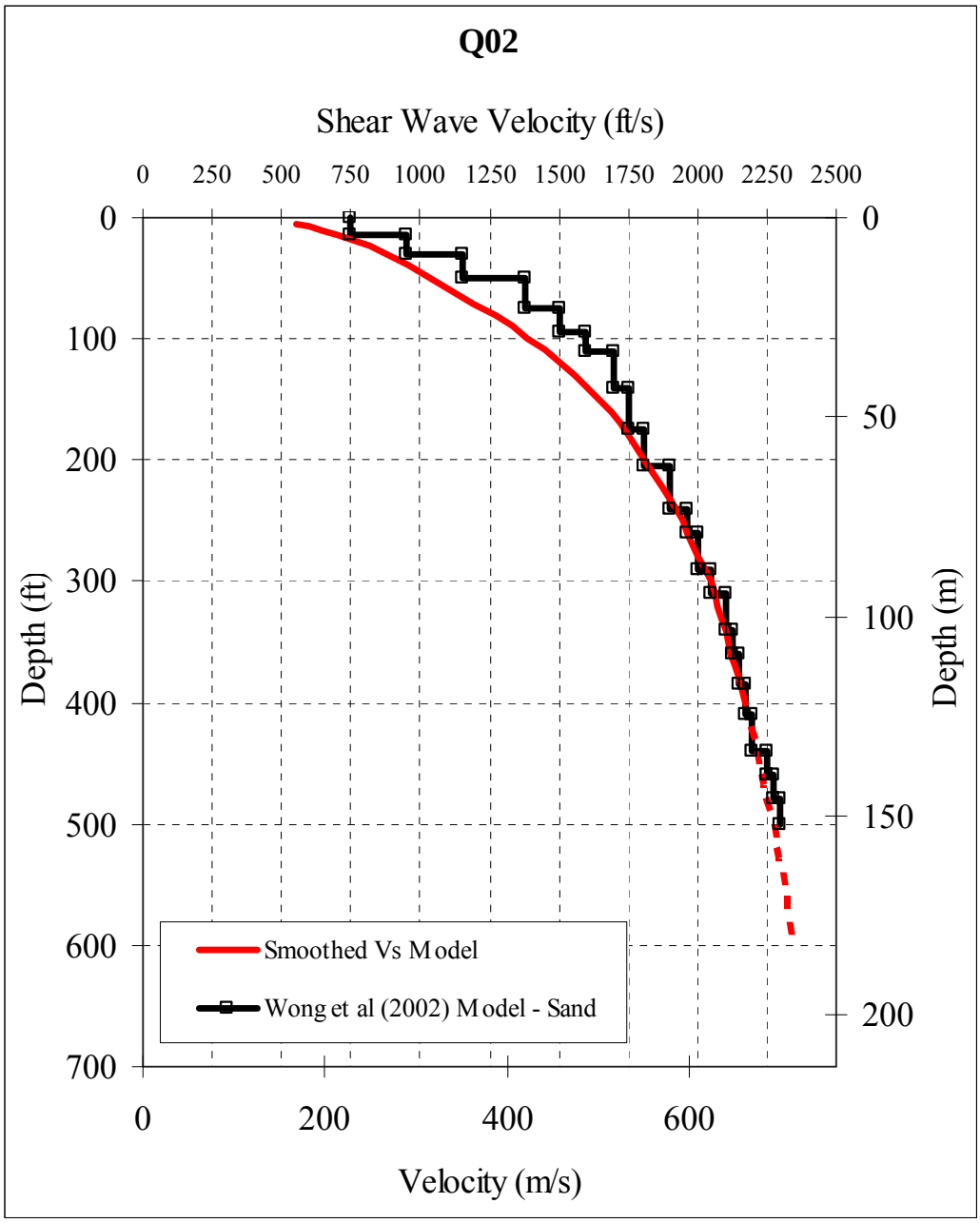

Figure 7.29 Comparison of smoothed Vs model for the Q02 Unit and the Vs model from Wong et al (2002) for lacustrine sand

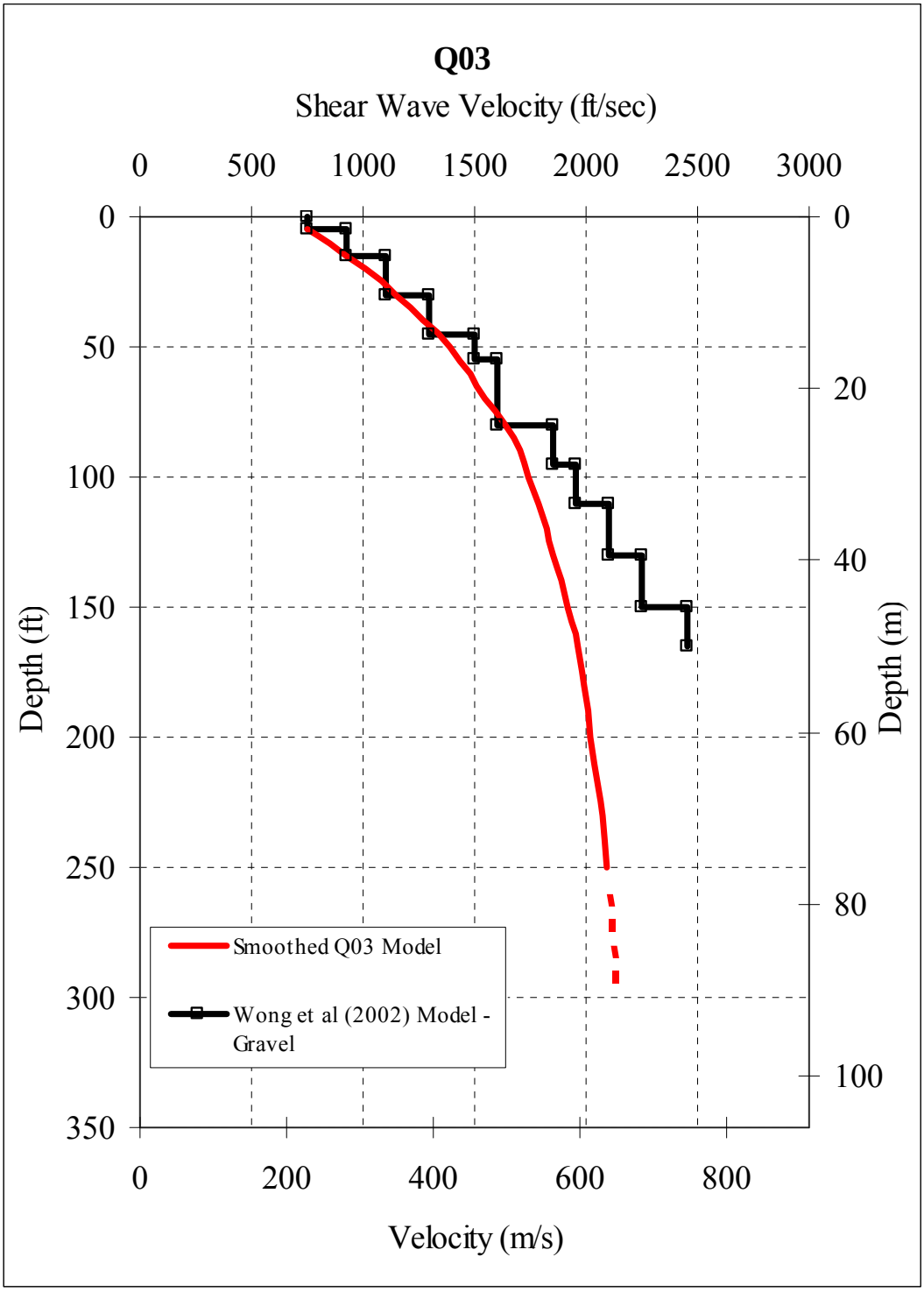

Figure 7.30 Comparison of smoothed Vs model for the Q03 Unit and the Vs model from Wong et al (2002) for lacustrine-alluvial gravel

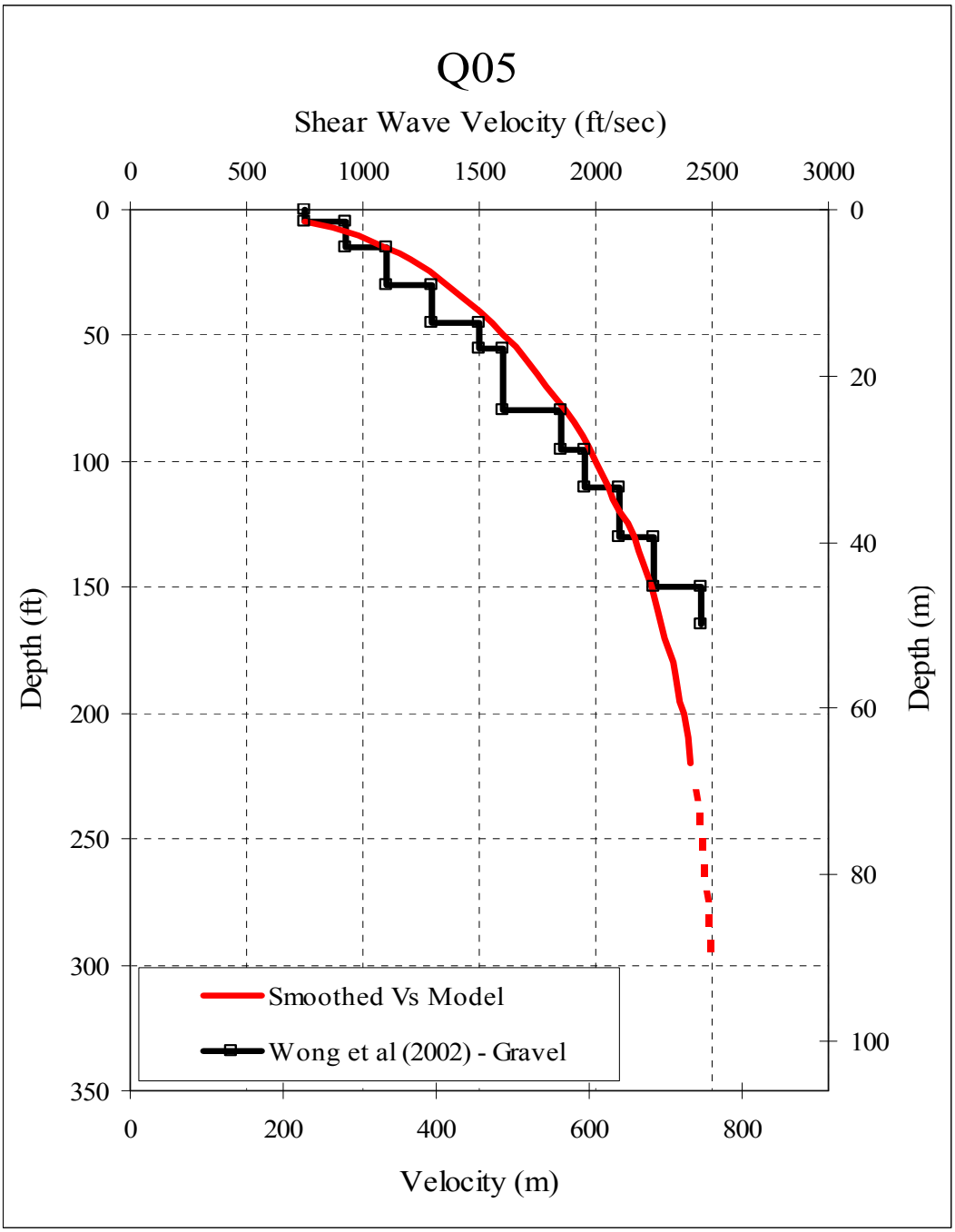

Figure 7.31 Comparison of smoothed Vs model for the Q05 Unit and the Vs model from Wong et al (2002) for lacustrine-alluvial gravel

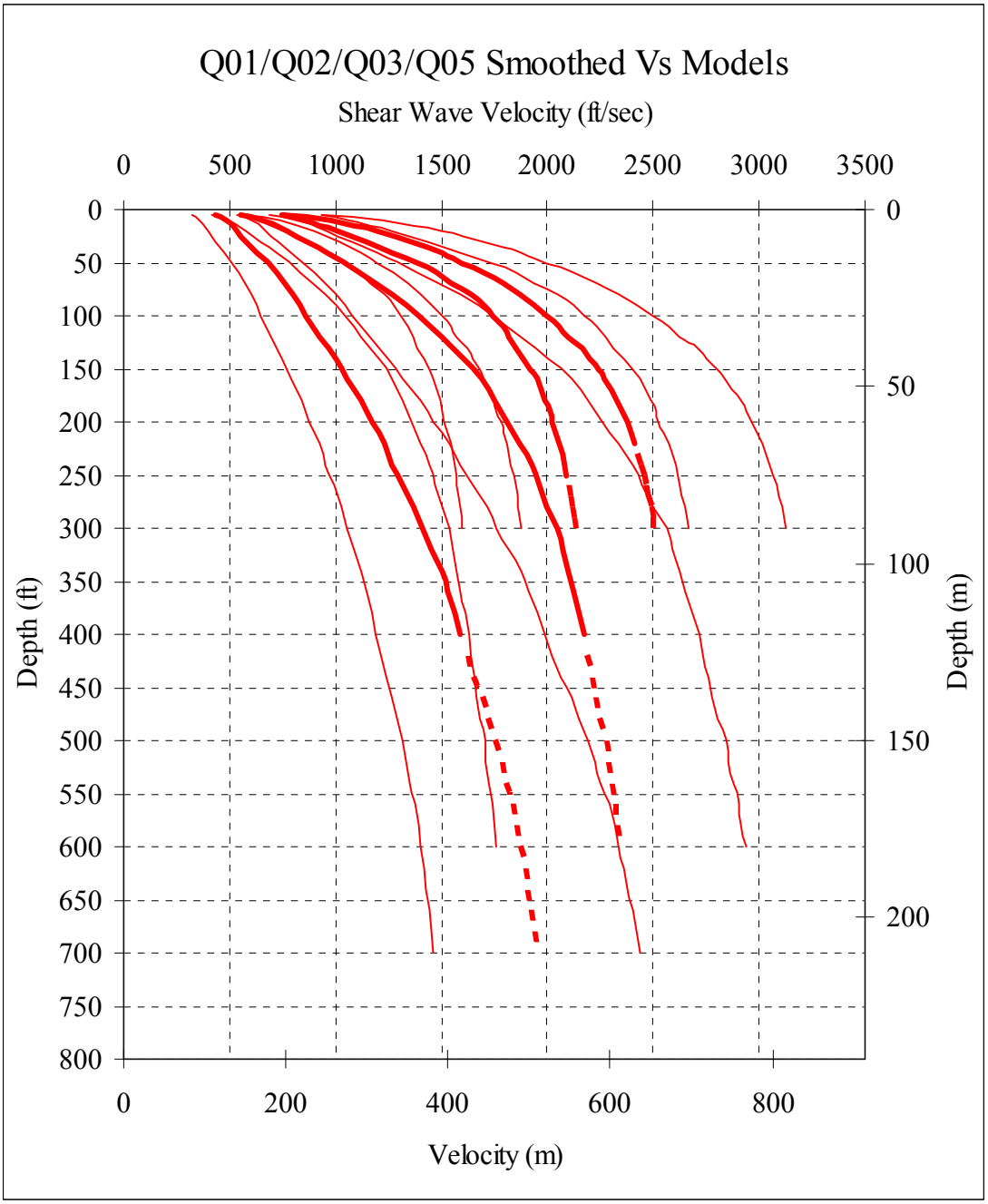

Figure 7.32 Comparison of the four smoothed models (Q01/Q02/Q03/Q05 Units)

7.4.1. Q01 Unit above the R1 Boundary

Figure 7.33 presents the combined Q01 Vs model that has both the unconsolidated sediments and the semi-consolidated materials below the R1 boundary. Two depths to the R1 boundary are shown in this figure to clarify the effect of the varying depth of the semi-consolidated material at different locations in the Salt Lake Valley. Two possible locations in the Salt Lake Valley for these two different depths to the R1 boundary are presented in Figure 7.34. The unconsolidated sediments portion of the Vs model extends to a depth of 500 ft (150 m).

7.4.2. Q02 Unit above the R1 Boundary

Figure 7.35 presents the combined Q02 Vs model that has both the unconsolidated sediments and the semi-consolidated materials below the R1 boundary. Two depths to the R1 boundary are shown in this figure to clarify the effect of the varying depth of the semi-consolidated material at different locations in the Salt Lake Valley. Two possible locations in the Salt Lake Valley for these two different depths to the R1 boundary are presented in Figure 7.34. The unconsolidated sediments portion of the Vs model extends to a depth of 500 ft (150 m).

7.4.3. Q03 Unit above the R1 Boundary

Figure 7.36 presents the combined Q03 Vs model that has both the unconsolidated sediments and the semi-consolidated materials below the R1 boundary. Only one depth to the R1 boundary is shown in this figure. The unconsolidated sediments portion of the Vs model extends to a depth of 240 ft (70 m).

7.4.4. Q05 Unit above the R1 Boundary

Figure 7.37 presents the combined Q05 Vs model that has both the unconsolidated sediments and the semi-consolidated materials below the R1

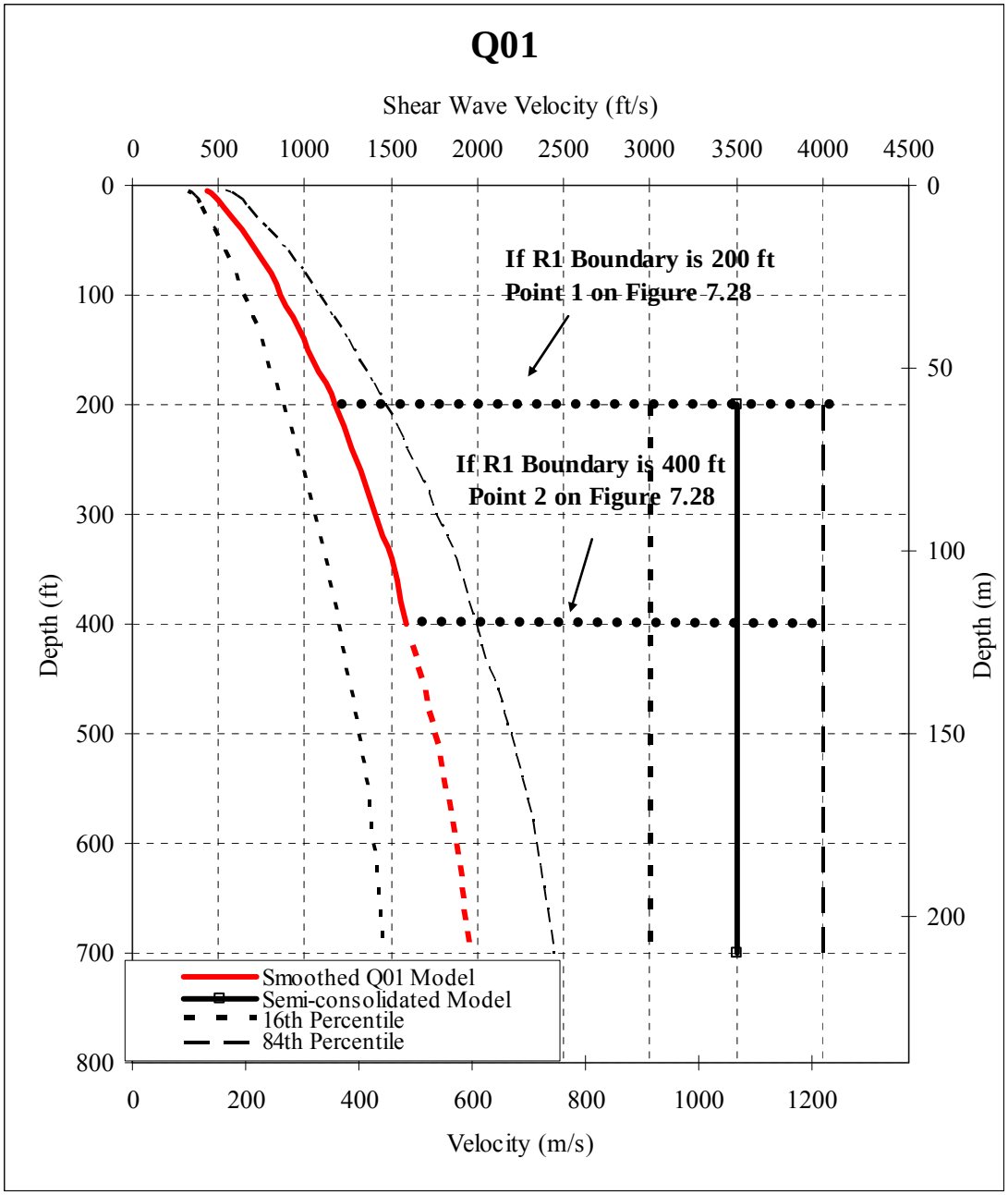

Figure 7.33 Model for the Q01 Unit and the semi-consolidated material below the R1 boundary

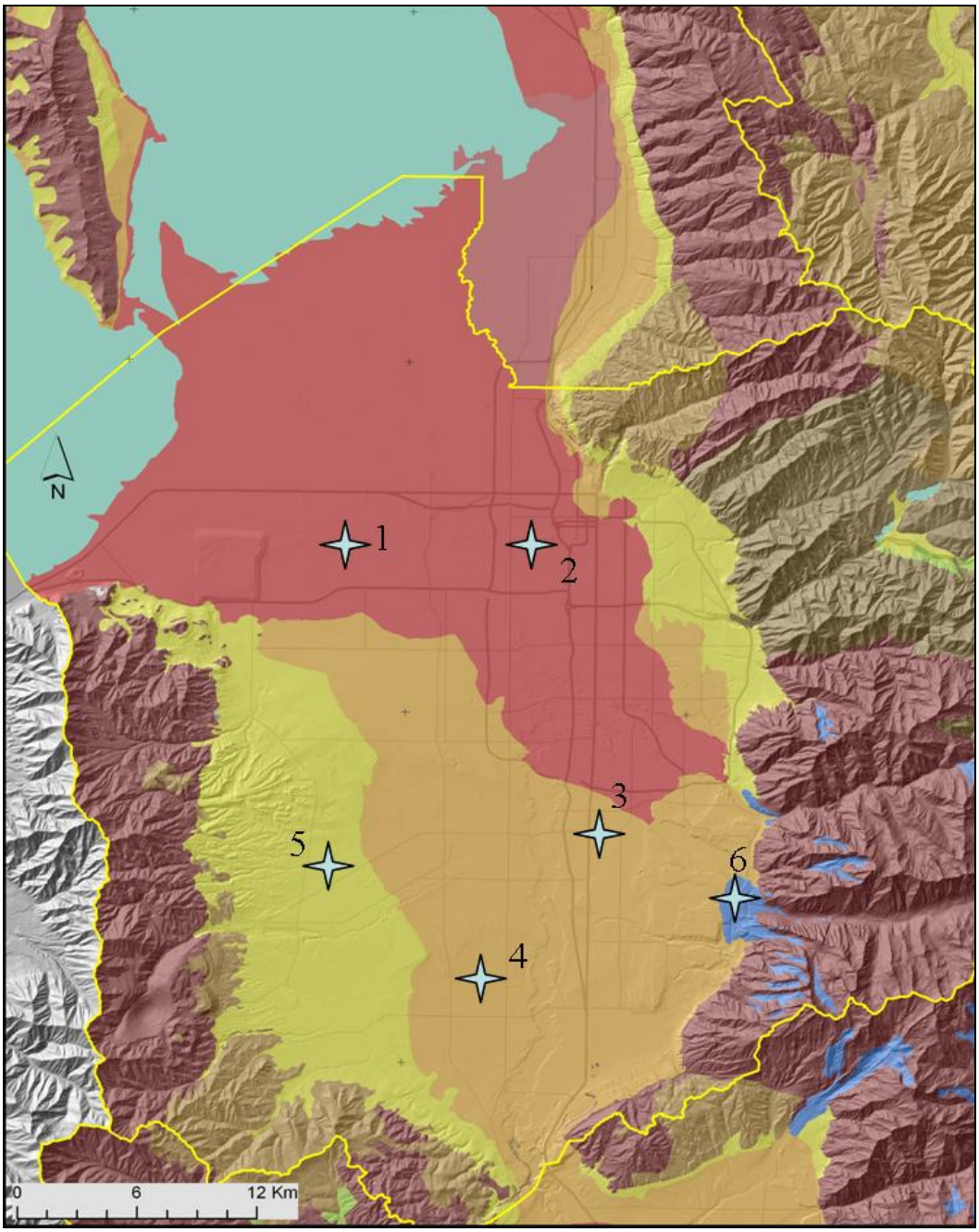

Figure 7.34 Map showing the different depths to R1 points presented in Figures 7.27, 7.29, 7.30, and 7.31

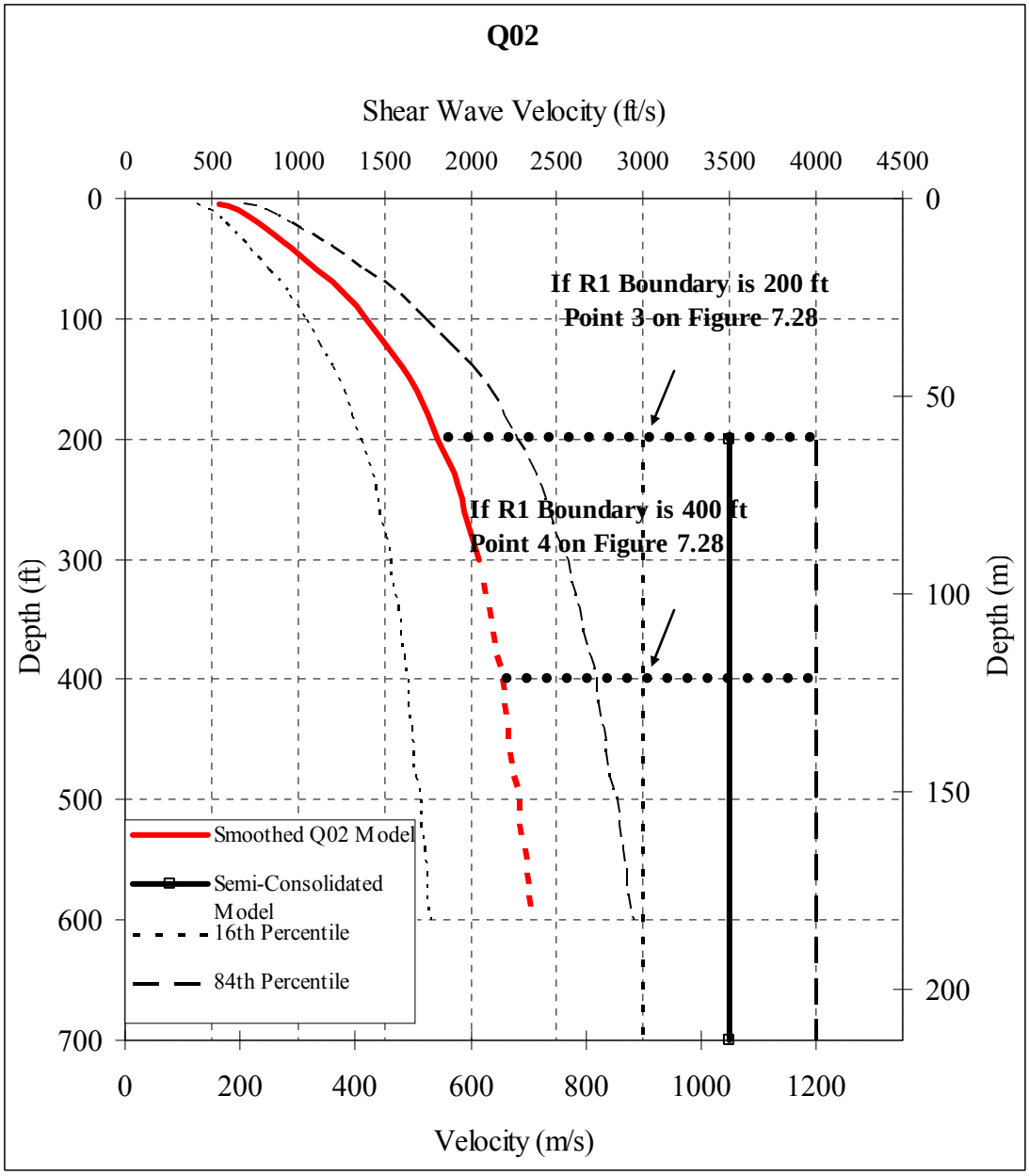

Figure 7.35 Model for the Q02 Unit and the semi-consolidated material below the R1 boundary

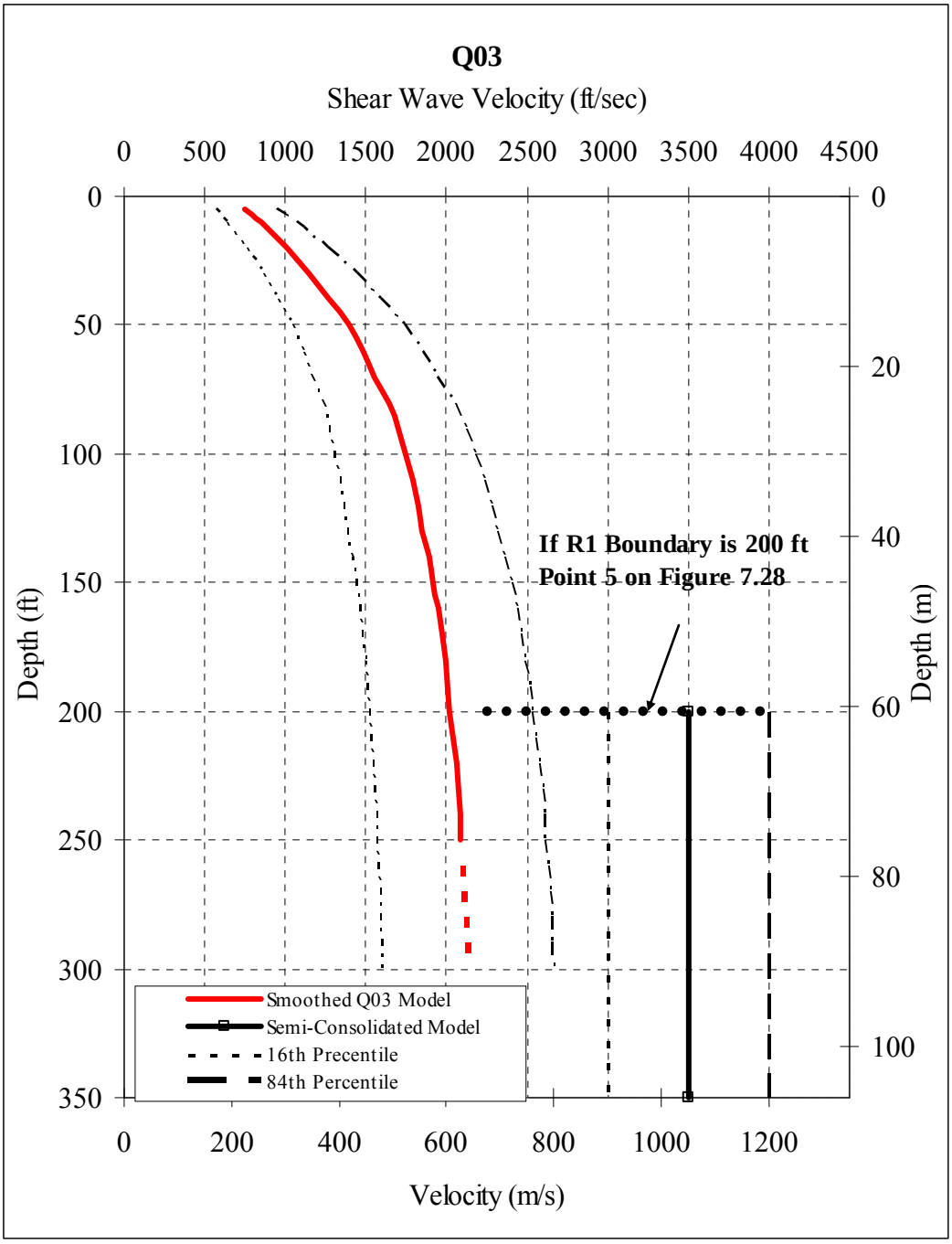

Figure 7.36 Model for the Q03 Unit and the semi-consolidated material below the R1 boundary

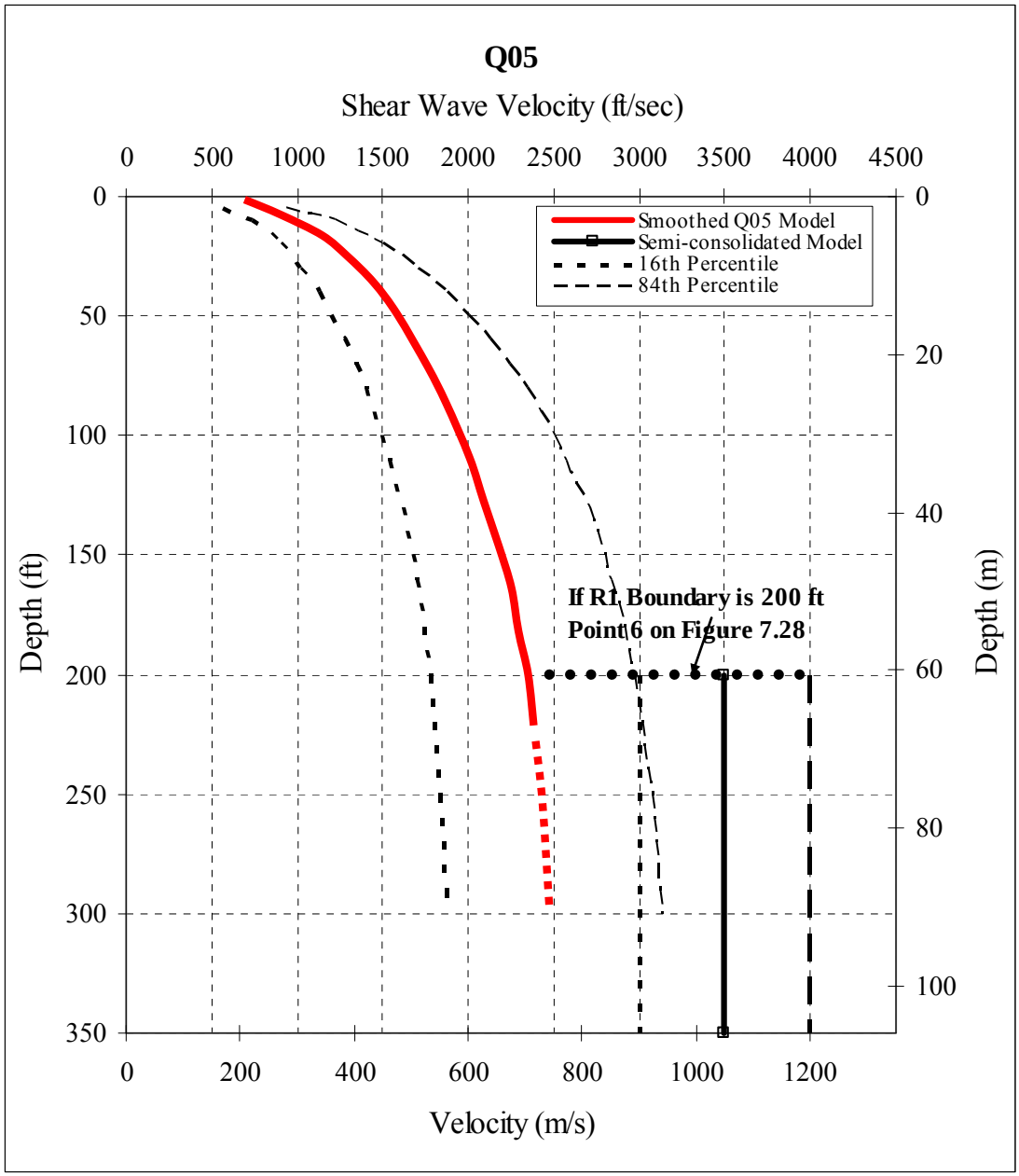

Figure 7.37 Model for the Q05 Unit and the semi-consolidated material below the R1 boundary

boundary. Only one depth to the R1 boundary is shown in this figure. The unconsolidated sediments portion of the Vs model extends to a depth of 225 ft (65 m).

7.5. Summary

To help develop the CVM smoothed Vs models were developed for four Quaternary units. The four Vs models include the unconsolidated sediments and the semi-consolidated materials beneath the R1 boundary. Vs profiles from previous investigations were analyzed as well as the eleven Vs profiles determined in this study. The Vs profiles from previous studies (139 profiles total) were revised to distinguish between the unconsolidated sediments and the semi-consolidated materials. For the unconsolidated sediments all material with a Vs value greater than 2500 ft/s (760 m/s) was removed from the analysis. The revised lognormal median was compared to the Vs profiles determined for this study. The Vs profiles from previous studies and the Vs profiles from this study were combined and the lognormal median, COV, and number of profiles were compared. A smooth Vs model was developed for the unconsolidated sediments based on the revised lognormal median and the individual Vs profiles from this study. The smooth models for the Quaternary units were compared to the previous models from Wong et al (2002) and were in good agreement. Four Vs models for the Quaternary units were combined with the one Vs model for the semi-consolidated material.

CHAPTER 8

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

8.1. Summary

The Utah Ground Shaking Working Group (WG) was formed in 2003 to develop a comprehensive earthquake preparedness program. One of the goals of the WG is to develop a ground-shaking map for the Salt Lake Valley region. To characterize the ground motions that would accompany a major earthquake, shear-wave velocity (Vs) profiles of the subsurface must be known. Therefore, one of the tasks of the WG is to develop a comprehensive set of Vs profiles for the Salt Lake Valley. This set of Vs profiles is referred to as the community velocity model (CVM).

The purpose of this study was to determine intermediate to deep shear wave velocity profiles in the Salt Lake Valley region. Intermediate depth profiles are defined as 250 ft (75 m) to 1250 ft (380 m) deep and deep profiles are defined as being deeper than 750 ft (230 m). Six deep and five intermediate depth 250 ft (75 m) to 750 ft (230 m) profiles were evaluated with the SASW test method. In addition, an unsuccessful attempt was made to test "hard" rock (Vs>4900 ft/s (1500 m/s)) at two sites with the SASW method. Testing was unsuccessful because of insufficient lateral extent to permit profiling through the surficial sediments.

Eleven sites were tested in this study. The Vs profiles from these sites were analyzed: (1) to try to develop model Vs profiles that fit the different material types in the Salt Lake Valley, (2) to determine the depths to the R1 and R2 boundaries based on Vs > 2500 ft/s (760 m/s) for the R1 boundary and Vs > 4900 ft/s (1500 m/s) for the R2 boundary, and (3) to compare the Vs profiles from this study with other studies.

8.2. Conclusions

The R1 boundary was determined at all eleven sites. The R2 boundary was not reached at any of the sites. The depth to the R1 boundary ranged from 120 ft (35 m) to 665 ft (205 m). In general, the depth to R1 was greatest in the northern and central portions of the Salt Lake Valley and the depth to R1 was the shallowest near the margins of the Salt Lake Valley. The shallow R1 boundary near the margins of Salt Lake Valley was expected because the perimeter of the valley is where rock outcrops occur and themountains begin.

The 11 Vs profiles were divided into four groups based on the surficial geology. Each group was then analyzed to determine/estimate a lognormal median Vs profile, the thickness of the unconsolidated sediment, the depth of the R1 boundary and the velocity in the semi-consolidated material below the R1 boundary. The SASW profiles were organized by Quaternary Unit (Q01, Q02, Q03, and Q05) and compared with existing shallow Vs profiles (original profiles, all Vs data included) in the Utah Geological Survey (UGS) database. The Q01, Q02, and Q05 groups show a good match between existing data and the SASW data from this study. The existing data for the Q03 group has higher Vs values than the SASW data. The higher Vs values are because the existing data that was provided by the Utah Geological Society includes some velocities greater than 2500 ft/s (750 m/s); hence, some data is below the R1 boundary.

The previous Vs data that was provided by the UGS (Greg McDonald) was revised so that all Vs data$\geq$2500 ft/s (760 m/s) was not included in the profiles for the unconsolidated sediments. A smoothed Vs model was added to the Vs profile of the unconsolidated sediment in each of the four groups (Q01, Q02, Q03, and Q05). The smoothed Vs models represent the unconsolidated sediments in each group and are based on the previous Vs data that has been revised and also on the Vs profiles determined in this study. The smoothed Vs model for the unconsolidated sediments

was added to the model for the semi-consolidated material to provide a composite Vs model. These models will be an important component in the CVM as they are the deepest Vs profiles to date in the Salt Lake Valley region. The smoothed Vs model for the Q01 Unit extends to a depth of 700 ft (210 m) while the previous data for the Q01 Unit extends to a depth of only 300 ft (90 m). The smoothed Vs model for the Q02 Unit extends to a depth of 600 ft (180 m) while the previous data for the Q02 Unit extends to a depth of only 250 ft (75 m). The smoothed Vs model for the Q03 Unit extends to a depth of 300 ft (90 m) while the previous data for the Q03 Unit extends to a depth of 250 ft (75 m). The smoothed Vs model for the Q05 Unit extends to a depth of 300 ft (90 m) while the previous data for the Q05 Unit extends to a depth of 225 ft (70 m).

The Vs profiles determined in this study are deeper than any previous studies in the Salt Lake Valley. The deepest profiles in the Salt Lake Valley prior to this study were a reflection profile presented in Figure 3.4 and two sonic logs presented in Figure 3.3. Shear wave velocities were determined from the P-wave velocities by assuming Vp/Vs=1.72 (Hill et al, 1990) and extend to depths of approximately 6000 ft (1800 m) 3300 ft (1000 m). The deepest Vs profiles from previous studies other than the two sonic logs were approximately 300 ft (90 m). Two Vs profiles determined in this study extend to a depth $\geq$ 1000 ft (300 m) and four Vs profiles determined in this study extend to a depth $\geq$ 750 ft (225 m). Ten of the eleven Vs profiles determined in this study extend to at least a depth of 300 ft (90 m).

8.3. Recommendations

The results from this study are intended to add to the existing CVM. An important component of the CVM is the depth to the R2 boundary (semi-consolidated/ consolidated boundary). The R2 boundary was not reached at any of the sites. By focusing on the R2 boundary when choosing future sites, it may be possible to reach the R2 boundary by selecting sites closer to the Salt Lake Valley

margins. It is believed that the R2 boundary is at shallower depths along the margins of the valley.

The SASW testing in this study was performed using an active source. It may be possible to reach the R2 boundary by using a passive surface-wave method. At sites with soft silt and clay materials (Sites 10 and 11) a passive surface-wave method may be able to profile deeper than accomplished in this study, although this difference remains to be evaluated. At these soft sites, below approximately 2 to 3 Hz, Liquidator was not capable of generating long wavelengths with enough energy to sample at depth. This difficulty arose because of the softness of the unconsolidated sediments in the Salt Lake Valley. Passive-source methods may be able to profile deeper than active methods if ambient low-frequency is present. Testing with ambient noise (a passive source) would also help compliment the Vs profiles determined in this study. Additional Vs testing using deep downhole seismic testing at a few key sites would also supplement, verify, and extend the existing Vs profiles.

Additional SASW testing would also give more Vs profiles in the semi-consolidated sediments (below the R1 boundary). Currently, the only Vs profiles below the R1 boundary are from one reflection profile, two sonic logs (Hill et al, 1990), and the 11 sites tested in this study. The additional Vs profiles would also allow more depths to the R1 boundary to be determined and more measurements in the unconsolidated sediments at depth to be made. Additional deeper Vs profiles would help to determine if additional groupings for the sediments in the Salt Lake Valley are needed as opposed to assuming the surficial geology is constant to the depth of the R1 boundary. Also, the additional Vs profiles would add important statistical information to the database which often has only two or three profiles in a given grouping.

APPENDIX

This appendix documents the findings from Spectral-Analysis-Surface-Waves (SASW) tests that were performed at 11 sites in Salt Lake City, UT. Appendices A through K contain the "raw" data (wrapped phase plots versus frequency) for Sites 1 through 11. Each appendix contains the table of source and receiver spacings, "raw data", composite experimental dispersion curve determined from the raw data, theoretical match to the experimental dispersion curve, shear wave velocity profile and table of shear wave profile parameters.

