EXPERIMENTAL INVESTIGATION OF THE HORIZONTAL-TO-VERTICAL SPECTRAL RATIO (HVSR) METHOD FOR ESTIMATING DEPTH OF BEDROCK IN CENTRAL MISSOURI

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ABSTRACT

Determining the depth to bedrock is important in geotechnical site investigations, especially for foundation, slope stability, and settlement problems. Although methods such as drilling can be used to determine the depth to bedrock, geophysical methods are excellent supplemental tools to fill in the space between borings. However, many geophysical methods require extensive equipment to deploy and expertise to interpret the data. A recent, simple method to estimate the depth to bedrock is the Horizontal-to-Vertical Spectral Ratio (HVSR) method, which is a single-station measurement that only requires ambient noise and can be easily deployed and completed by a single person within 15 minutes. The objective of this study is to determine if a reliable relationship of depth to bedrock could be developed for the University of Missouri (MU) campus using the HVSR method alone without shear wave velocity measurements.

In total, 65 HVSR measurements were performed around the MU campus over an approximate area of 1,200,000 m^2. Measurements were performed with a three-component geophone, hand-held data acquisition system, and laptop computer. Relationships were developed between HVSR frequency versus depth to bedrock for all data and subsets of data based on the bedrock conditions. The results showed a reliable relationship can be developed for soil over limestone profiles, where the average errors were within 12%, which is consistent with similar past studies. However, when shale was present, the bedrock depth predictions were unreliable with errors as large 58%. Therefore, in practice, the HVSR relationship developed in this study should only be used at sites where shale is known to be absent, based on supplemental information. The HVSR relationship developed in this study was applied at a major construction project

near the University of Missouri campus and showed good agreement between the prediction from HVSR and refraction results performed by another contractor. The errors in the depth predictions were within the range of 0.5 to 3.2 ft.

1. INTRODUCTION

1.1 Background

Geotechnical site characterization is a systematic study of subsurface conditions with the goal of developing a representative profile of subsurface strata over the depth range of interest. The main purpose of site characterization is to determine relevant soil and rock properties that can be used to predict the behavior of the subsurface for various engineering problems. Investigations performed for site characterization may include in-situ measurements like the Standard Penetration Test (SPT) and Cone Penetration Test (CPT); drilling and sampling; and numerous laboratory tests and techniques. One important parameter determined as part of a site investigation program is the depth to bedrock. Knowledge of the bedrock depth is important, for example, when constructing major structures which will be supported on deep foundations that extend into rock. Also, for many slope stability investigations, the soil/rock interface is of interest because it may be the plane of sliding or the limit of the depth of the slide. In settlement problems, defining the thickness of compressible layers above rock is important to accurately predict the settlement. In many cases inaccurate or assumed values of the depth to rock yields an over costly design. Thus, characterization of the depth to bedrock is needed in many geotechnical engineering applications.

The most common and straightforward method to determine the depth to rock at a specific location is to drill a borehole. However, in some cases, desired drilling locations may be difficult for the equipment to access, budget may limit extensive drilling to characterize borehole depth, or the locations of the foundation elements may change to locations where the depth to rock is unknown. Thus, often it is not possible to accurately characterize the spatial variability of bedrock depth from drilling alone. Therefore, geophysical methods are often a good supplement to the drilling program. For example, methods like electrical resistivity and seismic refraction can be used to determine the depth to rock. However, these methods require extensive equipment deployment and user expertise to reliably interpret the data. Therefore, these methods can be time-consuming to utilize. There is a need for an easily deployed, simple, economical, and non-destructive technique to determine depth to bedrock in modern geotechnical site characterization.

Recently, a single-station geophysical method, called the Horizontal-to-Vertical Spectral Ratio (HVSR) method, has found widespread use in seismological and geotechnical applications. It is performed by using a three-component seismometer to measure ambient energy in the horizontal and vertical directions at the desired location to estimate the fundamental frequency at a site. This fundamental frequency is directly related to bedrock depth and soil shear wave velocity. The primary advantage of the HVSR method is its quick and economical implementation, as it only requires a single station and no active source. Also, data processing requires little expertise and can be automated such that the results can be quickly interpreted by novice users.

Most of the early studies focused on seismic microzonation applications, where the spatial variability of site frequency is mapped over large regions (e.g., Martorana et al. 2018; Konno & Omachi, 1998; Gosar. 2017; Chen et. al. 2009). In addition, the HVSR method has found application for estimating the average shear wave velocity in deep basin studies, where borehole control of bedrock depth is available (e.g., Bodin et al. 2011; Rosenblad and Goetz. 2009). Lastly, the HVSR method has been used to develop relationships between the fundamental frequency and bedrock depth for regions over large spatial scale (i.e. tens of kilometers) and bedrock depths (i.e. thousand-meter deep) (e.g., Ibs-von Seht and Wohlenberg. 1999; Lane et. al. 2008; Dronfield et al. 2019). In this study, the focus is on investigating the application of the HVSR method for developing relationships to estimate shallow bedrock depths (i.e. 3 to 20 meters) over smaller spatial scales (i.e. hundreds of meters) in the geology of Central Missouri.

1.2 Objective

The primary objective of this study is to develop a local relationship between bedrock depth and site frequency determined from HVSR measurements for the University of Missouri campus. This relationship could be used in site investigation planning or as a supplement to conventional drilling and sampling. The hypothesis of this study is that a reliable relationship can be developed between the measured frequency from HVSR measurements and the depth to bedrock without the need for independent shear wave velocity profile measurements.

Additionally, secondary objectives of this study are to understand and quantify the reliability and accuracy of the bedrock depth estimates from the HVSR measurements. Specifically, these objectives are:

1. Quantify the uncertainty in depth estimates for different bedrock conditions.

2. Understand the effect of bedrock geology on the reliability of depth to bedrock estimations, specifically the effect of shale layer when it is present.

3. Develop best practices for data collection and analyses to obtain reliable and consistent results.

4. Investigate the possibility of using other attributes of the HVSR plots to infer site characteristics (i.e. shale versus limestone).

1.3 Scope of Work

The scope of work to satisfy the research objectives involved: (1) compiling existing borehole information from past construction projects around the University of Missouri campus (65 boreholes), (2) interpreting the depth to bedrock at each site from the borehole data, (3) collecting ambient noise data at each accessible borehole location, (4) processing the ambient noise records using the HVSR approach, (5) determining the HVSR peak frequency from HVSR graphs, and (6) developing relationships between depth to bedrock and the peak frequency.

Furthermore, the scope of this work also involved categorizing the data based on different bedrock conditions, studying the impact of site geology on the accuracy of the HVSR method, investigating the relationship between bedrock geology (i.e. presence of shale) and features of the HVSR plots, and examining factors affecting the consistency of the HVSR measurements.

1.4 Layout of the Thesis

This thesis consists of seven chapters. In Chapter 2, the general geology around the University of Missouri campus (i.e. study area) is described, the HVSR method is presented, and selected relevant past HVSR studies from the literature are presented. The site description of each location where measurements were performed are described in Chapter 3. Then, the details of the methods used for data collection, processing, and interpretation are presented in Chapter 4. The HVSR results and additional analyses are presented in Chapter 5. A discussion of the results as related to the objectives of the study are presented in Chapter 6. Lastly, Chapter 7 presents a summary of the findings, important conclusions from this work, and potential areas of future study.

2. BACKGROUND

2.1 Introduction

This chapter presents a brief overview of the geology of Central Missouri and the University of Missouri campus. This is followed by a discussion of the expected shear wave velocities (V_S) of the soil and rock in the study area. Lastly, an overview of the HVSR method is presented and relevant literature on the HVSR method are reviewed.

2.2 General Geology of the University of Missouri Campus

The geology of Boone County is described by A.G. Unklesbay in his book, *Geology of Boone County, Missouri* (1952). The following summary is largely based on the information from this book and is used to describe the general geology around the University of Missouri campus. The University of Missouri sits on top of glacial drift deposits and loess from the Pleistocene age. These deposits typically consist of lean or fat clay that are sometimes mixed with sand, silt, and gravel. Beneath these deposits is the bedrock from the Mississippian and early Pennsylvanian age, composed of shale and limestone. The shale is found inconsistently with various thickness around campus while limestone is common.

The general subsurface profile around campus consists of possible fill over clay over shale and/or limestone. Detailed profiles and descriptions for each measurement location used in this study are presented in Chapter 3. The limestone bedrock beneath the University of Missouri campus is the Burlington formation. The Burlington limestone is colored white to gray, with some chert inclusions, with an upper surface that is often eroded and irregular. Multiple geotechnical reports of campus projects show the Burlington limestone is found in the depth range of 10 to 55 ft, with the rock surface often being weathered and fractured. In addition, the shale bedrock of the Cherokee group is found around campus atop the limestone. Based on boring data, the shale thickness ranges from 0 ft to 29 ft and it is often in a weathered condition. For context, the depth to bedrock around Missouri is shown in Figure 2.1 with the study area indicated by the red square.

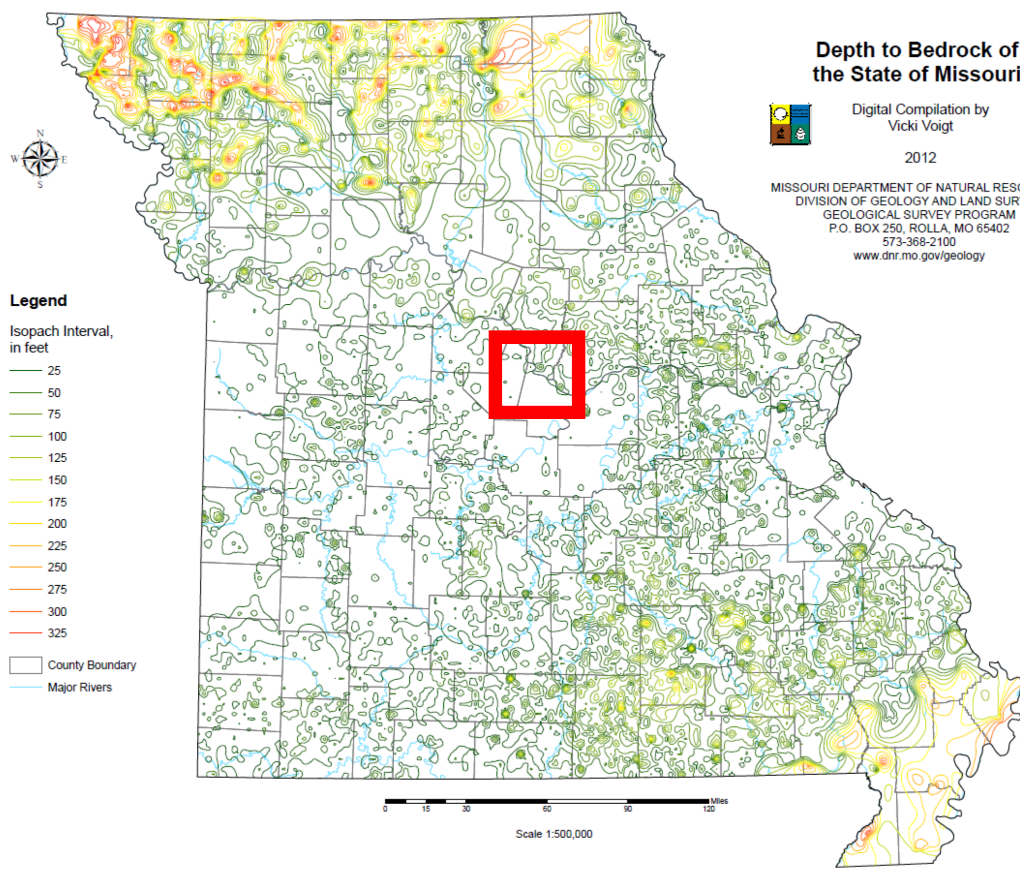


Figure 2. 1 Depth to Bedrock in Missouri (MoDNR 2012), with red square indicating the area of this study

2.3 Expected Shear Wave Velocities

The subsurface profile in the study area can be generally described as consisting of two or three major layers. The first layer is the fill and soil layer, the second layer is the inconsistent shale layer that may or may not be present, and the third layer is the limestone layer. Each layer may have additional layering on top or below them (i.e. silt and sand), however, these are the three main layers of interest for this study. As part of this study, only limited V_s measurements were performed of the soil/fill and limestone, and no velocity measurement of the shale were performed. However, based on past literature, as well as the general knowledge about these materials, a range of expected V_s of these materials can be estimated, as presented below. Based on the information described below, a simplified, general V_s profile is presented in Figure 2.2. It is important to note that the shale layer is absent at many sites or very thin, and the depths of all interfaces vary considerably across campus.

2.3.1 Soil/Fill

The V_s of the fill and soil depend on soil structure, soil type, void ratio, and the effective stress. A general relationship can be expressed as:

$$V_s = A(\sigma'_v)^m \qquad \text{(Eq. 2.1)}$$

where A = parameter that depends on the soil structure, type, and void ratio and m is an exponent with a value that is typically around 0.25.

Based on Eq. 2.1 and using representative values for A, the average shear wave velocity ($V_{s,AVG}$) of the soil/fill is expected to be in the range 400 ft/s to 800 ft/s for the depths of interest in this study. In addition, based on a few Spectral Analysis of Surface Waves (SASW) measurements performed at some of the study sites, the average V_s of 400 to 800 ft/s was found to be reasonable.

2.3.2 Shale

The V_s of shale is highly dependent on the degree of weathering and fracturing. No measurements were performed on the shale in this study. However, based on other measurements of V_s of shale in Missouri and the variable degree of weathering and fracturing in the rock, it is expected that V_s of shale will likely fall in a broad range of 1200 ft/s to 2500 ft/s in most cases.

2.3.3 Limestone

The V_s of limestone is also highly dependent on the degree of weathering and fracturing. Based on a few laboratory measurements of intact limestones from one of the campus projects, the V_s is expected to exceed 5000 ft/s in many cases. Lower values are possible when severe weathering is present. In addition, crosshole measurements performed at a nearby Central Missouri location, showed V_s of limestone of around 5000 ft/s or greater.

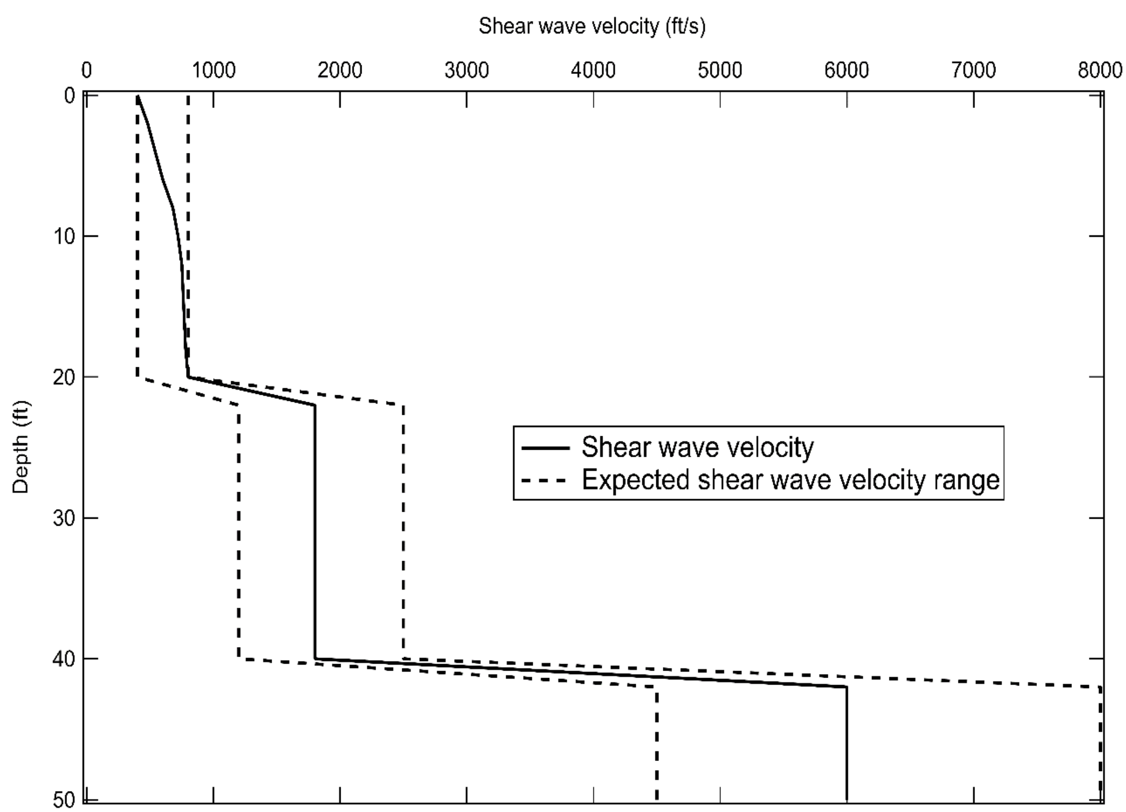


Figure 2. 2 Representative V_s profile of the study area with expected range of V_s values