A.1. APPENDIX A

Analysis of SASW Tests at Site 1

Table A.1 Table of Source and Receiver Spacings

Site Name	Set up	Source to Receiver #1	Receiver #1 to Receiver #2	Receiver #2 to Receiver #3
Site 1	1	3	3	6
	2 (1 Reversed)	3	3	6
	3	12.5	12.5	25
	4 (3 Reversed)	12.5	12.5	25
	5	25	25	50
	6	100	100	200
	7	400	400	800
	8	500	500	500

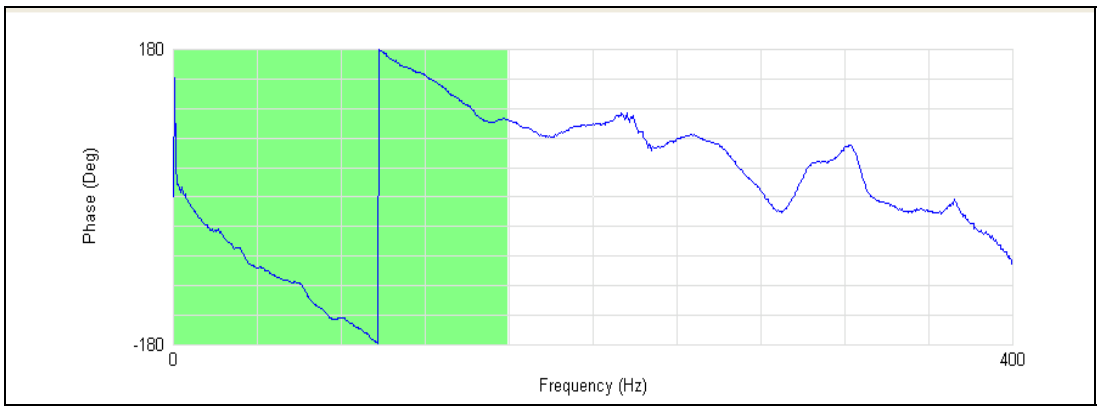

Figure A.1 Phase Plot Measured by SASW Testing; Setup #1; S-R1=3 ft, R1-R2=3ft

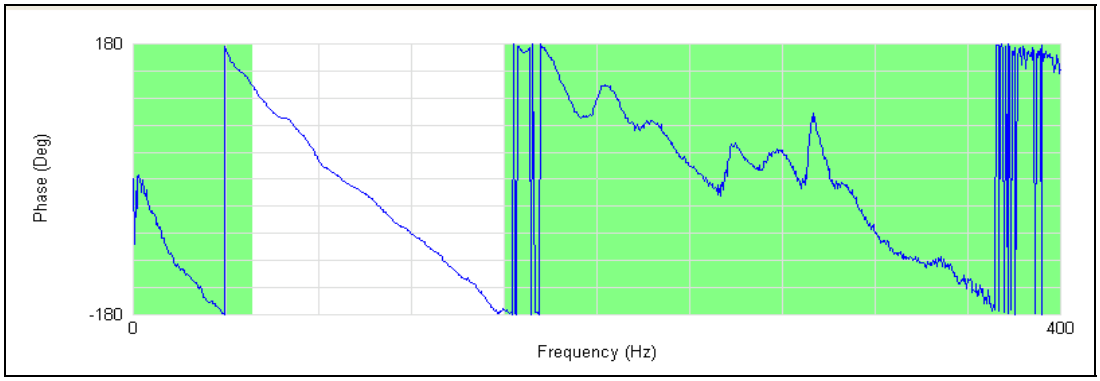

Figure A.2 Phase Plot Measured by SASW Testing; Setup #1; S-R2=6 ft, R2-R3=6ft

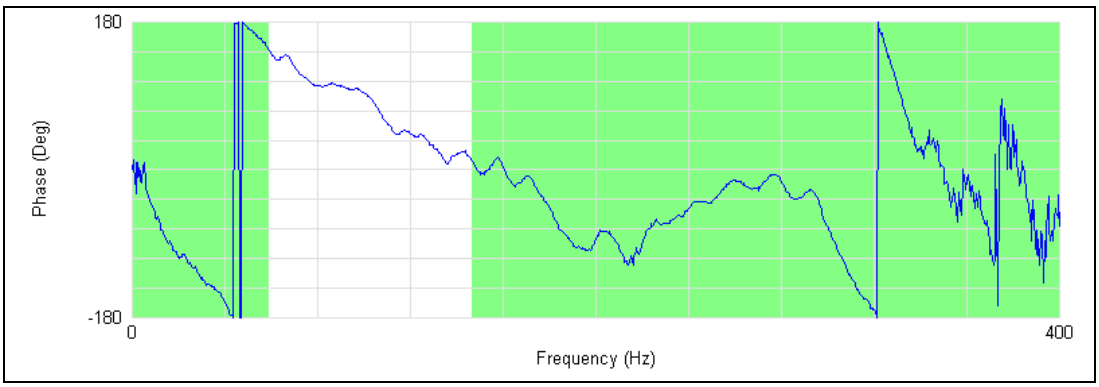

Figure A.3 Phase Plot Measured by SASW Testing; Setup #2; S-R1= 3 ft, R1-R2=3 ft

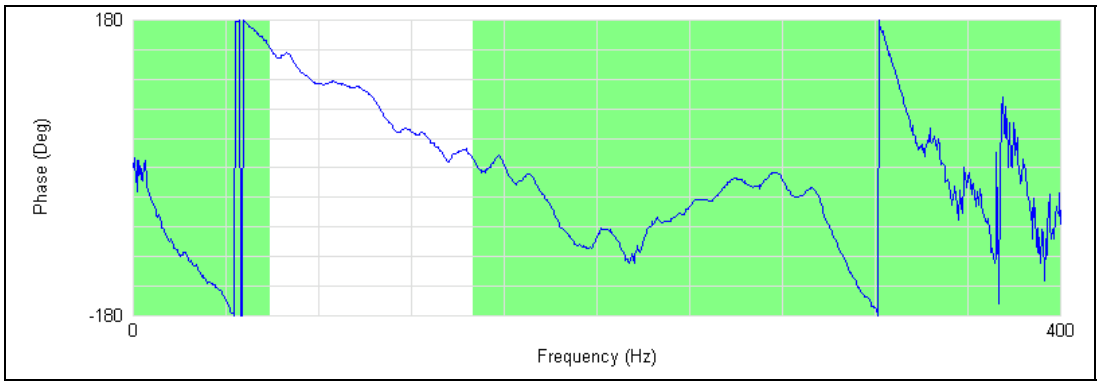

Figure A.4 Phase Plot Measured by SASW Testing; Setup #2; S-R2=6 ft, R2-R3=6 ft

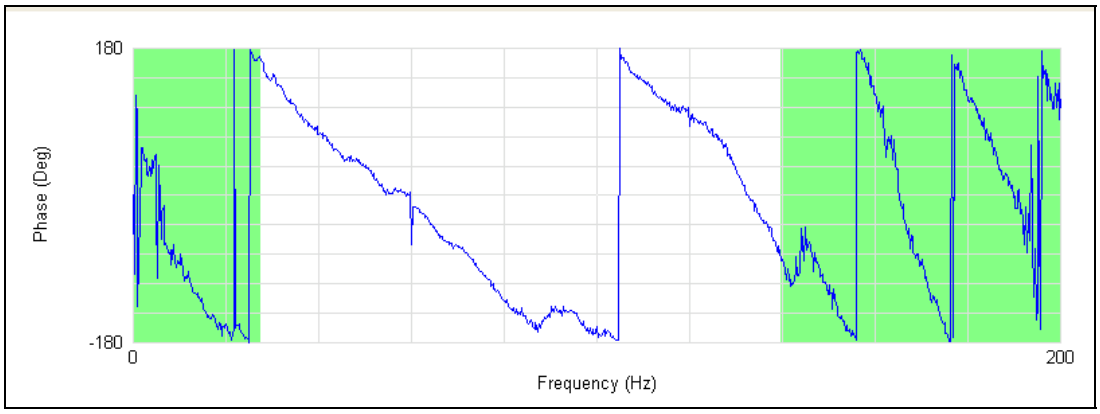

Figure A.5 Phase Plot Measured by SASW Testing; Setup #3; S-R1=12.5 ft, R1-R2=12.5 ft

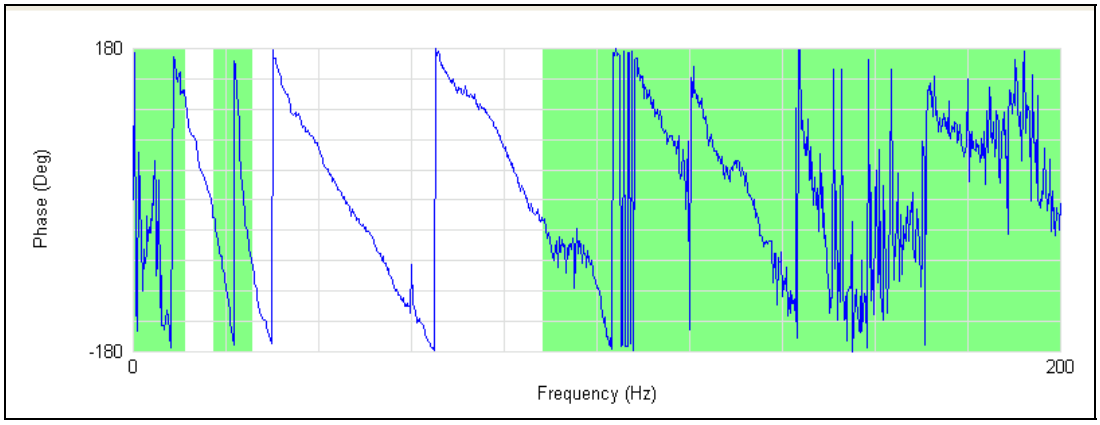

Figure A.6 Phase Plot Measured by SASW Testing; Setup #3; S-R2=25 ft, R2-R3=25 ft

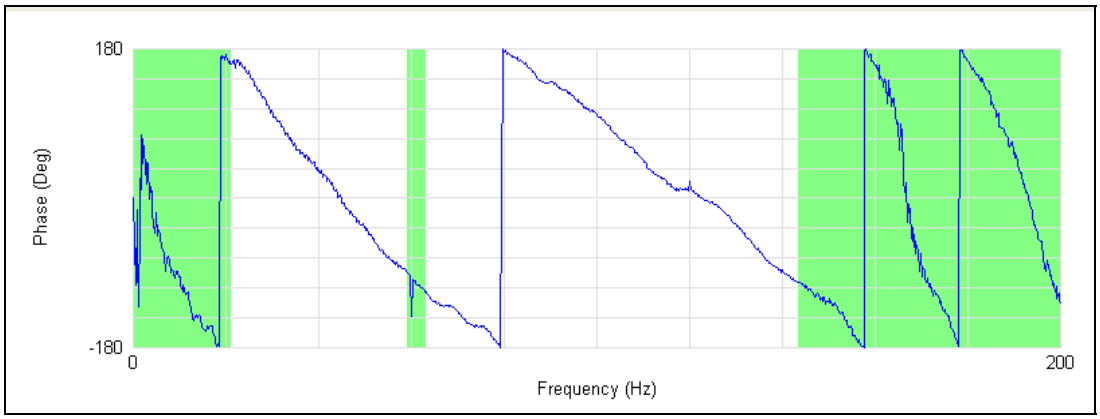

Figure A.7 Phase Plot Measured by SASW Testing; Setup #4; S-R1=12.5 ft, R1-R2=12.5 ft

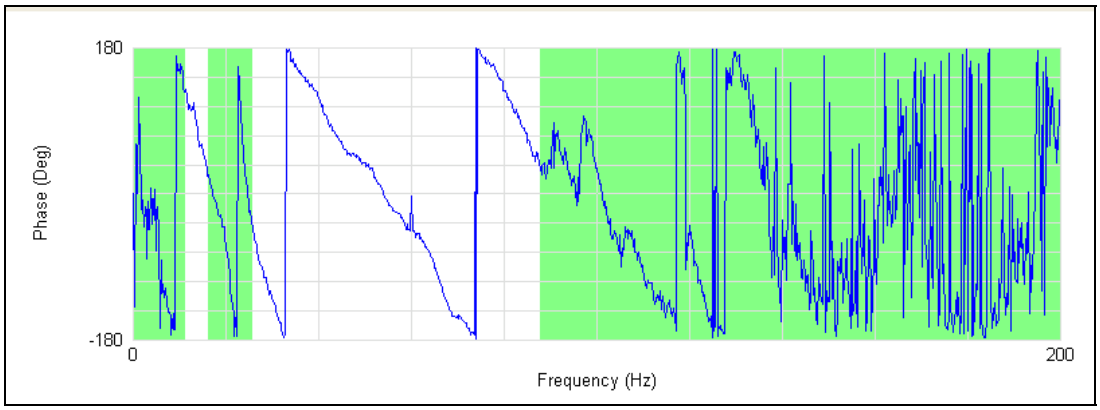

Figure A.8 Phase Plot Measured by SASW Testing; Setup #4; S-R2=25 ft, R2-R3=25 ft

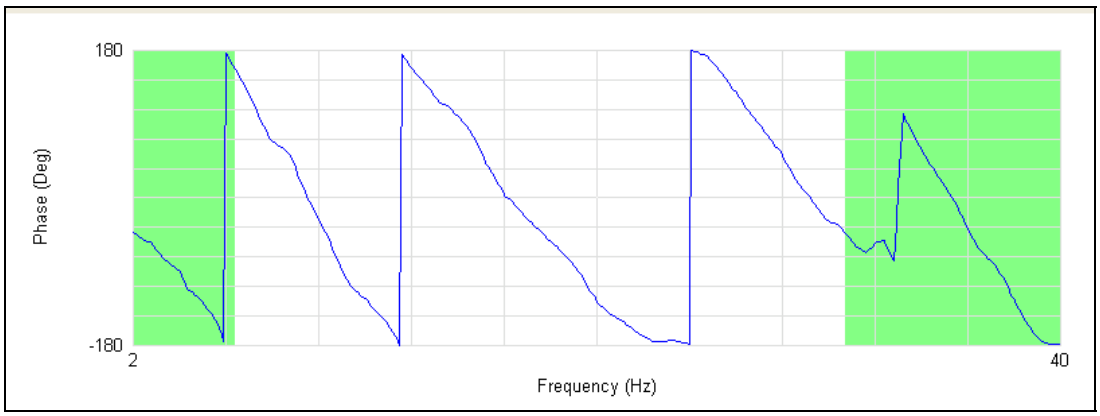

Figure A.9 Phase Plot Measured by SASW Testing; Setup #5; S-R2=50 ft, R2-R3=50 ft

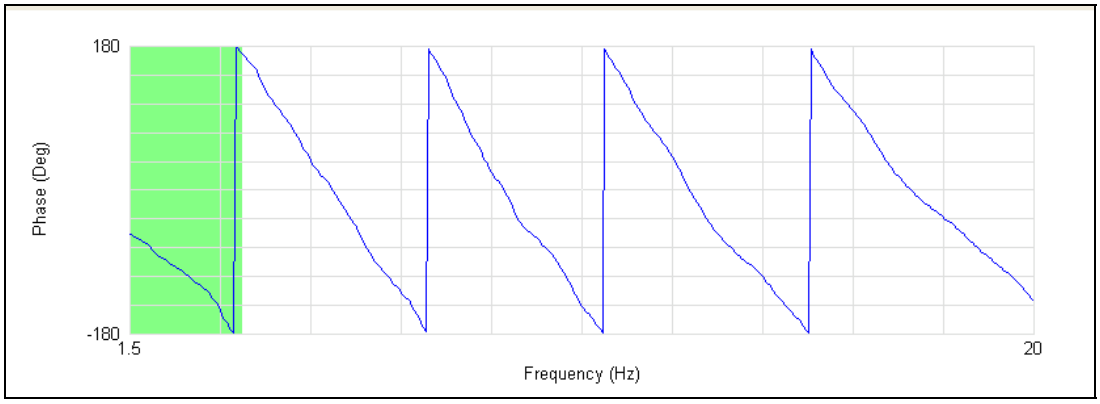

Figure A.10 Phase Plot Measured by SASW Testing; Setup #6; S-R1=100 ft, R1-R2=100 ft

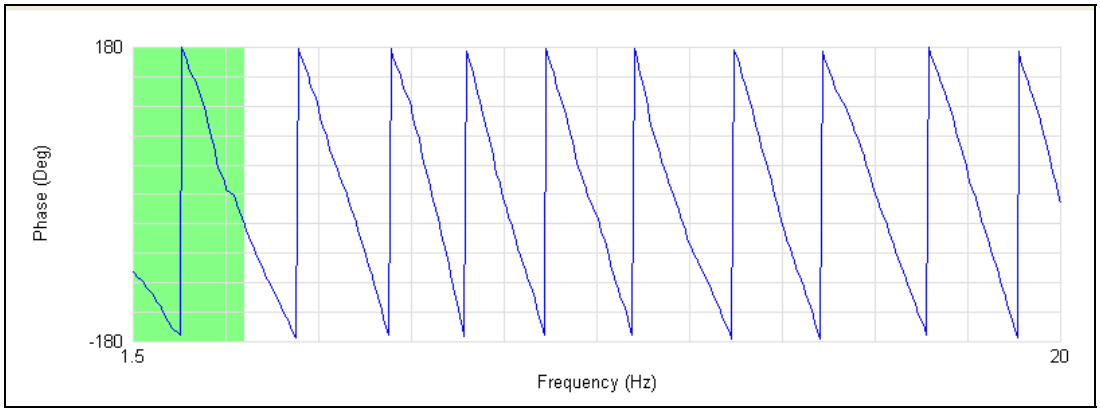

Figure A.11 Phase Plot Measured by SASW Testing: Setup #6; S-R2=200 ft, R2-R3=200 ft

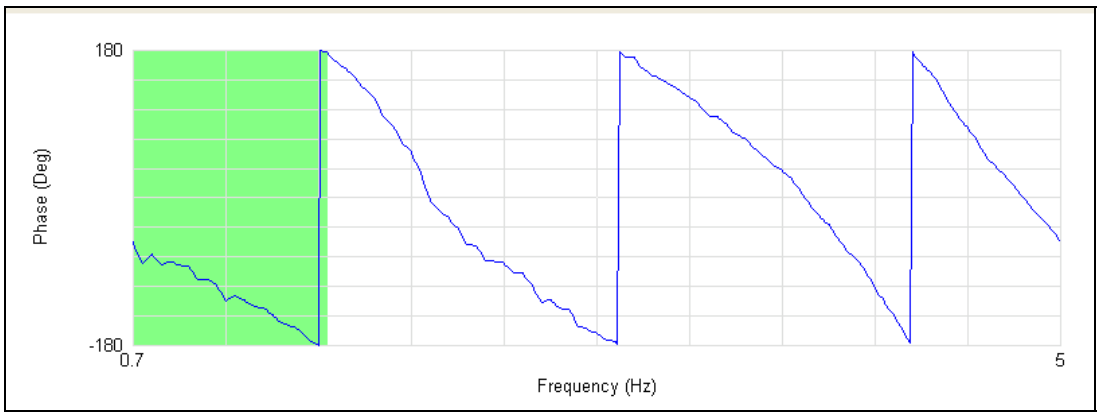

Figure A.12 Phase Plot Measured by SASW Testing; Setup #7; S-R1=400 ft, R1-R2=400 ft

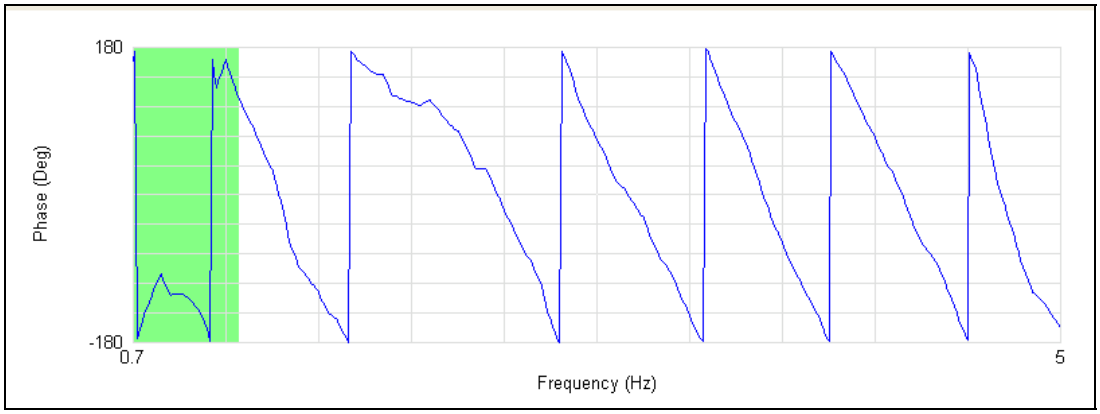

Figure A.13 Phase Plot Measured by SASW Testing; Setup #7; S-R2=800 ft, R2-R3=800 ft

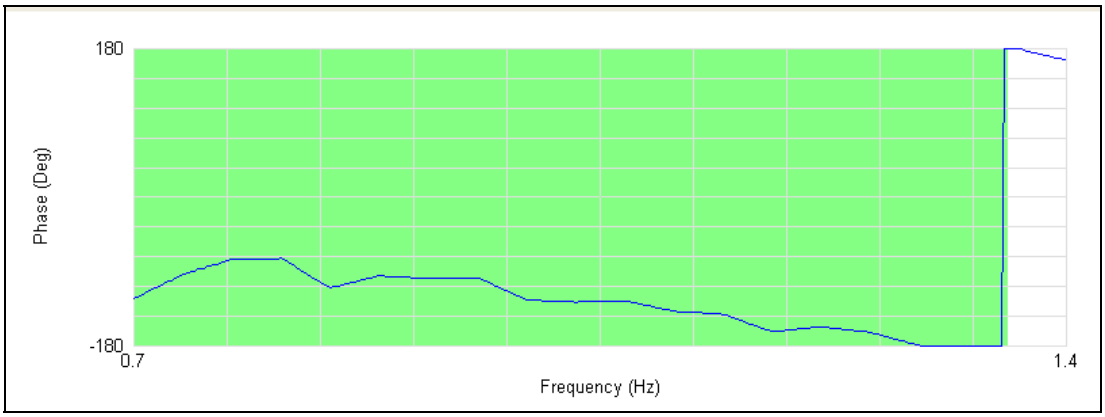

Figure A.14 Phase Plot Measured by SASW Testing; Setup #8; S-R1=500 ft, R1-R2=500 ft

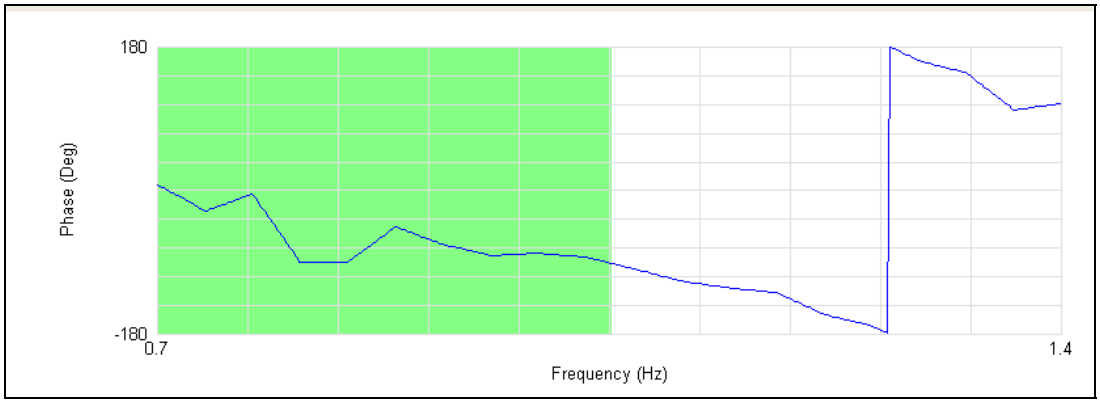

Figure A.15 Phase Plot Measured by SASW Testing; Setup #8; S-R2=1000 ft, R2-R3=500 ft

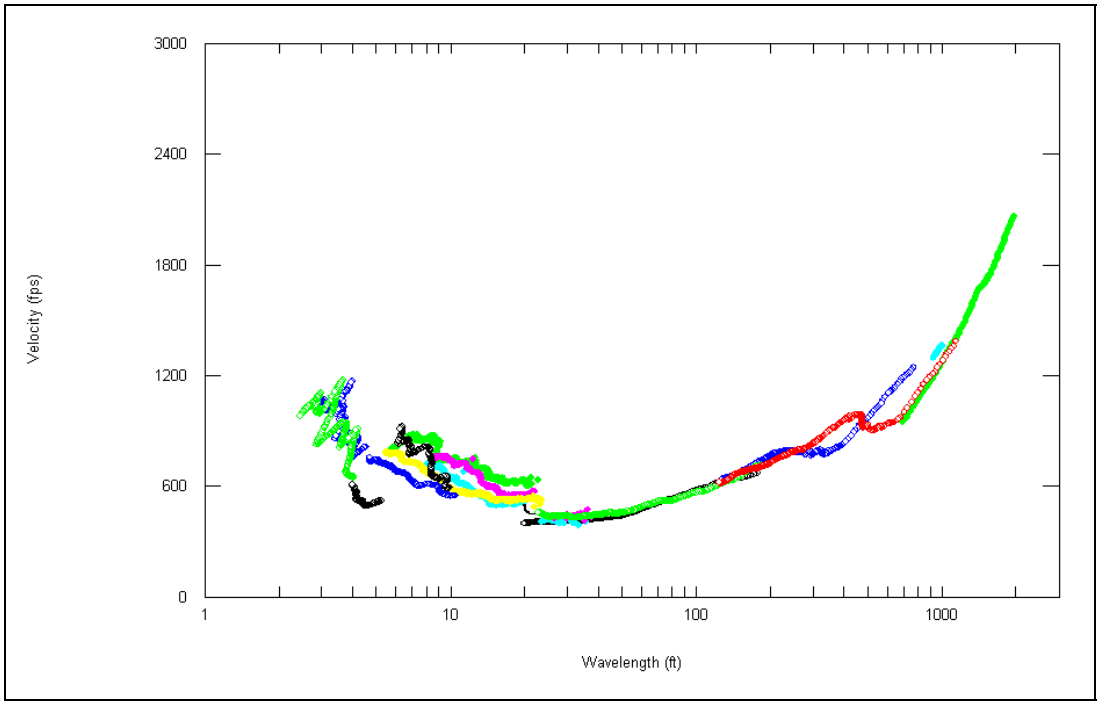

Figure A.16 Experimental Dispersion Curve Measured at Site 1

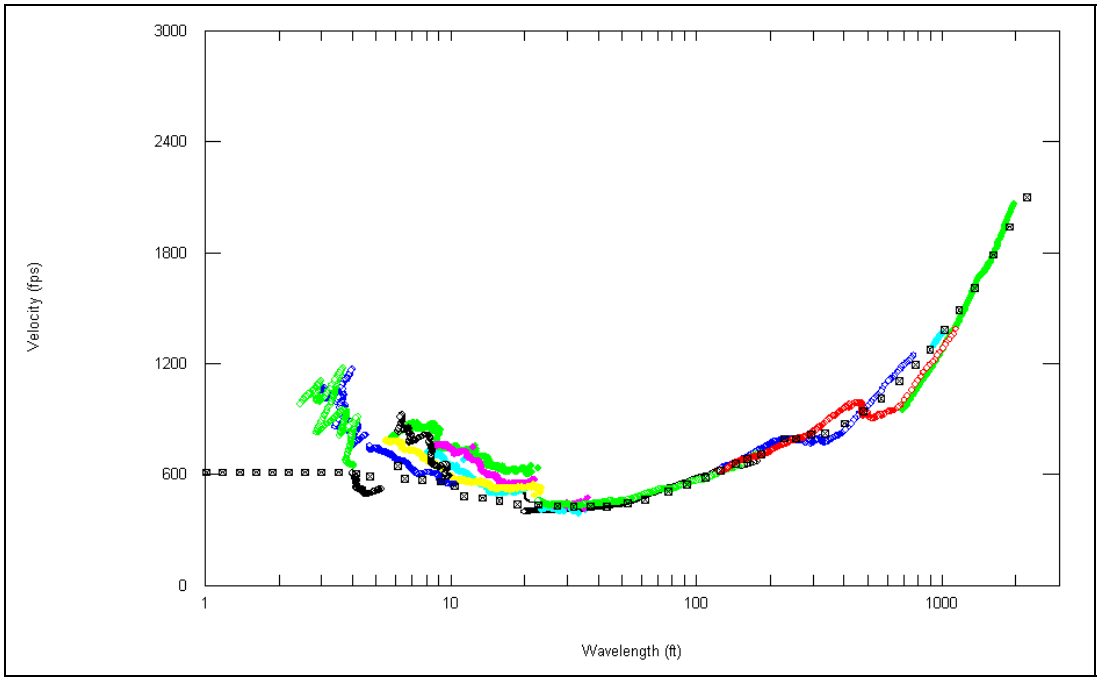

Figure A.17 Experimental and Theoretical Dispersion Curves from Site 1

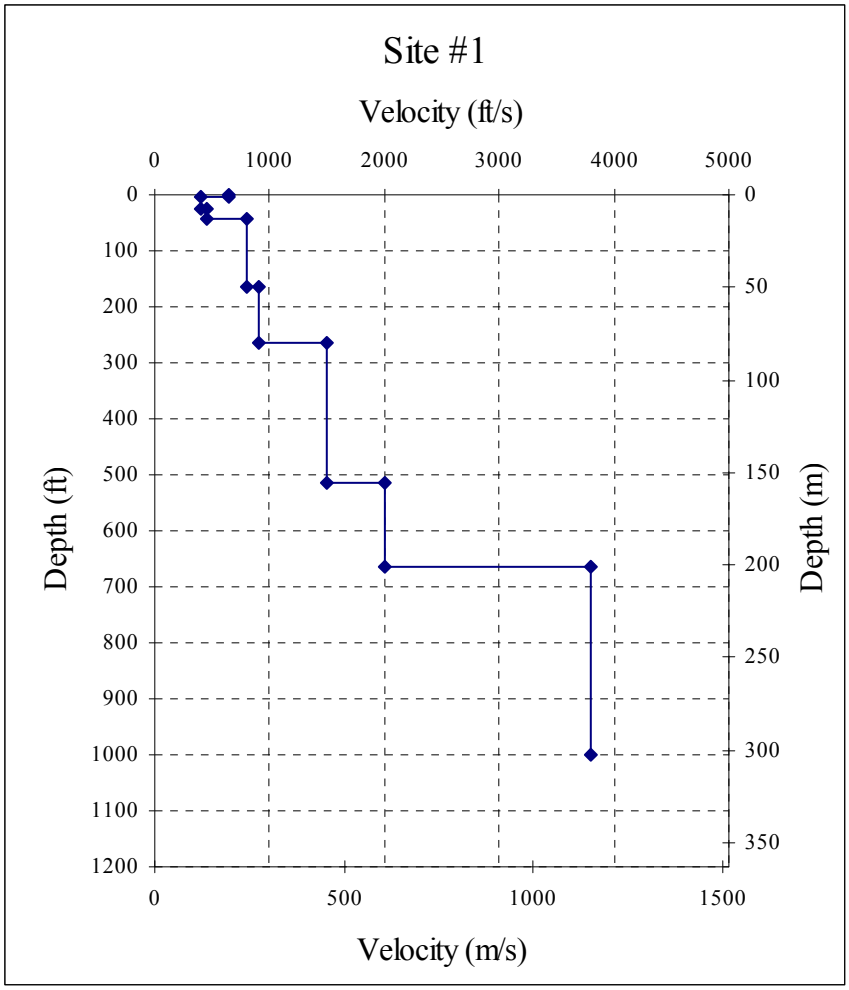

Figure A.18 Shear Wave Velocity Profile Determined at Site 1

Table A.2 Profile Parameters Used to Develop Theoretical Dispersion Curve at Site 1

Layer No.	Thickness, ft	P-Wave Velocity, ft/s	S-Wave Velocity, ft/s	Assumed Poisson's Ratio	Assumed Total Density, pcf
1	4	1216	650	0.30	120
2	20	5200*	400	0.497	120
3	20	5200	450	0.496	120
4	120	5200	800	0.488	120
5	100	5200	900	0.485	120
6	250	5200	1500	0.4555	120
7	150	5200	2000	0.413	120
8	∞	7109	3800	0.30	130

* Depth of Water Table is 4 ft.

B.1. APPENDIX B

Analysis of SASW Tests at Site 2

Table B.1 Table of Source and Receiver Spacings

Site Name	Set up	Source to Receiver #1	Receiver #1 to Receiver #2	Receiver #2 to Receiver #3
Site 2	1	3	3	6
	2 (1 Reversed)	3	3	6
	3	12.5	12.5	25
	4 (3 Reversed)	12.5	12.5	25
	5	25	25	50
	6	100	100	200
	7	300	300	600
	8	400	400	400

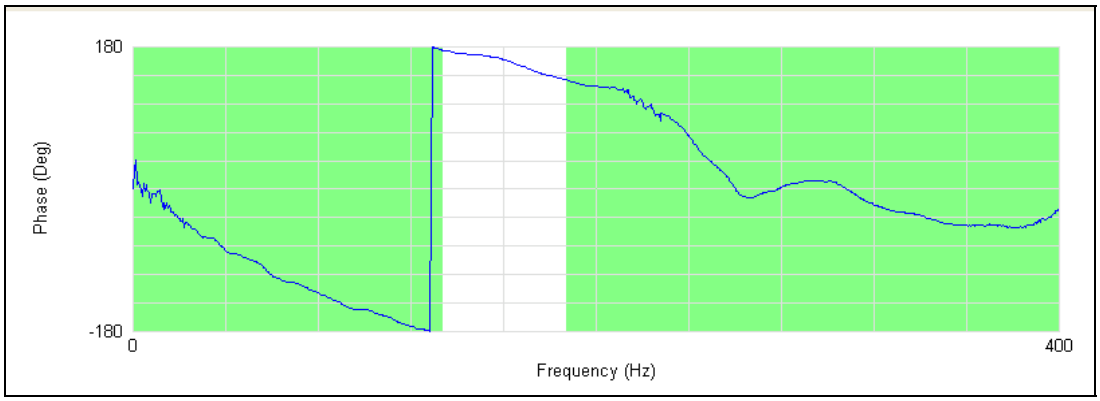

Figure B.1 Phase Plot Measured by SASW Testing; Setup #1; S-R1=3 ft, R1-R2=3ft

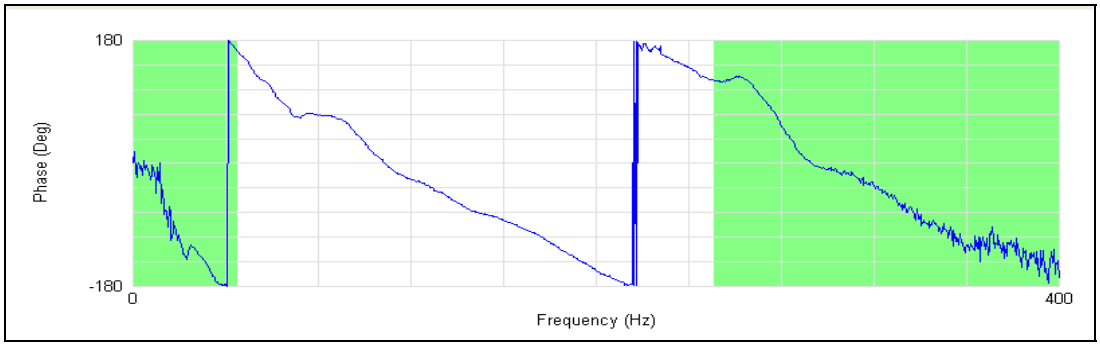

Figure B.2 Phase Plot Measured by SASW Testing; Setup #1; S-R2=6 ft, R2-R3=6ft

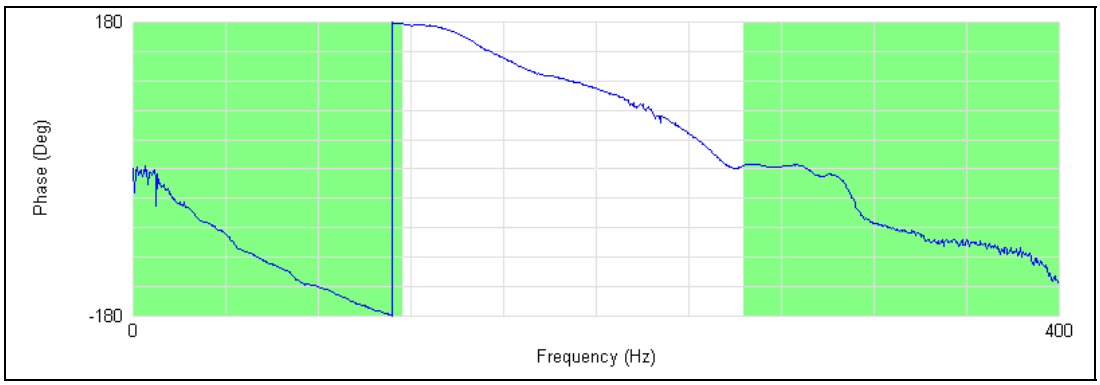

Figure B.3 Phase Plot Measured by SASW Testing; Setup #2; S-R1= 3 ft, R1-R2=3ft

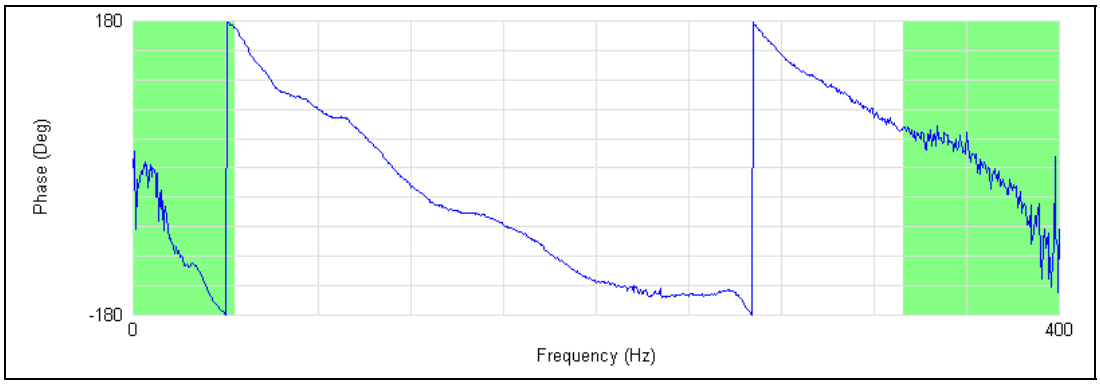

Figure B.4 Phase Plot Measured by SASW Testing; Setup #2; S-R2=6 ft, R2-R3=6ft

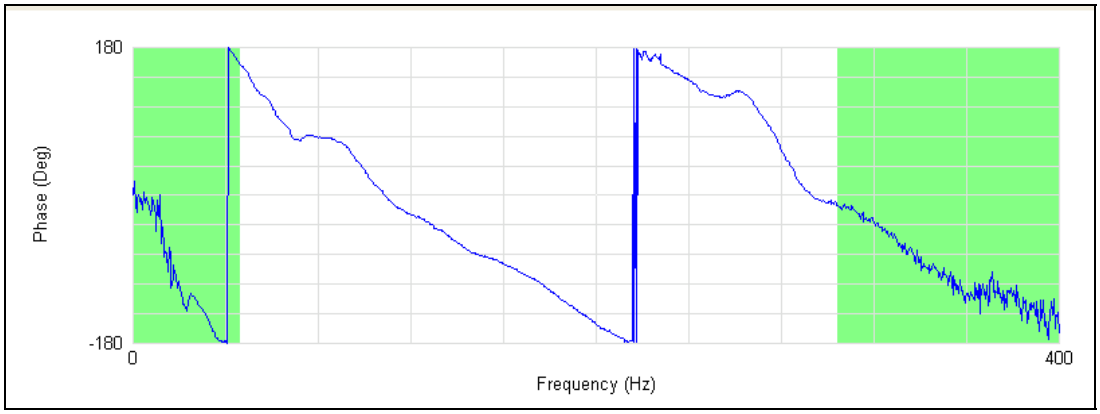

Figure B.5 Phase Plot Measured by SASW Testing; Setup #3; S-R1=12.5 ft, R1-R2=12.5 ft

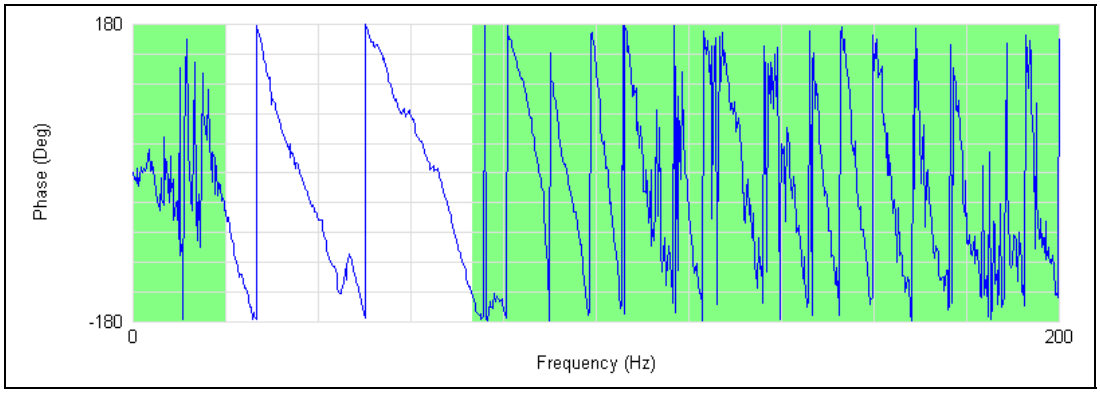

Figure B.6 Phase Plot Measured by SASW Testing; Setup #3; S-R2=25 ft, R2-R3=25 ft

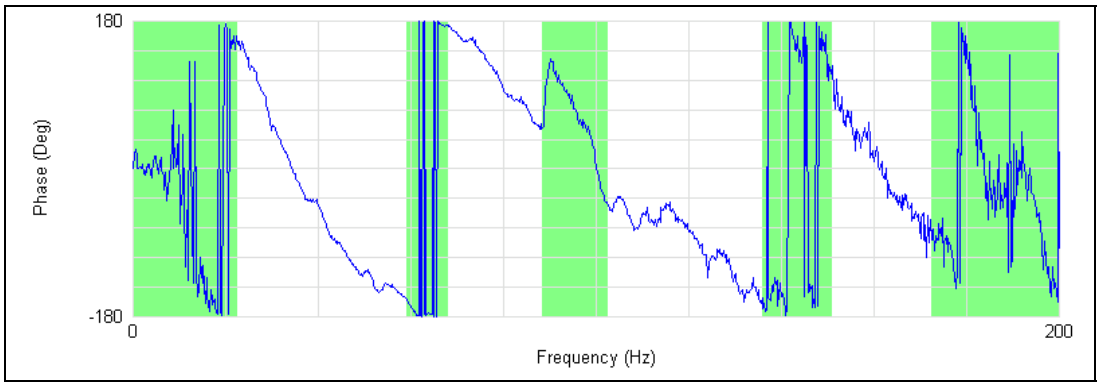

Figure B.7 Phase Plot Measured by SASW Testing; Setup #4; S-R1=12.5 ft, R1-R2=12.5 ft

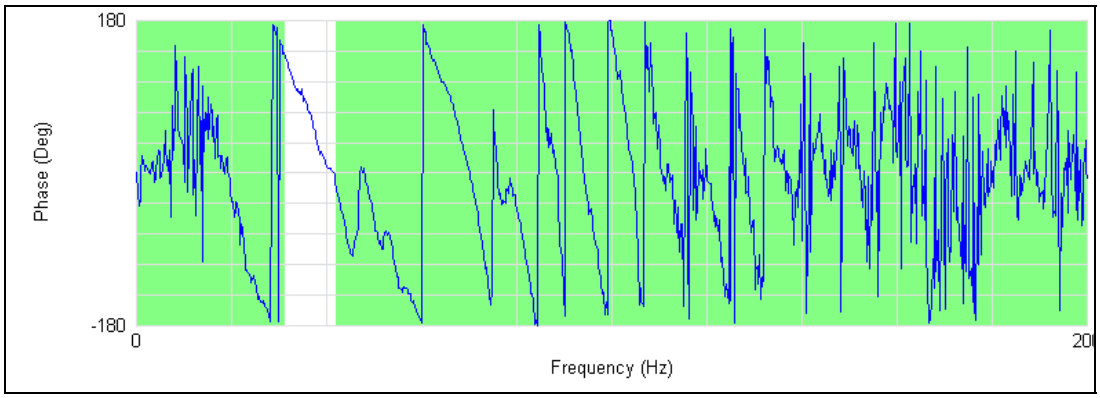

Figure B.8 Phase Plot Measured by SASW Testing; Setup #4; S-R2=25 ft, R2-R3=25 ft

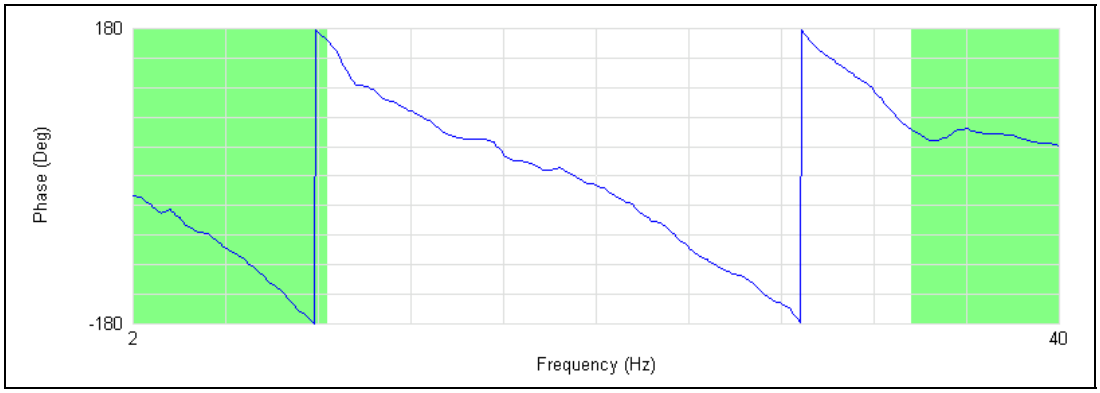

Figure B.9 Phase Plot Measured by SASW Testing; Setup #5; S-R1=25 ft, R1-R2=25 ft

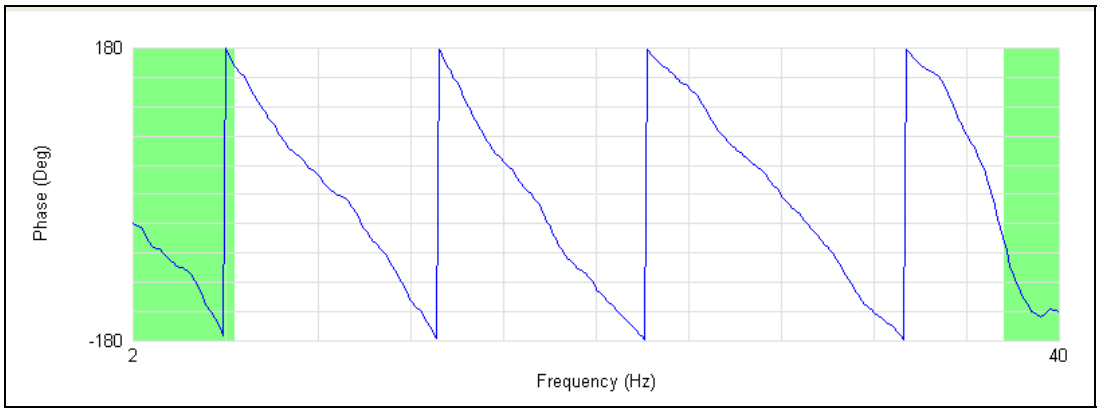

Figure B.10 Phase Plot Measured by SASW Testing; Setup #5; S-R2=50 ft, R2-R3=50 ft

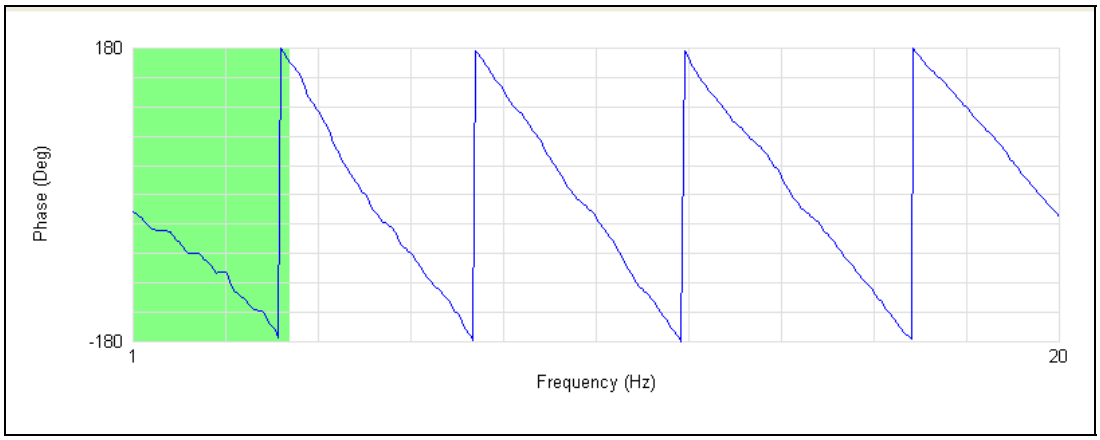

Figure B.11 Phase Plot Measured by SASW Testing; Setup #6, S-R1=100 ft, R1-R2=100ft

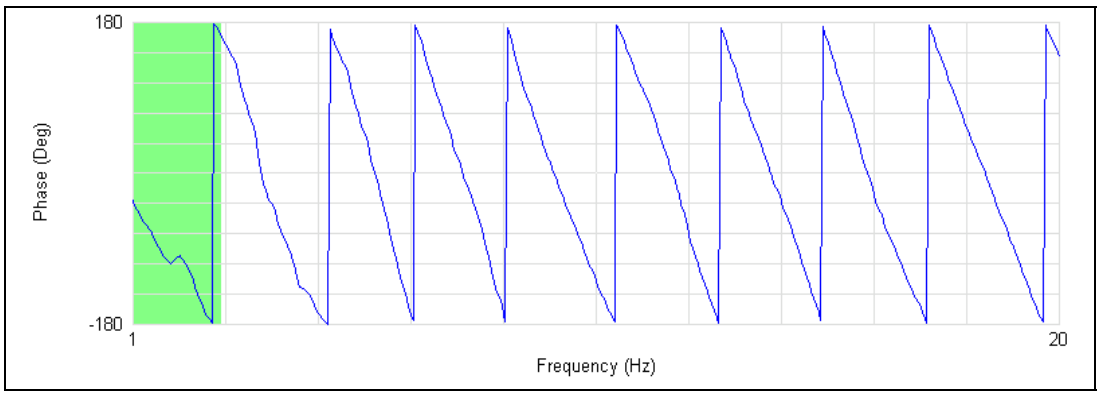

Figure B.12 Phase Plot Measured by SASW Testing; Setup #6, S-R2=200 ft, R2-R3=200ft

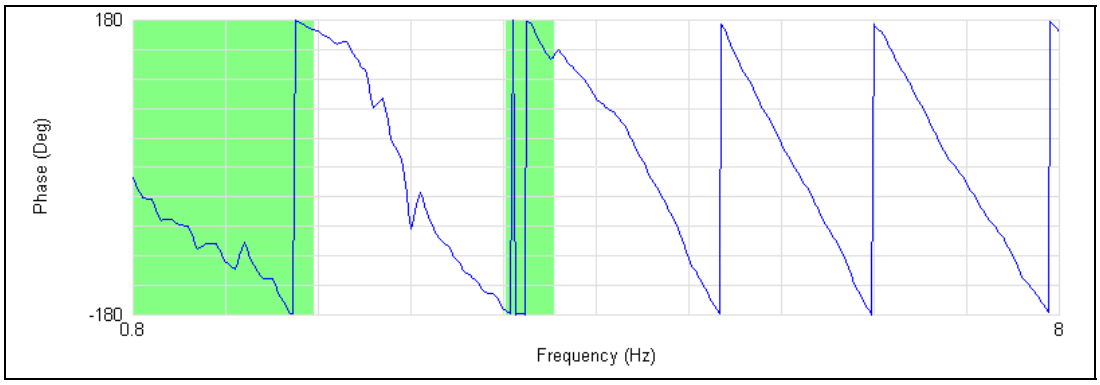

Figure B.13 Phase Plot Measured by SASW Testing; Setup #7, S-R1=300 ft, R1-R2=300ft

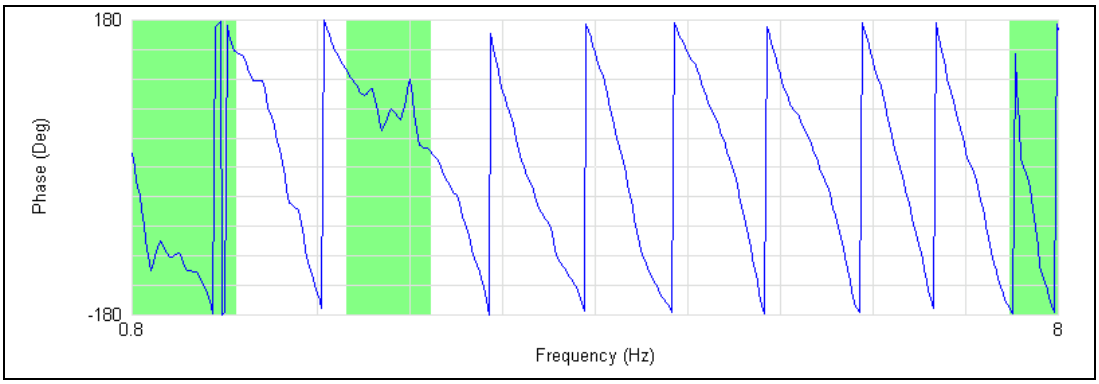

Figure B.14 Phase Plot Measured by SASW Testing; Setup #7, S-R2=600 ft, R2-R3=600ft

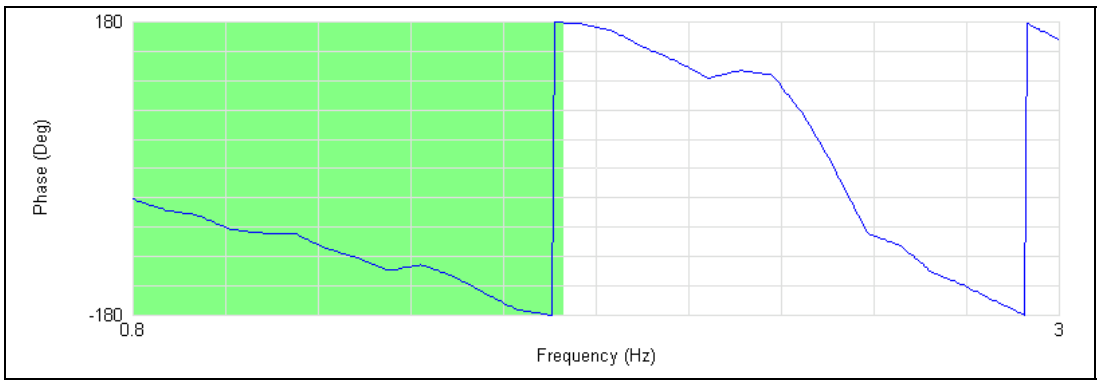

Figure B.15 Phase Plot Measured by SASW Testing; Setup #8, S-R1=400 ft, R1-R2=400ft

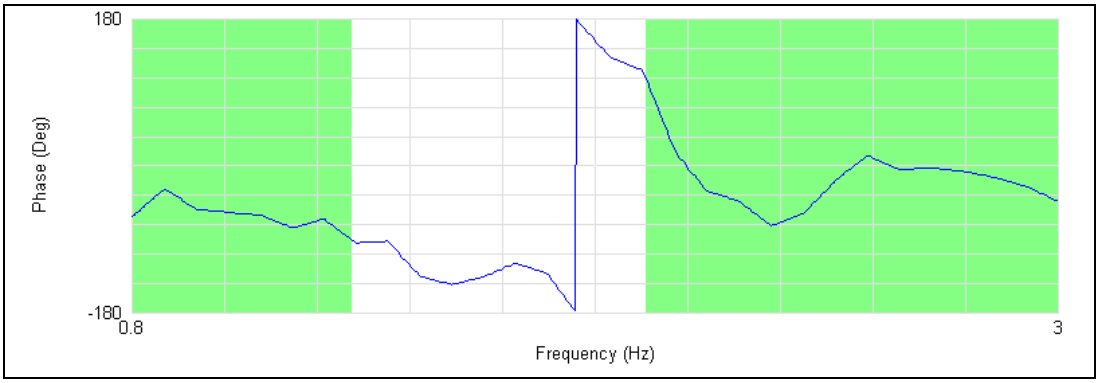

Figure B.16 Phase Plot Measured by SASW Testing; Setup #8, S-R2=800 ft, R2-R3=400ft