2.4 Overview of HVSR Method

The HVSR method is a single-station geophysical method used to estimate the resonant frequency of a site from ambient noise measurements. This technique was originally proposed by Nogoshi and Igarashi (1971) and popularized by Nakamura (1989). The HVSR method involves recording ambient vibrations for several minutes using a three-component, portable seismometer. Ambient vibrations below 1 Hz are typically from natural sources (ocean waves and wind), while ambient vibrations above 1 Hz are mostly due to human activity. The collected ambient noise records are divided into individual time windows and the Fast Fourier Transform (FFT) is applied to convert from the time domain to the frequency domain. The horizontal spectrums are merged and divided by the vertical spectrum and a HVSR plot is created for each window. The HVSR curves are then combined into an average HVSR curve. An example of selected number of windows is presented in Figure 2.3 and the HVSR plot is presented in Figure 2.4.

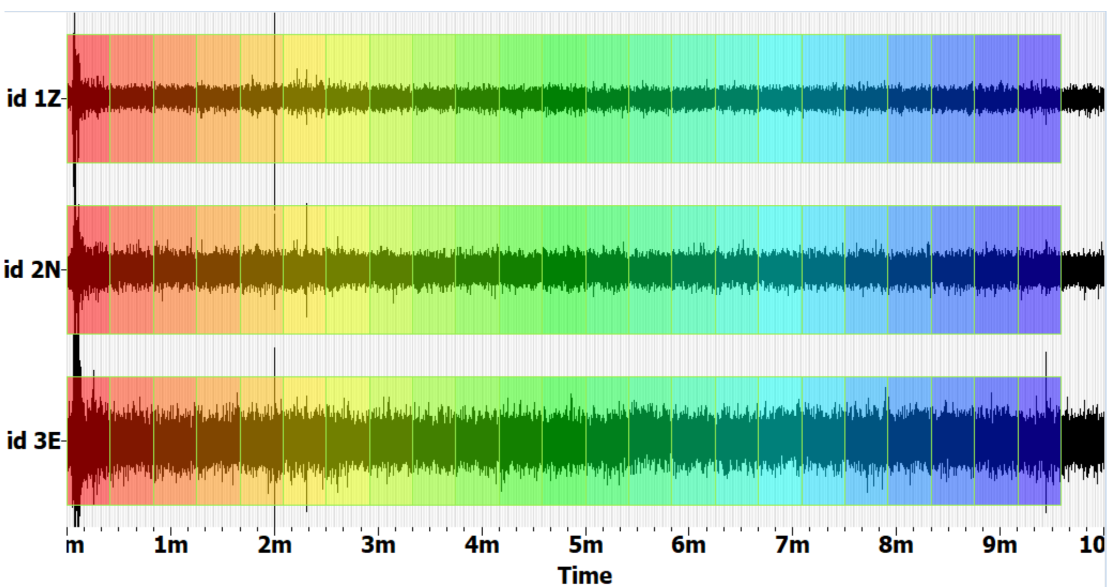


Figure 2.3 The HVSR ambient noise record showing the auto selected number of windows (23 windows) for Ellis Library BH 1

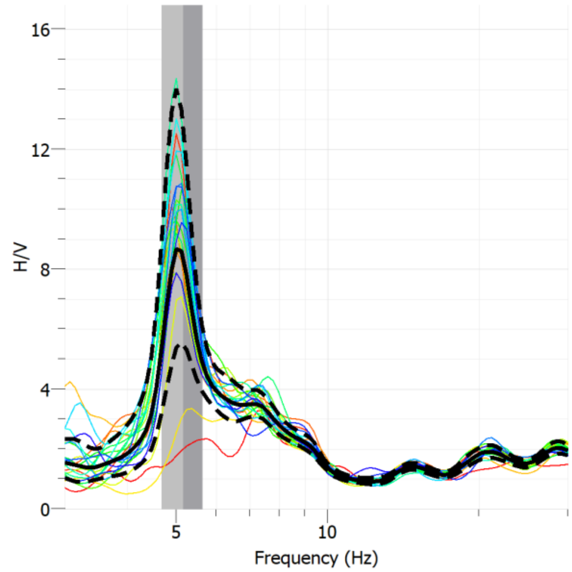


Figure 2. 4 Spectral HVSR ratio for 600 s (10 min) time window of ambient records at Ellis Library BH 1 (color lines). The mean (black continuous line) and standard deviation are indicated (black dashed lines). Each color curve represents the HVSR plot for a single window. In addition, the standard deviation of peak frequency (f_0) is indicated (grey bar)

The Nakamura technique assumed that when the horizontal spectrum (H) is divided by the vertical spectrum (V), the influence of the source effect is eliminated and the fundamental resonant frequency of the sublayer soil can be determined (Lermo and Chávez-García 1993). Thus, the HVSR peak frequency has a strong correlation with the resonant frequency of the site. For cases of a uniform layer over a rigid bedrock, the site frequency can be directly related to the sediment thickness and V_s, as:

$$f_r = V_s/4H \qquad \text{(Eq. 2.2)}$$

where the f_r is the resonant frequency of vertically propagating shear waves, V_s is the shear wave velocity and the H is sediment thickness.

Therefore, with some knowledge of the V_s and the measured frequency it is possible to infer the depth to bedrock from the HVSR measurements. If the V_s of the soil changes with depth (as is usually the case), then the following approximate relationship can be used:

$$f_r = V_{s,AVG}/4H \qquad \text{(Eq. 2.3)}$$

where f_r is the resonant frequency, $V_{s,AVG}$ is the average shear wave velocity of the layers and the H is sediment thickness.

Two averaging methods to estimate the $V_{s,AVG}$ of the materials have been used in the literature. The first one is the simple weighted average:

$$V_{s,AVG} = \frac{\sum V_i Z_i}{H} \qquad \text{(Eq. 2.4)}$$

where $V_{s,AVG}$ is the average V_s ; H is the total sediment thickness; V_i is the V_S at depth z; and Z_i is the sediment thickness of individual layers.

Another way to average the V_s is through the slowness average equation, as presented below:

$$V_{s,AVG} = \frac{H}{\sum \frac{Z_i}{V_i}} \qquad \text{(Eq. 2.5)}$$

where $V_{s,AVG}$ = average shear velocity; H = total sediment thickness; V_i = shear velocity at depth z; and Z_i= sediment thickness.

There are two interpretations on the origin of the HVSR frequency peak, namely, surface wave ellipticity and vertically propagating shear waves. Surface waves have both horizontal and vertical components and travel in the shallow zone near the free surface, with particle motions decreasing exponentially with depth. If an impedance contrast (e.g. soil over limestone) is encountered at depth, the amplitude of the vertical component will decrease to near zero at a frequency that is close to the fundamental frequency of shear wave resonance (Goetz and Rosenblad 2009). Therefore, the H/V plot will show a peak close to the fundamental mode of shear wave resonance.