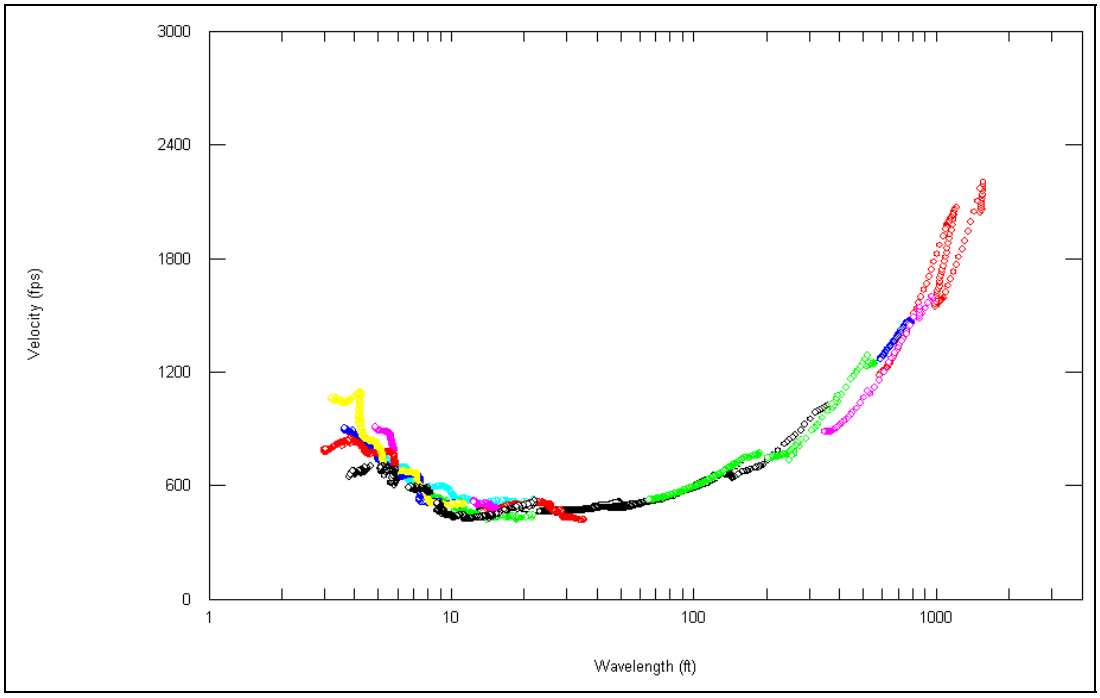

Figure B.17 Experimental Dispersion Curve Measured at Site 2

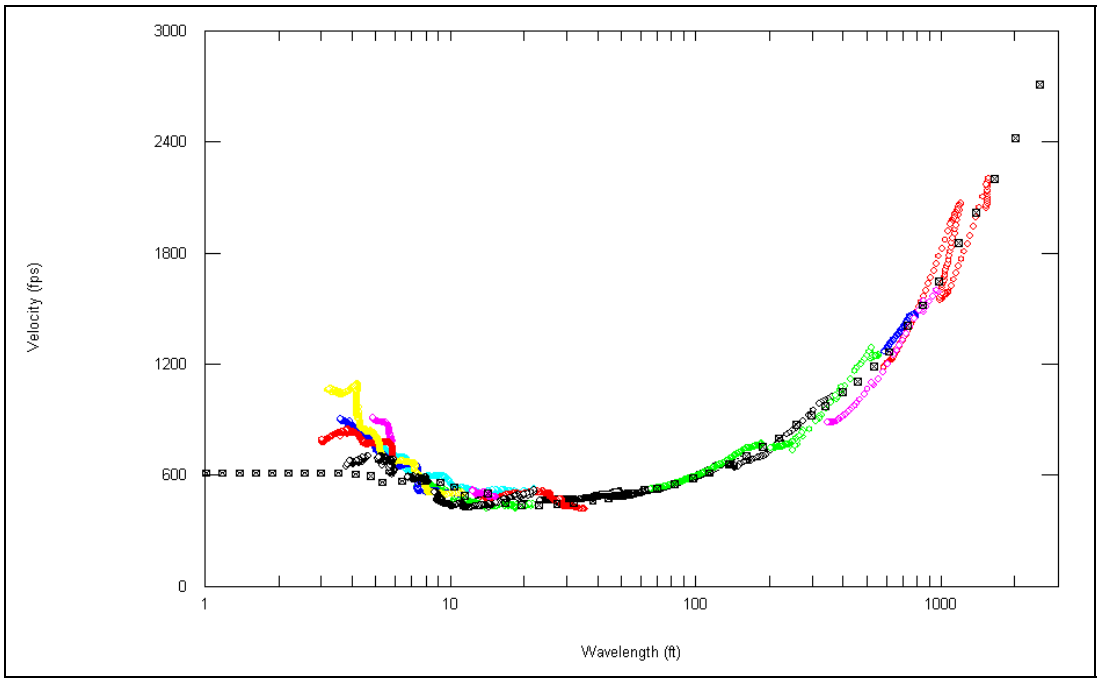

Figure B.18 Experimental and Theoretical Dispersion Curves from Site 2

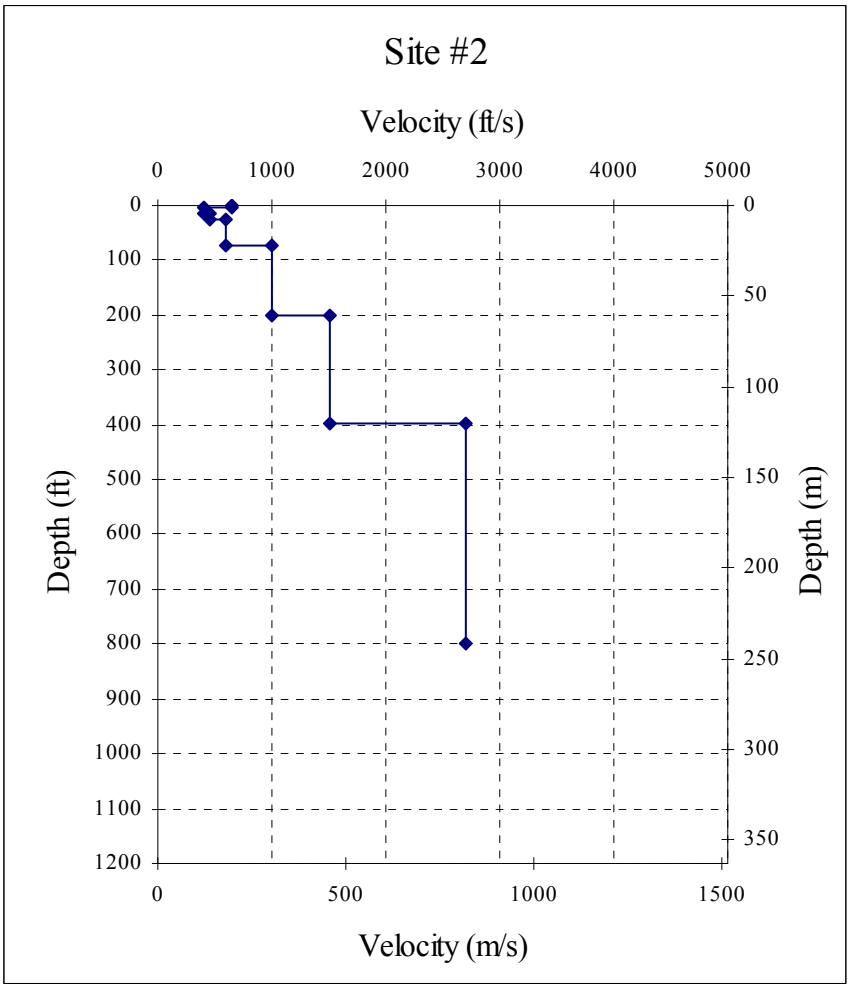

Figure B.19 Shear Wave Velocity Profile Determined at Site 2

Table B.2 Profile Parameters Used to Develop Theoretical Dispersion Curve at Site 2

Layer No.	Thickness, ft	P-Wave Velocity, ft/s	S-Wave Velocity, ft/s	Assumed Poisson's Ratio	P-Wave Velocity, ft/s
1	4	1216	650	0.30	120
2	10	5200*	400	0.497	120
3	10	5200	450	0.496	120
4	50	5200	600	0.495	120
5	125	5200	1000	0.481	120
6	200	5200	1500	0.455	120
7	∞	5200	2700	0.315	130

* Depth of Water Table is 4 ft

C.1. APPENDIX C

Analysis of SASW Tests at Site 3

Table C.1 Table of Source and Receiver Spacings

Site Name	Set up	Source to Receiver #1	Receiver #1 to Receiver #2	Receiver #2 to Receiver #3
Site 3	1	3	3	6
	2 (1 Reversed)	3	3	6
	3	12.5	12.5	25
	4 (3 Reversed)	12.5	12.5	25
	5	25	25	50
	6	100	100	200
	7	400	400	800
	8	1000	500	500

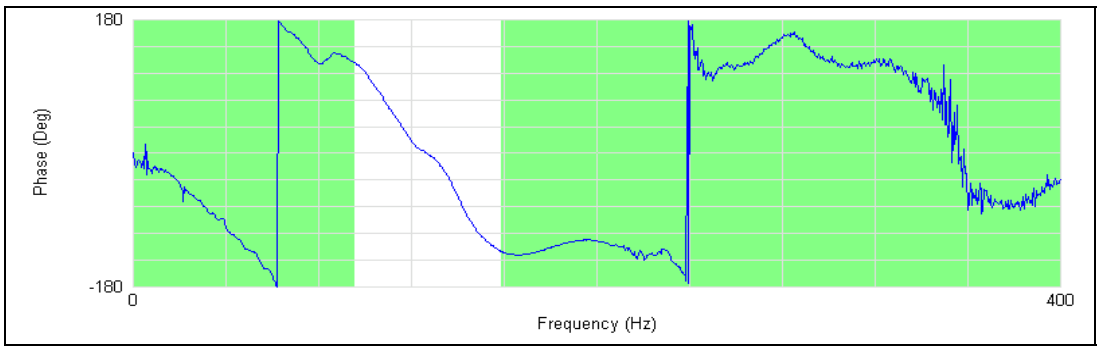

Figure C.1 Phase Plot Measured by SASW Testing; Setup #1; S-R1=3 ft, R1-R2=3ft

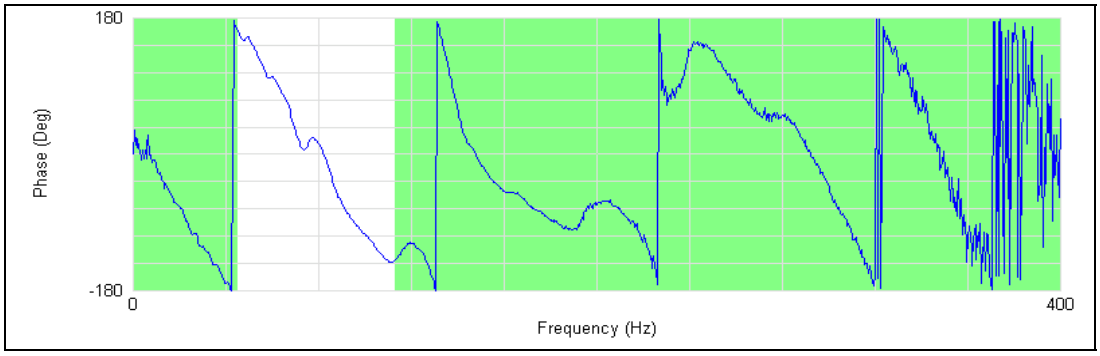

Figure C.2 Phase Plot Measured by SASW Testing; Setup #1; S-R2=6 ft, R2-R3=6ft

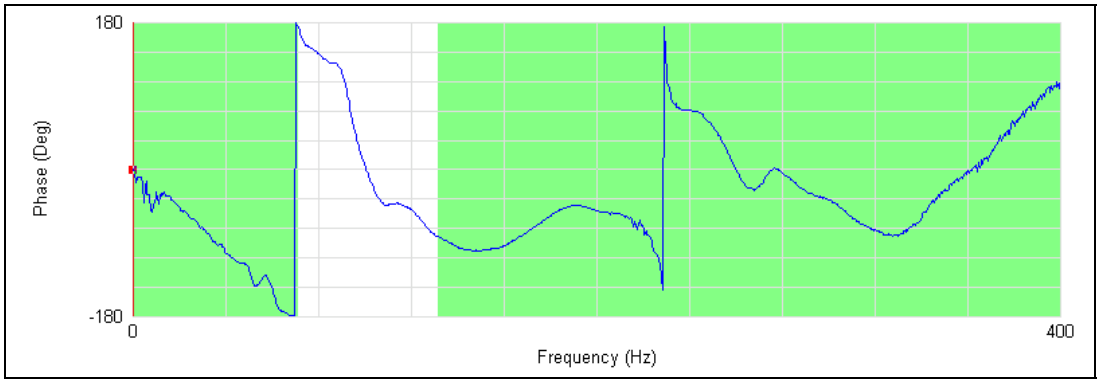

Figure C.3 Phase Plot Measured by SASW Testing; Setup #2; S-R1= 3 ft, R1-R2=3ft

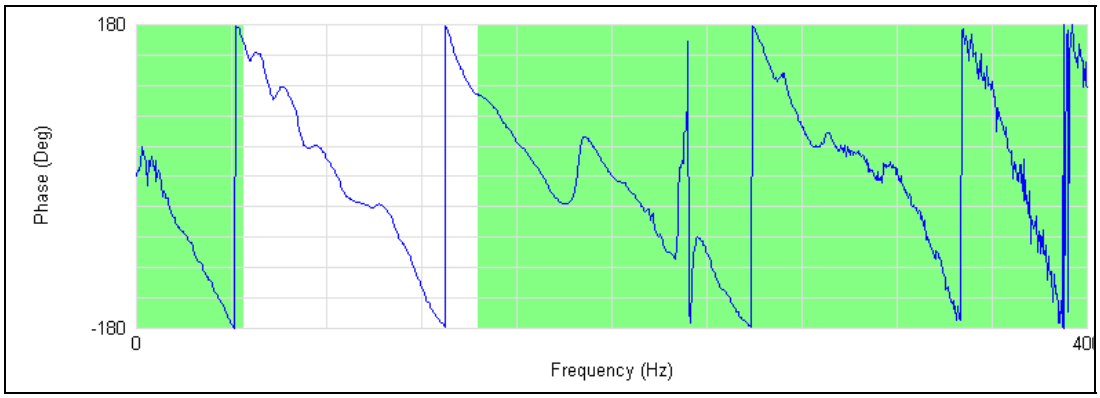

Figure C.4 Phase Plot Measured by SASW Testing; Setup #2; S-R2=6 ft, R2-R3=6ft

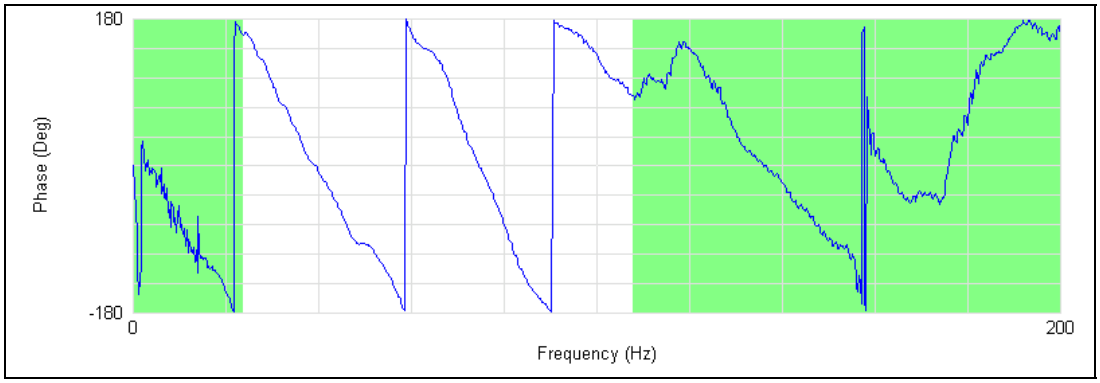

Figure C.5 Phase Plot Measured by SASW Testing; Setup #3; S-R1=12.5 ft, R1-R2=12.5 ft

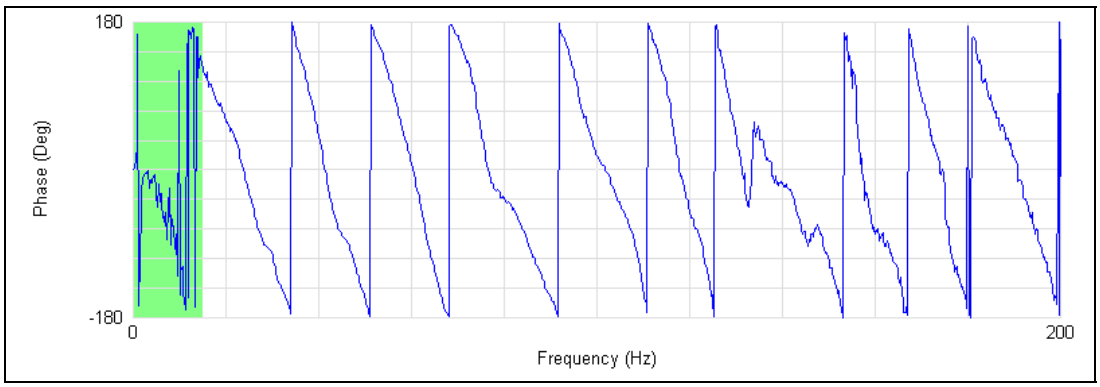

Figure C.6 Phase Plot Measured by SASW Testing; Setup #3; S-R2=25 ft, R2-R3=25 ft

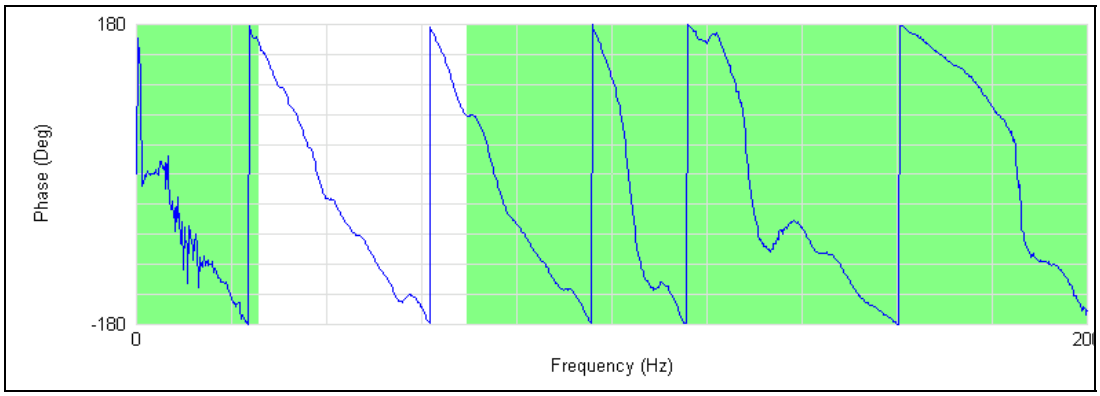

Figure C.7 Phase Plot Measured by SASW Testing; Setup #4; S-R1=12.5 ft, R1-R2=12.5 ft

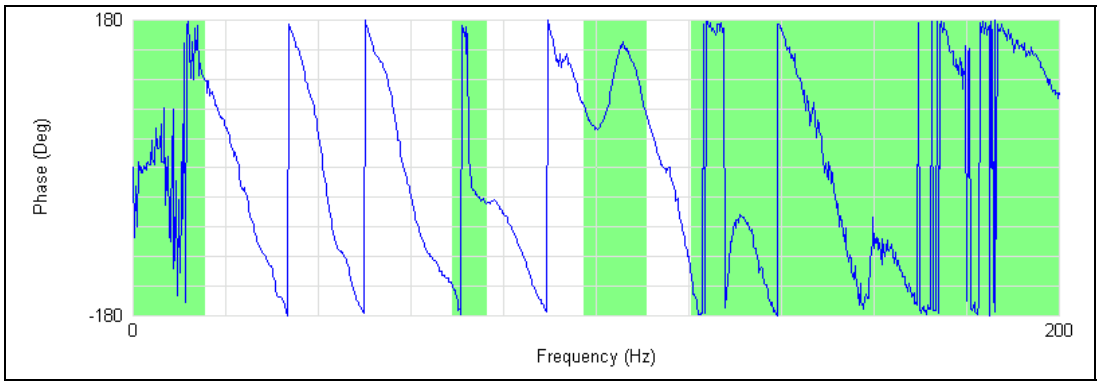

Figure C.8 Phase Plot Measured by SASW Testing; Setup #4; S-R2=25 ft, R2-R3=25 ft

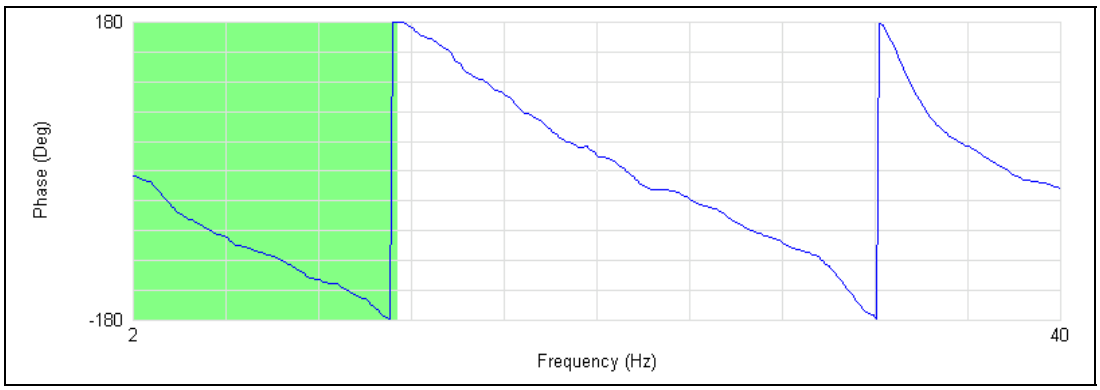

Figure C.9 Phase Plot Measured by SASW Testing; Setup #5; S-R1=25 ft, R1-R2=25 ft

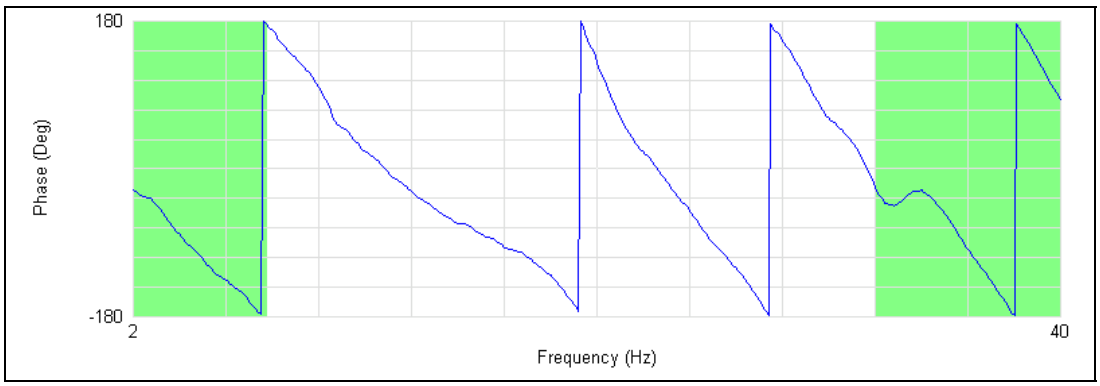

Figure C.10 Phase Plot Measured by SASW Testing; Setup #5; S-R2=50 ft, R2-R3=50 ft

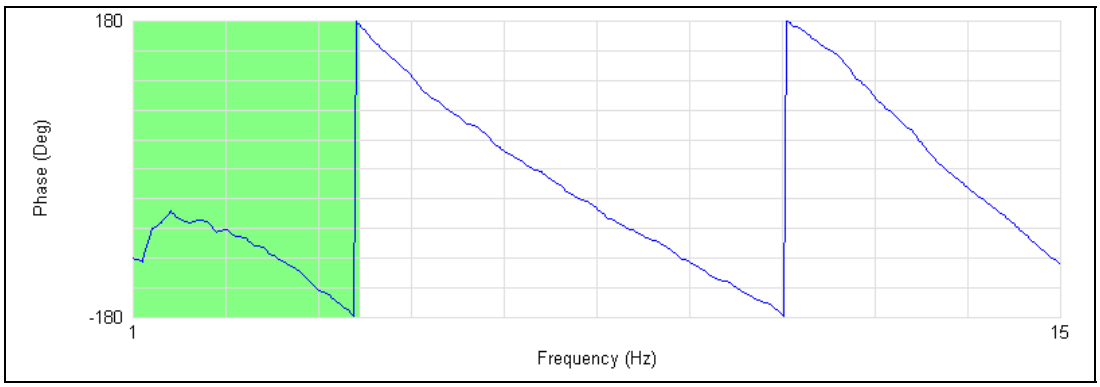

Figure C.11 Phase Plot Measured by SASW Testing; Setup #6, S-R1=100 ft, R1-R2=100ft

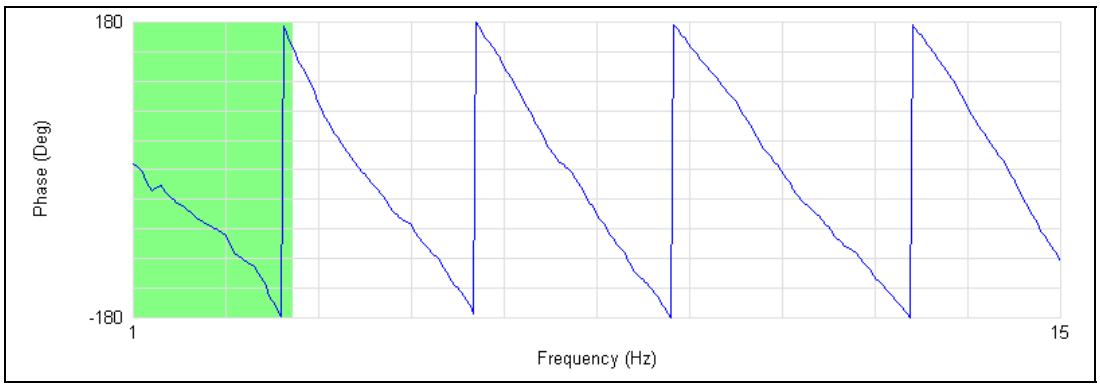

Figure C.12 Phase Plot Measured by SASW Testing; Setup #6, S-R2=200 ft, R2-R3=200ft

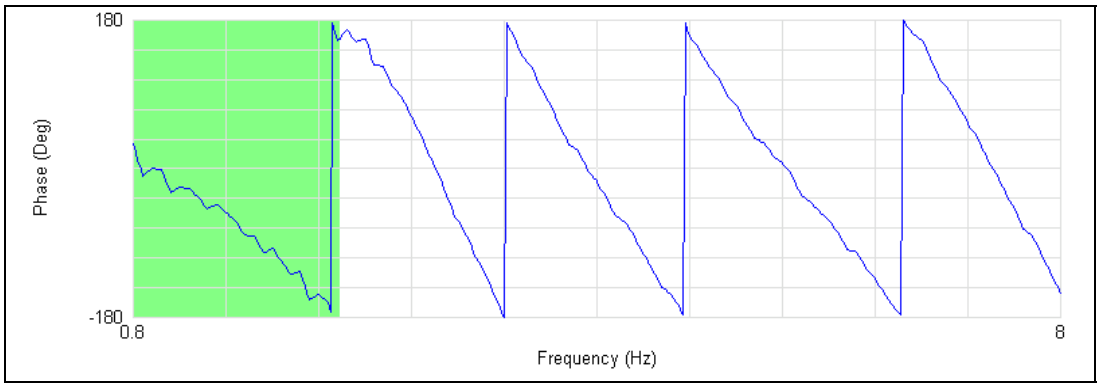

Figure C.13 Phase Plot Measured by SASW Testing; Setup #7, S-R1=400 ft, R1-R2=400ft

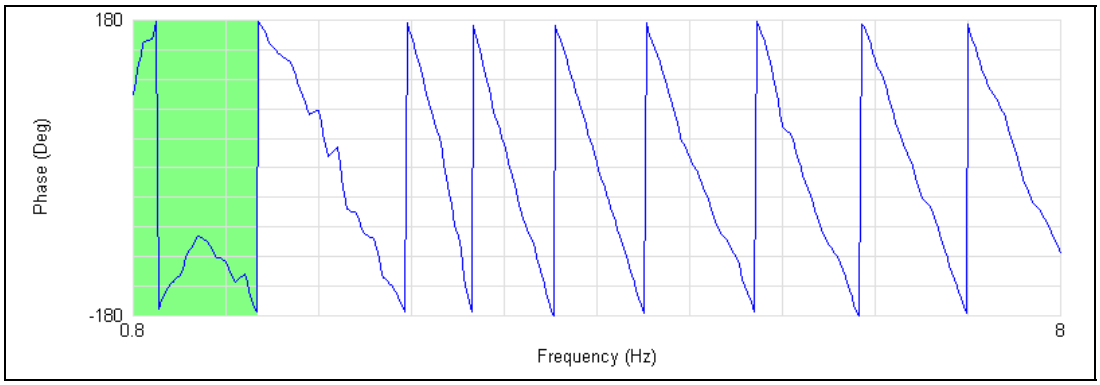

Figure C.14 Phase Plot Measured by SASW Testing; Setup #7, S-R2=800 ft, R2-R3=800ft

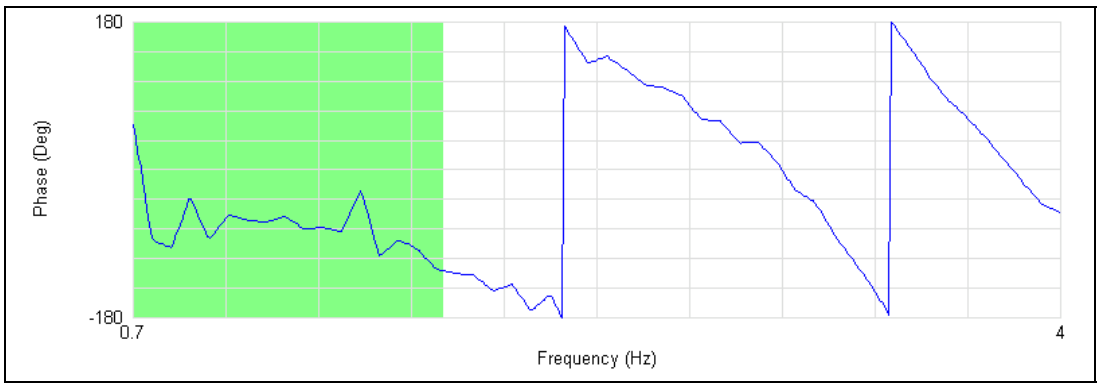

Figure C.15 Phase Plot Measured by SASW Testing; Setup #8, S-R1=1000 ft, R1-R2=500 ft

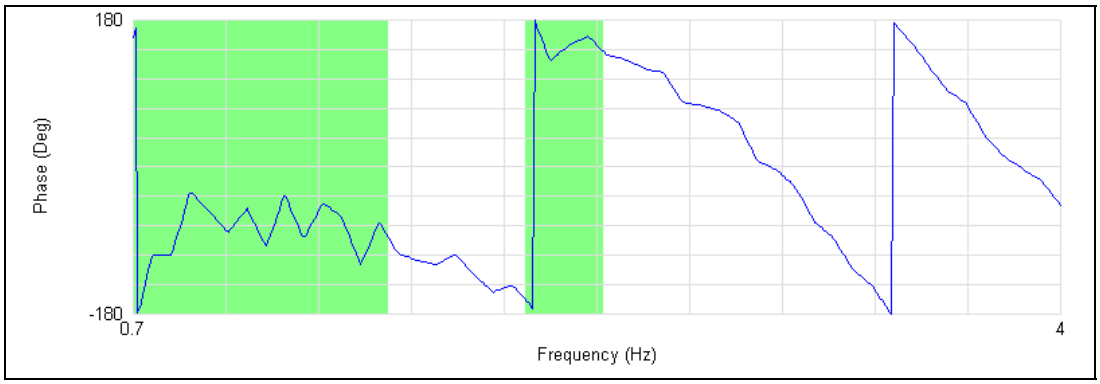

Figure C.16 Phase Plot Measured by SASW Testing; Setup #8, S-R2=1500 ft, R2-R3=500 ft

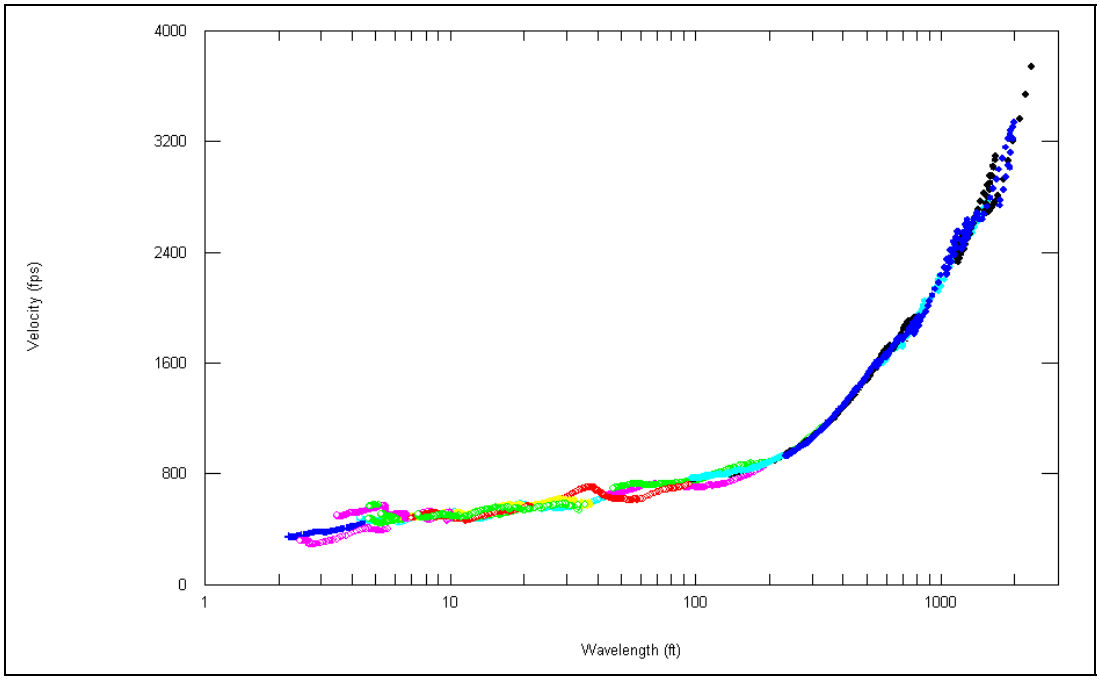

Figure C.17 Experimental Dispersion Curve Measured at Site 3

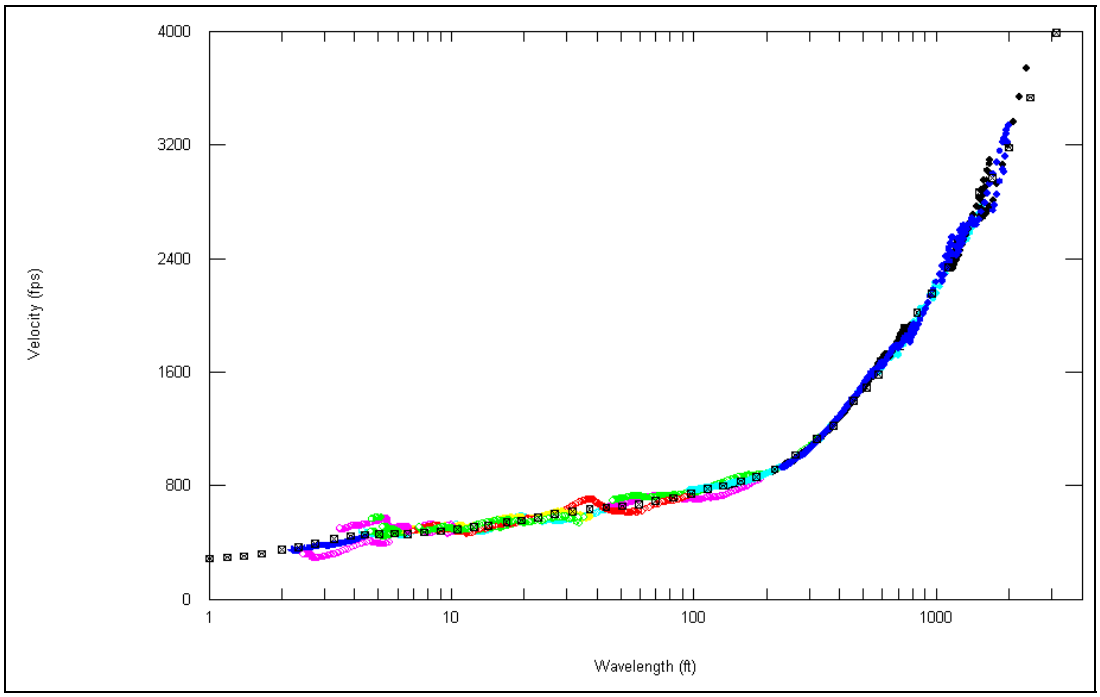

Figure C.18 Experimental and Theoretical Dispersion Curves from Site 3

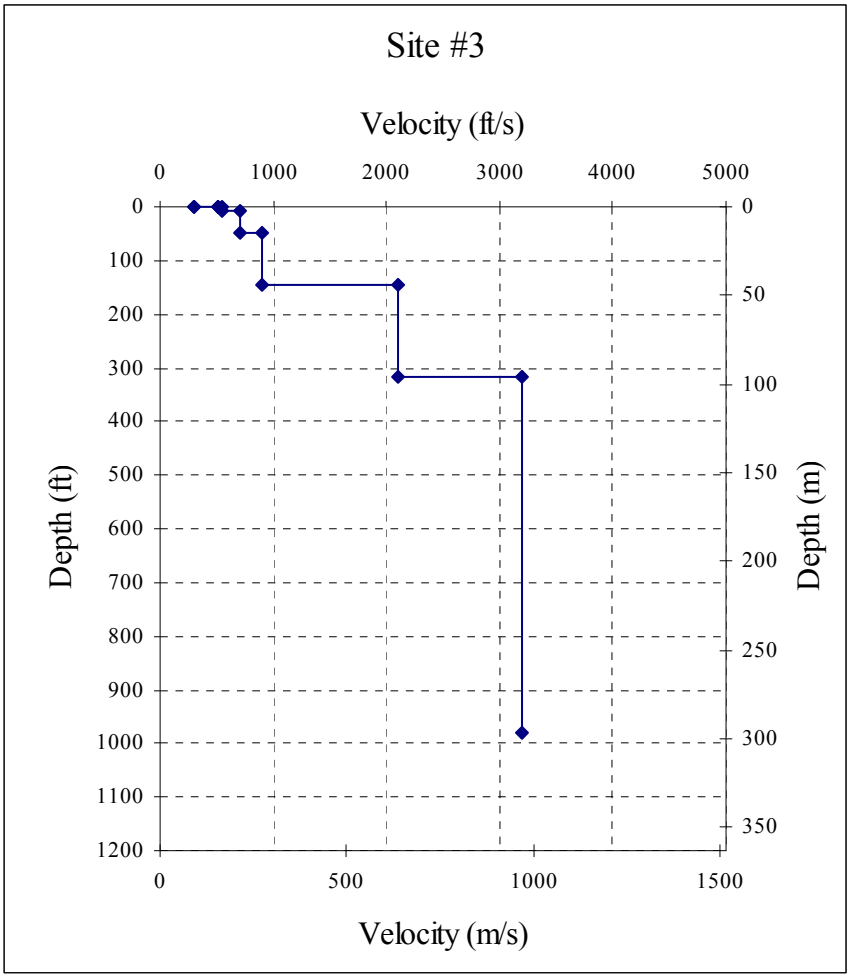

Figure C.19 Shear Wave Velocity Profile Determined at Site 3

Table C.2 Profile Parameters Used to Develop Theoretical Dispersion Curve at Site 3

Layer No.	Thickness, ft	P-Wave Velocity, ft/s	S-Wave Velocity, ft/s	Assumed Poisson's Ratio	Assumed Total Density, pcf
1	0.8	561.3	300	0.30	120
2	1	954.1	510	0.30	120
3	5	1010.3	540	0.30	120
4	40	5200*	700	0.491	120
5	100	5200	900	0.485	120
6	170	5200	2100	0.403	120
7	∞	5986.7	3200	0.30	130

* Depth of Water Table is 6.8 ft

D.1. APPENDIX D

Analysis of SASW Tests at Site 4

Table D.1.....Table of Source and Receiver Spacings

Site Name	Set up	Source to Receiver #1	Receiver #1 to Receiver #2	Receiver #2 to Receiver #3
Site 4	1	3	3	6
	2 (1 Reversed)	3	3	6
	3	12.5	12.5	25
	4 (3 Reversed)	12.5	12.5	25
	5	25	25	50
	6	100	100	200
	7	400	400	800
	8	1000	500	500

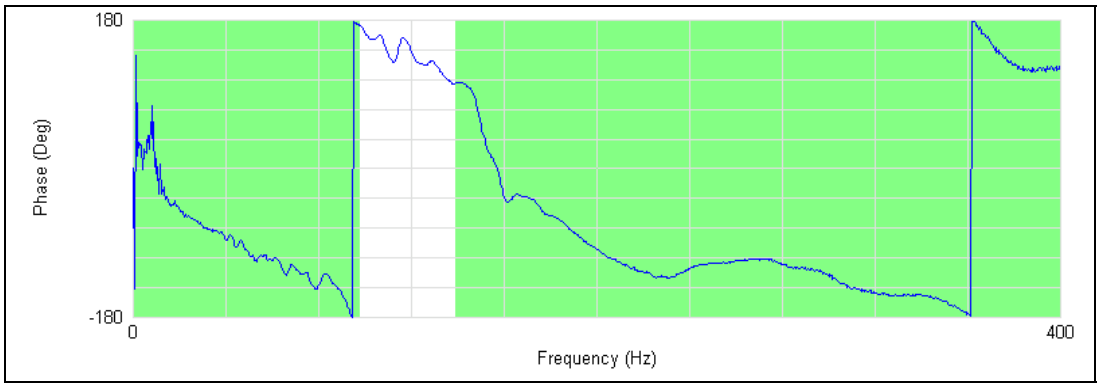

Figure D.1 Phase Plot Measured by SASW Testing; Setup #1; S-R1=3 ft, R1-R2=3ft

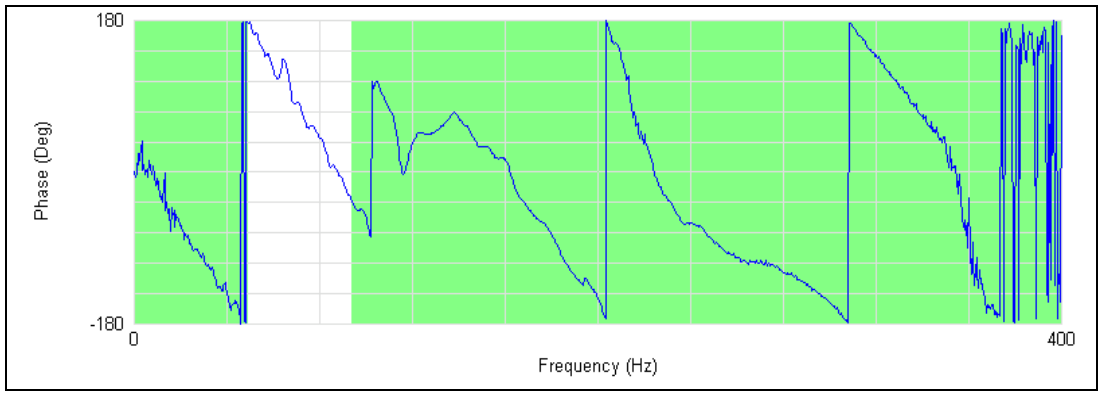

Figure D.2 Phase Plot Measured by SASW Testing; Setup #1; S-R2=6 ft, R2-R3=6ft

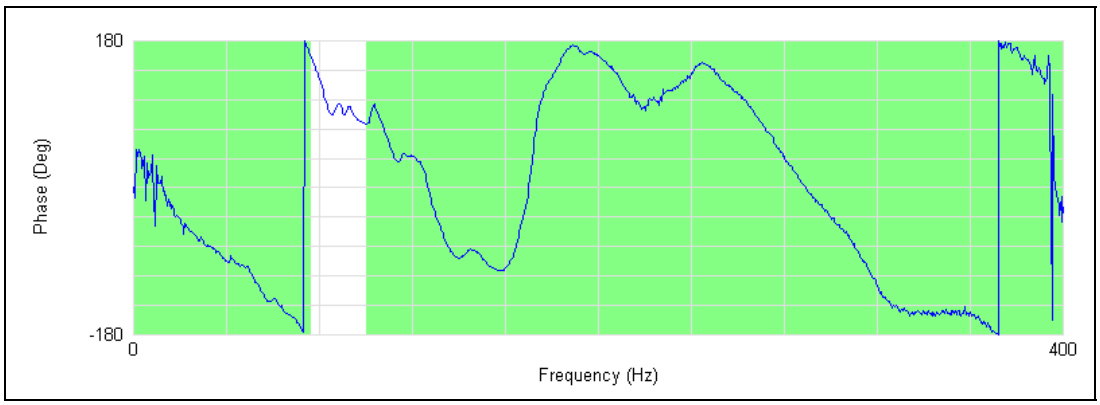

Figure D.3 Phase Plot Measured by SASW Testing; Setup #2; S-R1= 3 ft, R1-R2=3ft

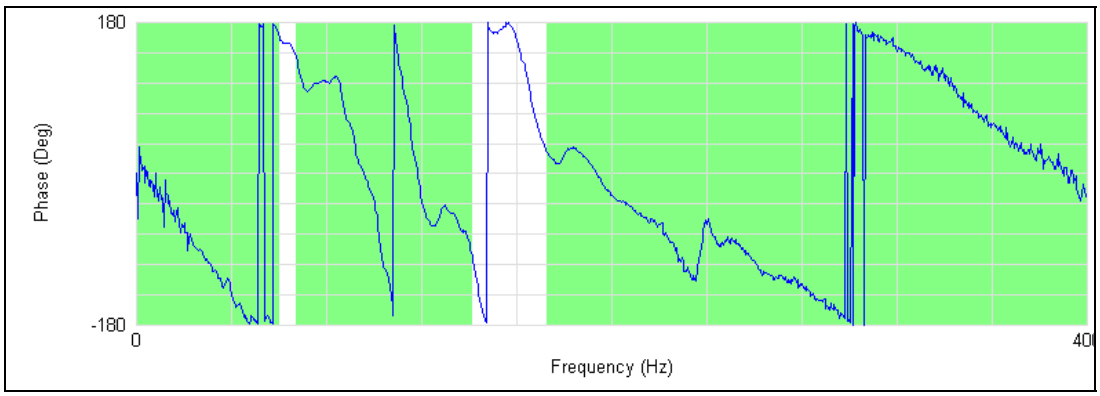

Figure D.4 Phase Plot Measured by SASW Testing; Setup #2; S-R2=6 ft, R2-R3=6ft

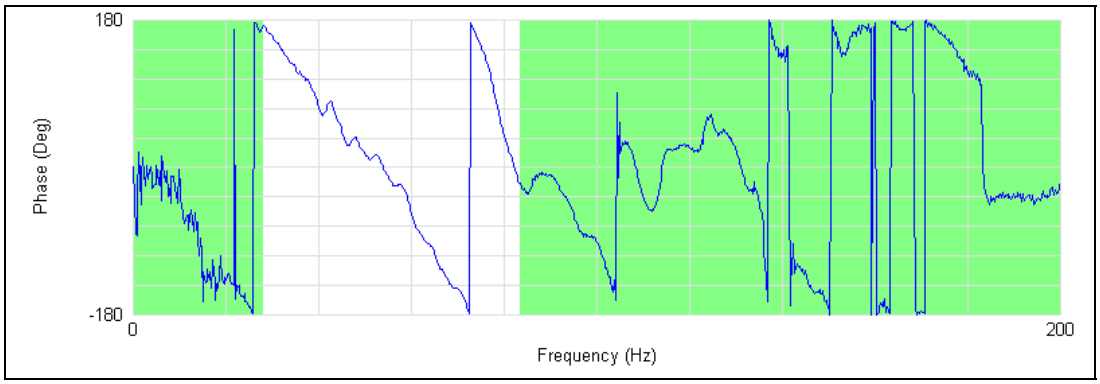

Figure D.5 Phase Plot Measured by SASW Testing; Setup #3; S-R1=12.5 ft, R1-R2=12.5 ft

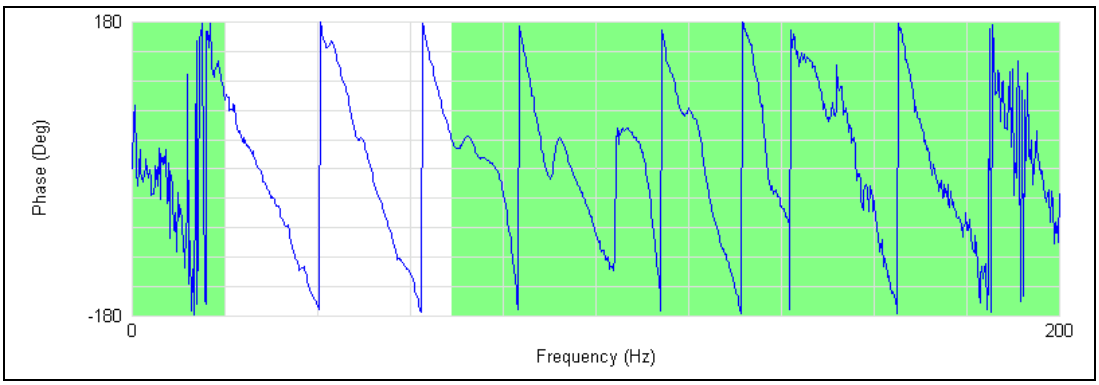

Figure D.6 Phase Plot Measured by SASW Testing; Setup #3; S-R2=25 ft, R2-R3=25 ft

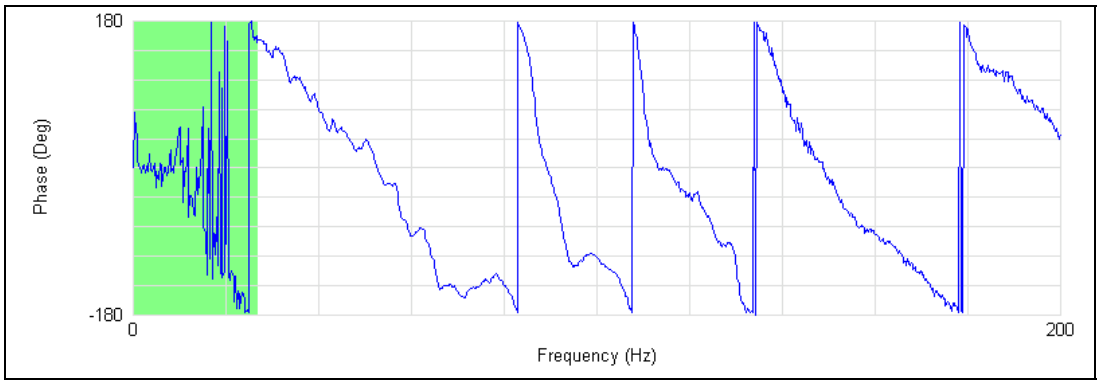

Figure D.7 Phase Plot Measured by SASW Testing; Setup #4; S-R1=12.5 ft, R1-R2=12.5 ft

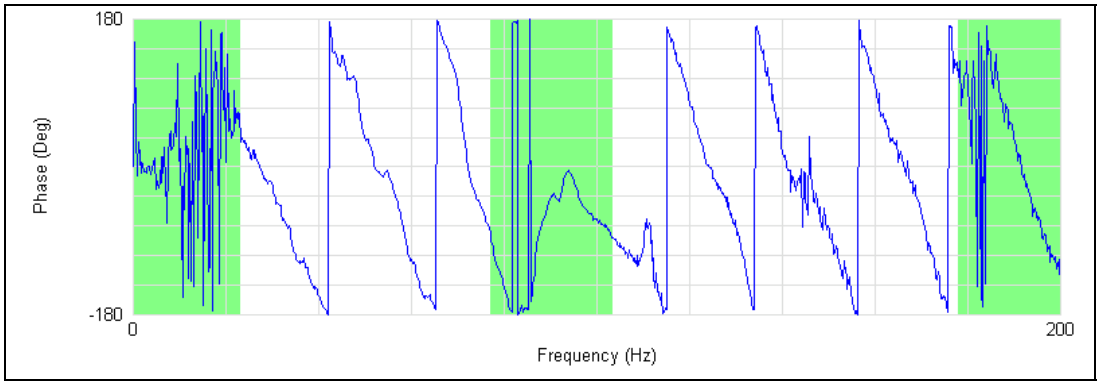

Figure D.8 Phase Plot Measured by SASW Testing; Setup #4; S-R2=25 ft, R2-R3=25 ft

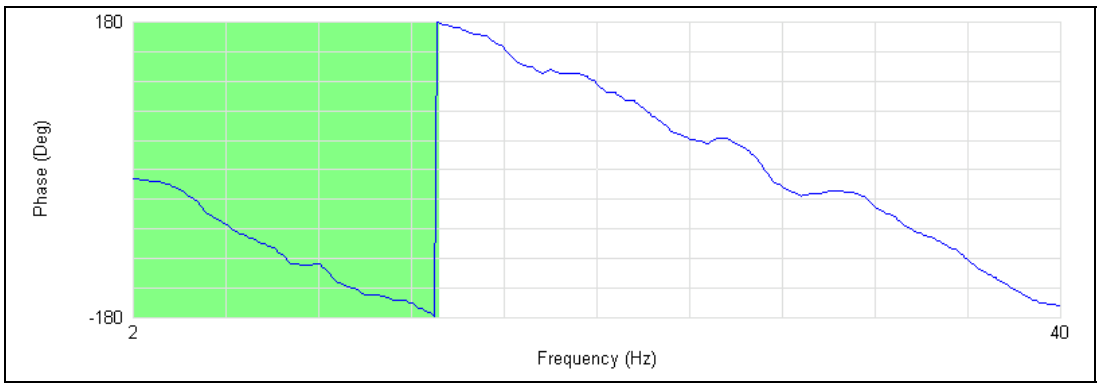

Figure D.9 Phase Plot Measured by SASW Testing; Setup #5; S-R1=25 ft, R1-R2=25ft

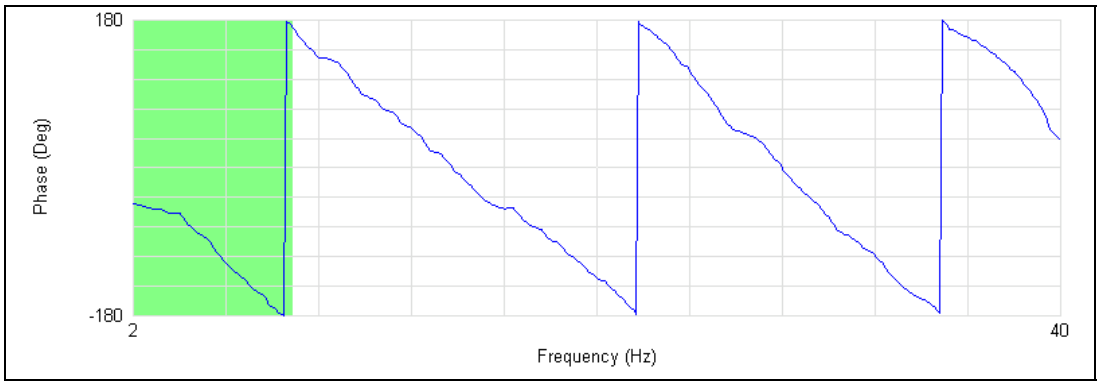

Figure D.10 Phase Plot Measured by SASW Testing; Setup #5; S-R2=50 ft, R2-R3=50 ft

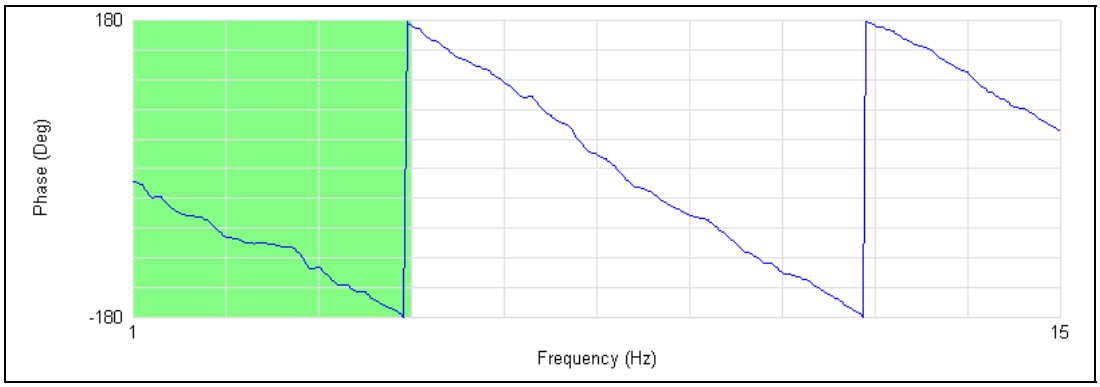

Figure D.11 Phase Plot Measured by SASW Testing; Setup #6; S-R1=100 ft, R1-R2=100 ft

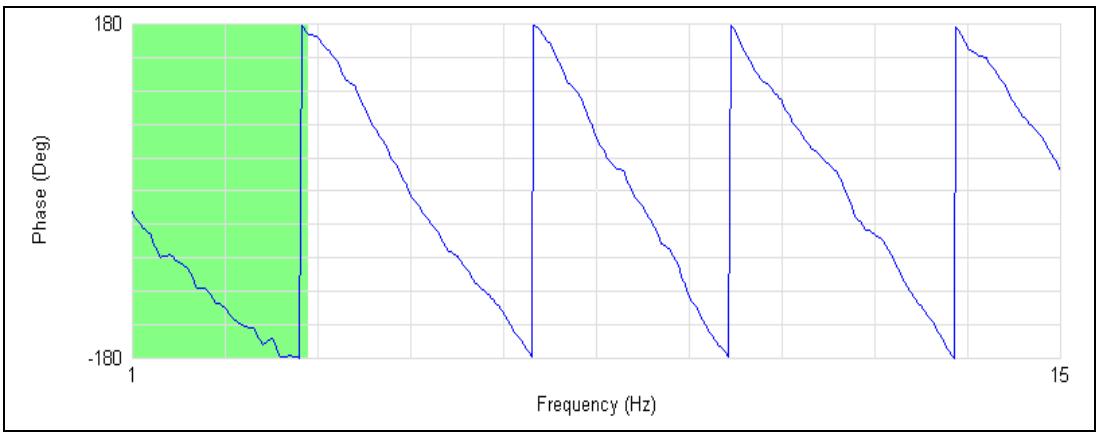

Figure D.12 Phase Plot Measured by SASW Testing; Setup #6; S-R2=200 ft, R2-R3=200ft

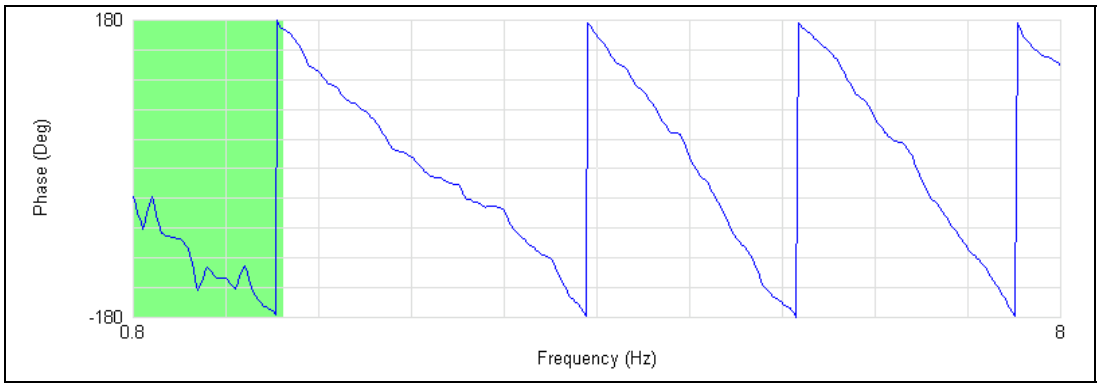

Figure D.13 Phase Plot Measured by SASW Testing; Setup #7; S-R1=400 ft, R1-R2=400 ft

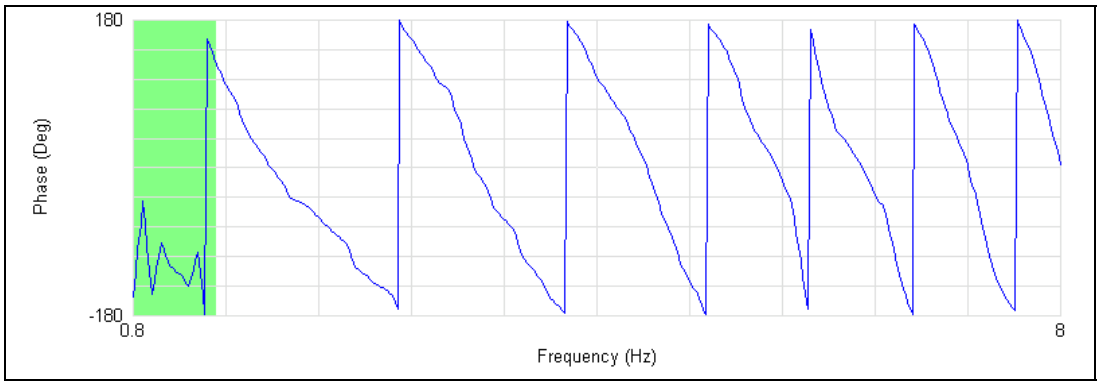

Figure D.14 Phase Plot Measured by SASW Testing; Setup #7; S-R2=800 ft, R2-R3=800ft

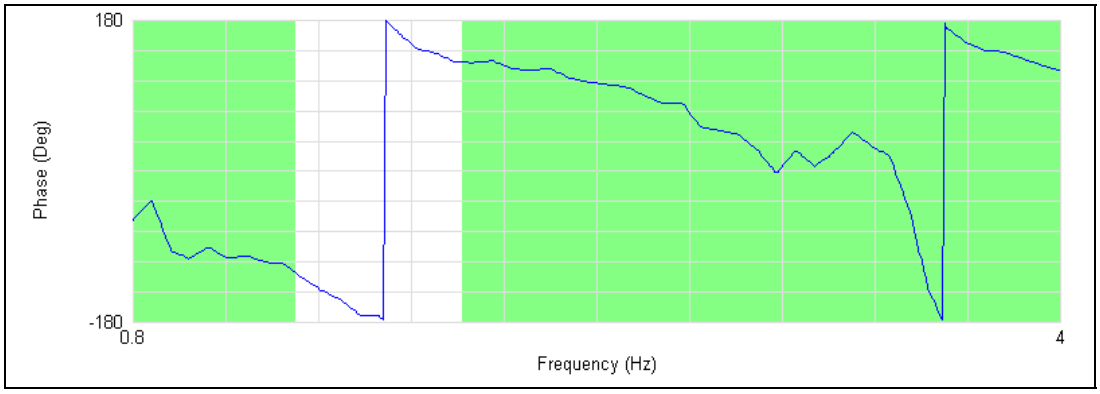

Figure D.15 Phase Plot Measured by SASW Testing; Setup #8; S-R1=1000 ft, R1-R2=500 ft

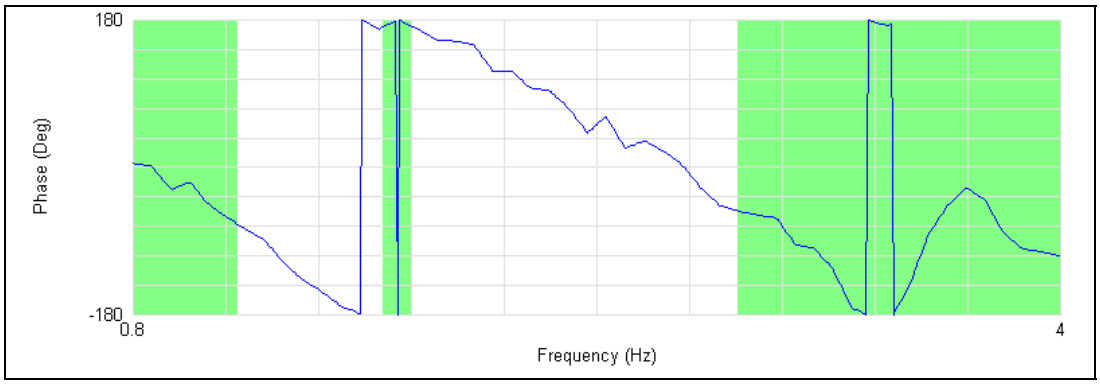

Figure D.16 Phase Plot Measured by SASW Testing; Setup #8; S-R2=1500 ft, R2-R3=500ft

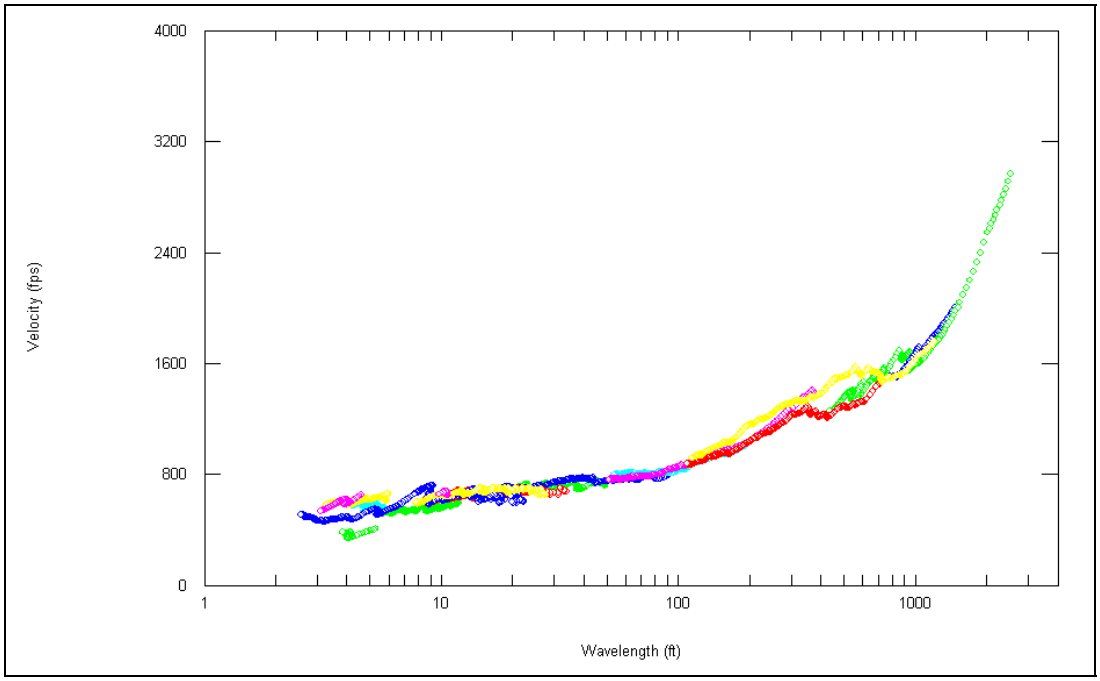

Figure D.17 Experimental Dispersion Curve Measured at Site 4

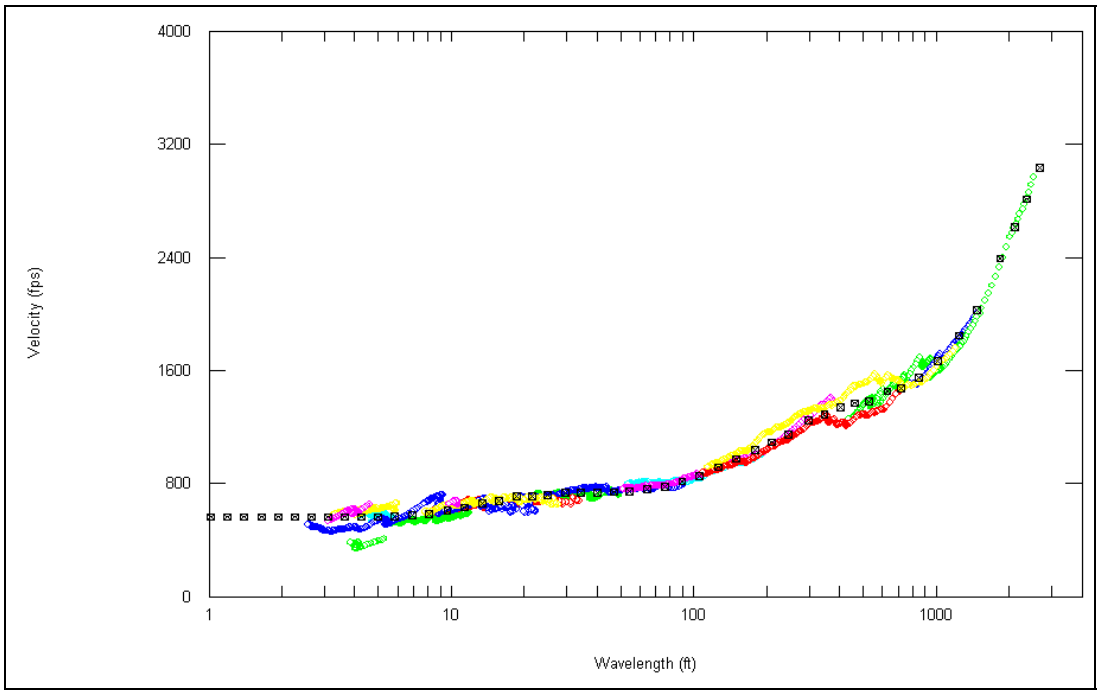

Figure D.18 Experimental and Theoretical Dispersion Curves from Site 4

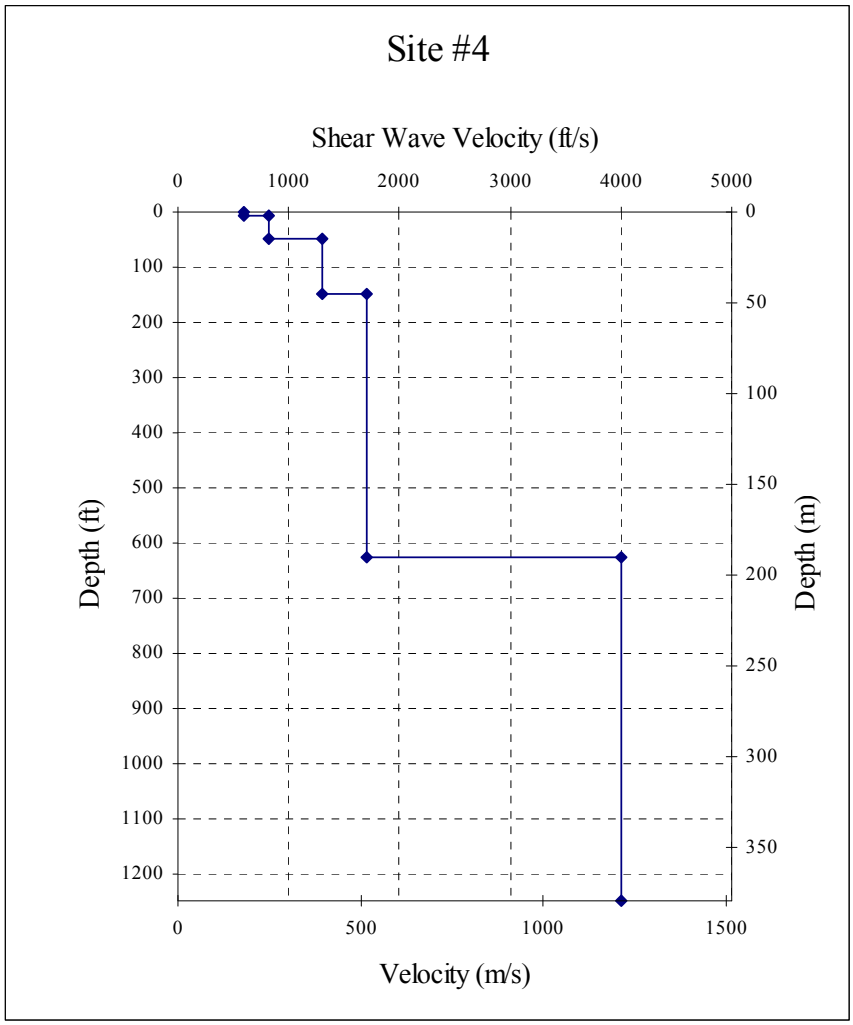

Figure D.19 Shear Wave Velocity Profile Determined at Site 4

Table D.2 Profile Parameters Used to Develop Theoretical Dispersion Curve at Site 4

Layer No.	Thickness, ft	P-Wave Velocity, ft/s	S-Wave Velocity, ft/s	Assumed Poisson's Ratio	P-Wave Velocity, ft/s
1	5	1122.5	600	0.30	120
2	45	1543.4	825	0.30	120
3	100	2432.1	1300	0.30	120
4	475	5200*	1700	0.440	120
5	∞	7483.3	4000	0.30	130

* Depth to Water Table is 150 ft

E.1. APPENDIX E

Analysis of SASW Tests at Site 5

Table E.1 Table of Source and Receiver Spacings

Site Name	Set up	Source to Receiver #1	Receiver #1 to Receiver #2	Receiver #2 to Receiver #3
Site 5	1	3	3	6
	2 (1 Reversed)	3	3	6
	3	12.5	12.5	25
	4 (3 Reversed)	12.5	12.5	25
	5	50	50	100
	6	75	75	150
	7	200	200	400
	8	400	400	400

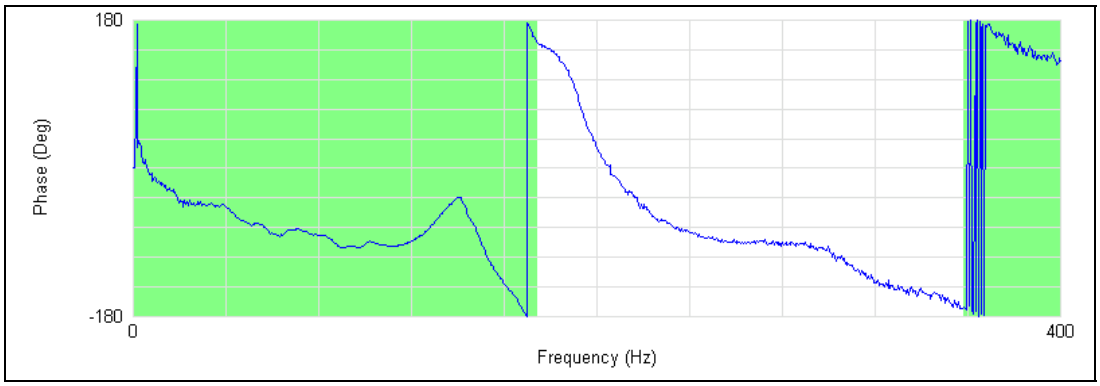

Figure E.1 Phase Plot Measured by SASW Testing; Setup #1; S-R1=3 ft, R1-R2=3ft

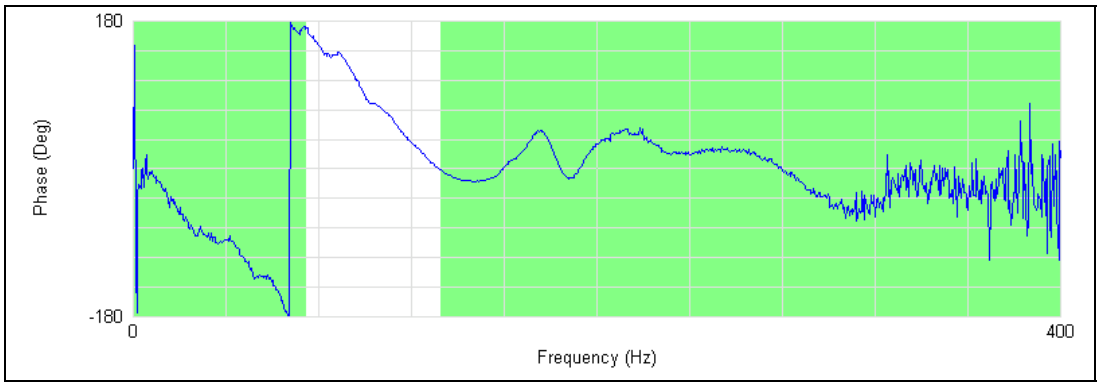

Figure E.2 Phase Plot Measured by SASW Testing; Setup #1; S-R2=6 ft, R2-R3=6 ft Spacing

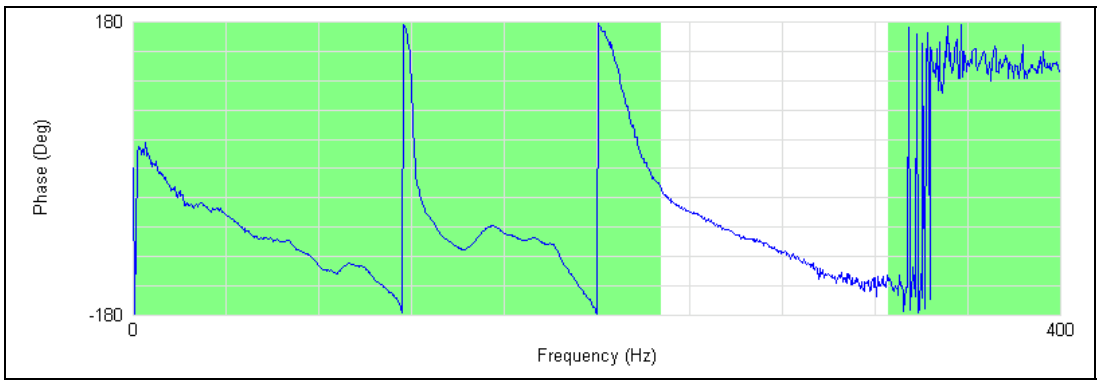

Figure E.3 Phase Plot Measured by SASW Testing; Setup #2; S-R1= 3 ft, R1-R2=3ft

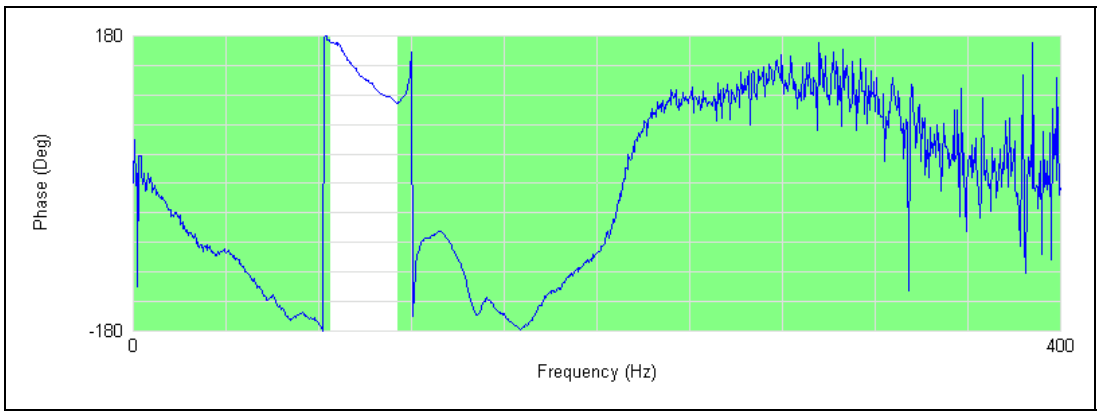

Figure E.4 Phase Plot Measured by SASW Testing; Setup #2; S-R2=6 ft, R2-R3=6ft

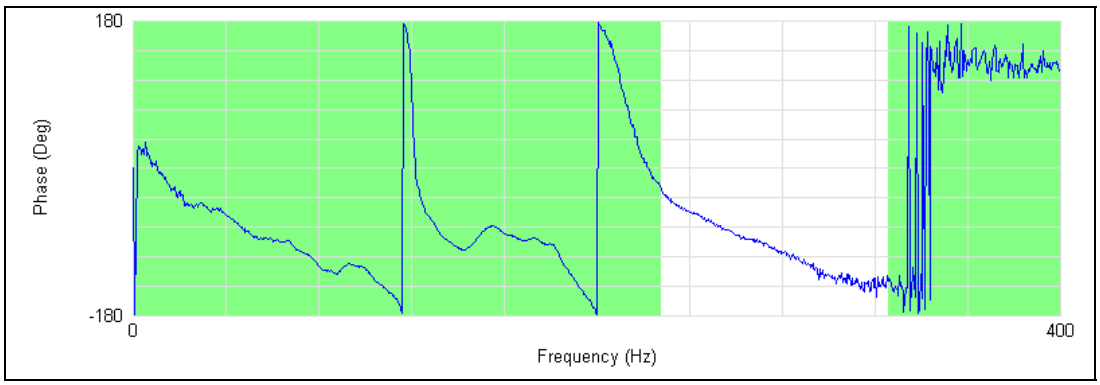

Figure E.5 Phase Plot Measured by SASW Testing; Setup #3; S-R1=12.5 ft, R1-R2=12.5 ft

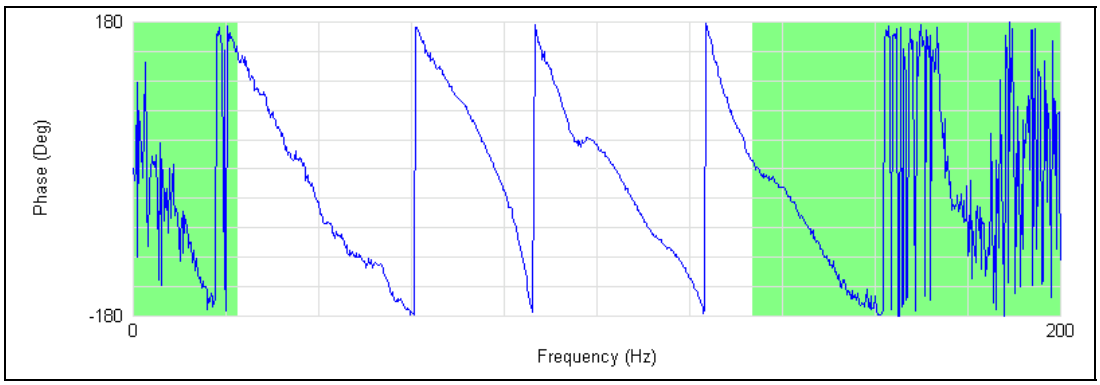

Figure E.6 Phase Plot Measured by SASW Testing; Setup #3; S-R2=25 ft, R2-R3=25 ft

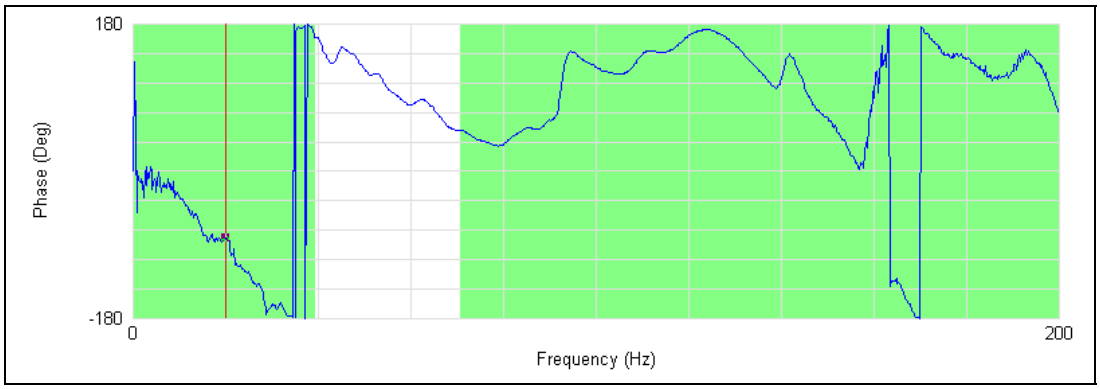

Figure E.7 Phase Plot Measured by SASW Testing; Setup #4; S-R1=12.5 ft, R1-R2=12.5 ft

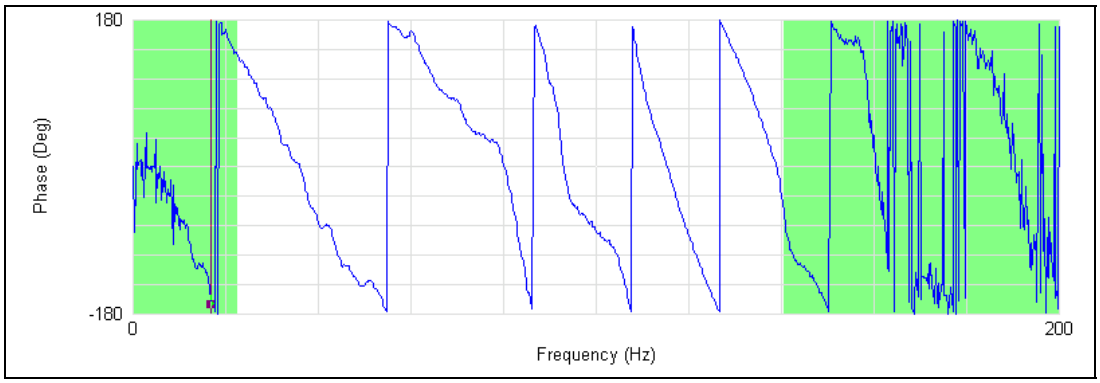

Figure E.8 Phase Plot Measured by SASW Testing; Setup #4; S-R2=25 ft, R2-R3=25 ft

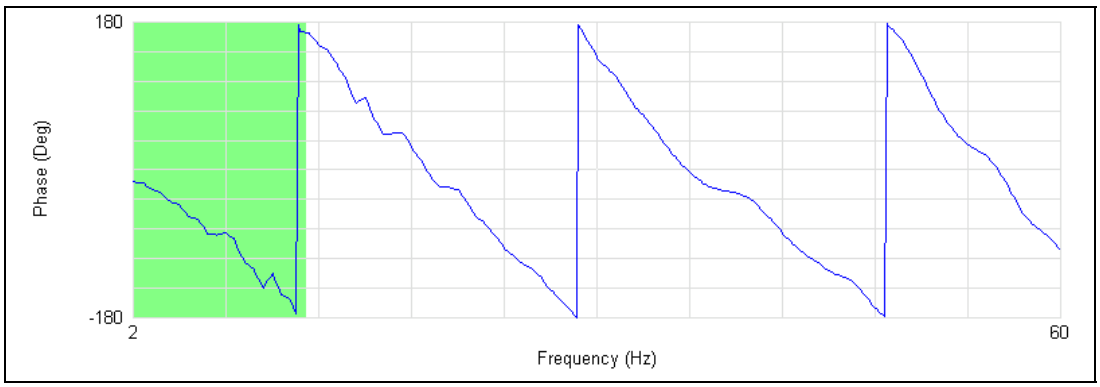

Figure E.9 Phase Plot Measured by SASW Testing; Setup #5; S-R1=50 ft, R1-R2=50ft

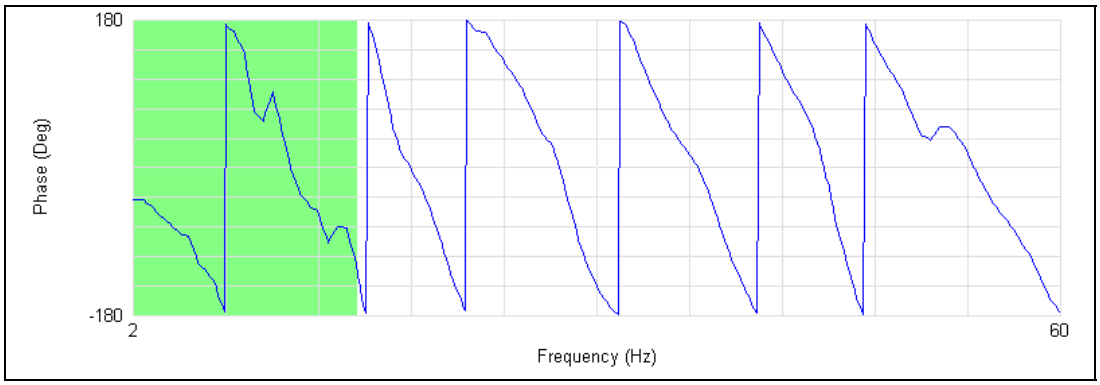

Figure E.10 Phase Plot Measured by SASW Testing; Setup #5; S-R2=100 ft, R2-R3=100 ft

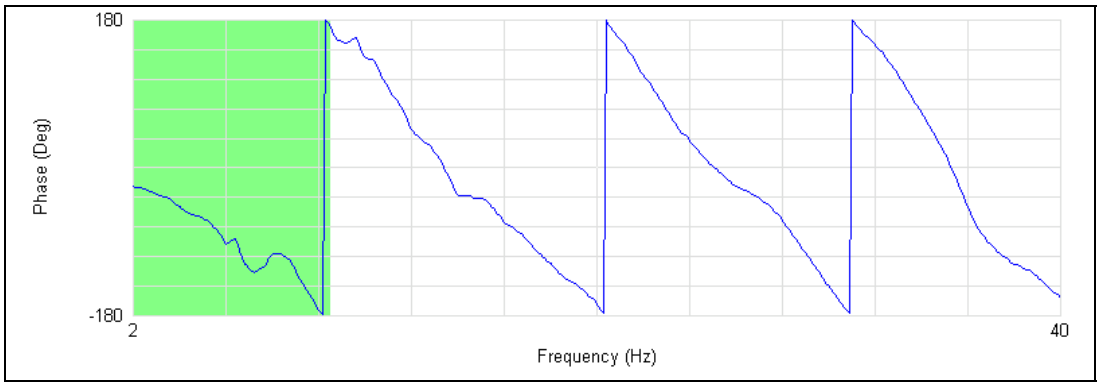

Figure E.11 Phase Plot Measured by SASW Testing; Setup #6; S-R1=75 ft, R1-R2=75ft

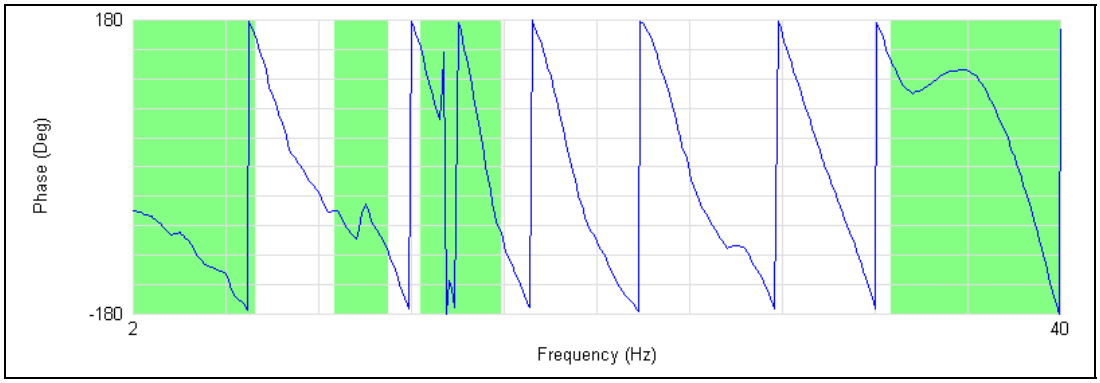

Figure E.12 Phase Plot Measured by SASW Testing; Setup #6; S-R2=150 ft, R2-R3=150ft

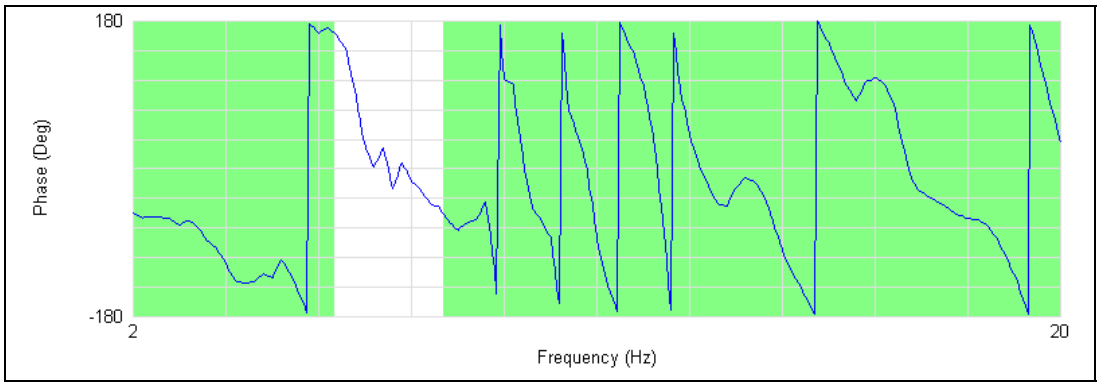

Figure E.13 Phase Plot Measured by SASW Testing; Setup #7; S-R1=200 ft, R1-R2=200 ft

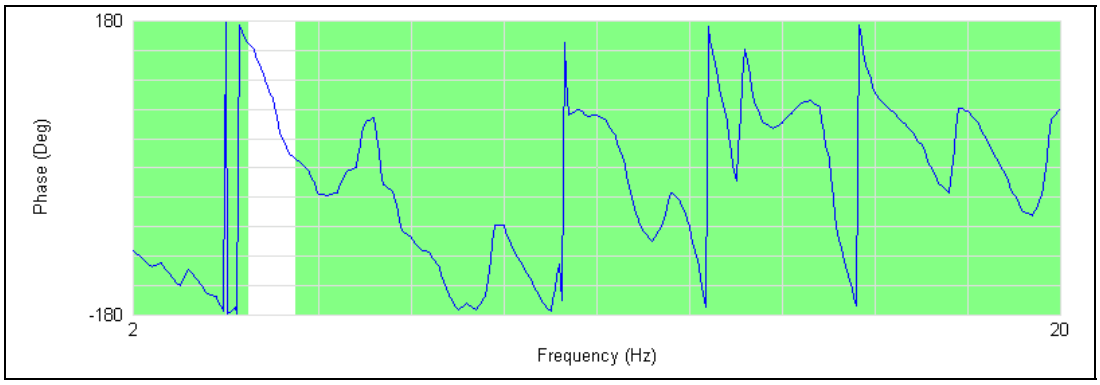

Figure E.14 Phase Plot Measured by SASW Testing; Setup #7; S-R2=400 ft, R2-R3=400ft

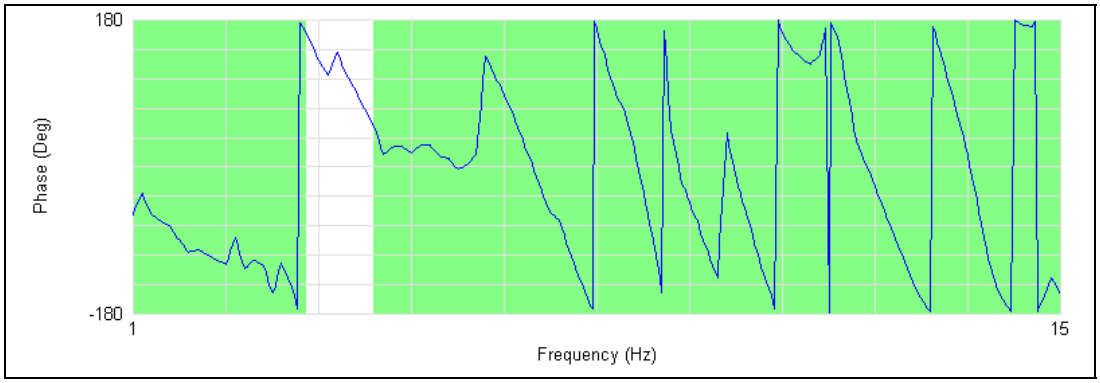

Figure E.15 Phase Plot Measured by SASW Testing; Setup #8; S-R1=400 ft, R1-R2=400 ft

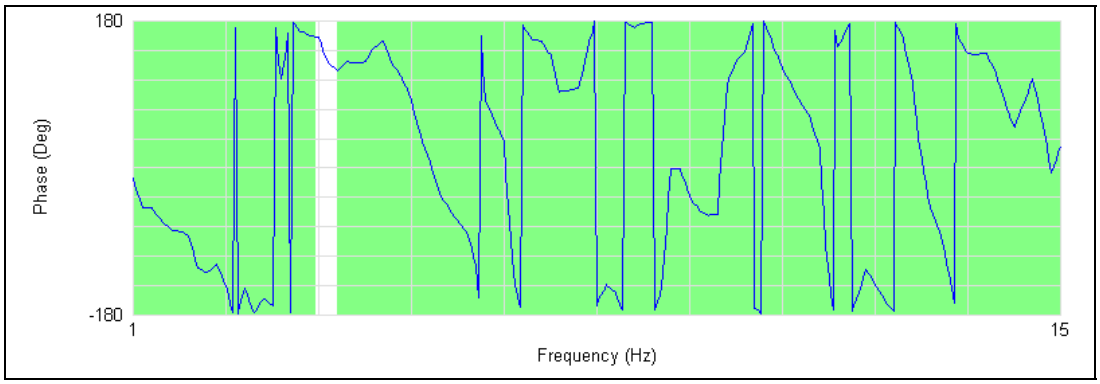

Figure E.16 Phase Plot Measured by SASW Testing; Setup #8; S-R2=800 ft, R2-R3=400ft