The body wave explanation attributes the peak directly to ambient vertically propagating, horizontally polarized shear waves. Ambient body waves consist of compression waves and shear waves which may propagate vertically through the ground and can reflect the through different material interfaces. When the body waves arrive at a HVSR recording station, the horizontal components of the body waves are dominated by the horizontal shear (SH) wave and the vertical component of the body waves is mainly the compressional (P) waves. Therefore, when the HVSR is calculated, a peak is observed at the frequency of shear wave resonance. (Goetz and Rosenblad 2009). Figure 2.5 demonstrates the HVSR for the body wave interpretation and for the surface wave interpretation (Goetz and Rosenblad 2009). In most cases, the HVSR frequency peak is likely composed of both body wave and surface wave energy. For the shallow depth study performed in this work, it is likely that the origin of the peak is primarily due to surface wave energy from nearby traffic and other man-made sources.

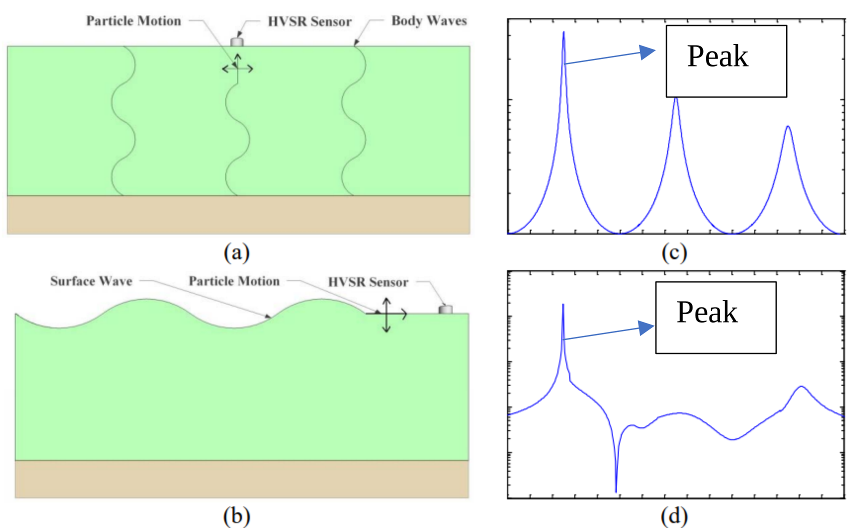


Figure 2.5 Two interpretations of the HVSR method in terms of body waves (a) and surface waves (b) showing the transfer function for 1D SH wave propagation (c) and the HVSR ratio for Rayleigh wave propagation (d) (Goetz and Rosenblad 2009), indicating that both wave types produce a peak at the same frequency

2.5 Past Studies of HVSR

2.5.1 Microzonation Studies

The HVSR method has been used extensively in earthquake microzonation studies. Microzonation is the process of evaluating the seismic hazard response from local site effects and site characterization for a specific area. In HVSR applications to microzonation studies, the focus is on quantifying the spatial variability of the site frequency to better understand expected earthquake response. Numerous microzonation studies using HVSR have been performed and a few examples are discussed in this section.

Gallipoli et al. (2010) used the HVSR technique to support emergency seismic microzonation in Italy after the 2009 Abruzzo earthquake, where heavy damage occurred in towns like Navelli. Over 200 HVSR measurements were performed in the Abruzzo region. In this study, the HVSR curve was compared to the Standard Spectral Ratio (SSR) curve obtained from earthquake recordings. The HVSR results showed the peak frequency was in good agreement with the peak frequency of the SSR curve. Thus, the study showed the microtremor investigation is an effective tool for assessment of local site response, especially when the available geological maps are unable to correlate with observed presence of amplification from the seismic measurements.

Stanko et al. (2019) used the HVSR method to assess the seismic site amplification in the City of Invanec. A total of 68 HVSR measurements were performed in the 12 km^2 area and interpolation was used in between the measurement locations to develop the respective frequency map. The frequency map of the City of Invanec showed a strong correlation with the local geologic conditions.

Fäh (1997) studied and developed a qualitative micronation map for the city of Basel, where the city has suffered multiple earthquakes in the past centuries. Fäh performed 232 HVSR measurements to obtain the HVSR peak frequency and the site amplification. One and two-dimensional numerical modelling were used to estimate the expected seismic ground motion during earthquakes. The developed qualitative microzonation map showed an acceptable agreement with the distribution of past earthquakes in the regions.

2.5.2 Average Shear Wave Velocity Determination

Based on Eq. 2.3, the site frequency and known bedrock depth can be used to estimate the $V_{s,AVG}$ for deep profiles where velocity profiles cannot be measured. Bodin et al. (2001) performed more than 100 HVSR measurements at sites around Memphis, Tennessee to infer the $V_{s,AVG}$ using this approach. The results show a strong correlation between peak periods (inverse of frequency) and sediment thickness at these sites. In addition, this study also concluded the $V_{s,AVG}$ was clearly a function of sediment thickness.

Goetz and Rosenblad (2009) performed HVSR measurements to explain different estimates of $V_{s,AVG}$ from Bodin (2001) and Chen (1996). A total of 11 HVSR measurements were collected in the upper Mississippi Embayment. The results, as presented in Figure 2.6, showed good agreement with values from Chen (1996) with the $V_{s,AVG}$ estimation from Bodin (2001) about 25% higher. These results showed the limitations of the $f_r = V_s/4h$ approach for estimating $V_{s,AVG}$ of more complex profiles.

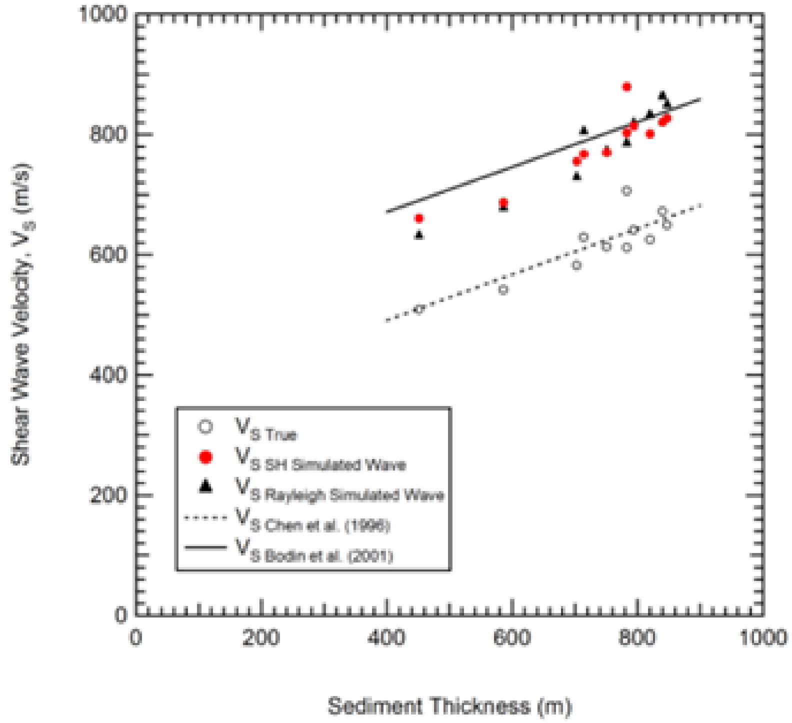


Figure 2. 6 V_s from HVSR measurements and simulated tests as a function of sediment thickness for 11 sites in upper Mississippi embayment, compare to V_S values from Bodin et al. (2001) and Chen et al. (1996) (Goetz & Rosenblad 2009)

2.5.3 Depth to Bedrock Estimation

Another application of the HVSR method is to develop a direct relationship between the frequency and sediment thickness for a specific region. The studies discussed below are the most relevant to this research.

Ibs-von Seht and Wohlenberg (1999) examined both the classic spectral ratio technique and the HVSR method. They collected 102 microtremor measurements in the western Lower Rhine Embayment, where the subsurface consists of soil over hard rock. The results showed that the classical spectral ratio approach tends to be influenced by the noise level and is less reliable in determining the resonant frequency of the sublayer soil. The HVSR method showed a strong correlation with the sediment thickness over depth ranges from tens of meters to thousands of meters. Thus, Ibs-von Seht & Wohlenberg (1999) developed a nonlinear relationship between the fundamental resonant frequency (f_r) of soil and sedimental thickness (h) of the following form:

$$h = a{f_r}^b \qquad \text{(Eq. 2.6)}$$

where a and b are unknown regression coefficients.