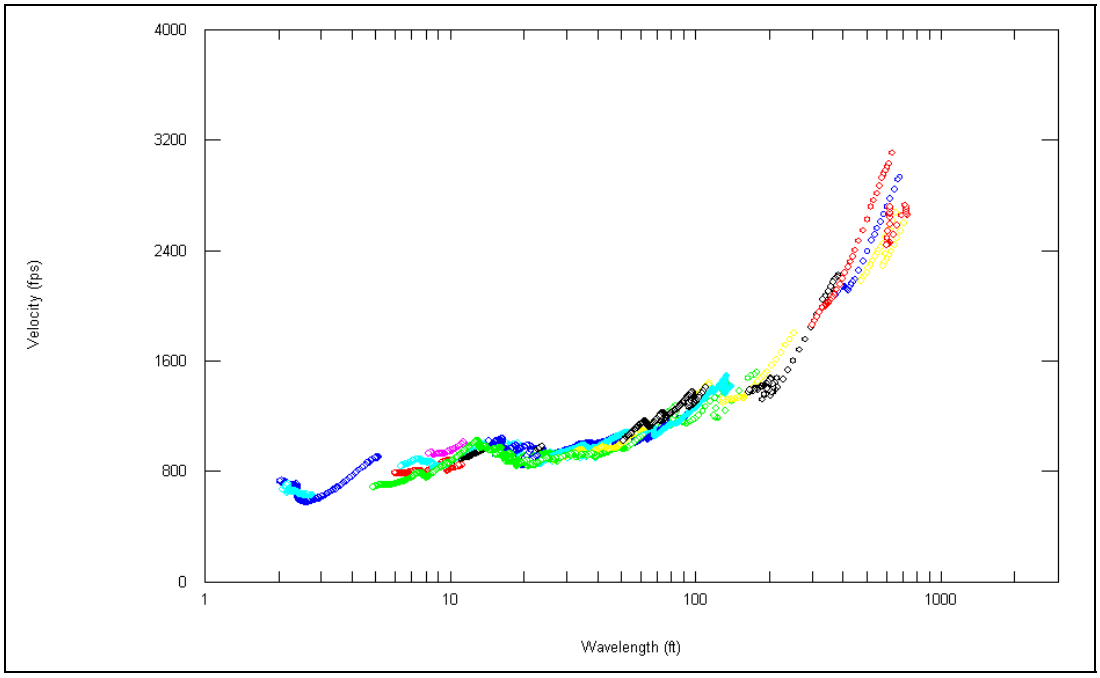

Figure E.17 Experimental Dispersion Curve Measured at Site 5

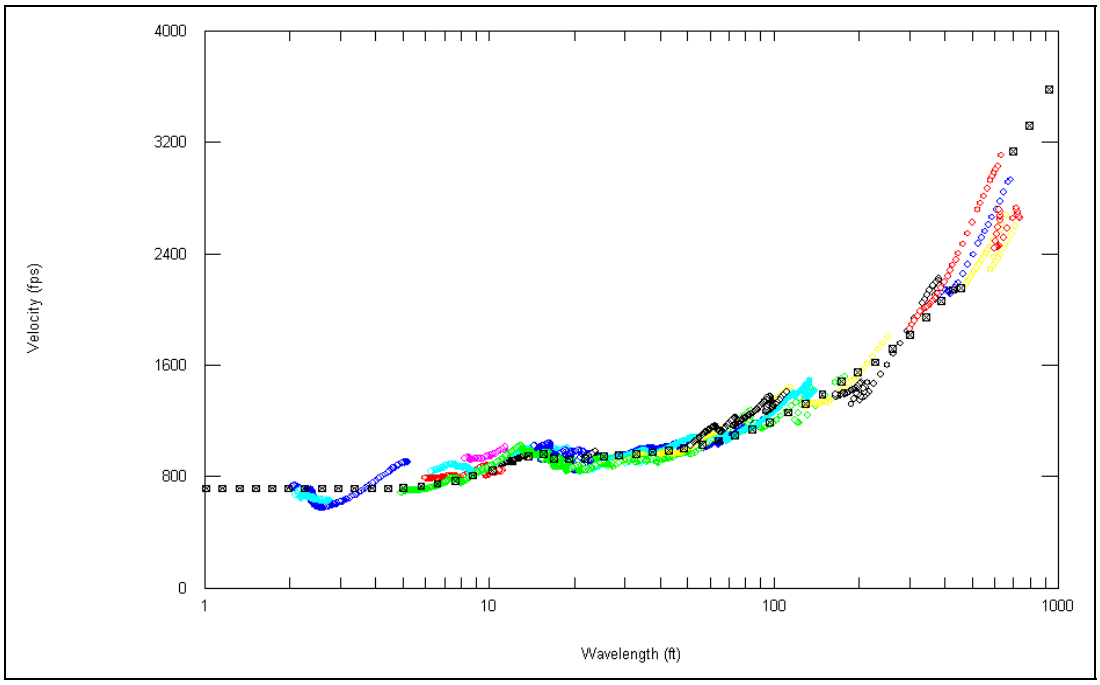

Figure E.18 Experimental and Theoretical Dispersion Curves from Site 5

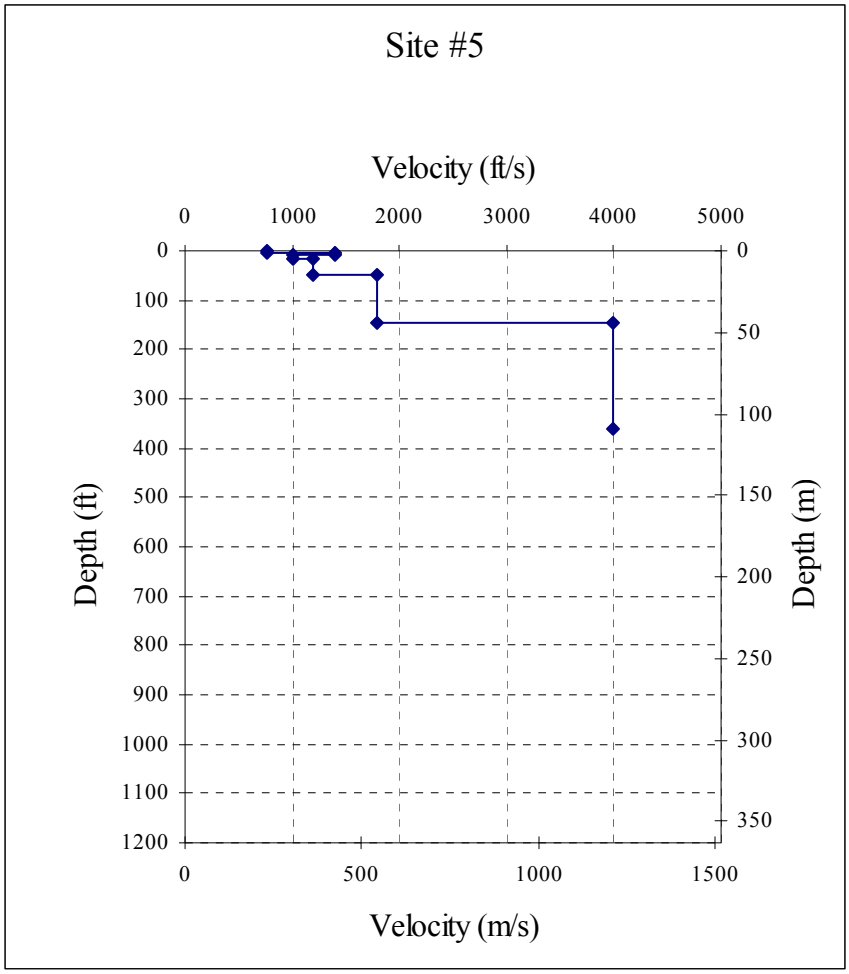

Figure E.19 Shear Wave Velocity Profile Determined at Site 5

Table E.2 Profile Parameters Used to Develop Theoretical Dispersion Curve at Site 5

Layer No.	Thickness, ft	P-Wave Velocity, ft/s	S-Wave Velocity, ft/s	Assumed Poisson's Ratio	Assumed Total Density, pcf
1	4.5	1421.8	760	0.30	120
2	3	2619.2	1400	0.30	120
3	10	1683.8	1000	0.30	120
4	30	2245	1200	0.30	120
5	100	3367.5	1800	0.30	120
6	∞	7483.3	4000	0.30	130

F.1. APPENDIX F

Analysis of SASW Tests at Site 6

Table F.1 Table of Source and Receiver Spacings

Site Name	Set up	Source to Receiver #1	Receiver #1 to Receiver #2	Receiver #2 to Receiver #3
Site 6	1	3	3	6
	2 (1 Reversed)	3	3	6
	3	12.5	12.5	25
	4 (3 Reversed)	12.5	12.5	25
	5	50	50	100
	6	75	75	150
	7	100	100	200
	8	200	200	400
	9	400	400	400

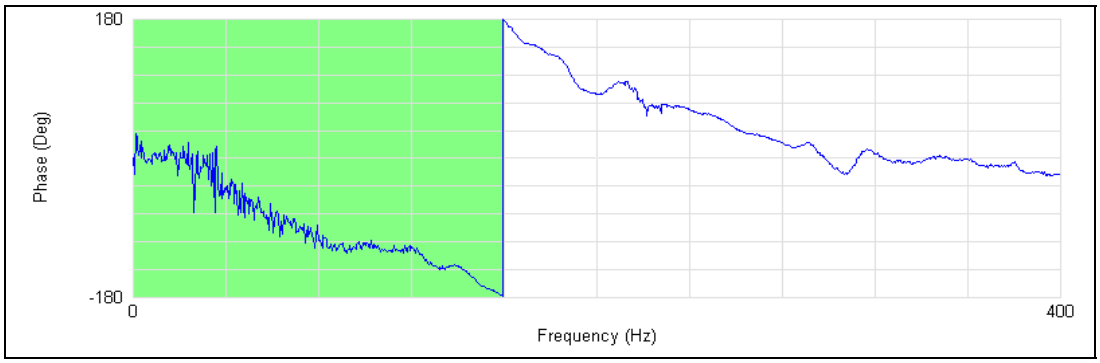

Figure F.1 Phase Plot Measured by SASW Testing; Setup #1; S-R1=3 ft, R1-R2=3ft

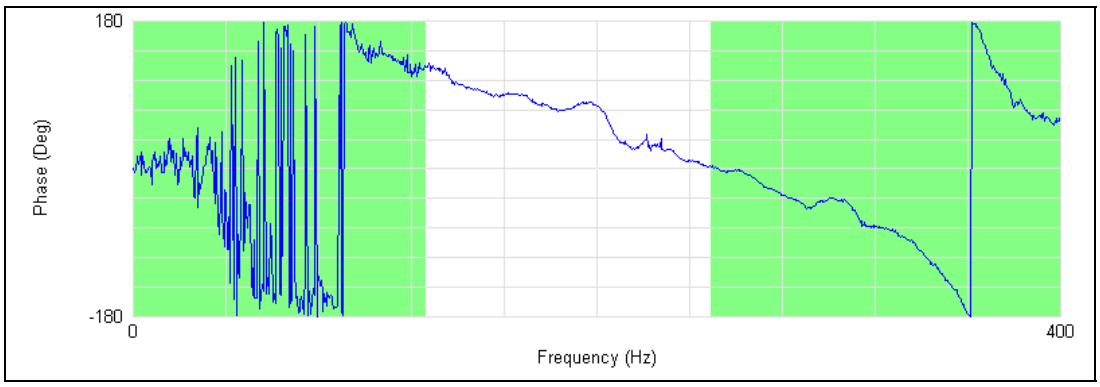

Figure F.2 Phase Plot Measured by SASW Testing; Setup #1; S-R2=6 ft, R2-R3=6ft

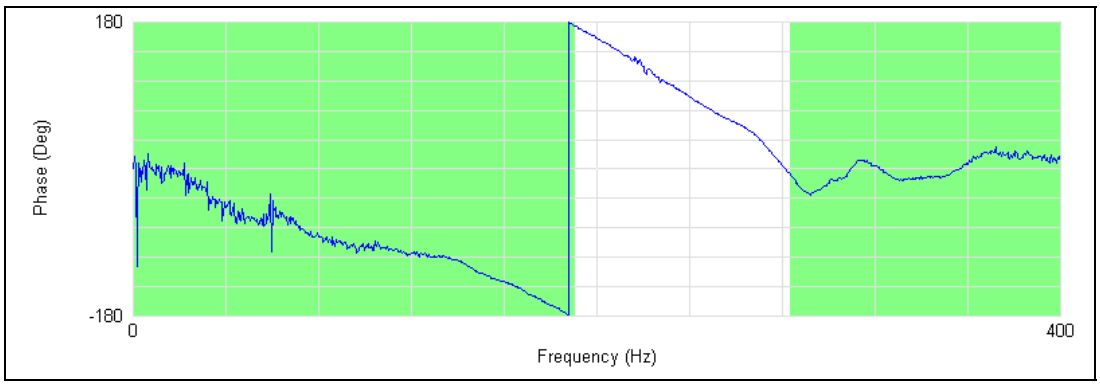

Figure F.3 Phase Plot Measured by SASW Testing; Setup #2; S-R1= 3 ft, R1-R2=3ft

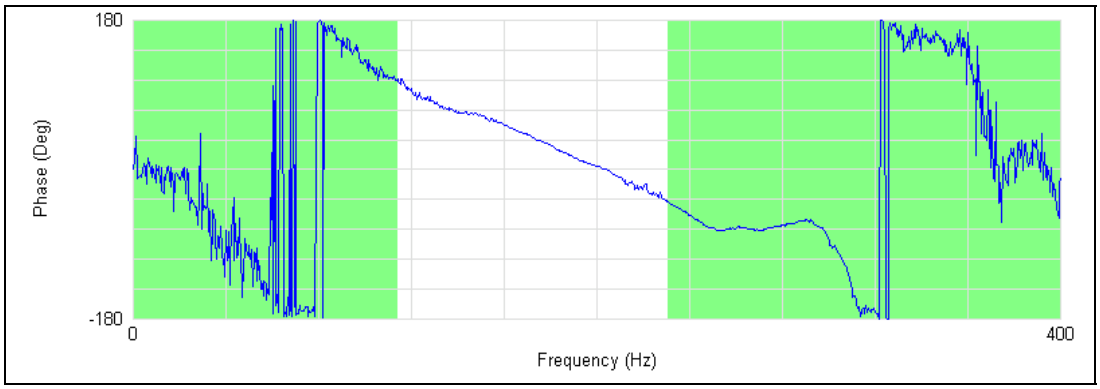

Figure F.4 Phase Plot Measured by SASW Testing; Setup #2; S-R2=6 ft, R2-R3=6ft

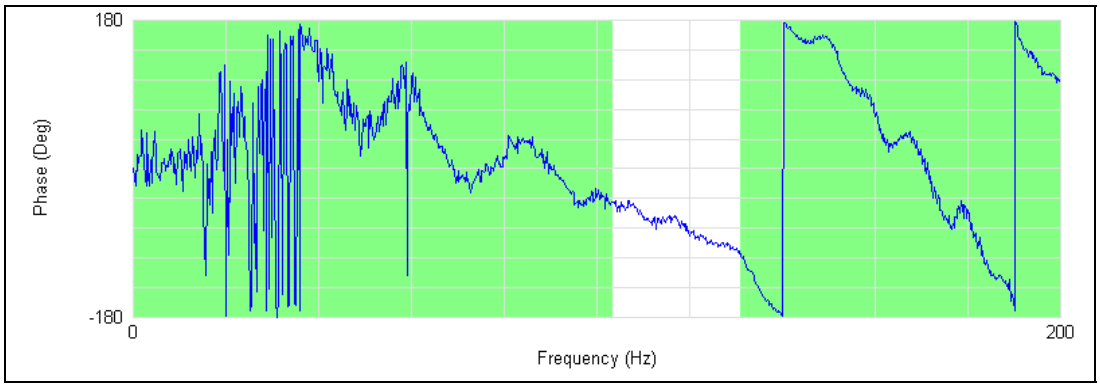

Figure F.5 Phase Plot Measured by SASW Testing; Setup #3; S-R1=12.5 ft, R1-R2=12.5 ft

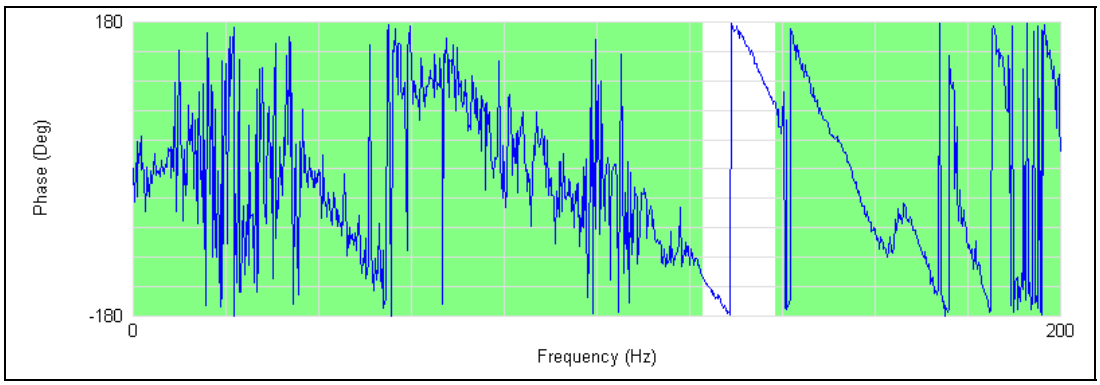

Figure F.6 Phase Plot Measured by SASW Testing; Setup #3; S-R2=25 ft, R2-R3=25 ft

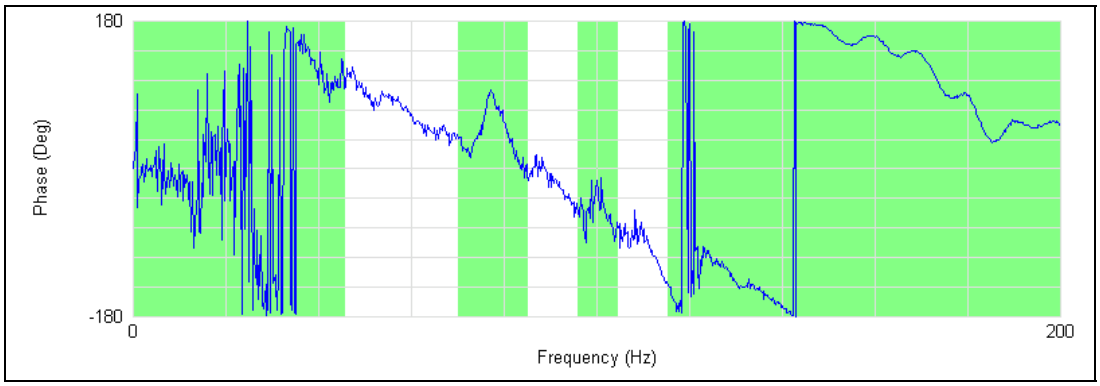

Figure F.7 Phase Plot Measured by SASW Testing; Setup #4; S-R1=12.5 ft, R1-R2=12.5 ft

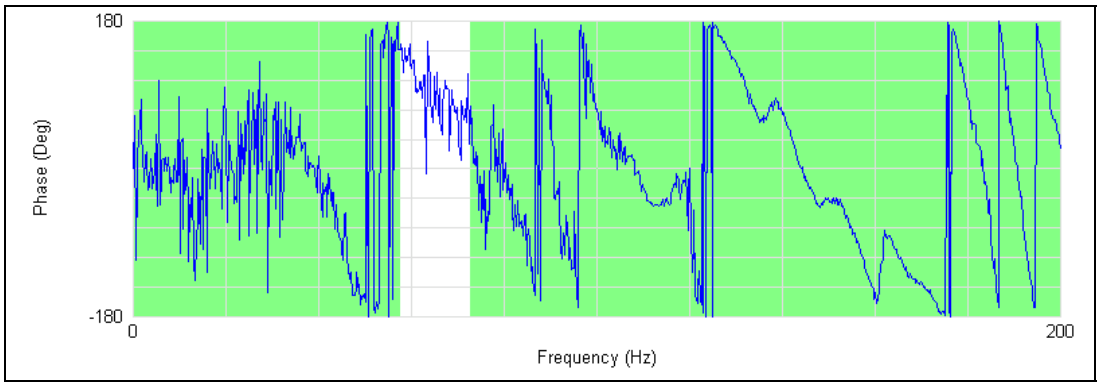

Figure F.8 Phase Plot Measured by SASW Testing; Setup #4; S-R2=25 ft, R2-R3=25 ft

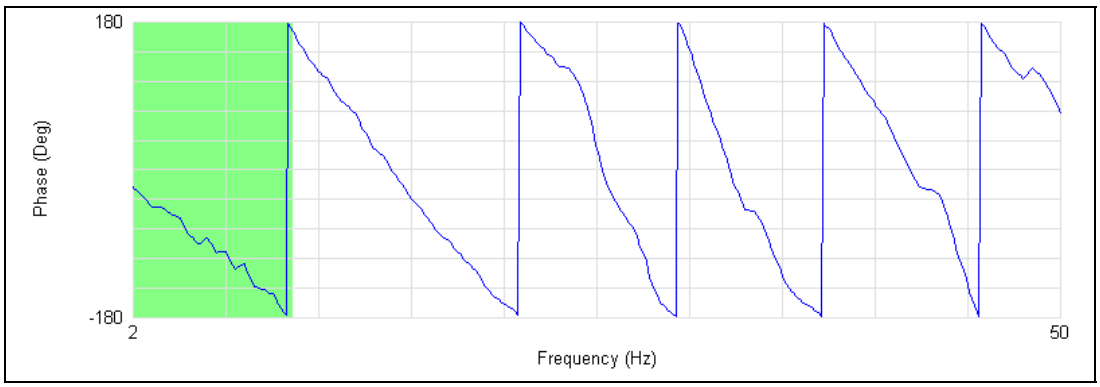

Figure F.9 Phase Plot Measured by SASW Testing; Setup #5; S-R1=50 ft, R1-R2=50ft

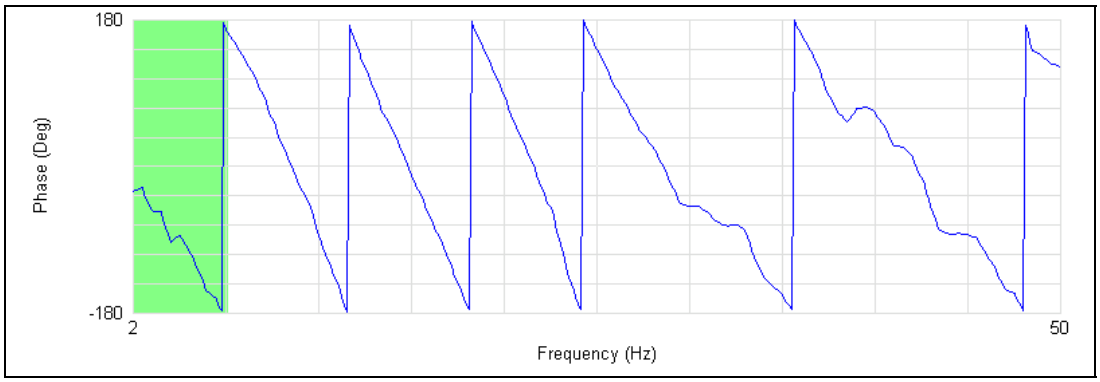

Figure F.10 Phase Plot Measured by SASW Testing; Setup #5; S-R2=100 ft, R2-R3=100 ft

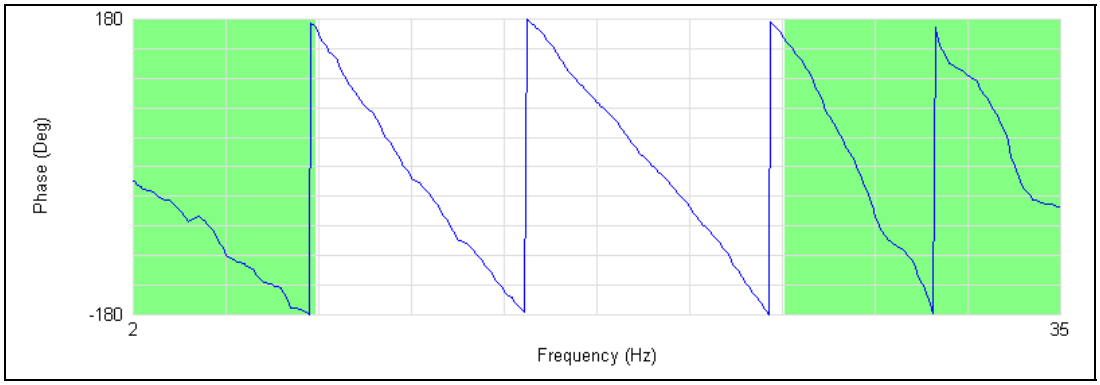

Figure F.11 Phase Plot Measured by SASW Testing; Setup #6; S-R1=75 ft, R1-R2=75ft

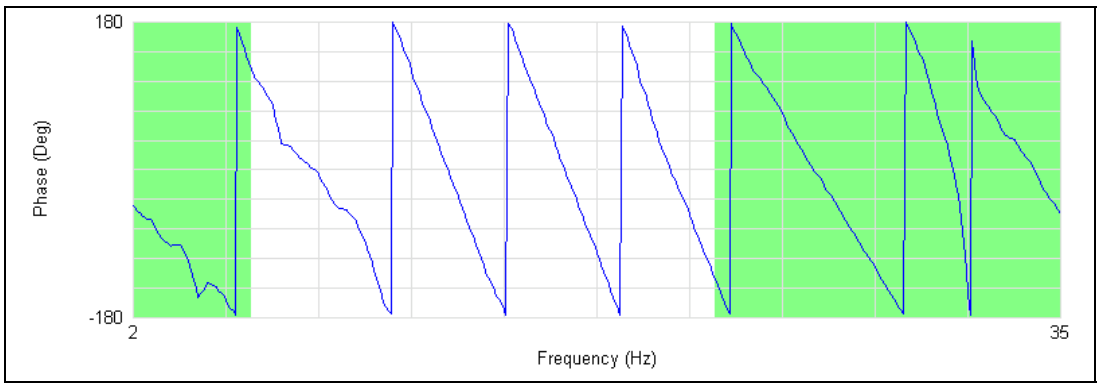

Figure F.12 Phase Plot Measured by SASW Testing; Setup #6; S-R2=150 ft, R2-R3=150ft

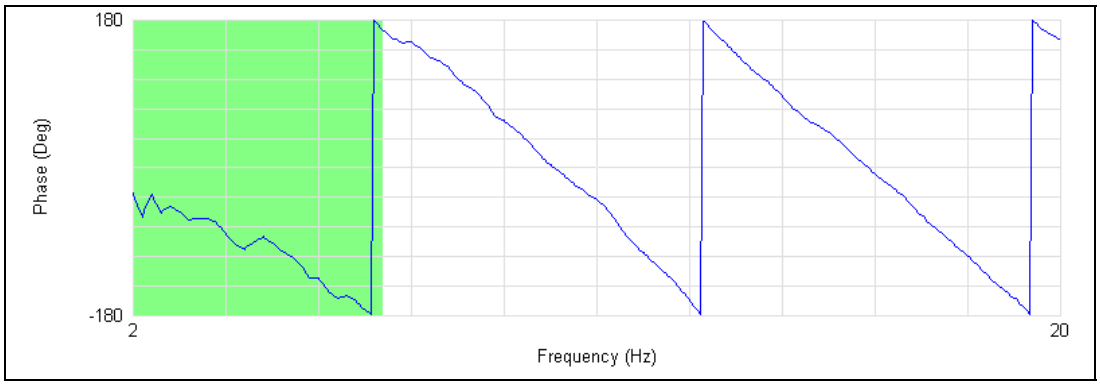

Figure F.13 Phase Plot Measured by SASW Testing; Setup #7; S-R1=100 ft, R1-R2=100ft

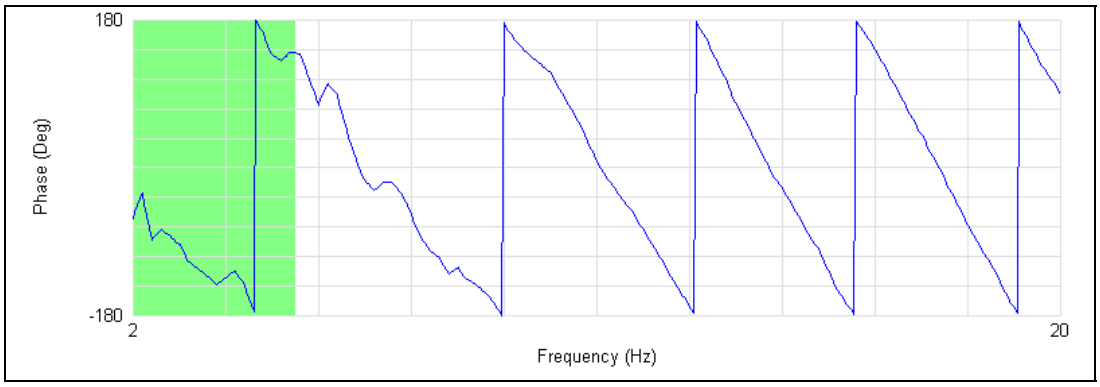

Figure F.14 Phase Plot Measured by SASW Testing; Setup #7; S-R2=200 ft, R2-R3=200ft

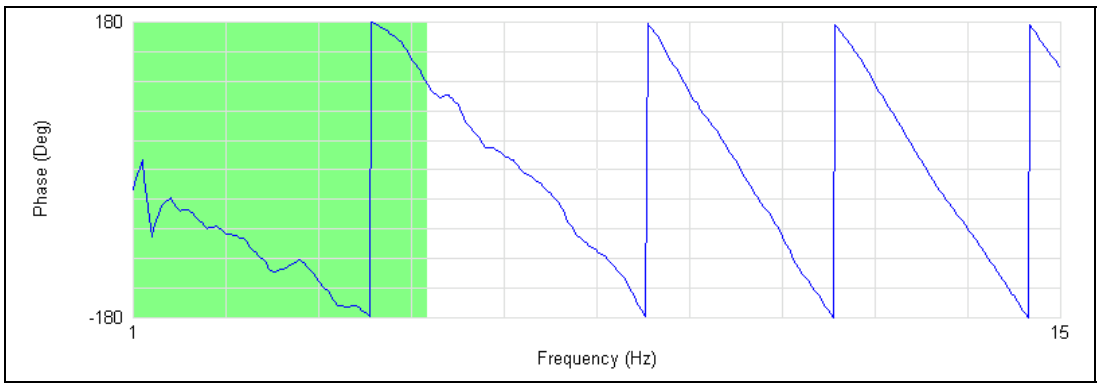

Figure F.15 Phase Plot Measured by SASW Testing; Setup #8; S-R1=200 ft, R1-R2=200ft

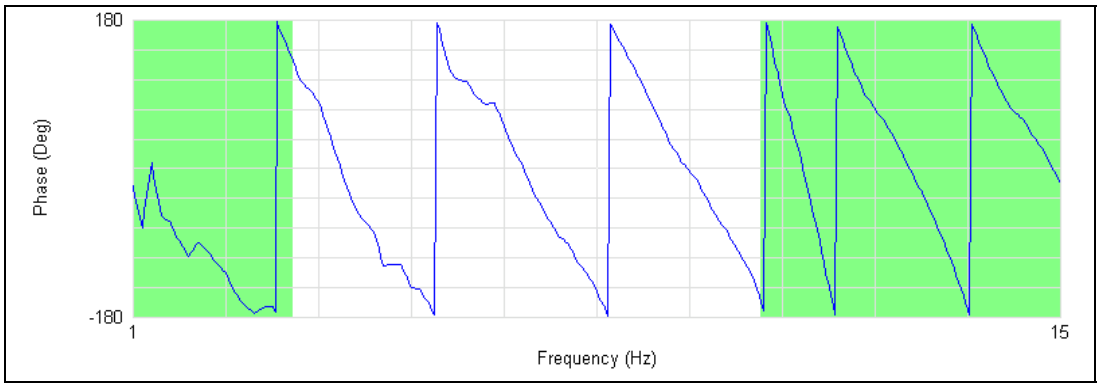

Figure F.16 Phase Plot Measured by SASW Testing; Setup #8; S-R2=400 ft, R2-R3=400ft

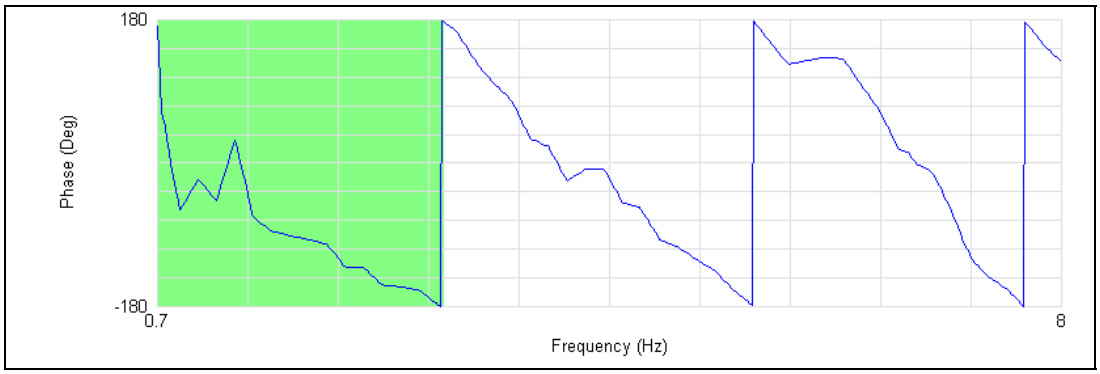

Figure F.17 Phase Plot Measured by SASW Testing; Setup #9; S-R1=400 ft, R1-R2=400ft

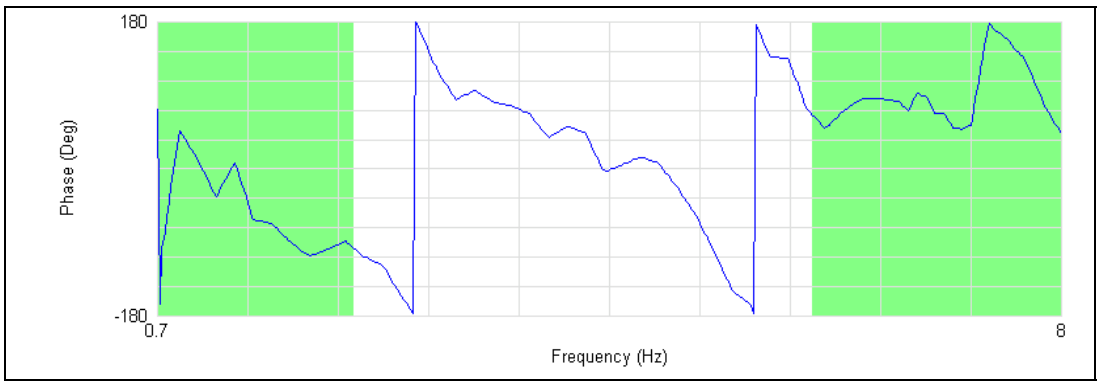

Figure F.18 Phase Plot Measured by SASW Testing; Setup #9; S-R2=800 ft, R2-R3=400ft

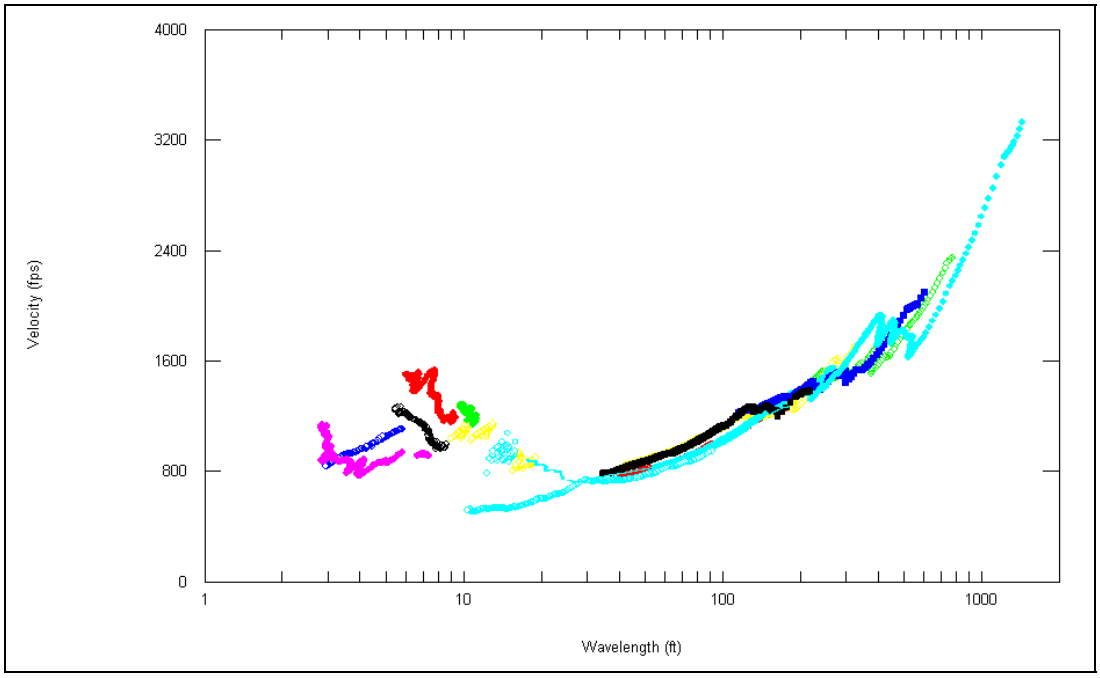

Figure F.19 Experimental Dispersion Curve Measured at Site 6

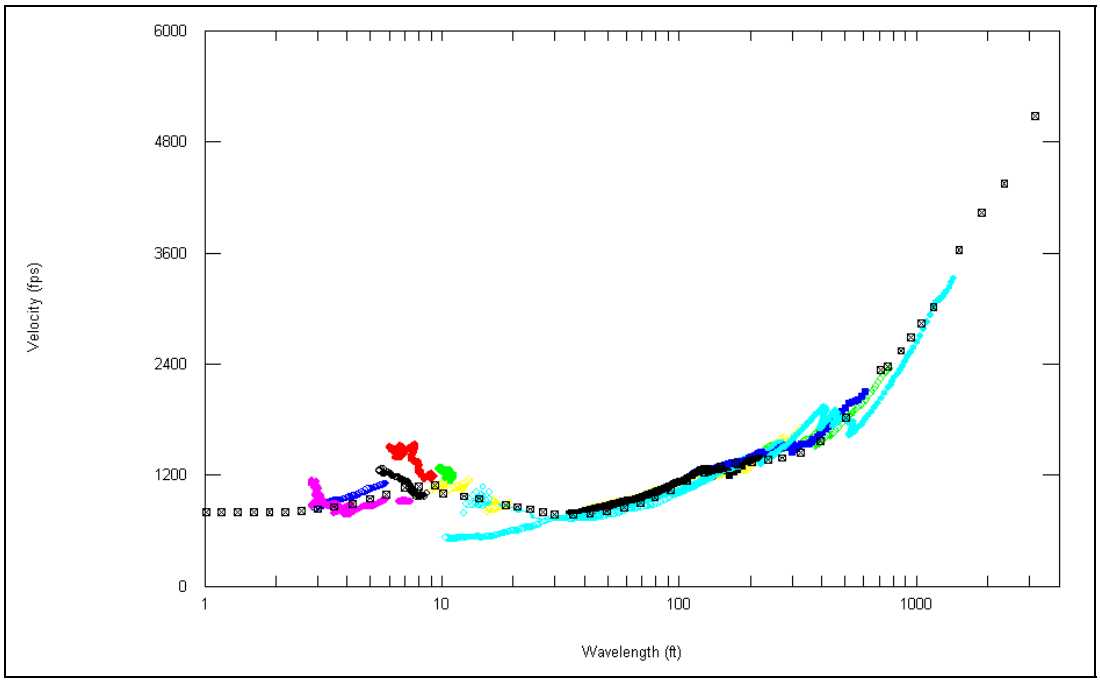

Figure F.20 Experimental and Theoretical Dispersion Curves from Site 6

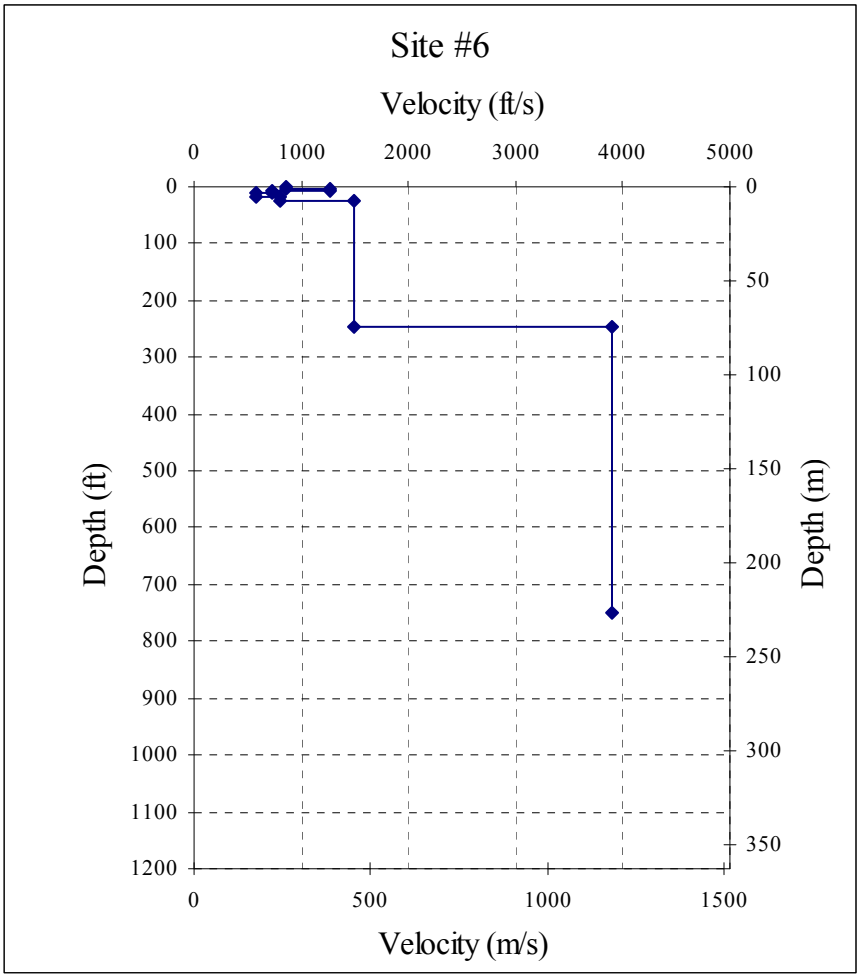

Figure F.21 Shear Wave Velocity Profile Determined at Site 6

Table F.2 Profile Parameters Used to Develop Theoretical Dispersion Curve at Site 6

Layer No.	Thickness, ft	P-Wave Velocity, ft/s	S-Wave Velocity, ft/s	Assumed Poisson's Ratio	Assumed Total Density, pcf
1	2	1590.2	850	0.30	120
2	6	2376	1270	0.30	120
3	3	1356.4	725	0.30	120
4	5	1075.7	575	0.30	120
5	10	1496.7	800	0.30	120
6	220	5200*	1500	0.455	120
7	∞	7296.2	3900	0.30	130

* Depth to Water Table is 26 ft

G.1. APPENDIX G

Analysis of SASW Tests at Site 7

Table G.1 Table of Source and Receiver Spacings

Site Name	Set up	Source to Receiver #1	Receiver #1 to Receiver #2	Receiver #2 to Receiver #3
Site 7	1	3	3	6
	2 (1 Reversed)	3	3	6
	3	12.5	12.5	25
	4 (3 Reversed)	12.5	12.5	25
	5	50	50	100
	6	150	150	300
	7	400	400	800
	8	500	500	500
	9	500	500	500

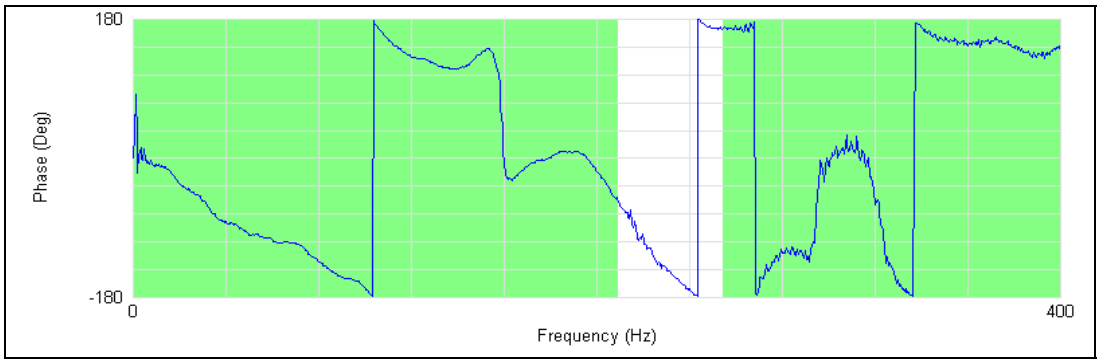

Figure G.1 Phase Plot Measured by SASW Testing; Setup #1; S-R1=3 ft, R1-R2=3ft

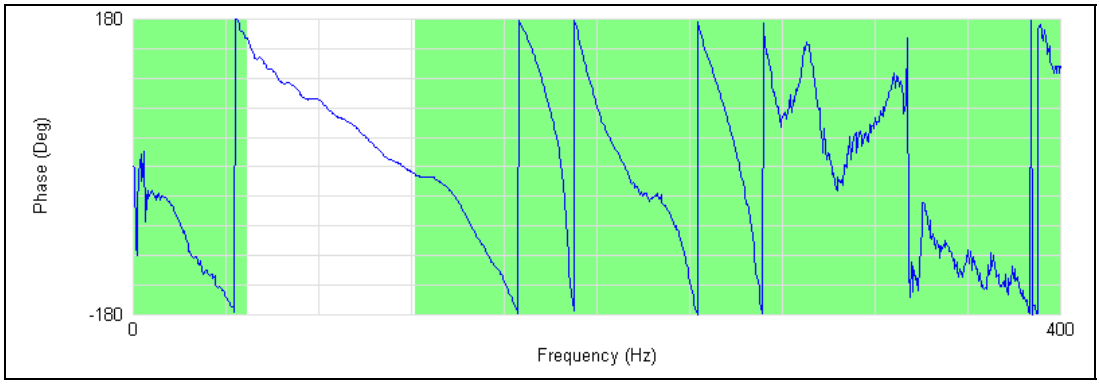

Figure G.2 Phase Plot Measured by SASW Testing; Setup #1; S-R2=6 ft, R2-R3=6ft

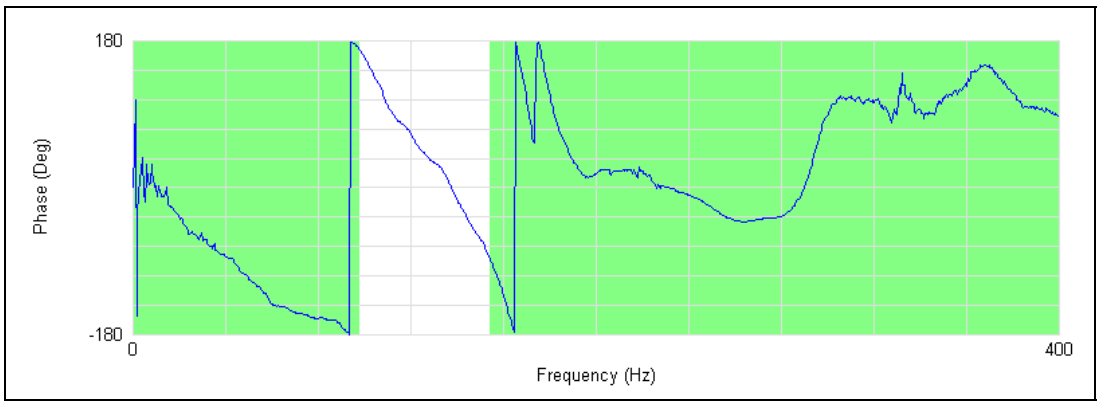

Figure G.3 Phase Plot Measured by SASW Testing; Setup #2; S-R1= 3 ft, R1-R2=3ft

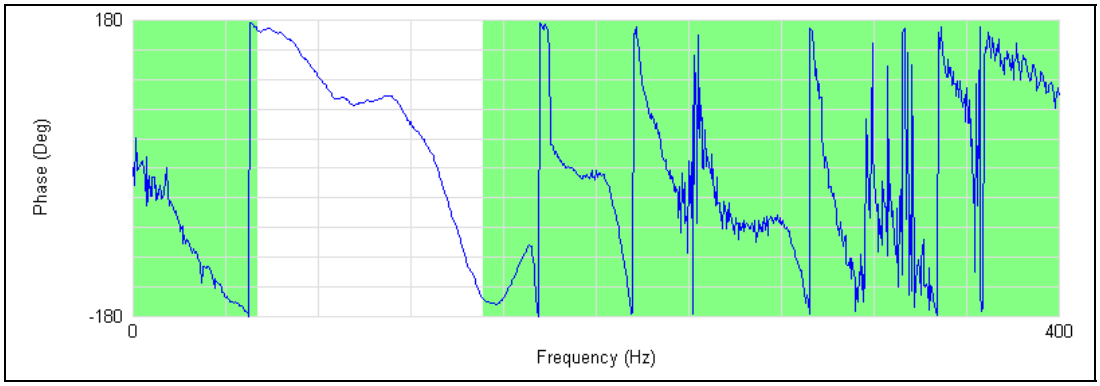

Figure G.4 Phase Plot Measured by SASW Testing; Setup #2; S-R2=6 ft, R2-R3=6ft

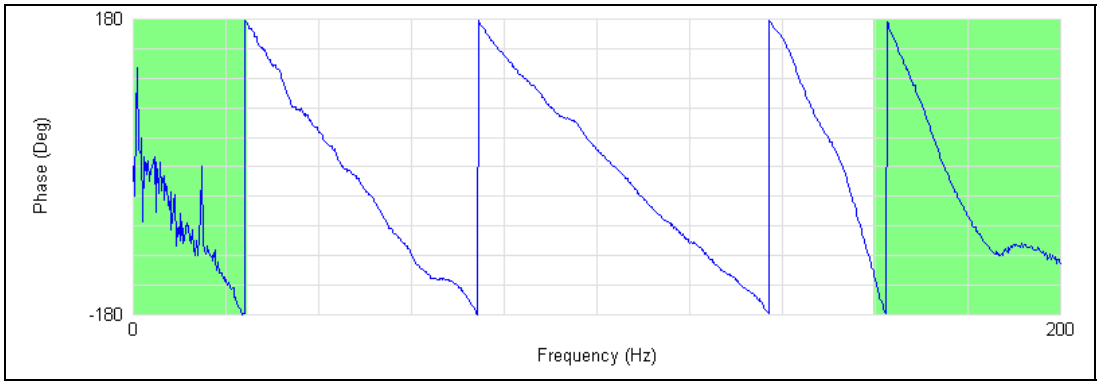

Figure G.5 Phase Plot Measured by SASW Testing; Setup #3; S-R1=12.5 ft, R1-R2=12.5 ft

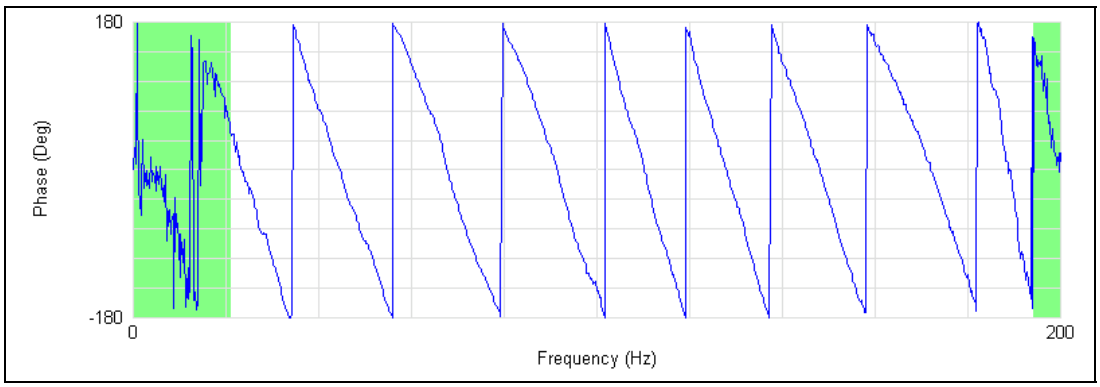

Figure G.6 Phase Plot Measured by SASW Testing; Setup #3; S-R2=25 ft, R2-R3=25 ft