The basis for this relationship comes from the simple formulation between the f_r of a flat-lying sediment layer with an average shear velocity of $V_{s,AVG}$ and thickness h overlying a hard-rock basement, as expressed in equation 2.3 (Lachetl & Bard 1994; Ibs-von Seht & Wohlenberg 1999).

One advantage of developing relationships of the form of Eq. 2.6 is that explicit measurement of V_s is not required. Ibs-von Seht and Wohlenberg (1999), Parolai et al. (2002) and Hinzen et al. (2004) have published equations relating sediment thickness to resonance frequency based on correlations to borings in Germany, as shown in Table 2.1.

Table 2. 1 HVSR Resonance Frequency- Power-Law-Function Fitting Parameters

Fitting Parameters			**Reference**
***a* (meters)**	***b***	***R*²**	
96	-1.388	0.981	Ibs-von Seht and Wohlenberg,1999
108	-1.551	-	Parolai et al., 2002
137	-1.190	-	Hinzen et al.,2004

Delgado (2000) investigated Eq. 2.6 in the Bajo Segura basin to evaluate its usage for a more complicated geotechnical area. The Bajo Segura basin was approximated as a two-layer soil profile by Delgado, where the upper layer is soft deposits like clay, silt and sand, the lower layer is either hardrock (limestone) or softrock (marl and conglomerate). A total of 33 microtremor measurements were performed at locations where the depth to bedrock is known. In addition, the V_s of the clayey soil was estimated through the relationship of Hardin (1978). The results showed a strong correlation between the HVSR frequency and the sediment thickness. Delgado (2000) claimed the average errors in the depth estimates were about 15 %. In addition, the data were also fit to Eq. 2.6 to obtain the a and b parameters, where the a parameter is in meter, this equation can be expressed as:

$$h = 55.54\, f^{-1.268} \qquad \text{(Eq. 2.7)}$$

In addition to Eq 2.7, this relationship may relate to shear velocity in the following form:

$$V_s = 222.57\, f^{-0.268} \qquad \text{(Eq. 2.8)}$$

The work by Delgado (2000) showed Eq. 2.6 is suitable for estimating sediment thickness using HVSR measurements. Degaldo (2000) claimed that the errors were likely due to the lateral subsurface variation from the assumed V_s profile.

Bignardi (2017) investigated the Ibs-von Seht and Wohlenberg's approach with focus on local subsurface variations from the modeling. First, Bignardi evaluated the errors with the simple relationship of Eq. 2.2. He simulated a 50 ft, two-layer soil profile (soil/hardrock), where the soil has various V_s while the rock has a fixed V_s. Both normally dispersive and inversely dispersive models were used in the simulation. The results showed the normally dispersive model has errors between 15 to 25% and the inversely dispersive model has errors exceeding 20%. Second, Bignardi computed the a and b parameters in Eq. 2.6 for both body wave propagation and surface wave propagation. The results showed the obtained a and b parameters from both wave propagations were very similar to the values obtained by Ibs-von Seht and Wohlenberg. Bignardi also verified that changing $V_{s,AVG}$ up to 10% at most introduces errors of 20% or less in the depth to bedrock estimation.

In addition, Lane et. al (2008) collected 11 HVSR measurements in Cape Cod, Massachusetts, and 13 measurements in eastern Nebraska. He used the power-law-function fitting parameter (Table 2.1) from Ibs-von Seht and Wohlenberg (1999) and Parolai et. al (2002) to estimate the depth to bedrock. The estimated rock depths were compared to the measured seismic refraction and/or the recorded depth to bedrock. Figure 2.7 displays the bedrock estimation from all three methods and the reference borehole depth at Cape Cod, Massachusetts. Lane et al (2008) shown the HVSR method can be an effective tool to estimated depth to bedrock.

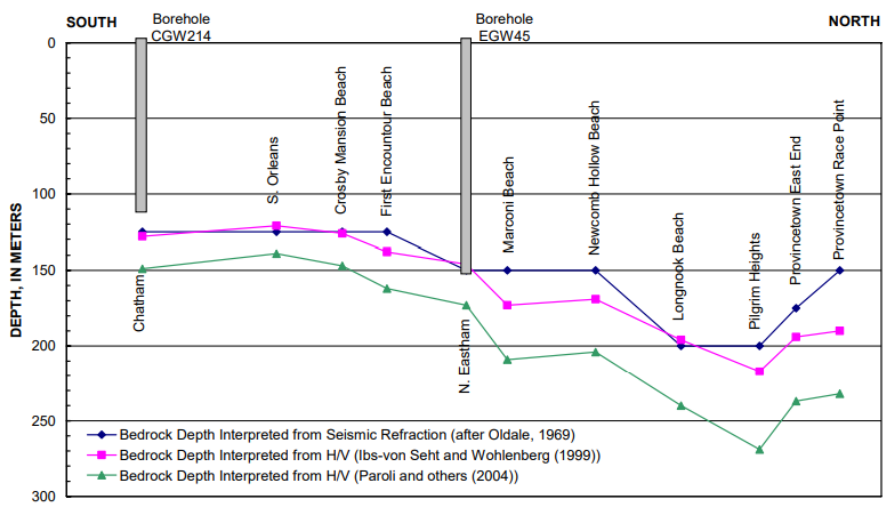


Figure 2. 7 Intrepreted bedrock surface profile at Cape Cod, Massachusetts. (Lane et al, 2008)

Other studies like Pazzi et. al (2016) examined the use of HVSR measurements as a tool for characterizing the landslide geometry in La Spezia, Italy and Grosseto, Italy. They collected roughly 100 HVSR measurements and gathered punctual depth measurements as referenced from boring logs. They interpolated the depth measured from HVSR and reconstructed the landslide slip surface curve. Pazzi concluded the HVSR measurements can serve as an effective tool to characterize the interface between soil and rock.

Dronfield et al. (2019) collected 65 HVSR measurements in the north-west part of the Wilga Basin in Western Australia, which is difficult to access and has limited subsurface information. The basin has approximately 250 meters of shallow sediment. The HVSR data were normalized based on the maximum and minimum of the HVSR amplitude, the data were then gridded along the survey transverse in cross-section view, as shown in Figure 2.8. The results showed the effectiveness of the HVSR method in the shallow basin, where little subsurface information is available. Dronfield showed that the HVSR method is suitable for infer depth to rock when boring log information is limited.

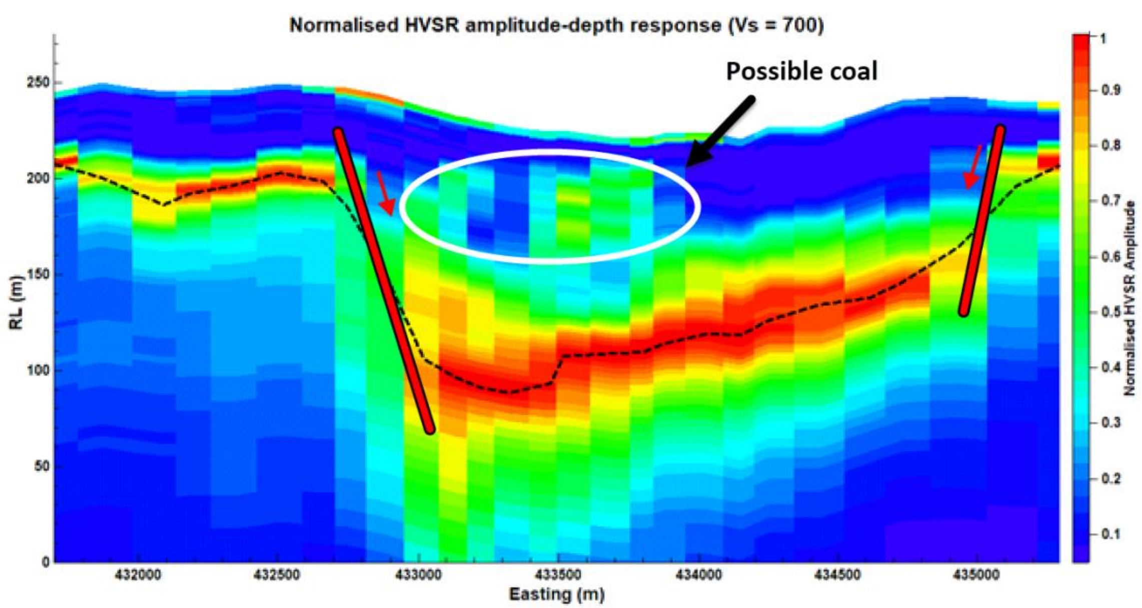


Figure 2. 8 Normalised HVSR data cross-section for one of the survey lines in the western Wilga Basin. The black dash line highlighting the modeled base of the sedimentary basin, and the interpreted normal fault in red. A possible coal seams is indicated in white (Dronfield et al. 2019)

2.5.4 Factors Influencing HVSR Values

As mentioned in the earlier sections, the peak in the HVSR measurements, termed f_p, for a two-layer model, is only an approximation to the natural resonant frequency of the site (f_r). Thus, Eq 2.2 provides only an approximation of the depth and is only truly valid in a two-layer system with a uniform V_S over rigid rock. Therefore, investigators such as Tuan (2009) have looked at the factors influencing the validity of this approximation.

Tuan showed the impedance ratio between the soil and the rock ($\beta 1/ \beta 2$) and Poisson's Ratio ($\upsilon 1$) have major effects on the validity of the approximation. For small impedance ratios (i.e. large impedance contrasts), such as for soil over limestone, and Poisson's Ratio of 0.25 or higher (which are expected for soil), the error from using Eq 2.2 falls between 5 and 10 %, as shown in Figure 2.9. For larger impedance ratios (i.e. small impedance contrasts) the error can be as high as 40%.

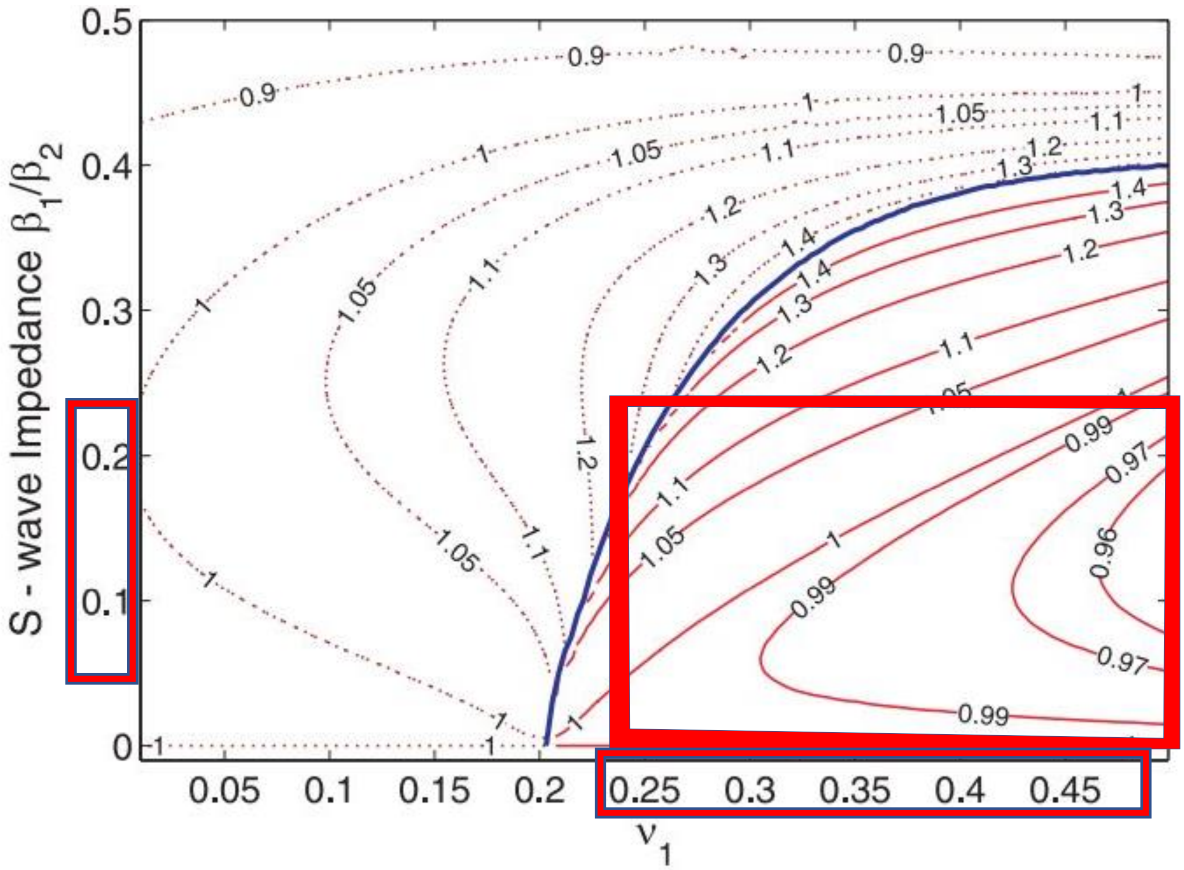


Figure 2. 9 Contours of $(f_p)/(f_r)$ as a function of υ_1 and β1/ β2. The region with red continuous lines indicates a clear single peak in the HVSR curve. The red square indicates the high Poisson ratio values typical of soil and small impedance ratio (large contrast between soil and rock)

Tuan also investigated how these site factors influenced different attributes of the HVSR plot, including the frequency of the trough and the frequency of the peak. An example is shown in Figure 2.10, which showed a ratio of the frequency of the trough to peak can vary significantly with impedance contrast. Tuan suggested a low impedance contrast will have a closer spacing between the peak and trough and a high impedance contrast will have a wider spacing.

In this thesis, the use of these attributes to identify subsurface conditions from the real HVSR measurements was studied.

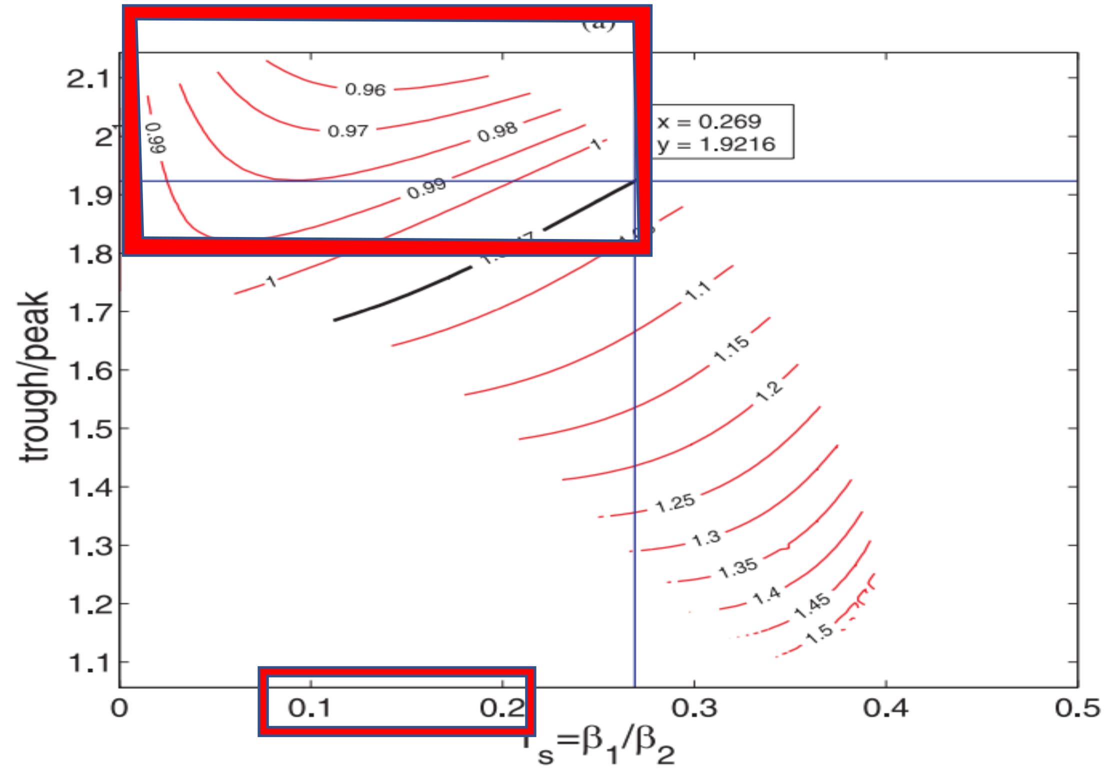


Figure 2. 10 Contours of $(f_p)/(f_r)$ as a function of trough/peak and β1/ β2. The red continuous lines are the region with a clear single peak in the HVSR curve