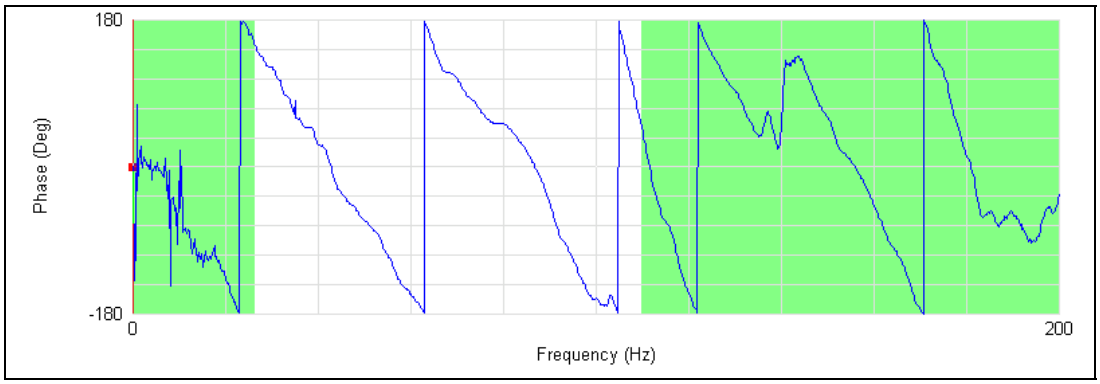

Figure G.7 Phase Plot Measured by SASW Testing; Setup #4; S-R1=12.5 ft, R1-R2=12.5 ft

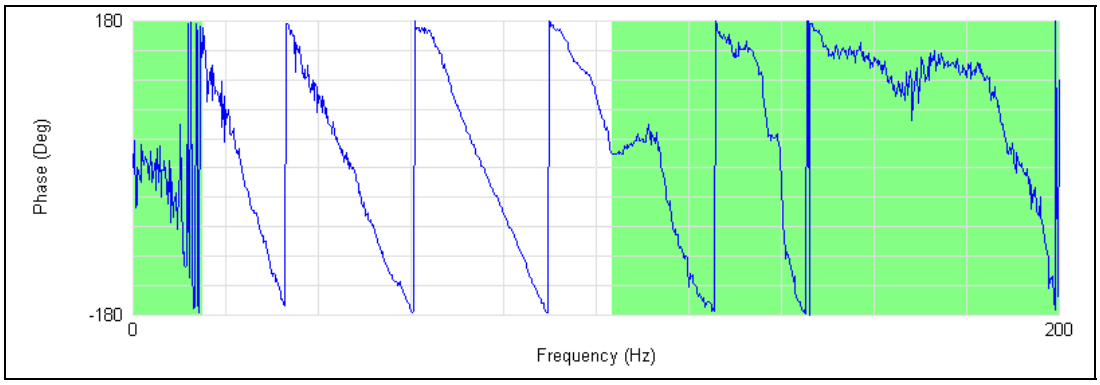

Figure G.8 Phase Plot Measured by SASW Testing; Setup #4; S-R2=25 ft, R2-R3=25 ft

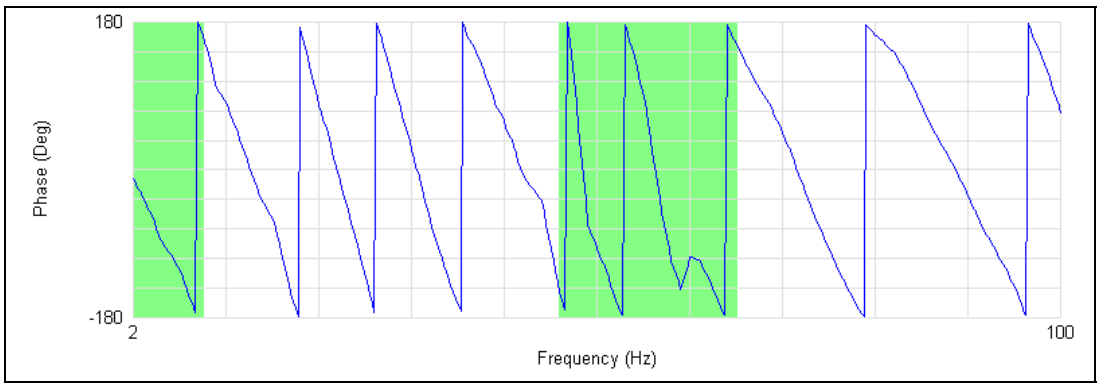

Figure G.9 Phase Plot Measured by SASW Testing; Setup #5; S-R1=50 ft, R1-R2=50 ft

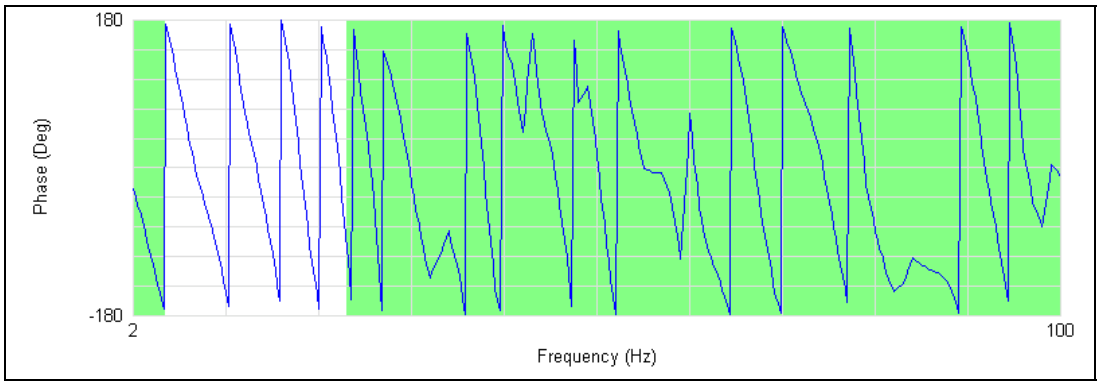

Figure G.10 Phase Plot Measured by SASW Testing; Setup #5; S-R2=100 ft, R2-R3=100 ft

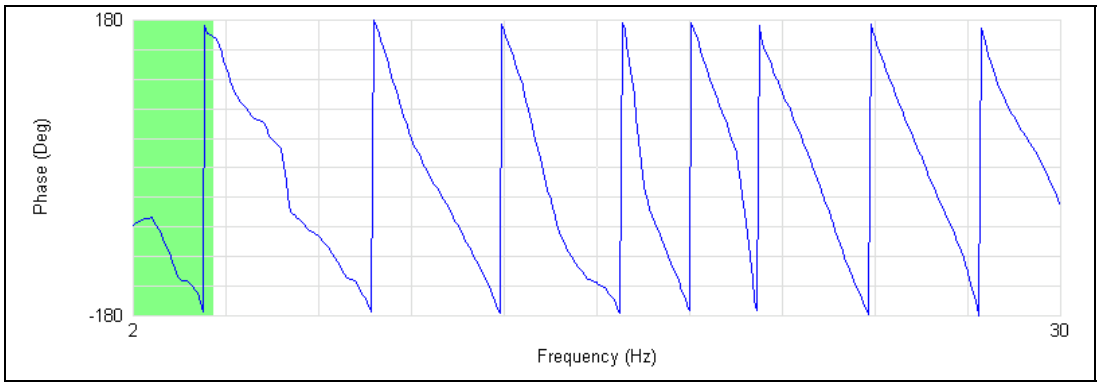

Figure G.11 Phase Plot Measured by SASW Testing; Setup #6; S-R1=150 ft, R1-R2=150 ft

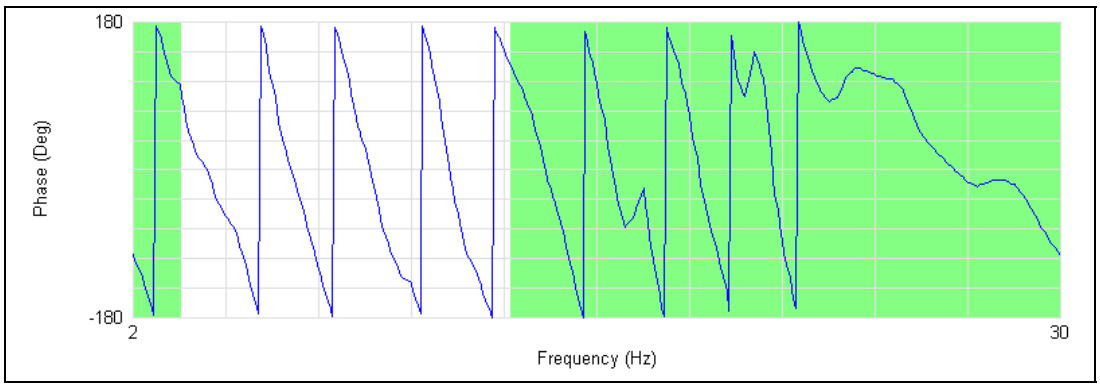

Figure G.12 Phase Plot Measured by SASW Testing; Setup #6; S-R2=300 ft, R2-R3=300 ft

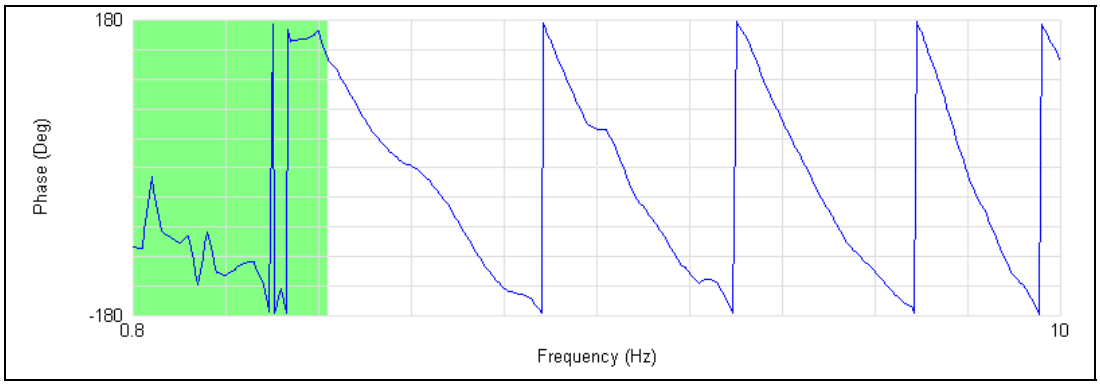

Figure G.13 Phase Plot Measured by SASW Testing; Setup #7; S-R1=400 ft, R1-R2=400ft

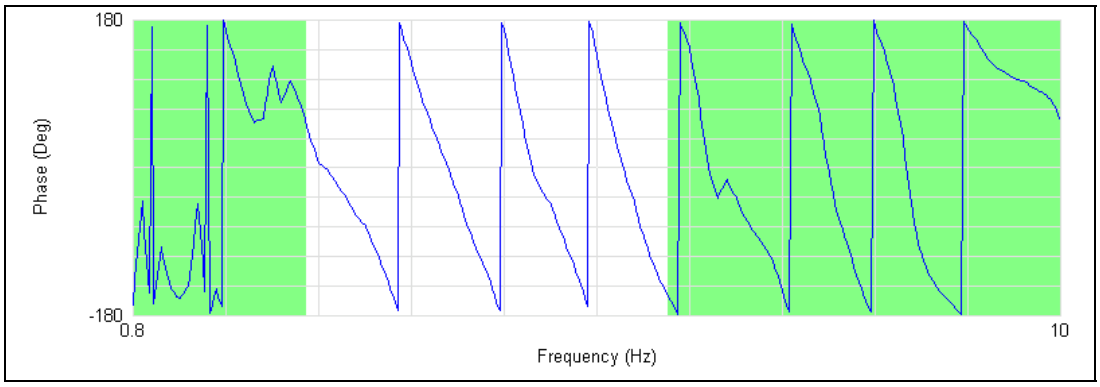

Figure G.14 Phase Plot Measured by SASW Testing; Setup #7; S-R2=800 ft, R2-R3=800ft

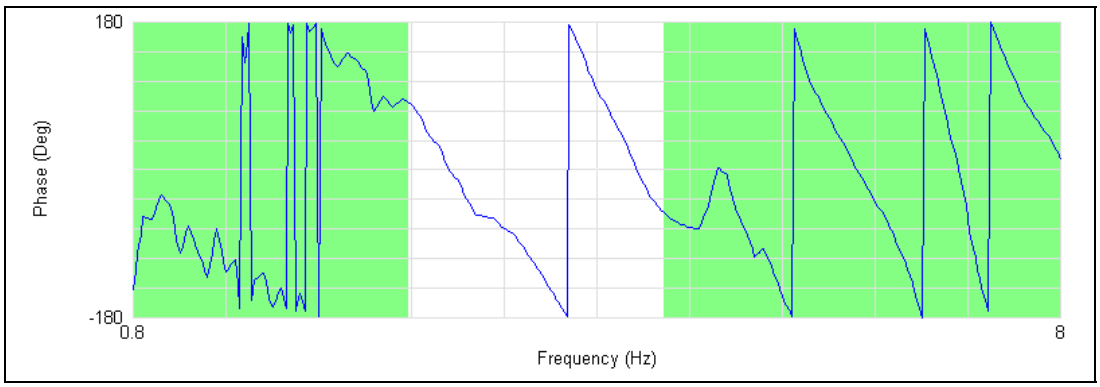

Figure G.15 Phase Plot Measured by SASW Testing; Setup #8; S-R1=500 ft, R1-R2=500ft

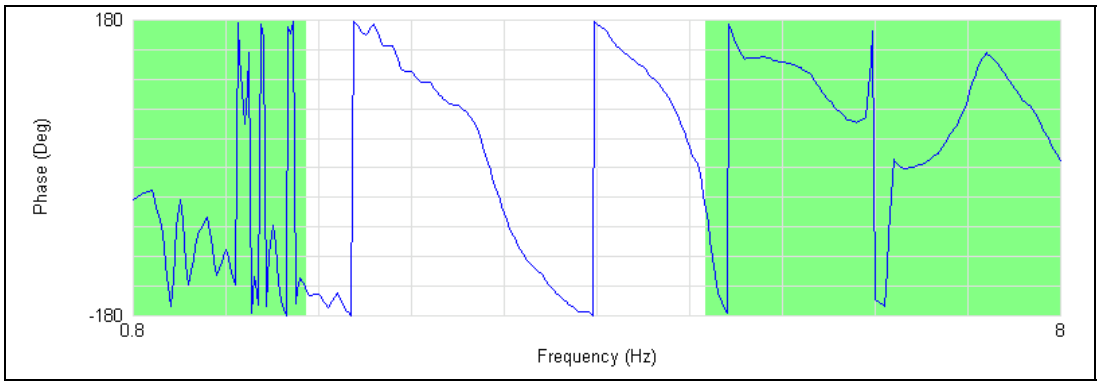

Figure G.16 Phase Plot Measured by SASW Testing; Setup #8; S-R2=1000 ft, R2-R3=500ft

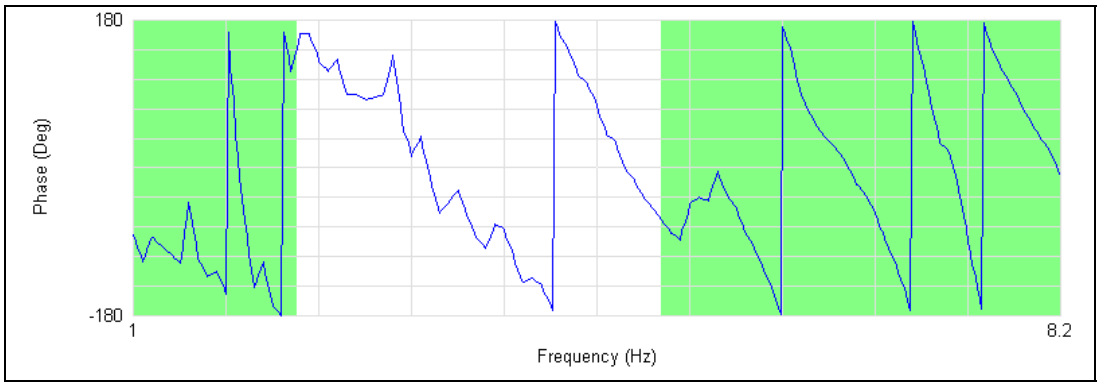

Figure G.17 Phase Plot Measured by SASW Testing; Setup #9; S-R1=500 ft, R1-R2=500ft

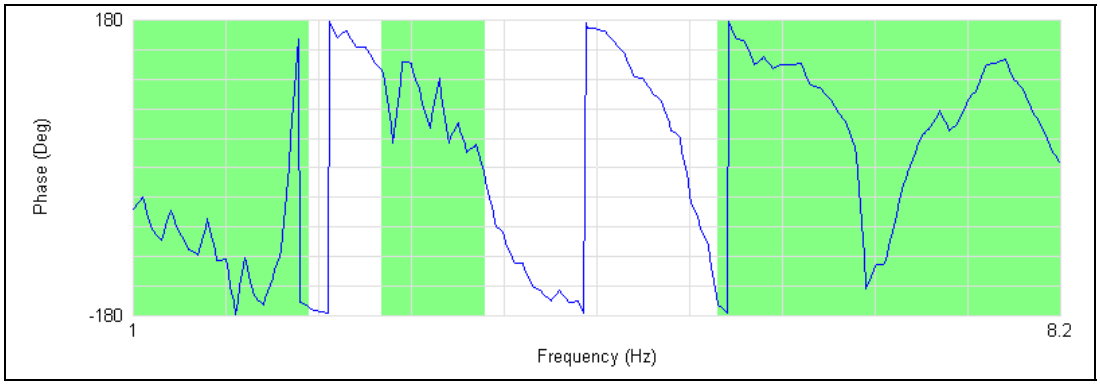

Figure G.18 Phase Plot Measured by SASW Testing; Setup #9; S-R2=1000 ft, R2-R3=500ft

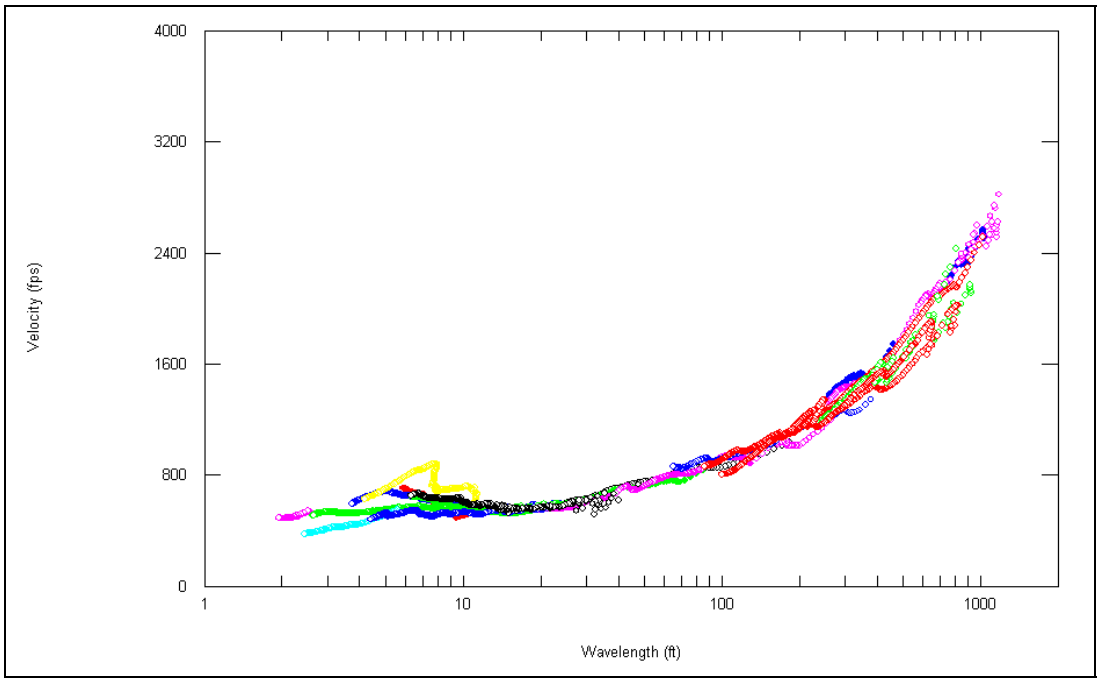

Figure G.19 Experimental Dispersion Curve Measured at Site 7

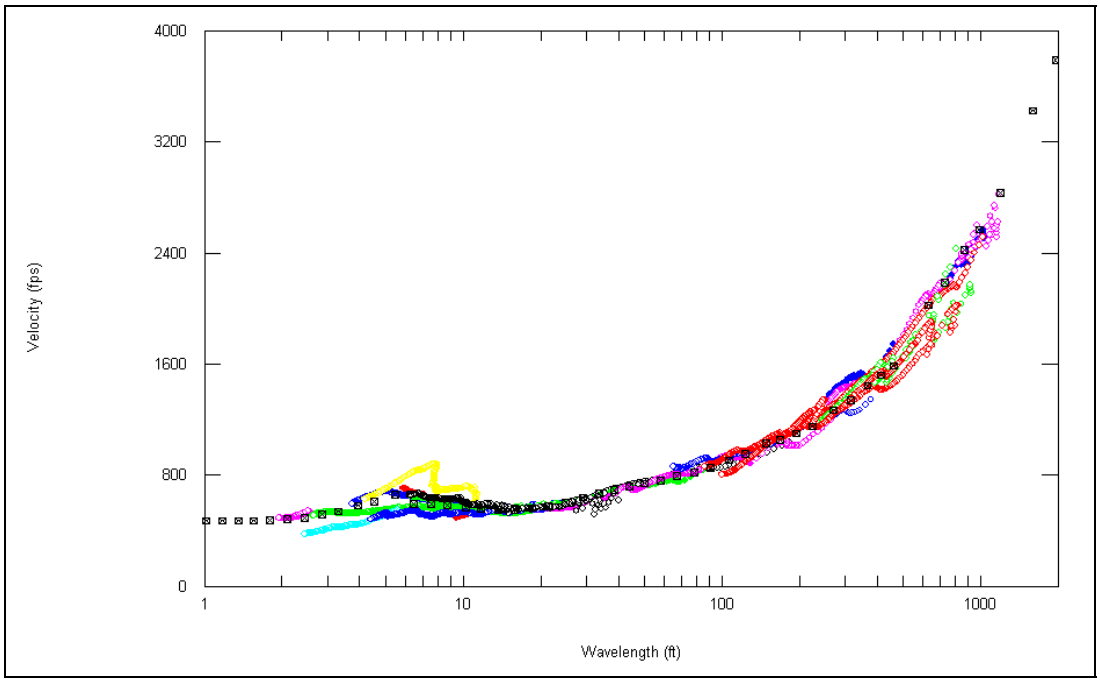

Figure G.20 Experimental and Theoretical Dispersion Curves from Site 7

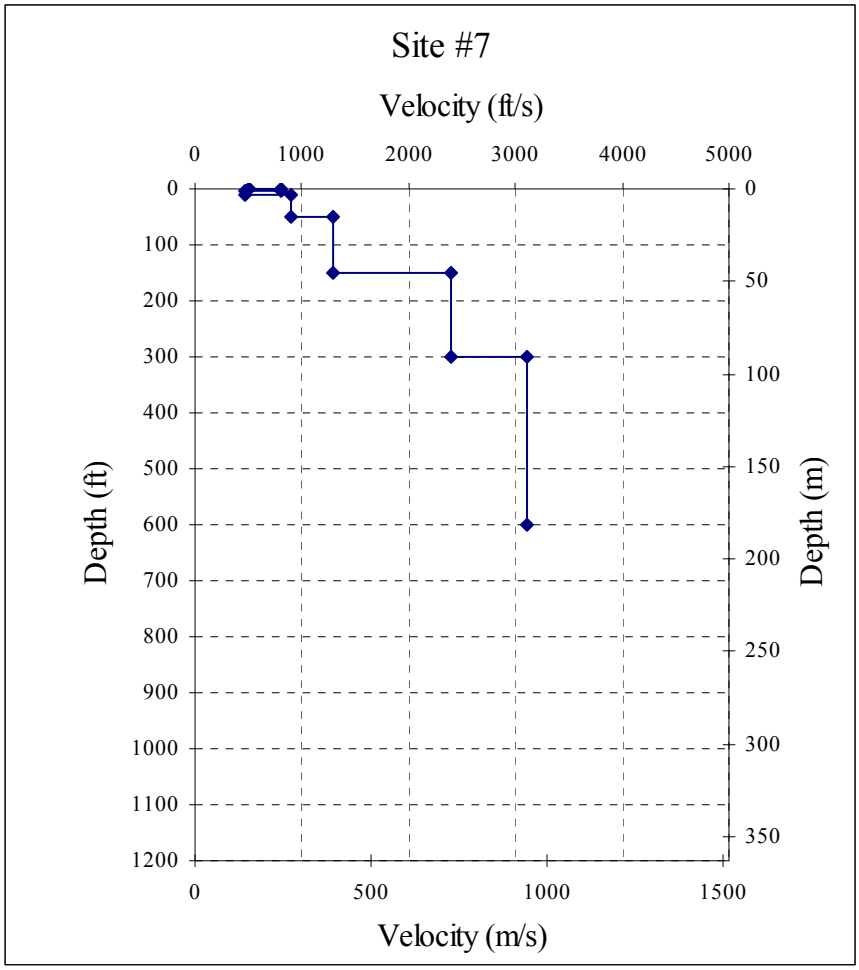

Figure G.21 Shear Wave Velocity Profile Determined at Site 7

Table G.2 Profile Parameters Used to Develop Theoretical Dispersion Curve at Site 7

Layer No.	Thickness, ft	P-Wave Velocity, ft/s	S-Wave Velocity, ft/s	Assumed Poisson's Ratio	Assumed Total Density, pcf
1	1.5	1122.5	500	0.30	120
2	3	1496.7	800	0.30	120
3	5	888.6	475	0.30	120
4	40	1216	900	0.30	120
5	100	2806.2	1300	0.30	120
6	150	5200*	2400	0.365	120
7	∞	5799.6	3100	0.30	130

* Depth to Water Table is 150 ft

H.1. APPENDIX H

Analysis of SASW Tests at Site 8

Table H.1 Table of Source and Receiver Spacings

Site Name	Set up	Source to Receiver #1	Receiver #1 to Receiver #2	Receiver #2 to Receiver #3
Site 8	1	3	3	6
	2 (1 Reversed)	3	3	6
	3	12.5	12.5	25
	4 (3 Reversed)	12.5	12.5	25
	5	50	50	100
	6	260	260	260

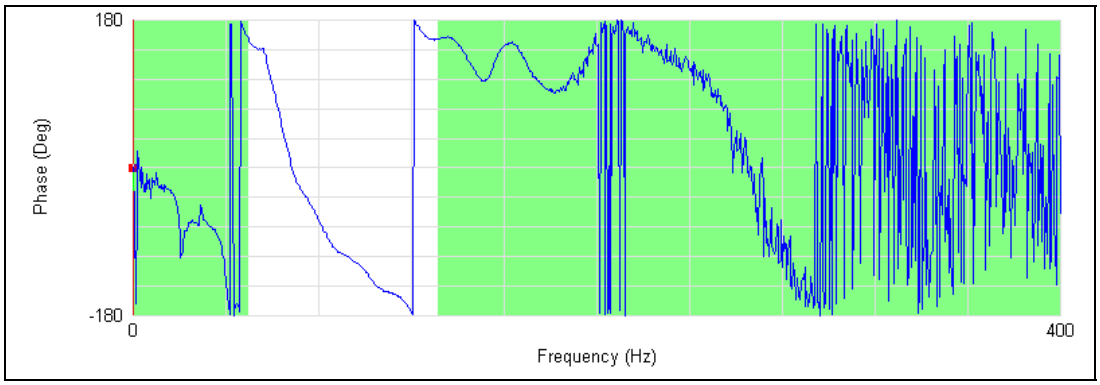

Figure H.1 Phase Plot Measured by SASW Testing; Setup #1; S-R1=3 ft, R1-R2=3ft

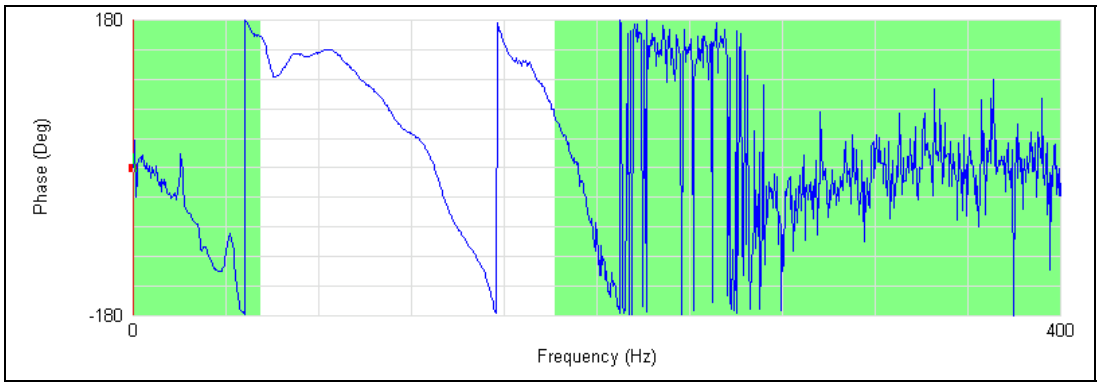

Figure H.2 Phase Plot Measured by SASW Testing; Setup #1; S-R2=6 ft, R2-R3=6ft

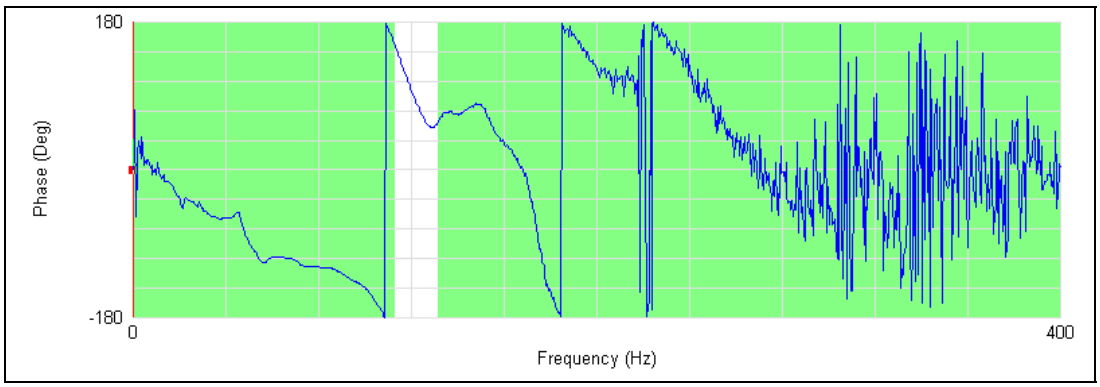

Figure H.3 Phase Plot Measured by SASW Testing; Setup #2; S-R1= 3 ft, R1-R2=3ft

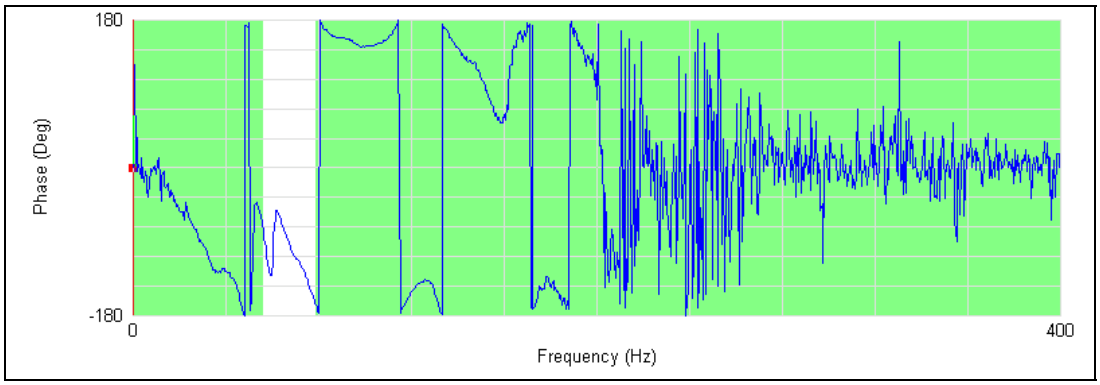

Figure H.4 Phase Plot Measured by SASW Testing; Setup #2; S-R2=6 ft, R2-R3=6ft

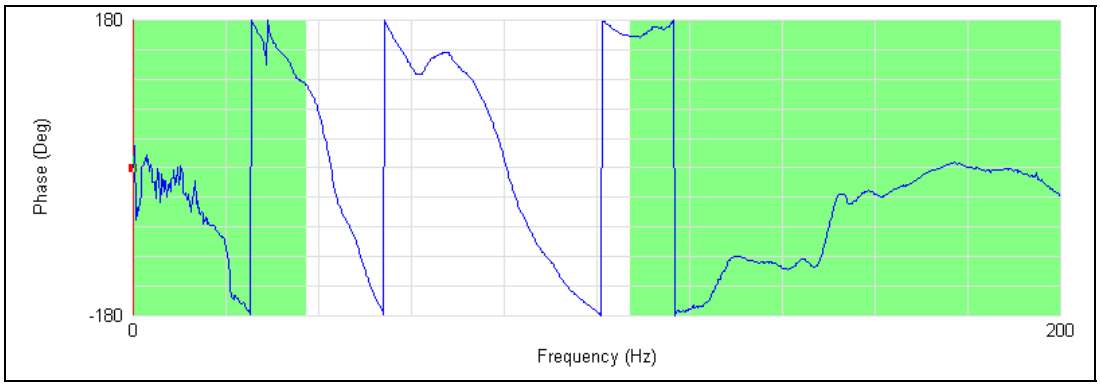

Figure H.5 Phase Plot Measured by SASW Testing; Setup #3; S-R1=12.5 ft, R1-R2=12.5 ft

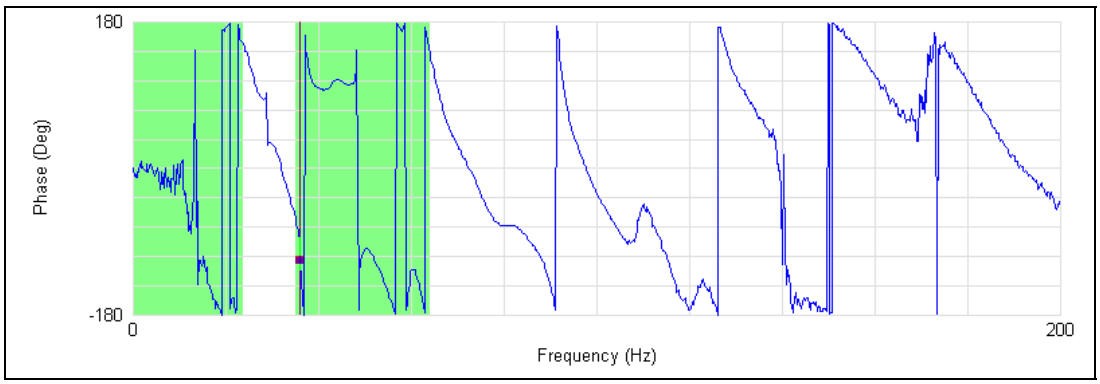

Figure H.6 Phase Plot Measured by SASW Testing; Setup #3; S-R2=25 ft, R2-R3=25 ft

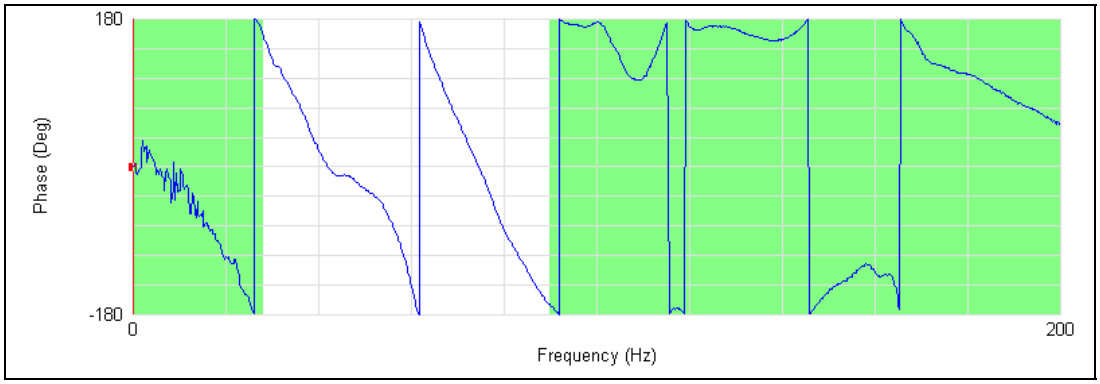

Figure H.7 Phase Plot Measured by SASW Testing; Setup #4; S-R1=12.5 ft, R1-R2=12.5 ft

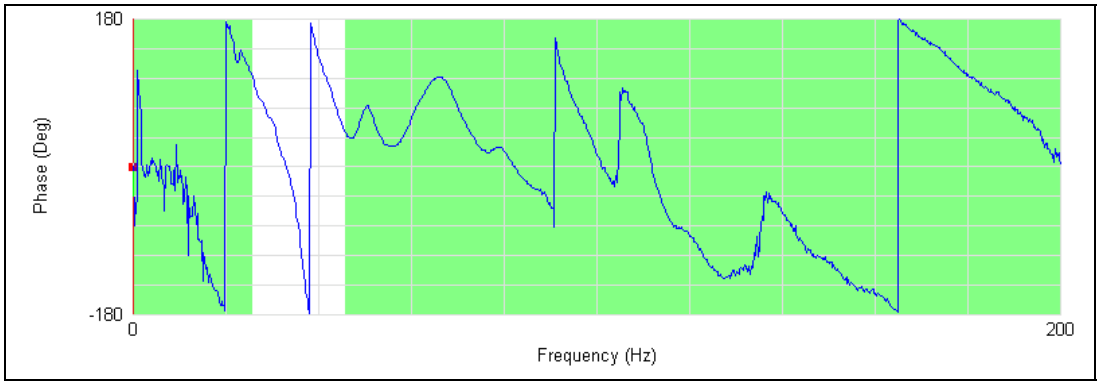

Figure H.8 Phase Plot Measured by SASW Testing; Setup #4; S-R2=25 ft, R2-R3=25 ft

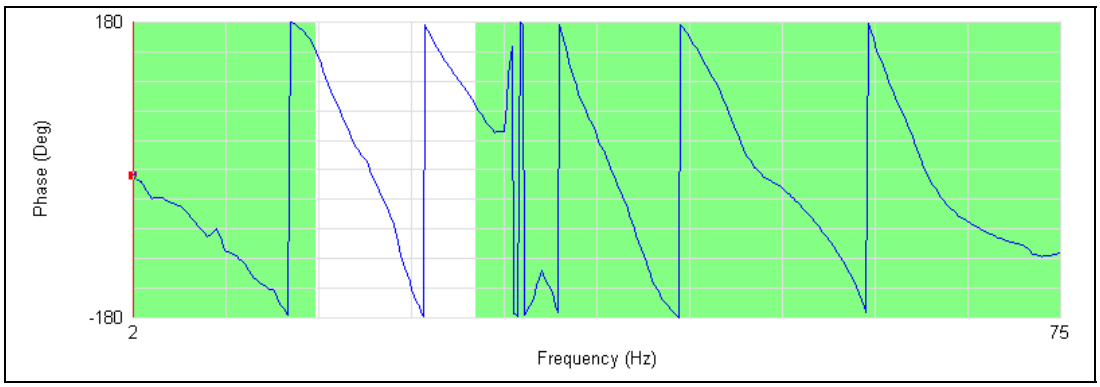

Figure H.9 Phase Plot Measured by SASW Testing; Setup #5; S-R1=50 ft, R1-R2=50 ft

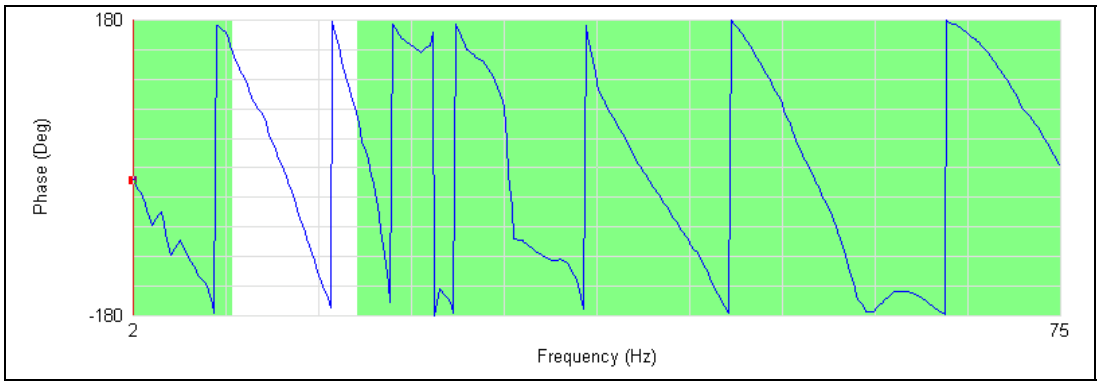

Figure H.10 Phase Plot Measured by SASW Testing; Setup #5; S-R2=100 ft, R2-R3=100 ft

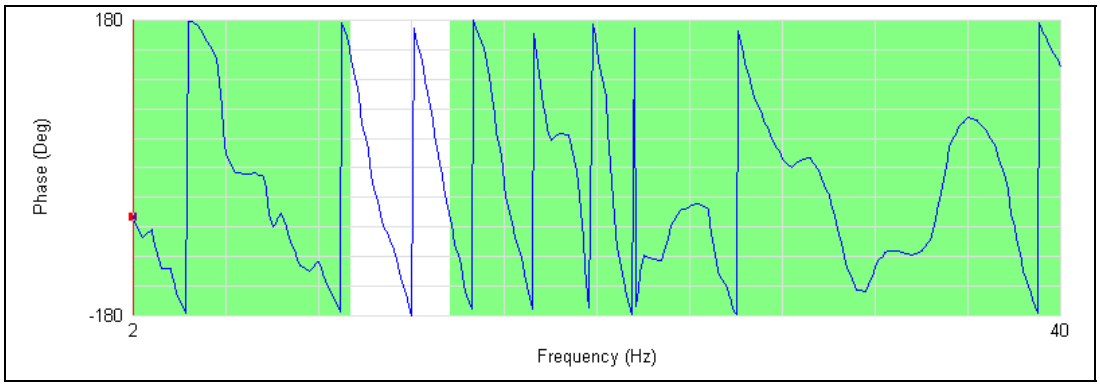

Figure H.11 Phase Plot Measured by SASW Testing; Setup #6; S-R1=260 ft, R1-R2=260ft

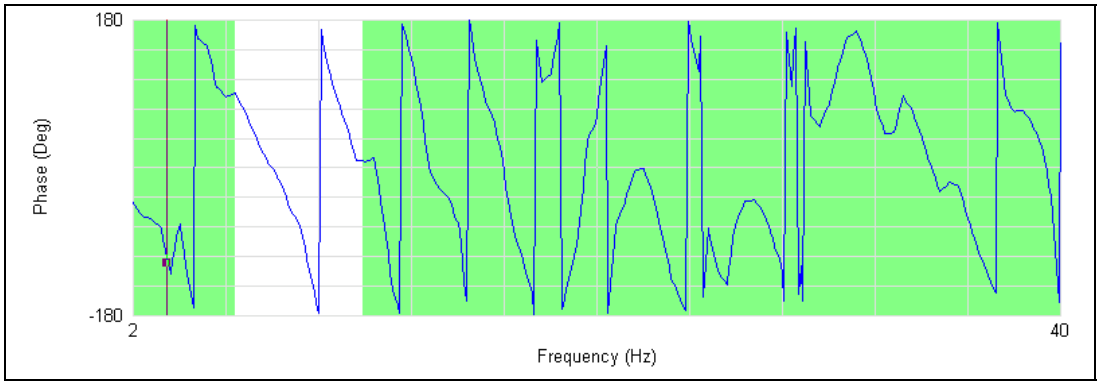

Figure H.12 Phase Plot Measured by SASW Testing; Setup #6; S-R2=520 ft, R2-R3=260ft

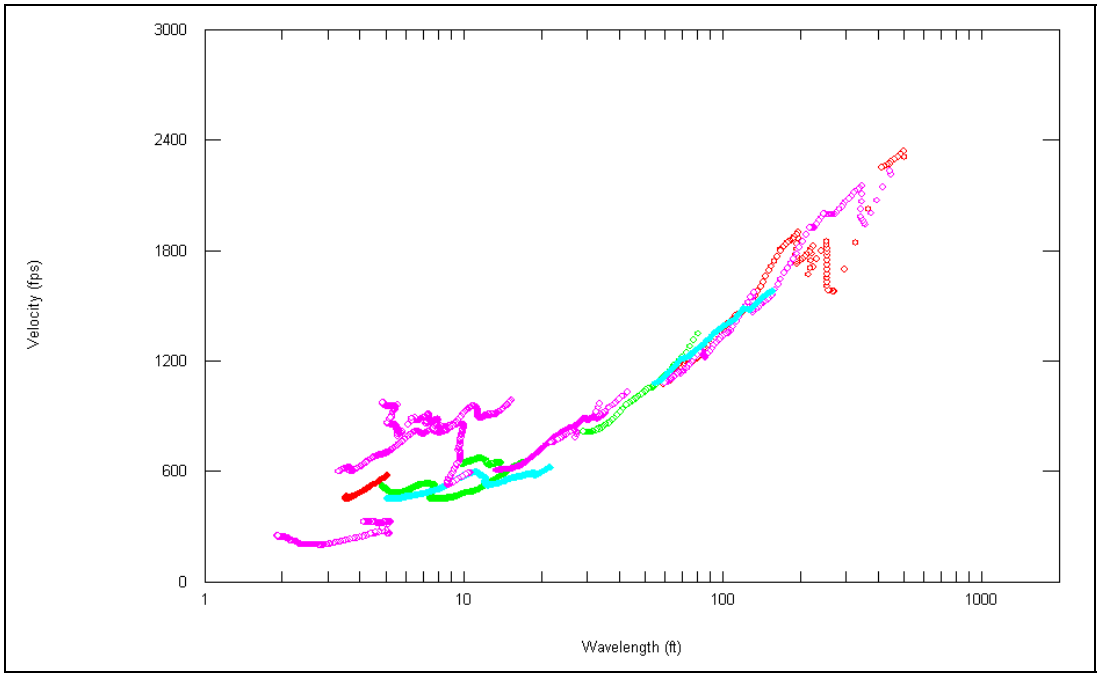

Figure H.13 Experimental Dispersion Curve Measured at Site 8

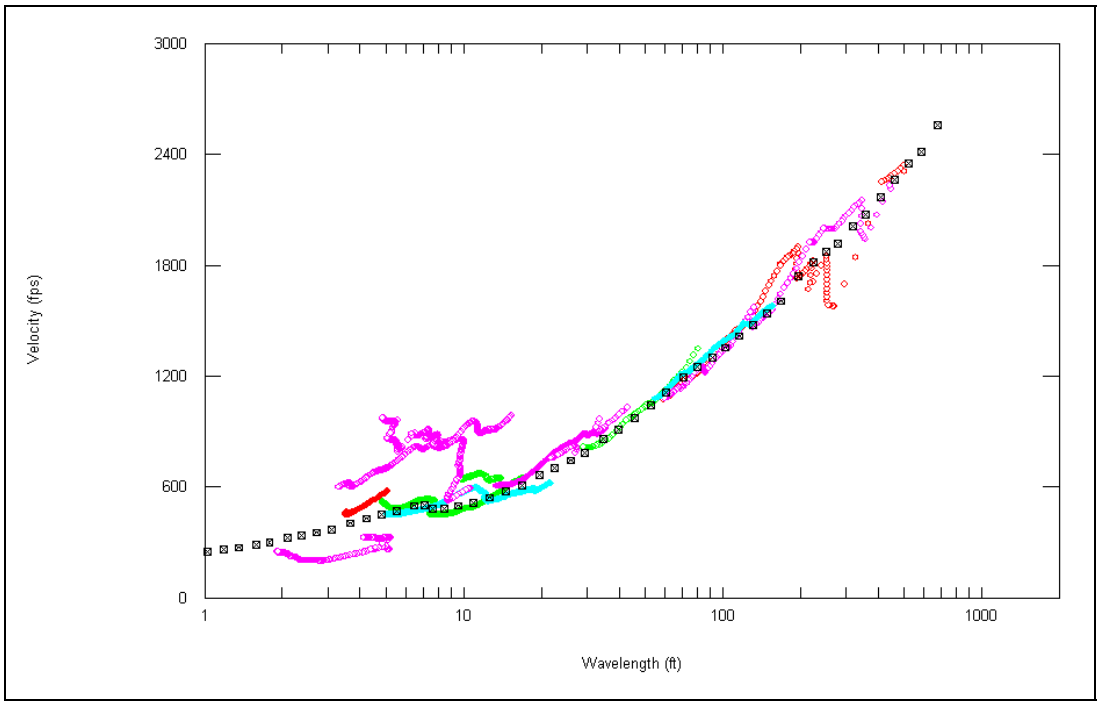

Figure H.14 Experimental and Theoretical Dispersion Curves from Site 8

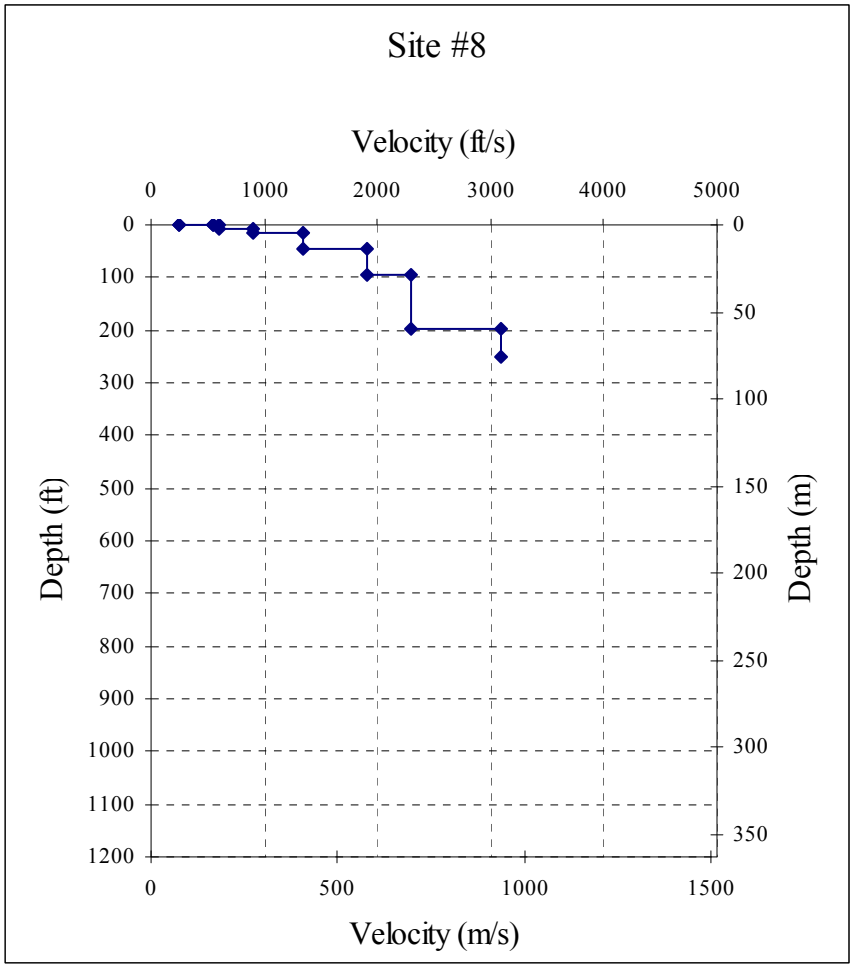

Figure H.15 Shear Wave Velocity Profile Determined at Site 8

Table H.2 Profile Parameters Used to Develop Theoretical Dispersion Curve at Site 8