2.6: Summary

This chapter presented a brief description of the geology around the University of Missouri campus as well as the expected V_s of the soil/fill, shale, and limestone. The HVSR method was described along with selected relevant literature to illustrate the wide usage of the HVSR method in seismological and geotechnical engineering applications.

3. SITE DESCRIPTIONS

3.1 Introduction

This chapter presents site descriptions and subsurface conditions at each of the measurement locations around campus. A total of nine test areas were selected around the University of Missouri campus, as shown in Figure 3.1. The sites were widely distributed around the campus and sampled a range of subsurface conditions. A total of 134 boreholes were identified at these nine areas, 81 borehole locations were accessible such that HVSR measurements could be performed (the others were under existing buildings), and 65 measurements were used to develop the relationships presented later in this thesis because 16 locations did not have bedrock identified from borehole investigations. The information at these locations were compiled and used to develop ground-truth data to examine the accuracy of bedrock depth predictions from the HVSR measurements.

The depth to limestone, shale (if present) and SPT refusal were identified from the borehole data and are presented later in this chapter for each study area. Unfortunately, the boring data from the older buildings did not include coordinates of the borehole locations. Therefore, the coordinates shown for each borehole location were determined from visual inspection of the borehole map and identifying the same points on Google Earth imagery using obvious landmarks (e.g. buildings, trees, sidewalks). In most cases, the estimated coordinates are expected to be within about 3 ft of the true borehole locations. For two sites (MUHC and Roy Blunt NextGen Precision Health Building), the HVSR measurements were performed shortly after the drilling was completed, so the actual boring location could be easily identified for the two sites. The HVSR measurements were performed within 1 foot of the boring.

No surveys of ground elevations were performed as part of this study. Ground elevations were supplied on each boring log with an accuracy of about 0.5 ft. For the MUHC and NextGen sites, these elevations were unchanged at the time of the HVSR measurements. For older boring data, the boring log elevations were compared to a Digital Elevation Model (DEM) developed from LiDAR measurements performed in 2015. Any changes in elevations were used to correct the depth to bedrock determined from the borings, as shown in the tables below. Additionally, Google Earth images were used to confirm that no major topographic changes had occurred since the time of the LiDAR measurements. For one site (State Historical Society of Missouri Center for Missouri), the boring data were collected after the LiDAR data. In this case, visual evidence from Google Earth was used and found no obvious changes in ground elevations so no corrections to the boring log elevations were applied. In general, the study area has depth to shale ranging from 6.5 ft to 44.2 ft and the depth to limestone ranging from 8.2 ft to 53.6 ft.

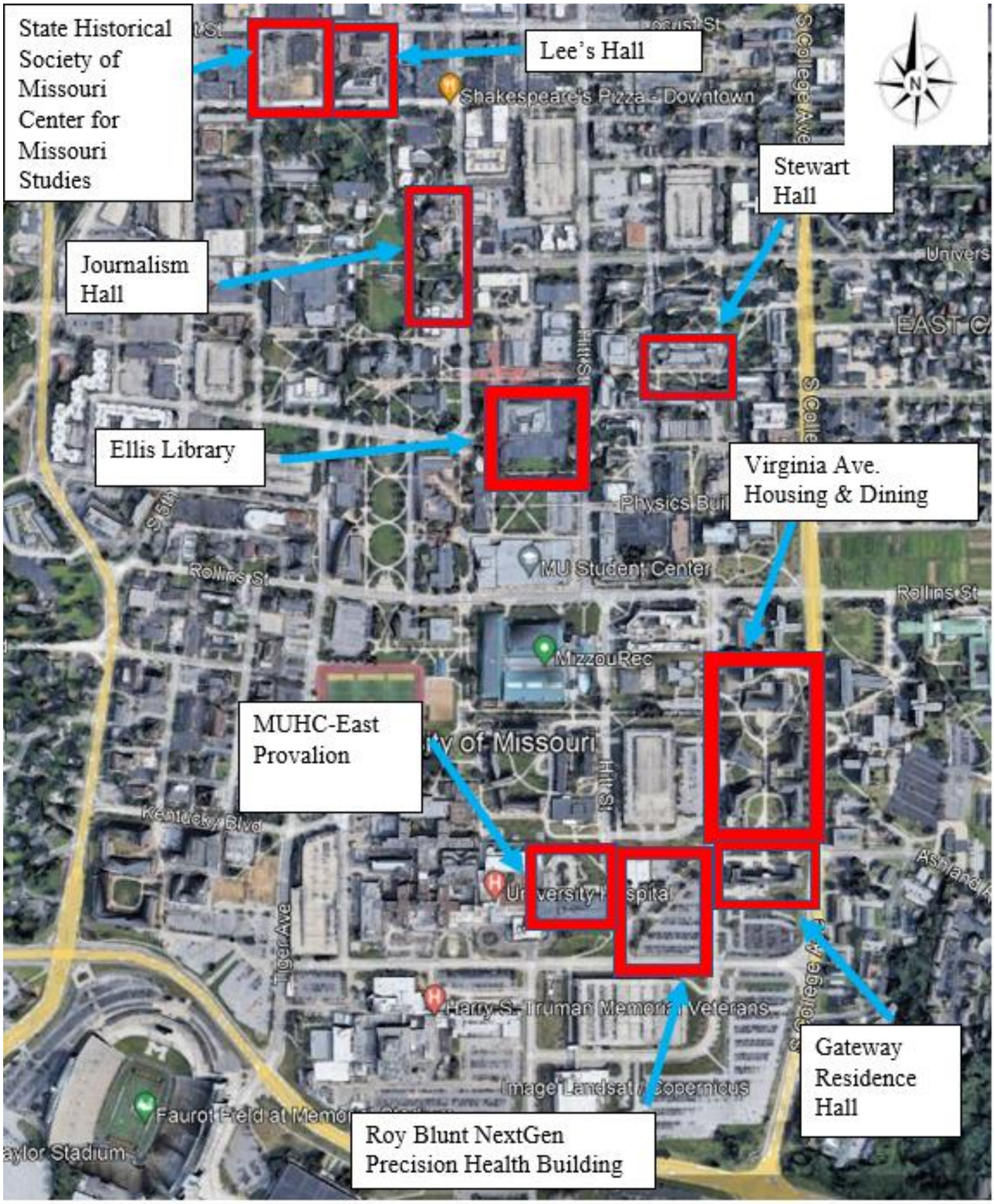


Figure 3. 1 Test areas around the University of Missouri campus where HVSR measurements were performed and ground-truth borehole data was available (Google Earth, 2022).

3.2: Site Descriptions and Subsurface Conditions

3.2.1: Ellis Library Addition

The site investigation of the Ellis Library Addition project was completed in 1983, and included six borehole locations, as shown in Figure 3.2. Four of these borehole locations were accessible for the HVSR measurements, as indicated with red boxes in Figure 3.2. The general subsurface profile at the Ellis Library site consists of fill over stiff clay over rock. The depth to rock is generally uniform across the site, with the thickness of fill and clay above the rock ranging from 36.5 ft. to 41.5 ft. The rock is fractured limestone and there is no indication of shale from the borehole logs at this location. A summary of the rock depth identifications are provided in Table 3.1 and the detailed boring logs can be found in Appendix A-1.