Layer No.	Thickness, ft	P-Wave Velocity, ft/s	S-Wave Velocity, ft/s	Assumed Poisson's Ratio	Assumed Total Density, pcf
1	0.6	467.7	250	0.30	120
2	1	1029	550	0.30	120
3	5	1122.5	600	0.30	120
4	10	1683.8	900	0.30	120
5	30	2525.6	1350	0.30	120
6	50	3554.6	1900	0.30	120
7	100	4302.9	2300	0.30	120
8	∞	5799.6	3100	0.30	130

I.1. APPENDIX I

Analysis of SASW Tests at Site 9

Table I.1 Table of Source and Receiver Spacings

Site Name	Set up	Source to Receiver #1	Receiver #1 to Receiver #2	Receiver #2 to Receiver #3
Site 9	1	3	3	6
	2 (1 Reversed)	3	3	6
	3	12.5	12.5	25
	4 (3 Reversed)	12.5	12.5	25
	5	50	50	100
	6	150	150	300
	7	350	350	350
	8	500	500	500

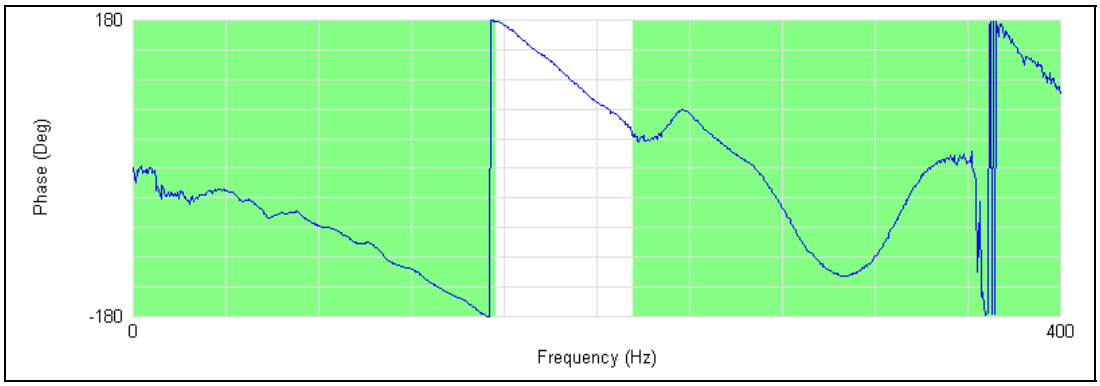

Figure I.1 Phase Plot Measured by SASW Testing; Setup #1; S-R1=3 ft, R1-R2=3ft

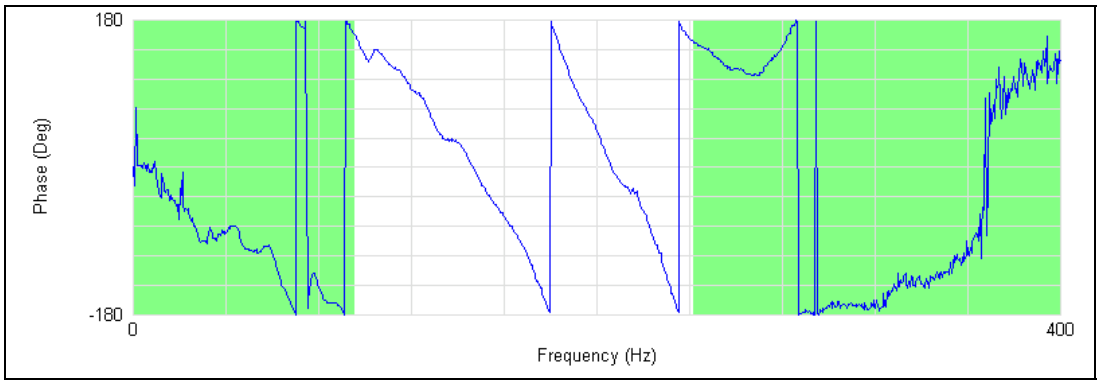

Figure I.2 Phase Plot Measured by SASW Testing; Setup #1; S-R2=6 ft, R2-R3=6ft

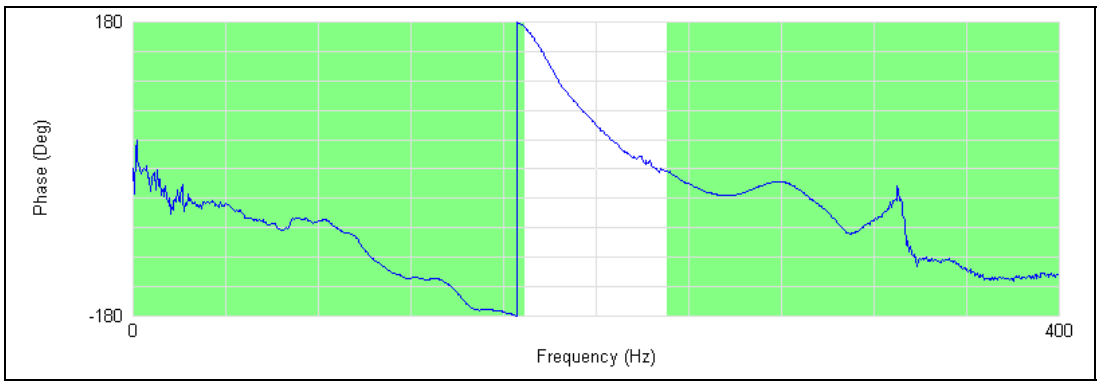

Figure I.3 Phase Plot Measured by SASW Testing; Setup #2; S-R1= 3 ft, R1-R2=3ft

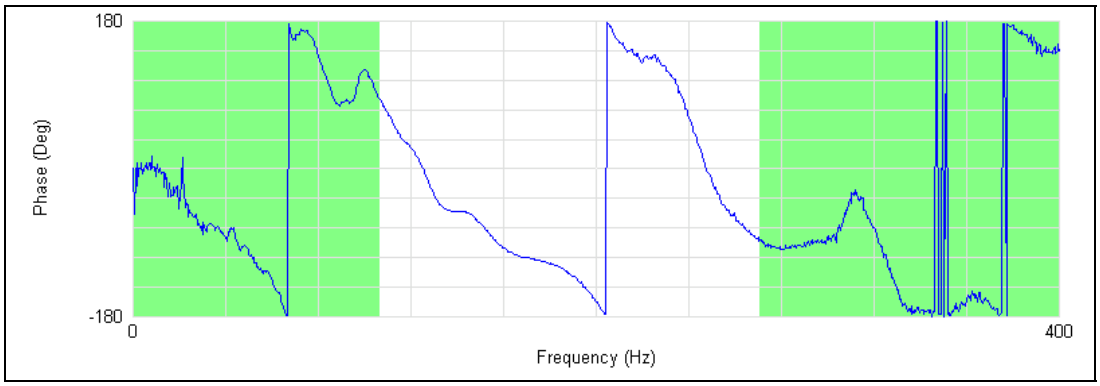

Figure I.4 Phase Plot Measured by SASW Testing; Setup #2; S-R2=6 ft, R2-R3=6ft

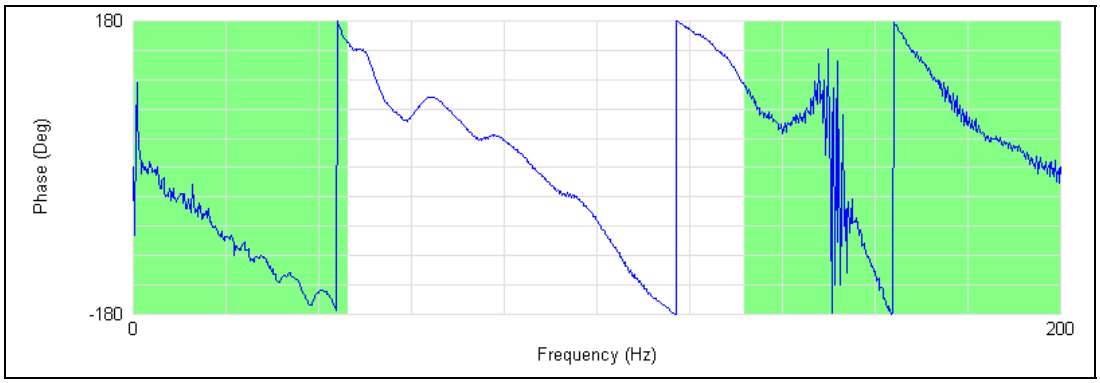

Figure I.5 Phase Plot Measured by SASW Testing; Setup #3; S-R1=12.5 ft, R1-R2=12.5 ft

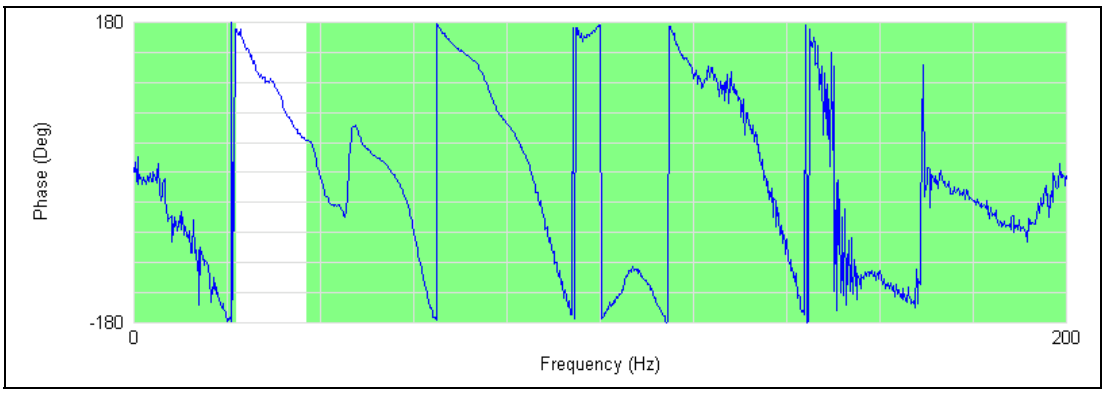

Figure I.6 Phase Plot Measured by SASW Testing; Setup #3; S-R2=25 ft, R2-R3=25 ft

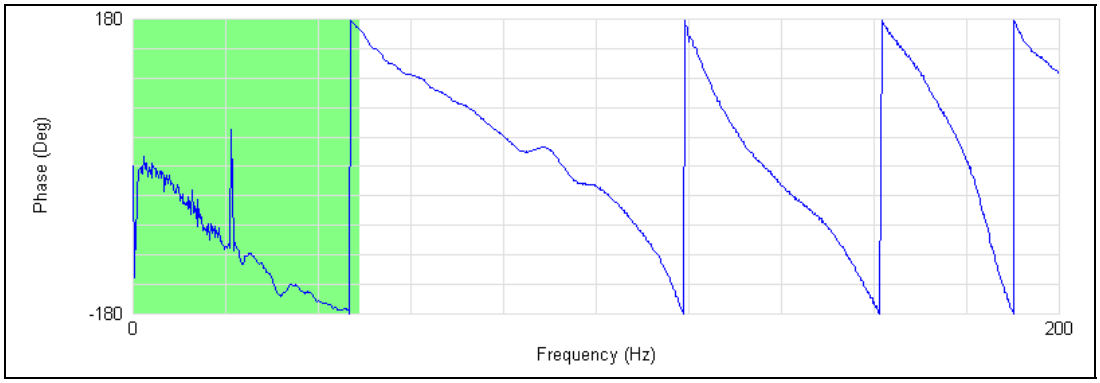

Figure I.7 Phase Plot Measured by SASW Testing; Setup #4; S-R1=12.5 ft, R1-R2=12.5 ft

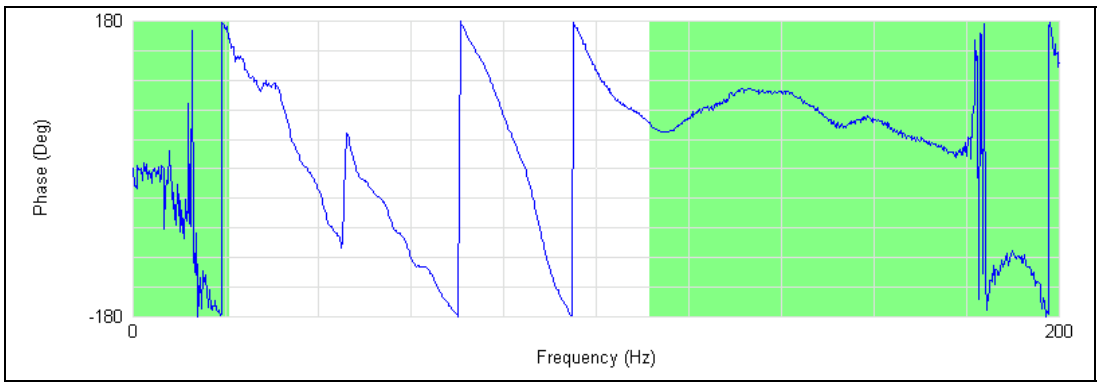

Figure I.8 Phase Plot Measured by SASW Testing; Setup #4; S-R2=25 ft, R2-R3=25 ft

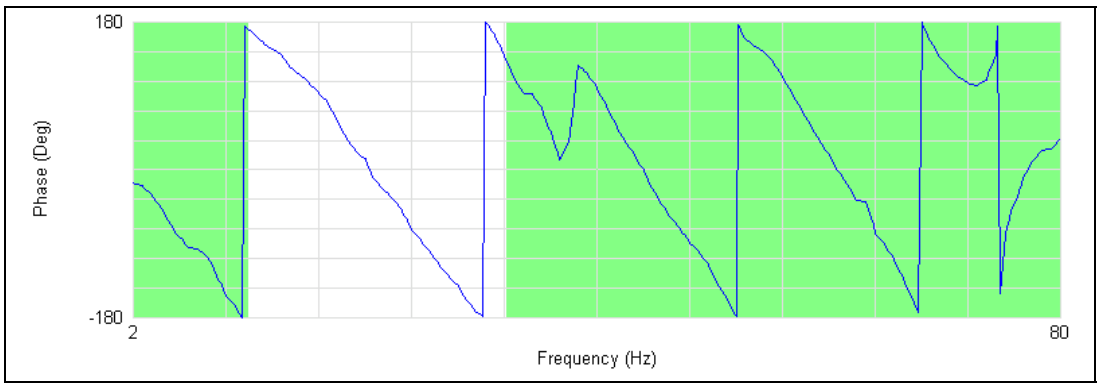

Figure I.9 Phase Plot Measured by SASW Testing; Setup #5; S-R1=50 ft, R1-R2=50 ft

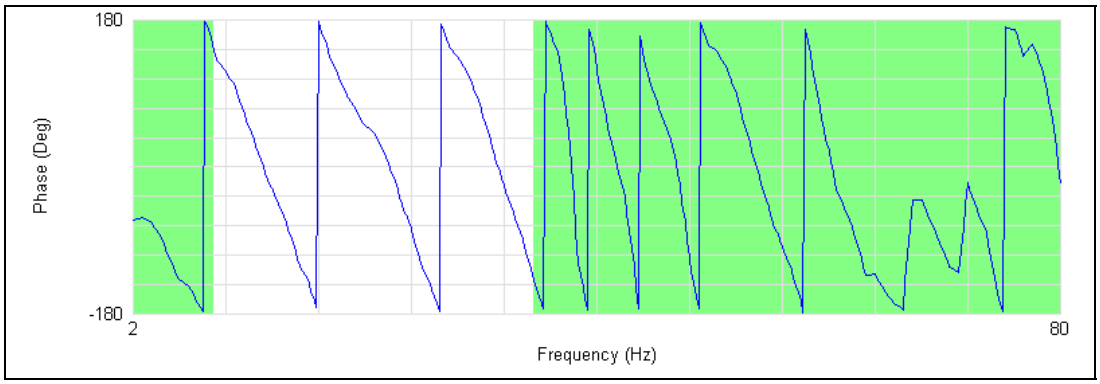

Figure I.10 Phase Plot Measured by SASW Testing; Setup #5; S-R2=100 ft, R2-R3=100 ft

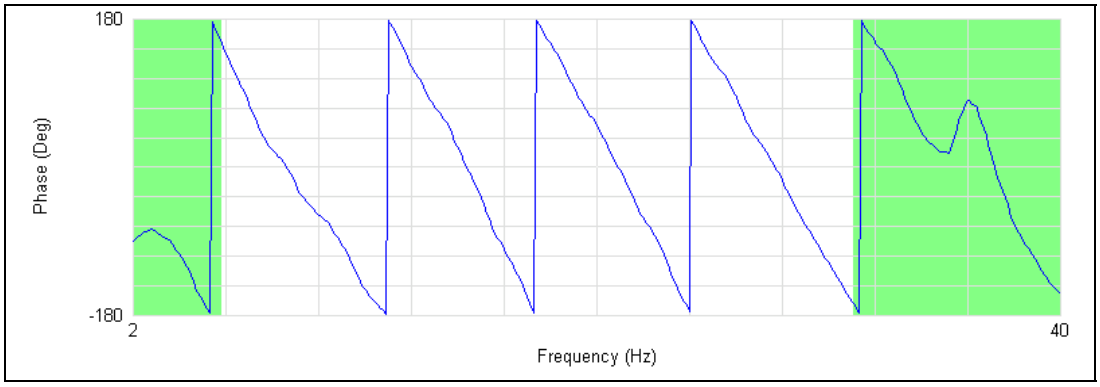

Figure I.11 Phase Plot Measured by SASW Testing; Setup #6; S-R1=150 ft, R1-R2=150ft

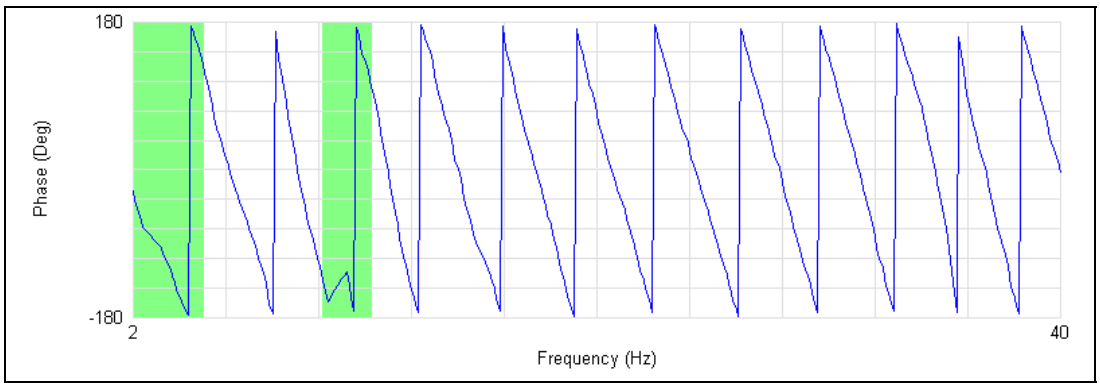

Figure I.12 Phase Plot Measured by SASW Testing; Setup #6; S-R2=300 ft, R2-R3=300 ft

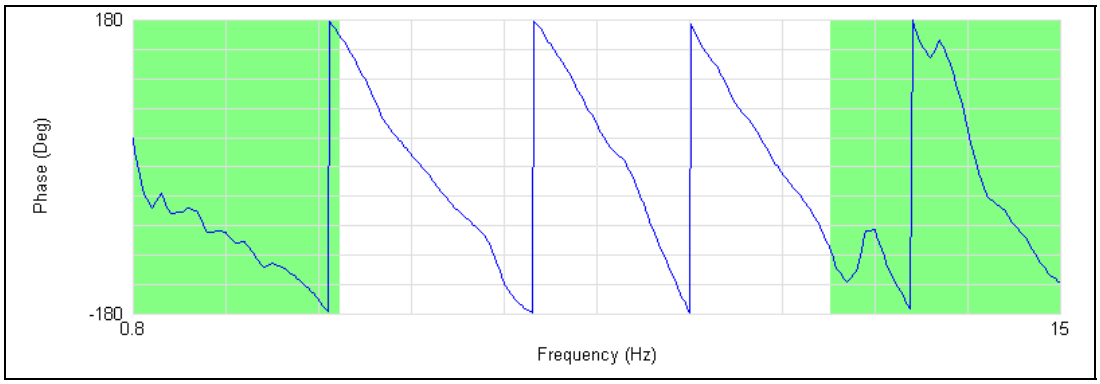

Figure I.13 Phase Plot Measured by SASW Testing; Setup #7; S-R1=350 ft, R1-R2=350ft

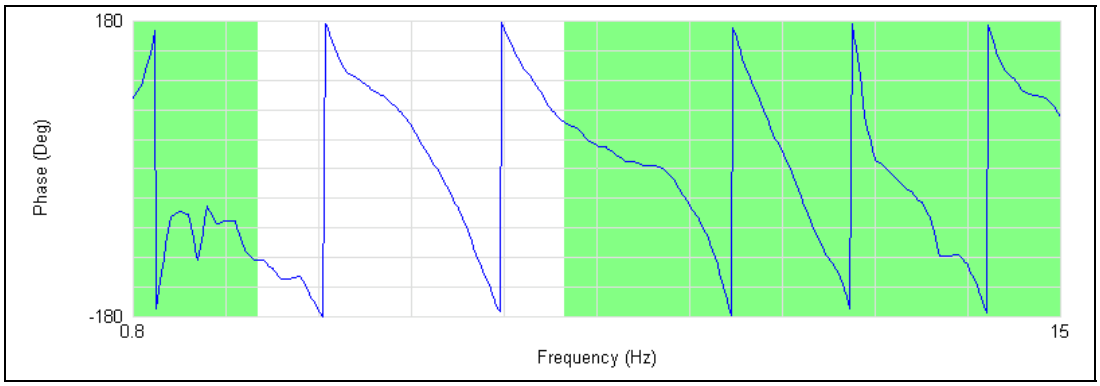

Figure I.14 Phase Plot Measured by SASW Testing; Setup #7; S-R2=700 ft, R2-R3=350 ft

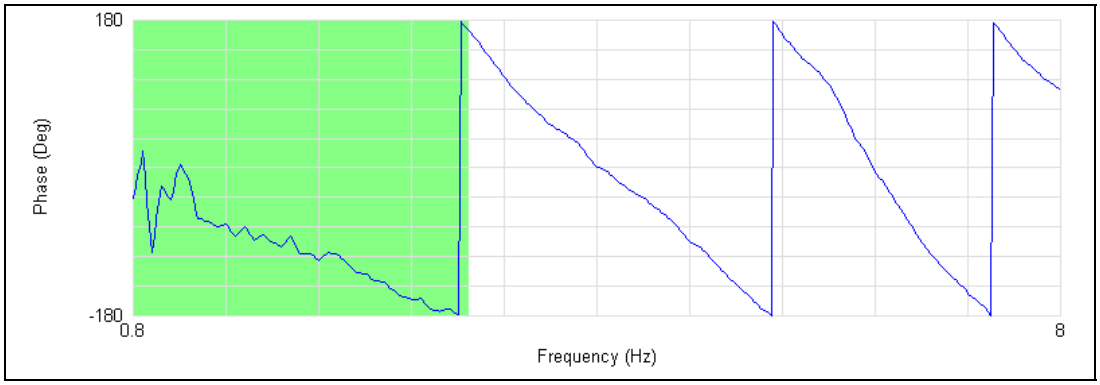

Figure I.15 Phase Plot Measured by SASW Testing; Setup #8; S-R1=500 ft, R1-R2=500ft

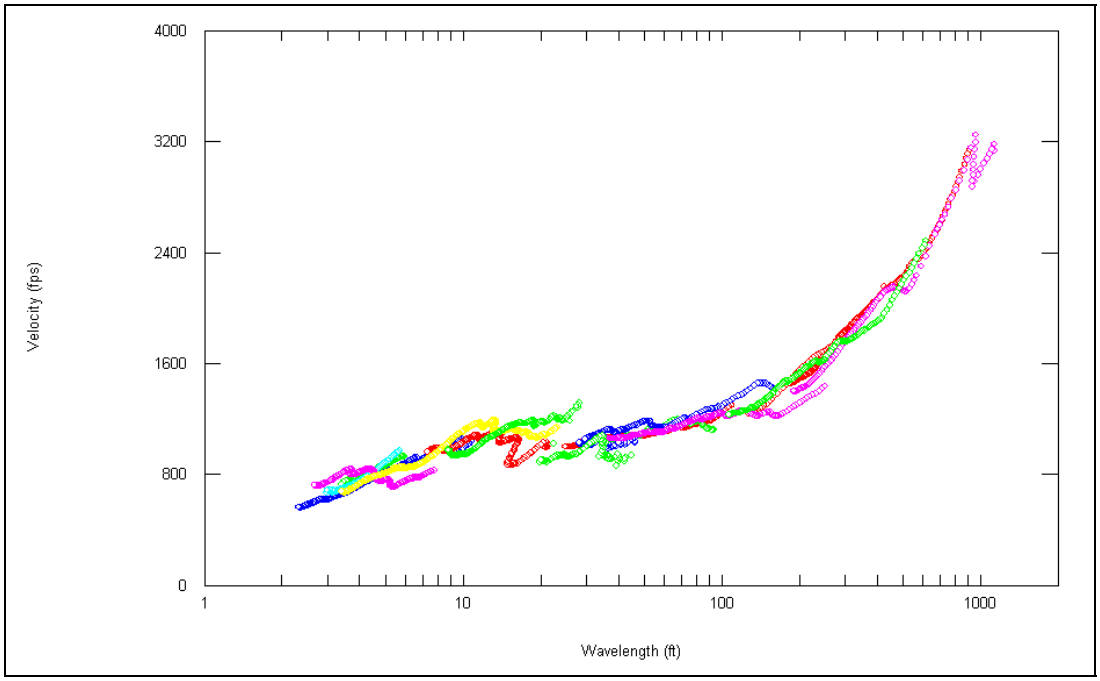

Figure I.16 Experimental Dispersion Curve Measured at Site 9

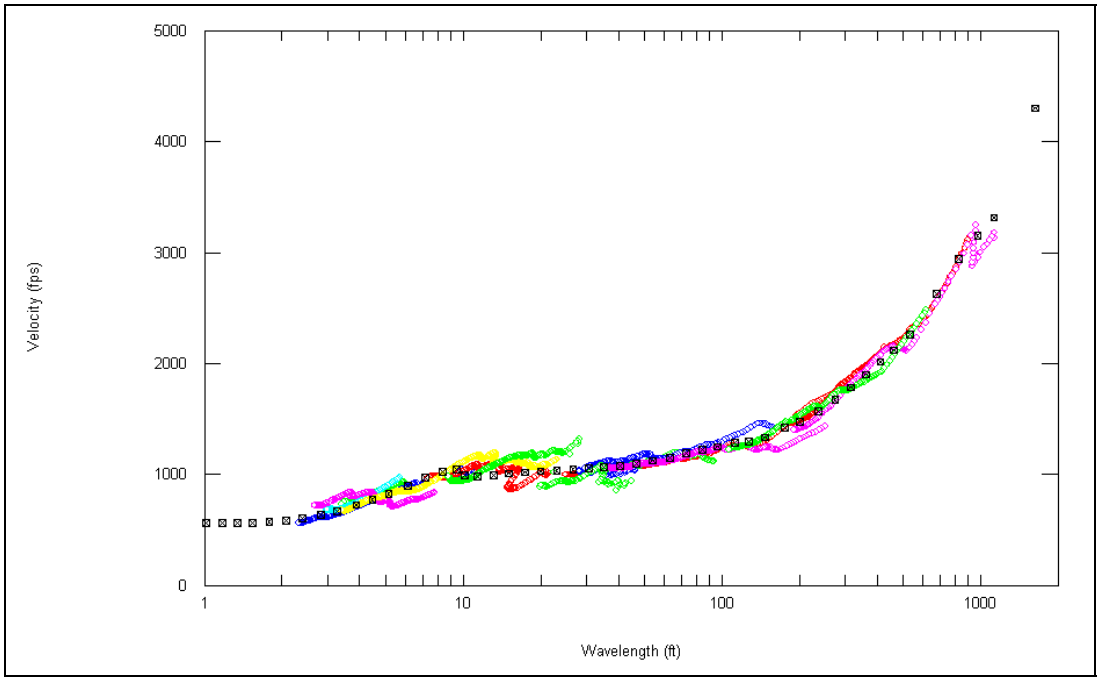

Figure I.17 Experimental and Theoretical Dispersion Curves from Site 9

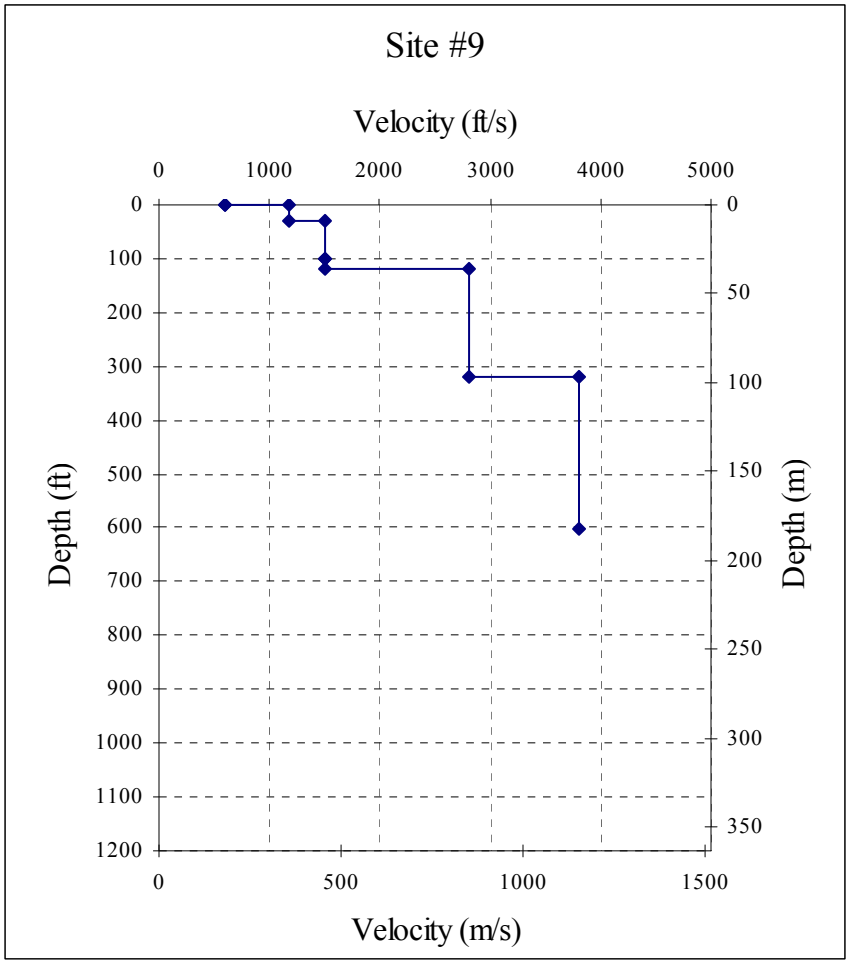

Figure I.18 Shear Wave Velocity Profile Determined at Site 9

Table I.2 Profile Parameters Used to Develop Theoretical Dispersion Curve at Site 9

Layer No.	Thickness, ft	P-Wave Velocity, ft/s	S-Wave Velocity, ft/s	Assumed Poisson's Ratio	Assumed Total Density, pcf
1	1.5	1122.5	600	0.30	120
2	30	2198.2	1175	0.30	120
3	68	2806.2	1500	0.30	120
4	20	5200*	1500	0.455	120
5	200	5238.3	2800	0.30	120
6	∞	7109.2	3800	0.30	130

* Depth to Water Table is 99.5 ft

J.1. APPENDIX J

Analysis of SASW Tests at Site 10

Table J.1 Table of Source and Receiver Spacings

Site Name	Set up	Source to Receiver #1	Receiver #1 to Receiver #2	Receiver #2 to Receiver #3
Site 10	1	3	3	6
	2 (1 Reversed)	3	3	6
	3	12.5	12.5	25
	4 (3 Reversed)	12.5	12.5	25
	5	50	50	100
	6	150	150	300
	7	400	400	400
	8	500	500	500
	9	750	750	750

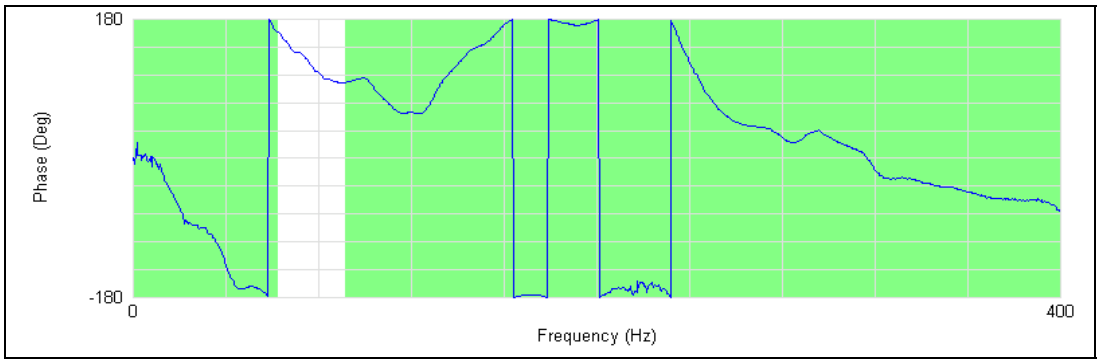

Figure J.1 Phase Plot Measured by SASW Testing; Setup #1; S-R1=3 ft, R1-R2=3ft

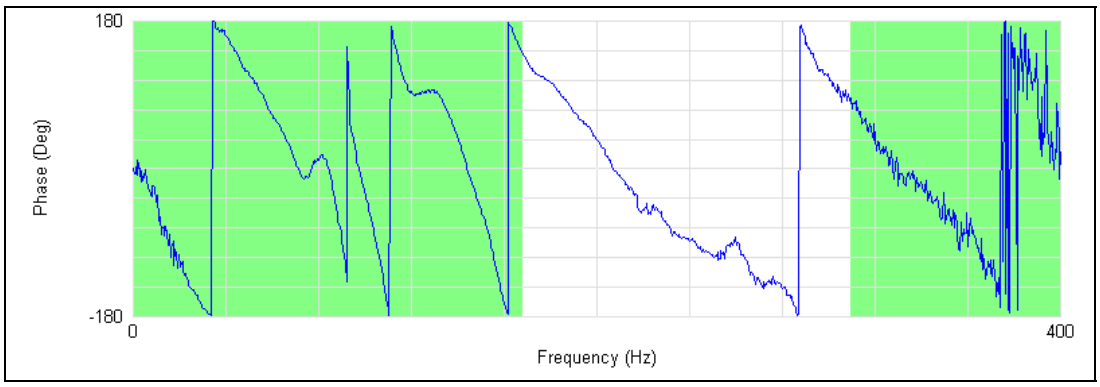

Figure J.2 Phase Plot Measured by SASW Testing; Setup #1; S-R2=6 ft, R2-R3=6ft

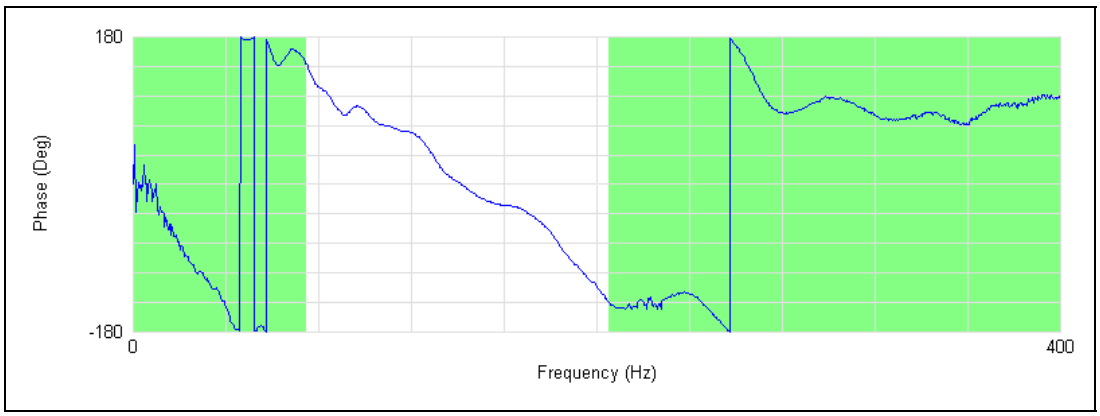

Figure J.3 Phase Plot Measured by SASW Testing; Setup #2; S-R1= 3 ft, R1-R2=3 ft

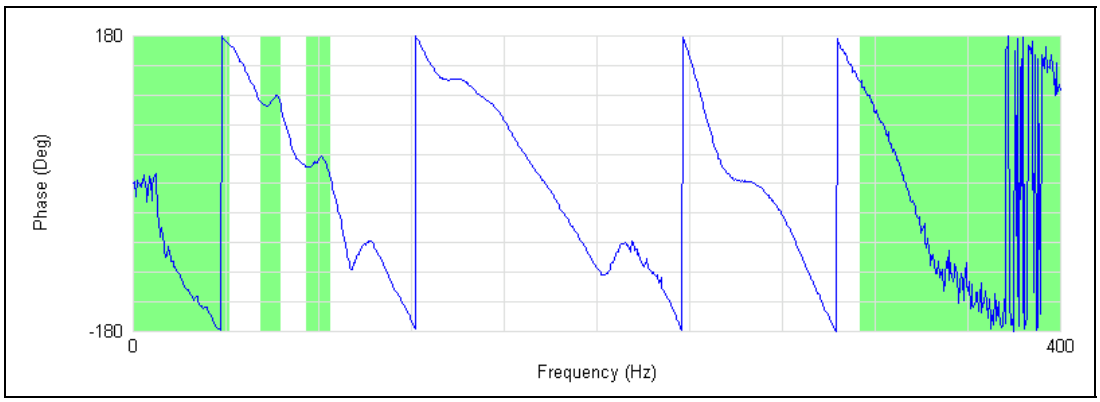

Figure J.4 Phase Plot Measured by SASW Testing; Setup #2; S-R2=6 ft, R2-R3=6 ft

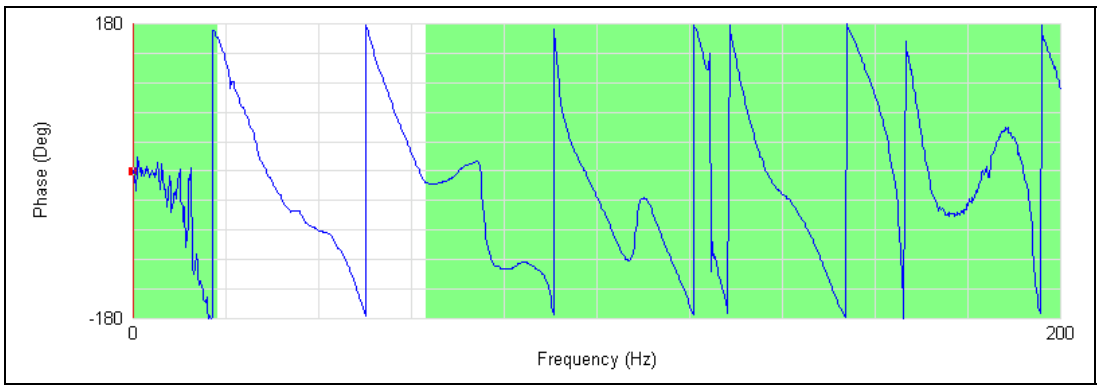

Figure J.5 Phase Plot Measured by SASW Testing; Setup #3; S-R1=12.5 ft, R1-R2=12.5 ft

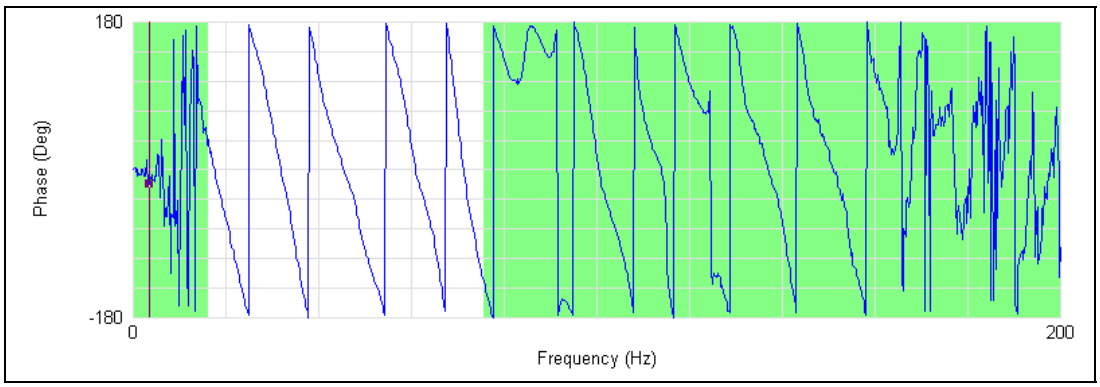

Figure J.6 Phase Plot Measured by SASW Testing; Setup #3; S-R2=25 ft, R2-R3=25ft

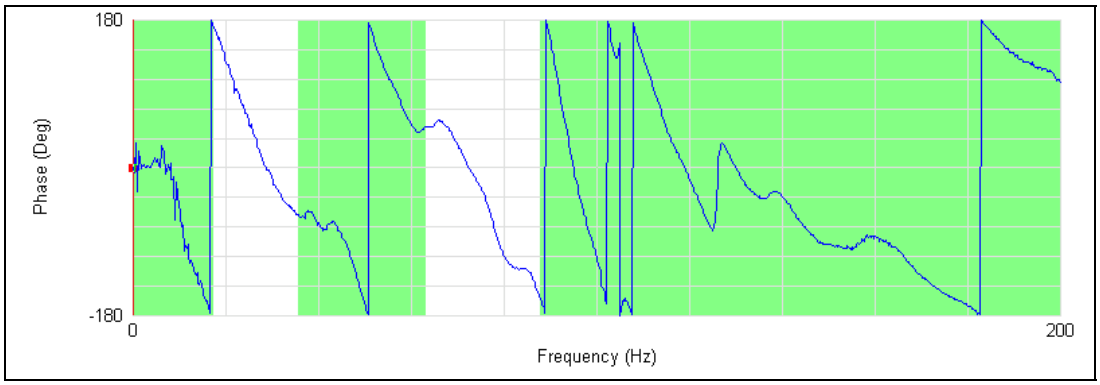

Figure J.7 Phase Plot Measured by SASW Testing; Setup #4; S-R1=12.5 ft, R1-R2=12.5 ft

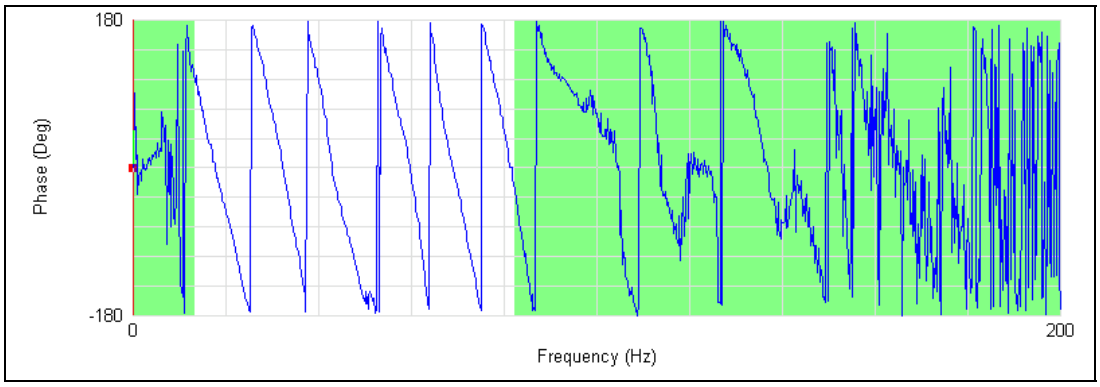

Figure J.8 Phase Plot Measured by SASW Testing; Setup #4; S-R2=25 ft, R2-R3=25 ft

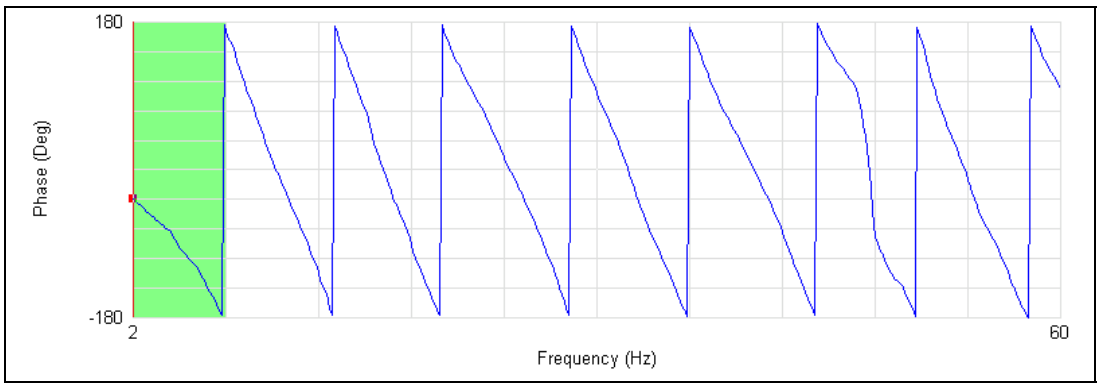

Figure J.9 Phase Plot Measured by SASW Testing; Setup #5; S-R1=50 ft, R1-R2=50 ft

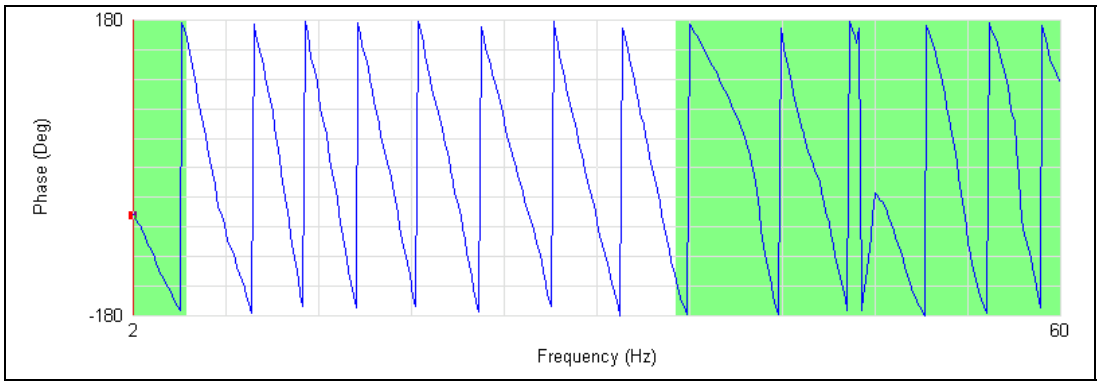

Figure J.10 Phase Plot Measured by SASW Testing; Setup #5; S-R2=100 ft, R2-R3=100 ft

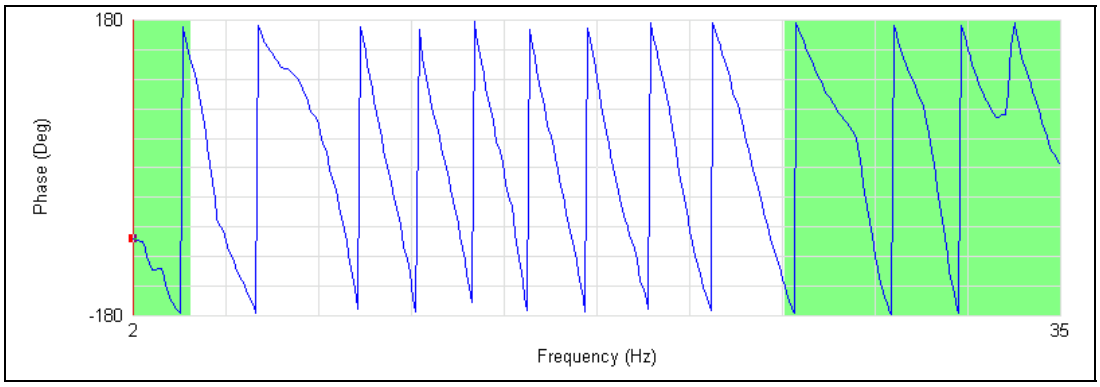

Figure J.11 Phase Plot Measured by SASW Testing; Setup #6; S-R1=150 ft, R1-R2=150ft

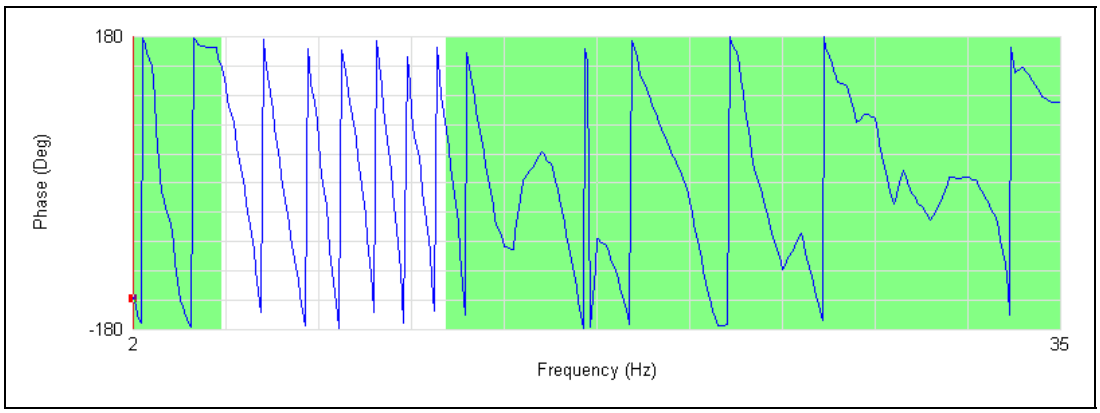

Figure J.12 Phase Plot Measured by SASW Testing; Setup #6; S-R2=300 ft, R2-R3=300 ft

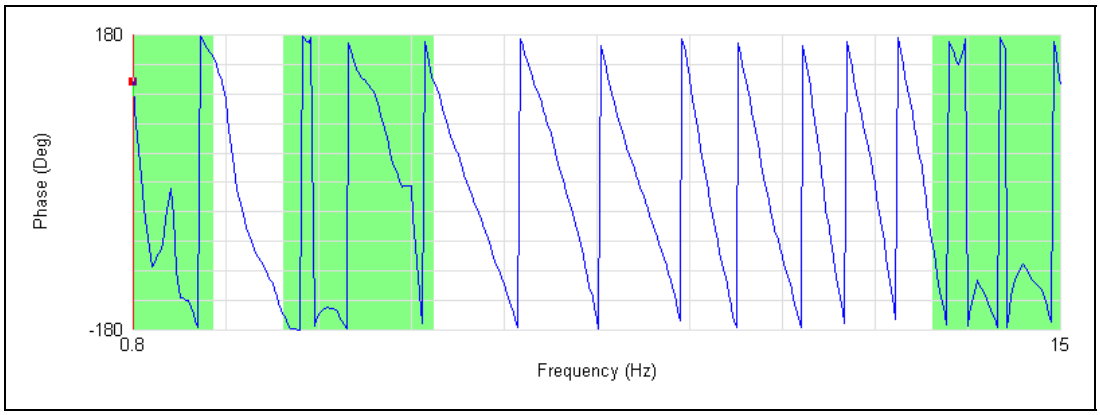

Figure J.13 Phase Plot Measured by SASW Testing; Setup #7; S-R1=400 ft, R1-R2=400ft

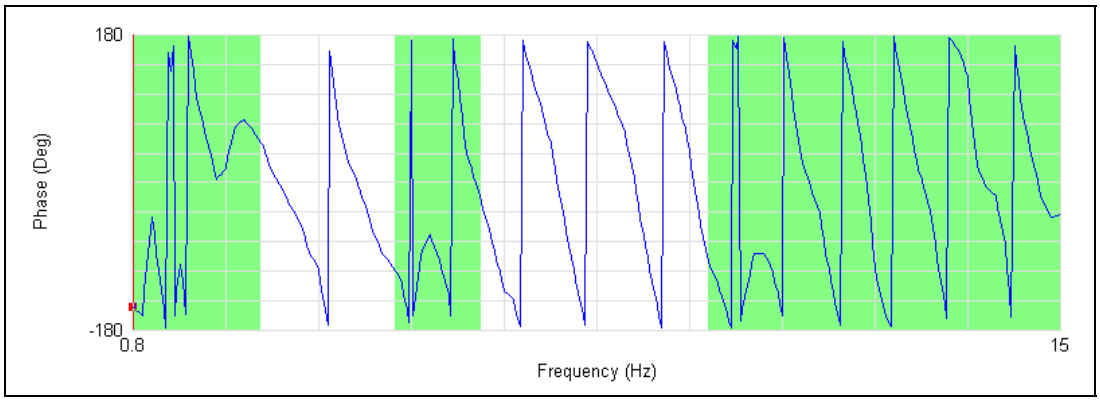

Figure J.14 Phase Plot Measured by SASW Testing; Setup #7; S-R2=800 ft, R2-R3=400 ft

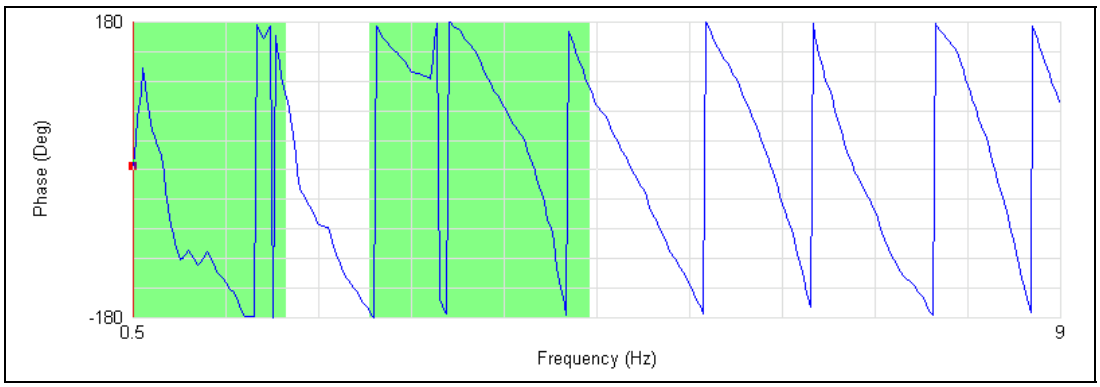

Figure J.15 Phase Plot Measured by SASW Testing; Setup #8; S-R1=500 ft, R1-R2=500ft

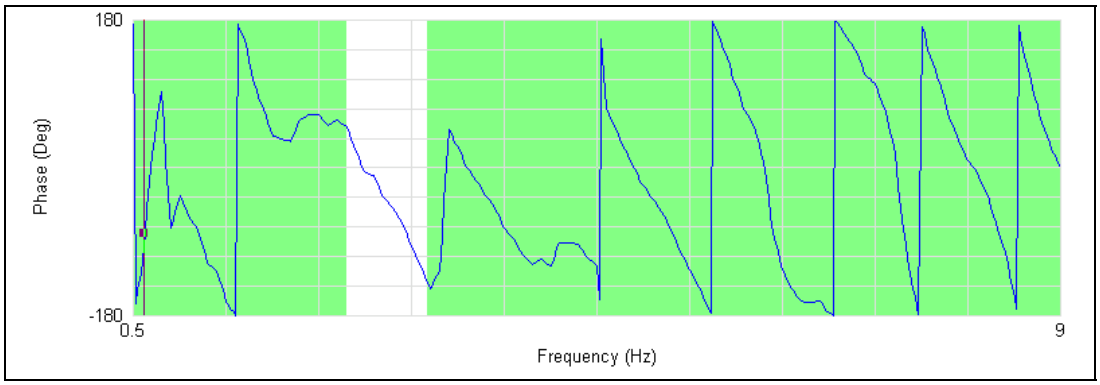

Figure J.16 Phase Plot Measured by SASW Testing; Setup #8; S-R2=1000 ft, R2-R3=500 ft

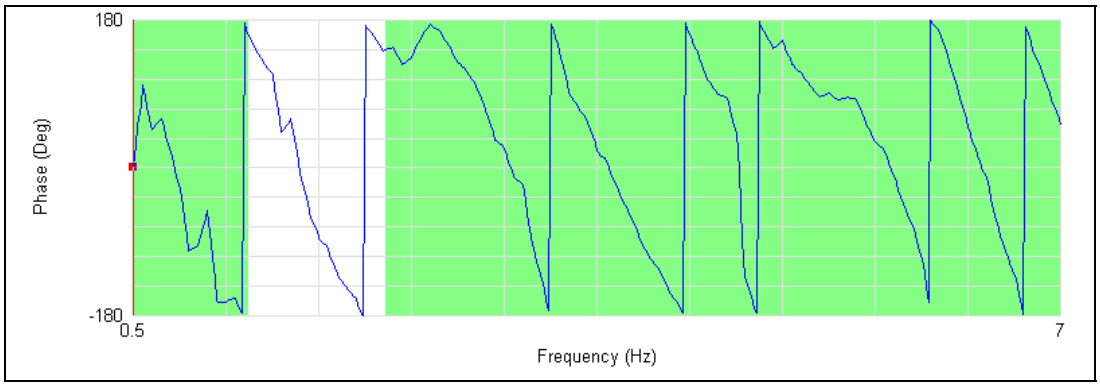

Figure J.17 Phase Plot Measured by SASW Testing; Setup #9; S-R1=750 ft, R1-R2=750ft

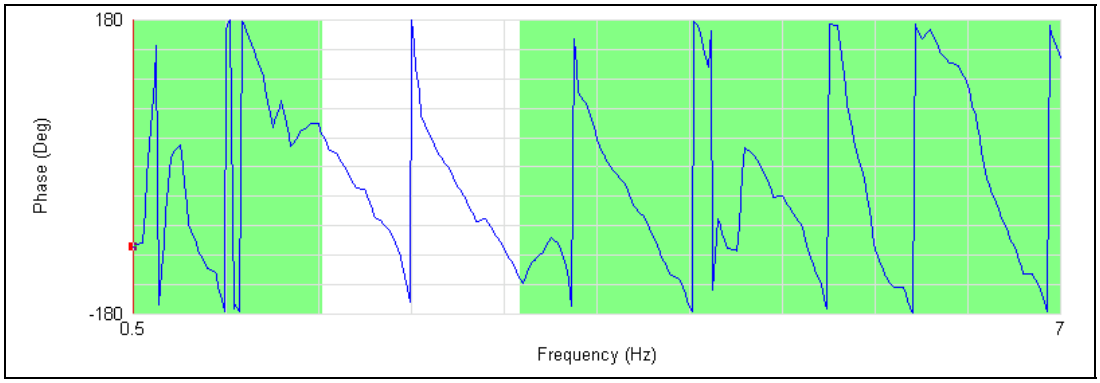

Figure J.18 Phase Plot Measured by SASW Testing; Setup #8; S-R2=1500 ft, R2-R3=750 ft

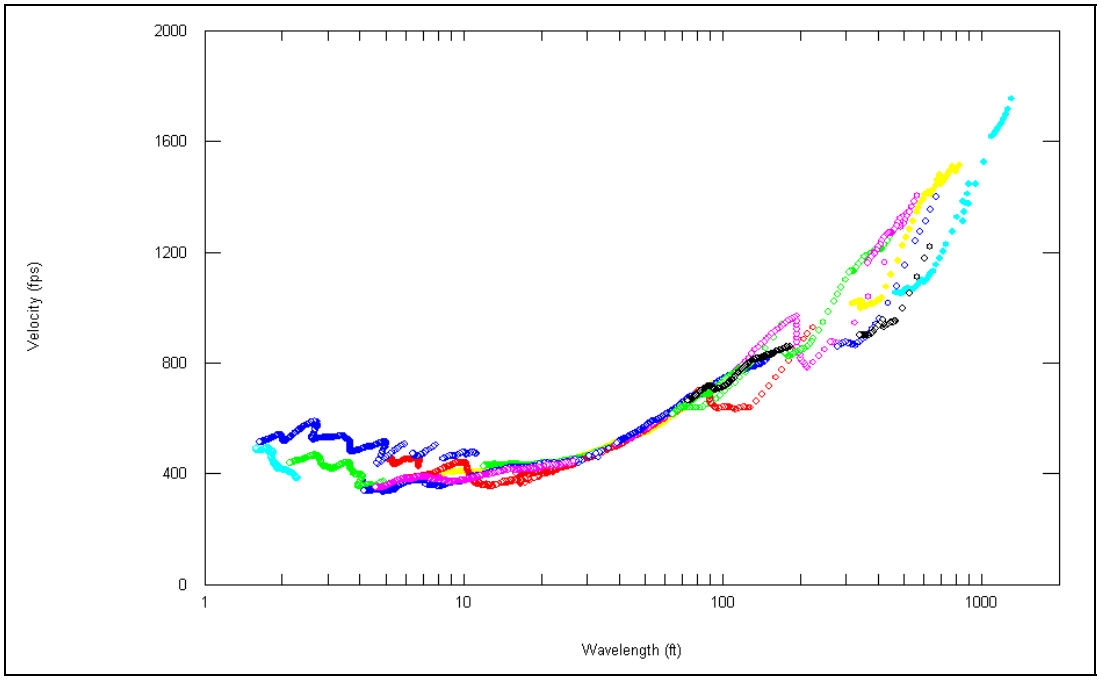

Figure J.19 Experimental Dispersion Curve Measured at Site 10

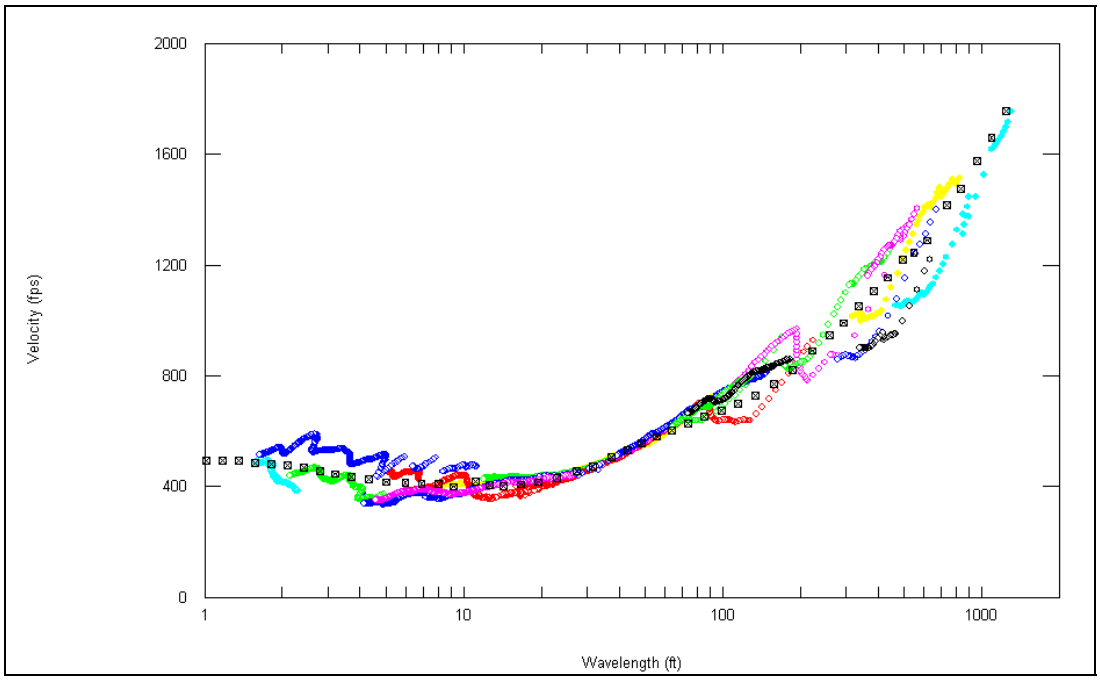

Figure J.20 Experimental and Theoretical Dispersion Curves from Site 10

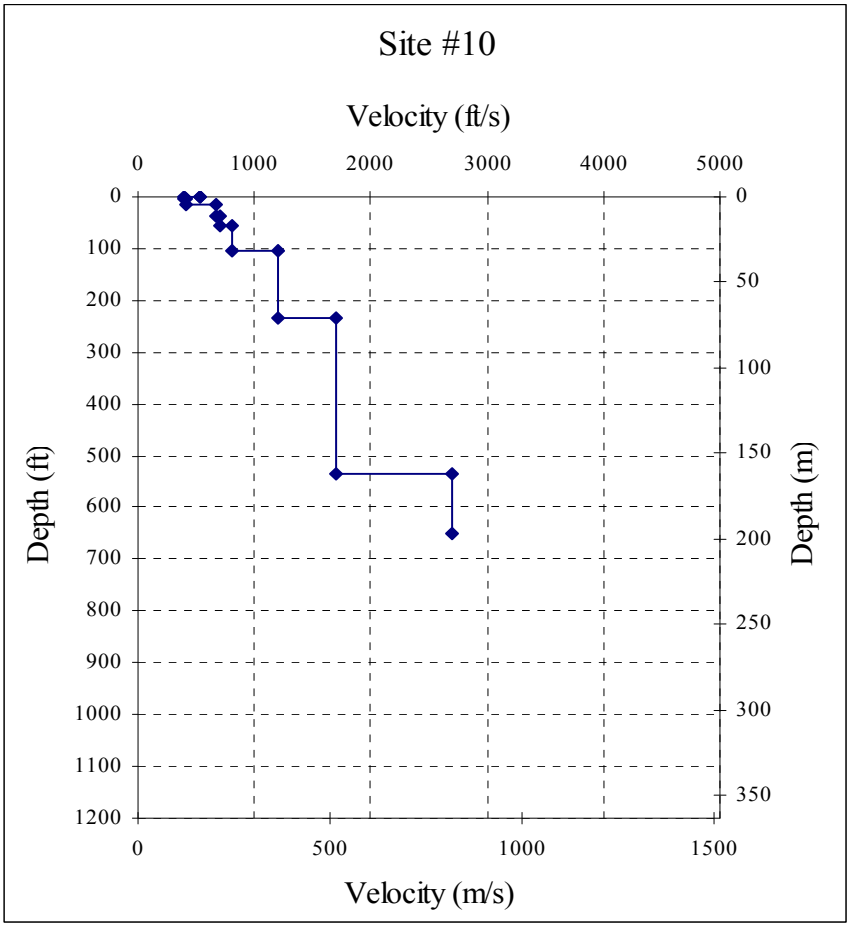

Figure J.21 Shear Wave Velocity Profile Determined at Site 10

Table J.2 Profile Parameters Used to Develop Theoretical Dispersion Curve at Site 10

Layer No.	Thickness, ft	P-Wave Velocity, ft/s	S-Wave Velocity, ft/s	Assumed Poisson's Ratio	Assumed Total Density, pcf
1	1.5	982.2	525	0.30	120
2	4	739	395	0.30	120
3	10	5200*	415	0.497	120
4	20	5200	675	0.491	120
5	20	5200	700	0.491	120
6	50	5200	800	0.488	120
7	130	5200	1200	0.472	120
8	300	5200	1700	0.440	120
9	∞	5200	2700	0.315	130

* Depth to Water Table is 5.5 ft

K.1. APPENDIX K

Analysis of SASW Tests at Site 11

Table K.1 Table of Source and Receiver Spacings

Site Name	Set up	Source to Receiver #1	Receiver #1 to Receiver #2	Receiver #2 to Receiver #3
Site 11	1	3	3	6
	2 (1 Reversed)	3	3	6
	3	12.5	12.5	25
	4 (3 Reversed)	12.5	12.5	25
	5	50	50	100
	6	150	150	300
	7	400	400	400
	8	500	500	500

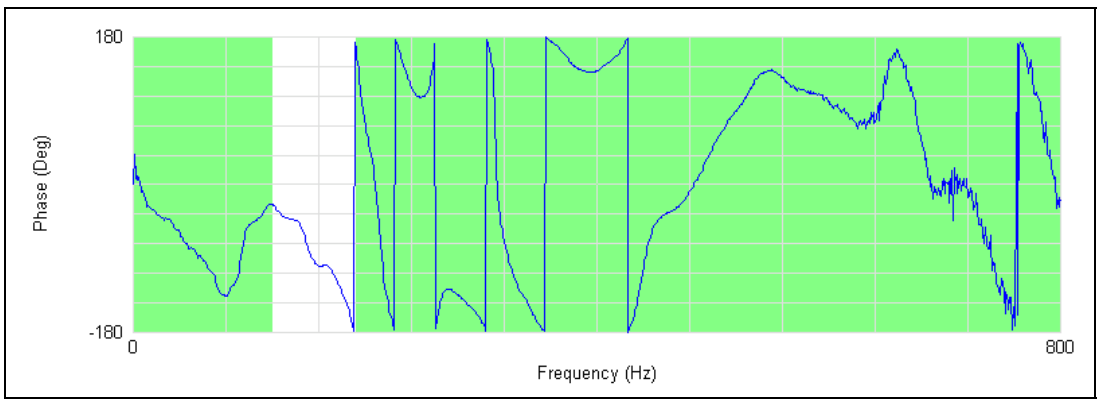

Figure K.1 Phase Plot Measured by SASW Testing; Setup #1; S-R1=3 ft, R1-R2=3ft

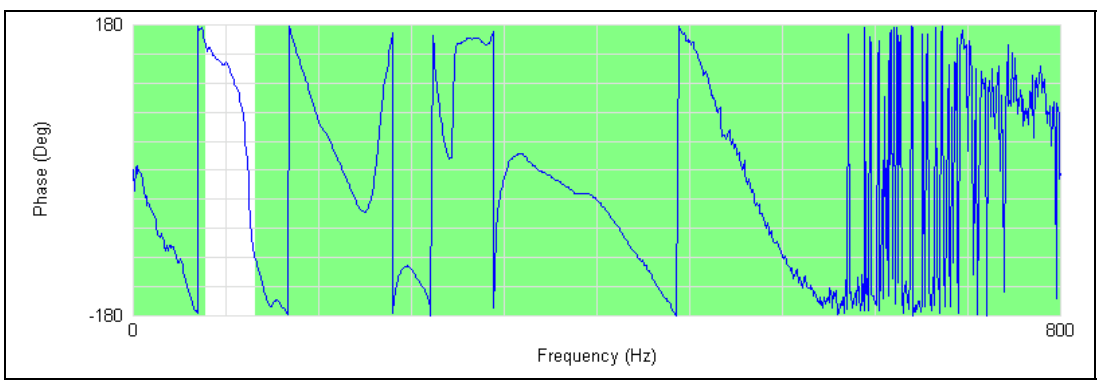

Figure K.2 Phase Plot Measured by SASW Testing; Setup #1; S-R2=6 ft, R2-R3=6ft

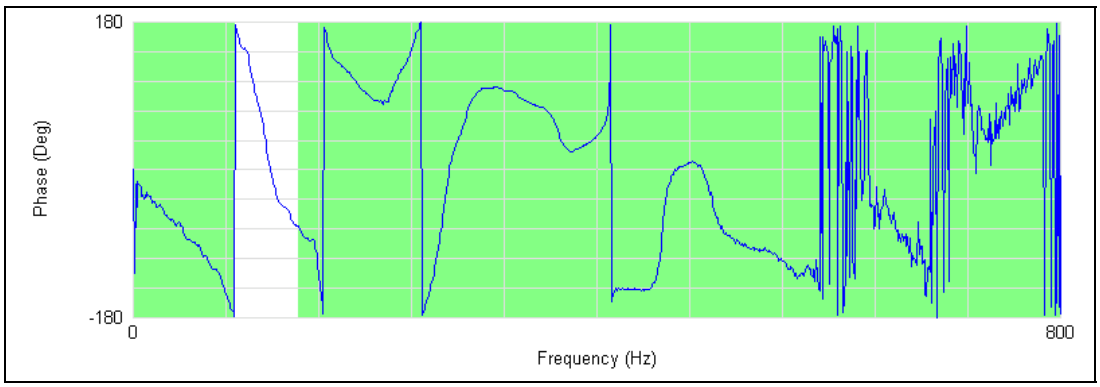

Figure K.3 Phase Plot Measured by SASW Testing; Setup #2; S-R1= 3 ft, R1-R2=3ft

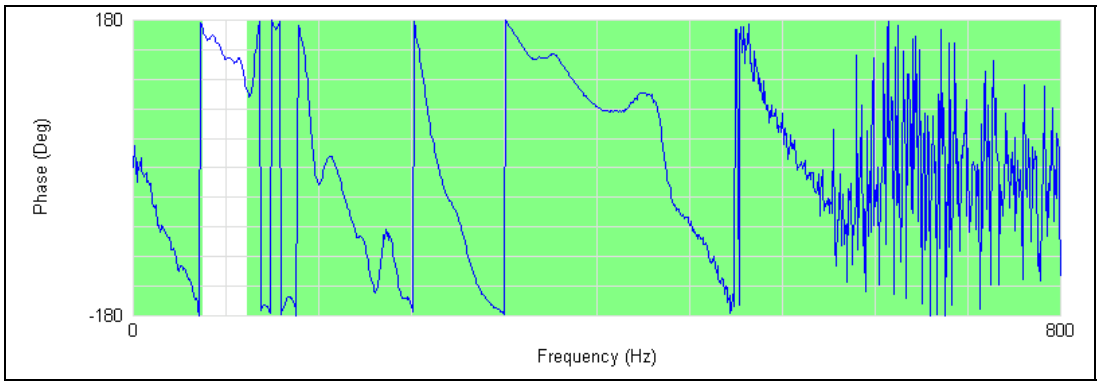

Figure K.4 Phase Plot Measured by SASW Testing; Setup #2; S-R2=6 ft, R2-R3=6 ft

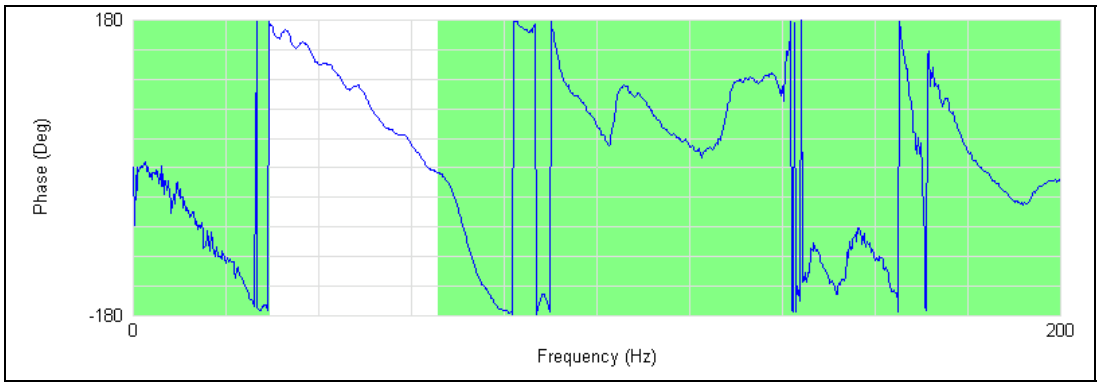

Figure K.5 Phase Plot Measured by SASW Testing; Setup #3; S-R1=12.5 ft, R1-R2=12.5 ft

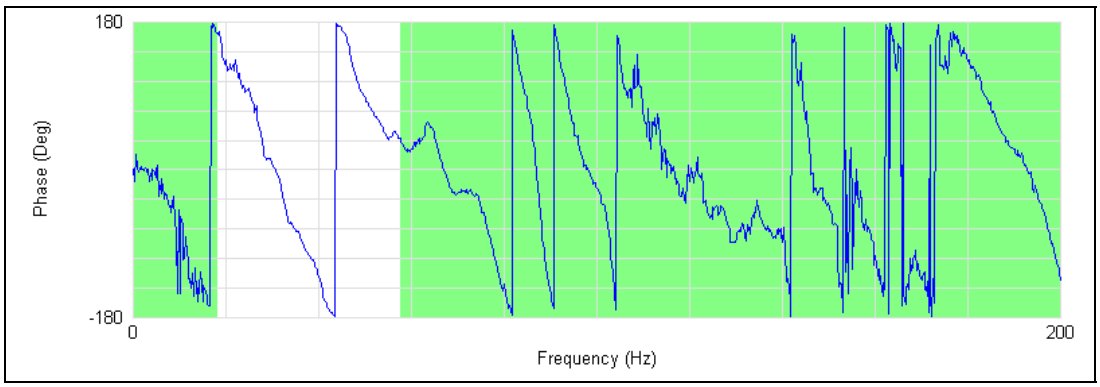

Figure K.6 Phase Plot Measured by SASW Testing; Setup #3; S-R2=25 ft, R2-R3=25ft

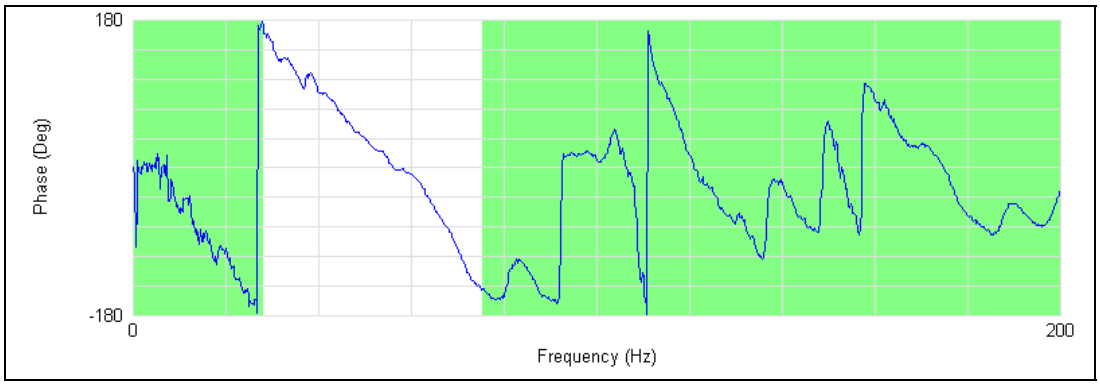

Figure K.7 Phase Plot Measured by SASW Testing; Setup #4; S-R1=12.5 ft, R1-R2=12.5 ft

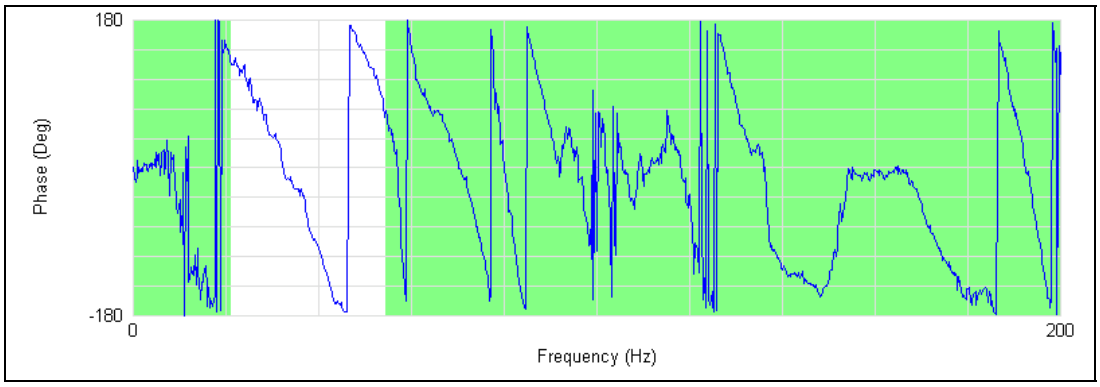

Figure K.8 Phase Plot Measured by SASW Testing; Setup #4; S-R2=25 ft, R2-R3=25 ft

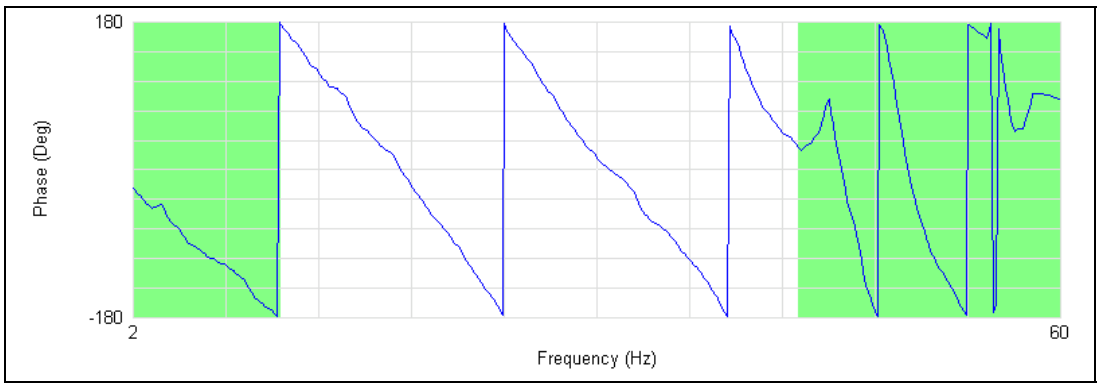

Figure K.9 Phase Plot Measured by SASW Testing; Setup #5; S-R1=50 ft, R1-R2=50 ft

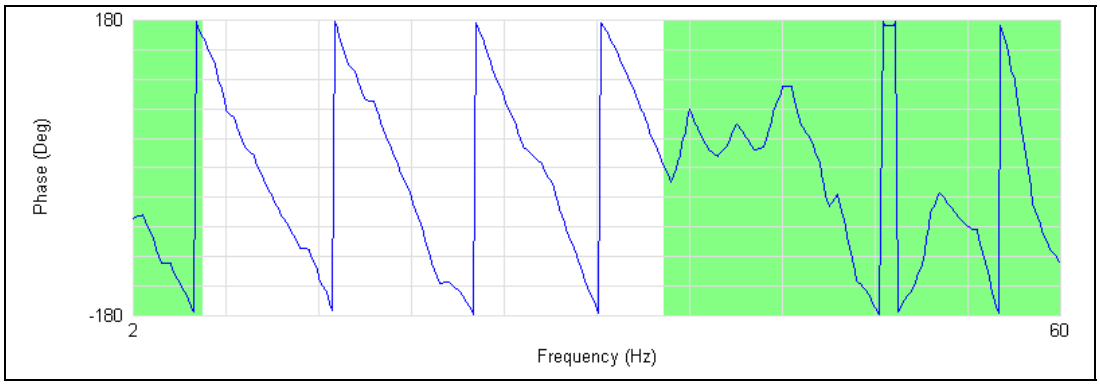

Figure K.10 Phase Plot Measured by SASW Testing; Setup #5; S-R2=100 ft, R2-R3=100 ft

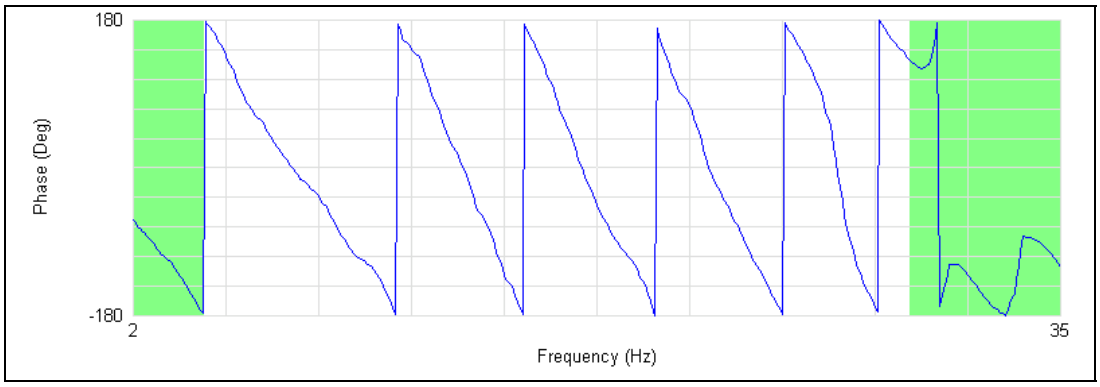

Figure K.11 Phase Plot Measured by SASW Testing; Setup #6; S-R1=150 ft, R1-R2=150ft

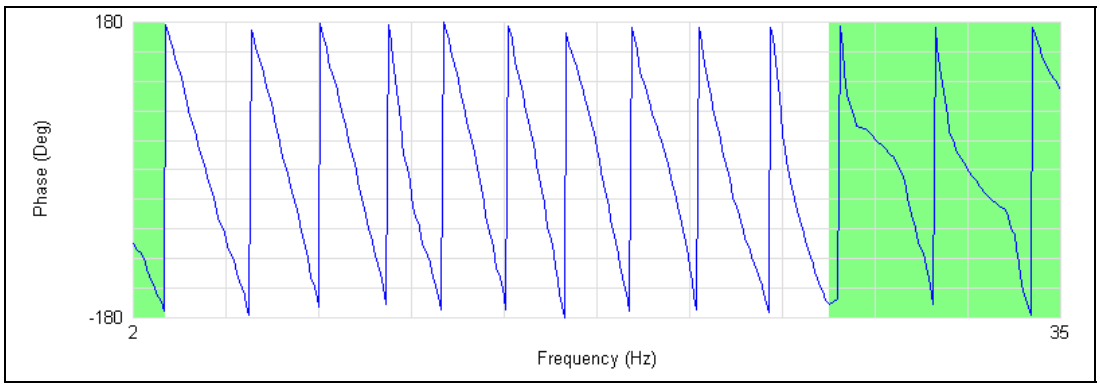

Figure K.12 Phase Plot Measured by SASW Testing; Setup #6; S-R2=300 ft, R2-R3=300 ft

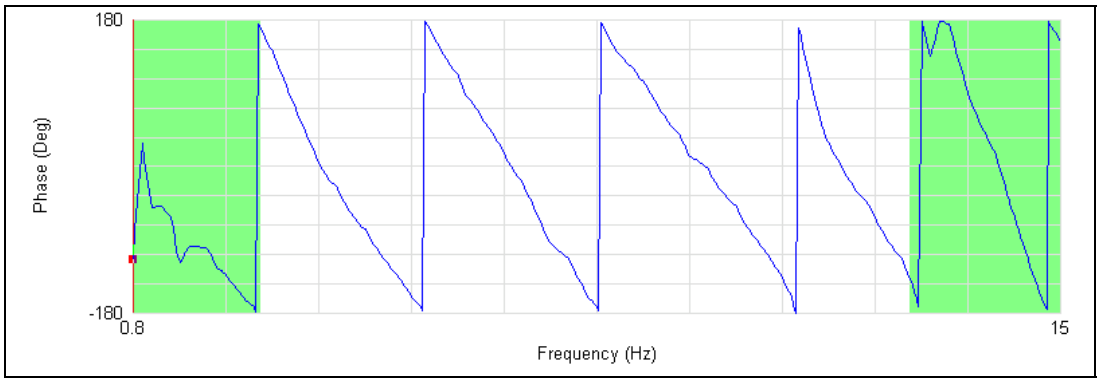

Figure K.13 Phase Plot Measured by SASW Testing; Setup #7; S-R1=400 ft, R1-R2=400ft

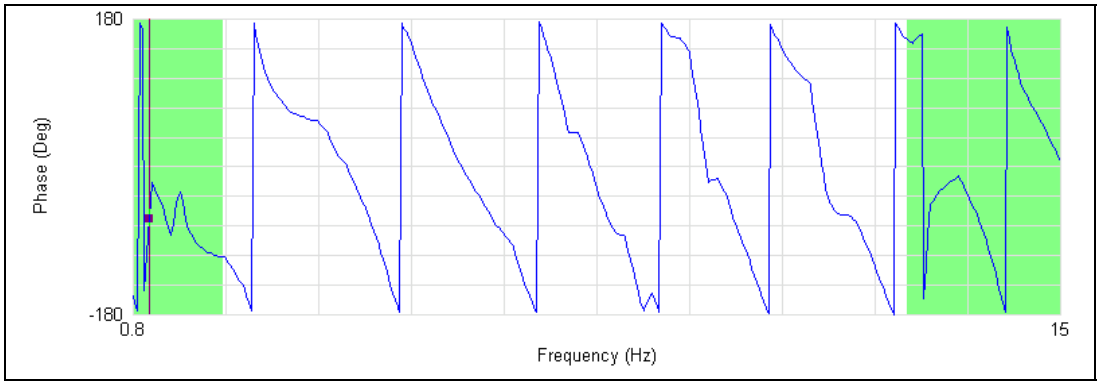

Figure K.14 Phase Plot Measured by SASW Testing; Setup #7; S-R2=800 ft, R2-R3=400 ft

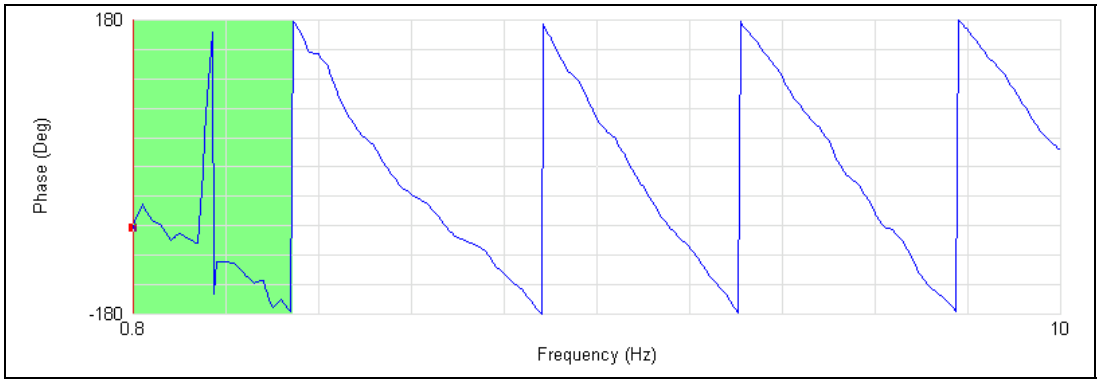

Figure K.15 Phase Plot Measured by SASW Testing; Setup #8; S-R1=500 ft, R1-R2=500ft

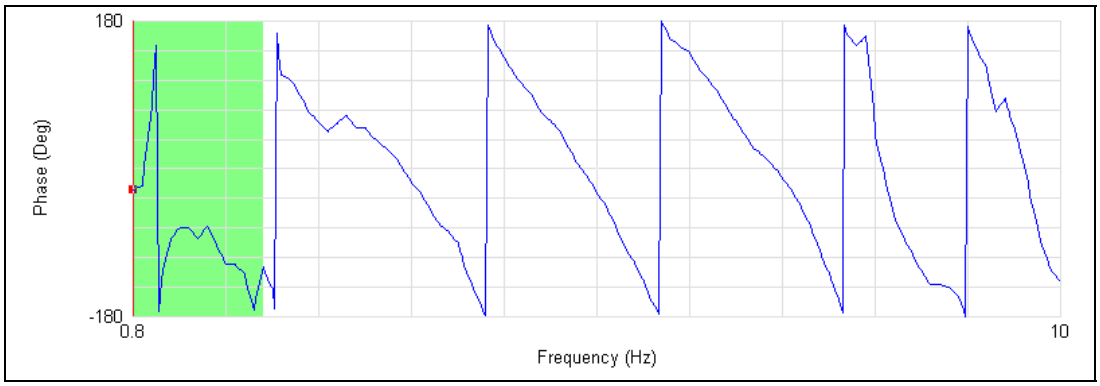

Figure K.16 Phase Plot Measured by SASW Testing; Setup #8; S-R2=1000 ft, R2-R3=500 ft

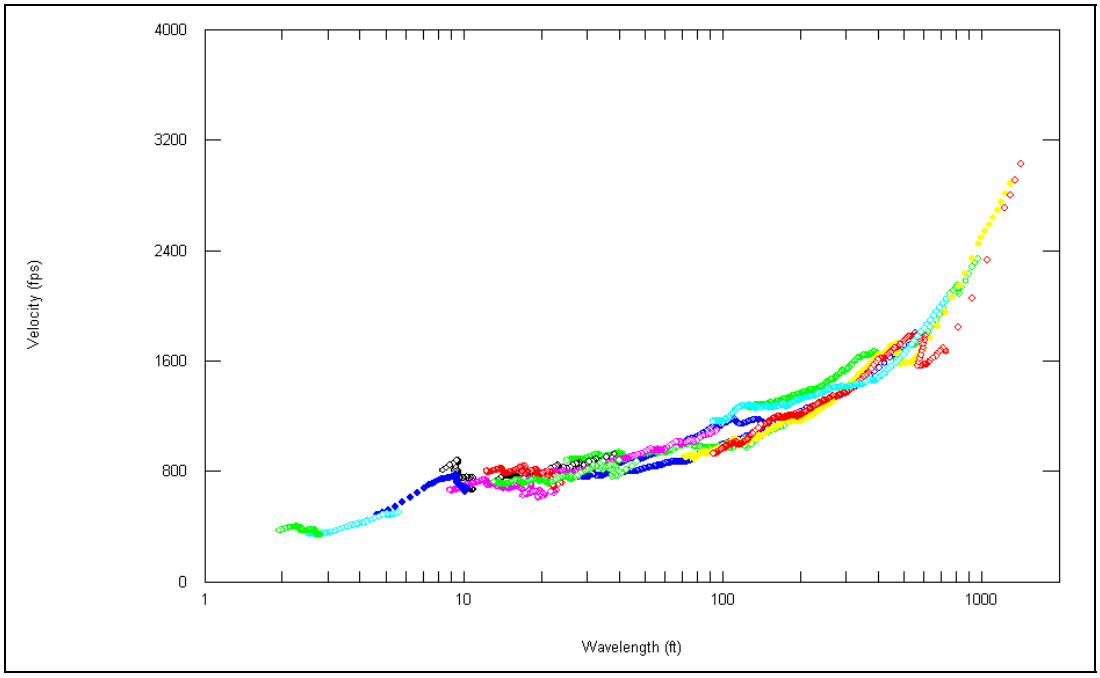

Figure K.17 Experimental Dispersion Curve Measured at Site 11

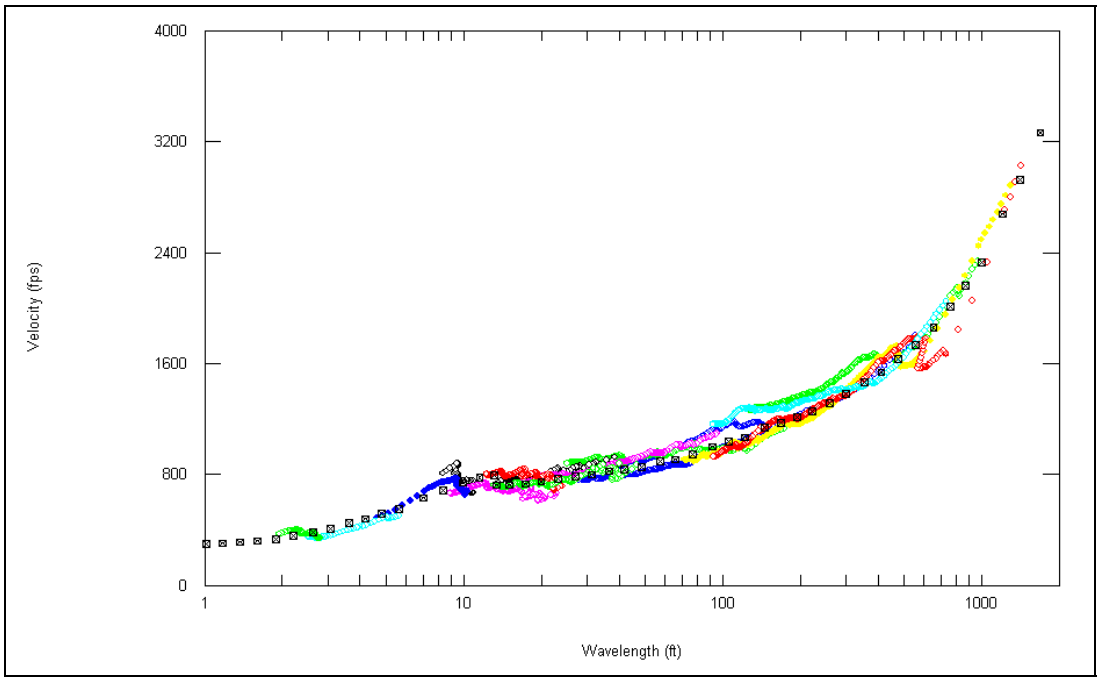

Figure K.18 Experimental and Theoretical Dispersion Curves from Site 11

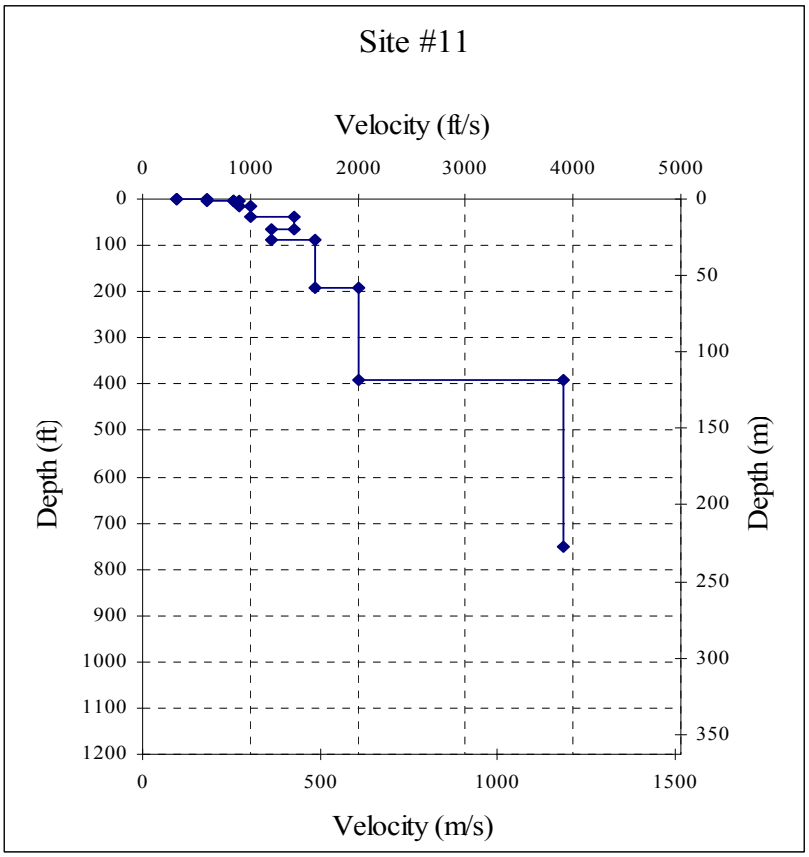

Figure K.19 Shear Wave Velocity Profile Determined at Site 11

Table K.2 Profile Parameters Used to Develop Theoretical Dispersion Curve at Site 11

Layer No.	Thickness, ft	P-Wave Velocity, ft/s	S-Wave Velocity, ft/s	Assumed Poisson's Ratio	Assumed Total Density, pcf
1	1	598.7	320	0.3	120
2	1.5	1122.5	600	0.3	120
3	2.5	1590.2	850	0.3	120
4	10	1683.8	900	0.3	120
5	25	1870.8	1000	0.3	120
6	25	2619.2	1400	0.3	120
7	25	5200*	1200	0.4719	120
8	100	5200	1600	0.4477	120
9	200	5720.2	2000	0.4304	120
10	∞	7296.2	3900	0.3	130

* Depth to Water Table is 65 ft

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