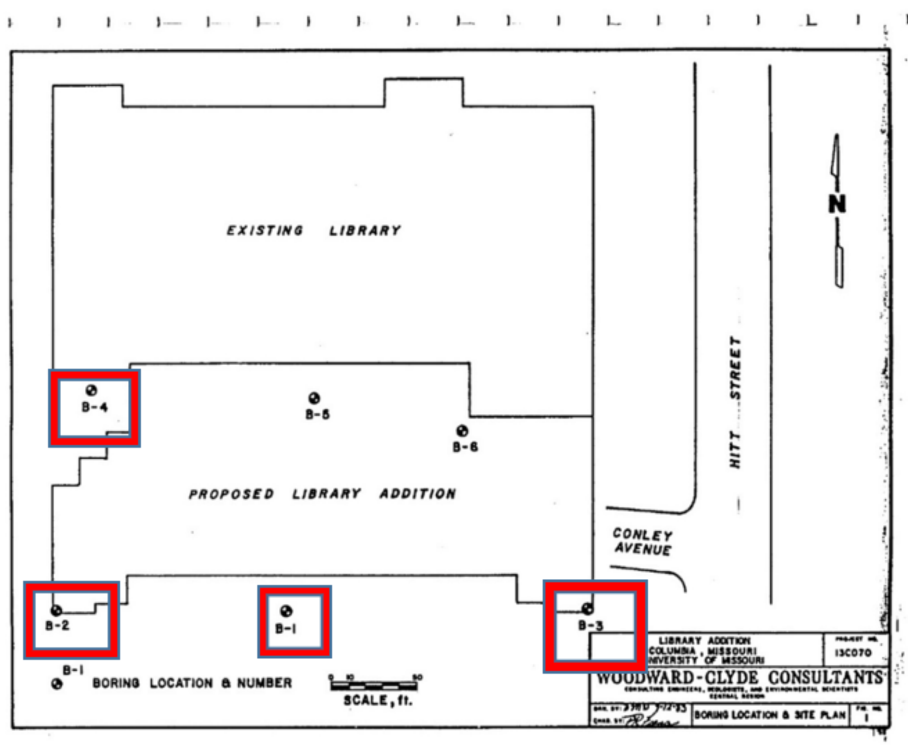


Figure 3. 2 Ellis Library boring plan from 1983 (Aerial View), prepared by Woodward-Clyde Consultants. Red square indicates location of HVSR measurements for this study.

Table 3. 1 Depth to rock summary for Ellis Library boreholes

Borehole Name	Approximate Coordinate	Elevation (Boring) (1983)(ft)	Elevation (LiDAR) (2015)(ft)	Change in Elevation (ft)	Depth to Shale *(ft)	Depth to Limestone (ft)	Depth to Refusal (ft)
B-1	38°56'38.01"N 92°19'35.52"W	765	764.8	0.2	NP	41.3	41.3
B-2	38°56'37.99"N 92°19'37.47"W	765	763.6	1.4	NP	39.6	39.6
B-3	38°56'37.62"N 2°19'33.15"W	764	764.9	-0.9	NP	37.4	37.4
B-4	38°56'39.22"N 92°19'37.20"W	761	759	2	NP	41.5	41.5

*NP indicates not present

3.2.2: Gateway Residence Hall

The site investigation of the Gateway Residence Hall was completed in 2012. A total of eleven boreholes were drilled and five of them were accessible to perform the HVSR measurements, as indicated in Figure 3.3. The general subsurface profile at the Gateway Residence Hall is fill over stiff clay over shale and/or over limestone. The thickness of fill and clay ranges from 23.5 ft to 33ft. The depth to rock varies considerably at the Gateway Residence Hall site, with the depth to shale ranging from 23.5 ft to 39.5 ft and the depth to limestone ranging from 36.5 ft to 41.5 ft. Both shale and limestone are moderately weathered at this site. A summary of the depth to limestone, shale and refusal is presented in Table 3.2 and the detailed boring logs for this site can be found in Appendix A-2.

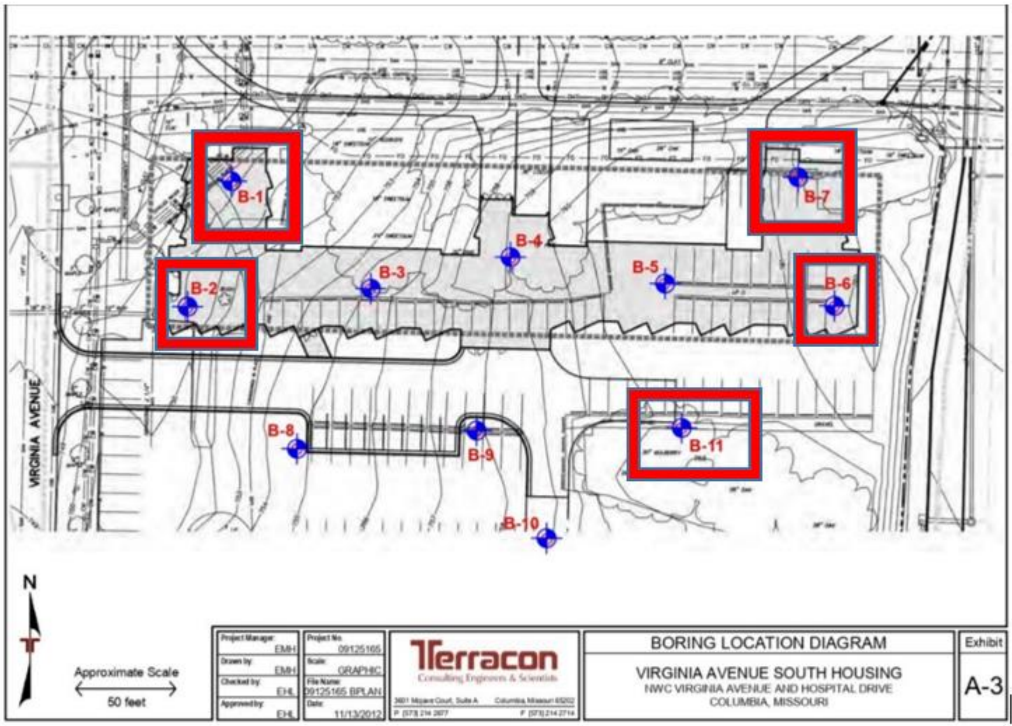


Figure 3. 3 Gateway Residence Hall boring plan (Aerial View), prepared by Terracon Consulting Engineers & Scientists. Red square indicates location of HVSR measurements for this study

Table 3. 2 Depth to rock summary for Gateway Residence Hall boreholes

Borehole Name	Approximate Coordinate	Elevation (Boring) (2012)(ft)	Elevation (LiDAR) (2015)(ft)	Change in Elevation (ft)	Depth to Shale *(ft)	Depth to Limestone (ft)	Depth to Refusal (ft)
B-1	38°56'19.70"N 92°19'24.21"W	750	749	1	NP	25	25.3
B-2	38°56'18.67"N 92°19'24.55"W	750	746.9	3.1	20.4	29.7	39.7
B-6	38°56'18.58"N 92°19'20.57"W	760.5	756.8	3.7	NP	28.8	38.8
B-7	38°56'19.55"N 92°19'20.82"W	761	757.7	3.4	36.1	41.6	44.6
B-11	38°56'18.37"N 92°19'21.64"W	762	760.7	1.3	NP	31.7	32

*NP indicates not present

3.2.3: Donald W. Reynolds Journalism Building

The site investigation of the Donald W. Reynolds Journalism Building was completed in 2004. A total of nine boreholes were drilled and the HVSR measurements were performed on four accessible borehole locations, as indicated with red boxes in Figure 3.4. The general subsurface profile at the Journalism Building is fill over silty clay over shale and/or over limestone. The thickness of fill and clay layers ranges from 21 ft to 27 ft. The depth to shale when present ranges from 25 to 27 ft and the depth to limestone varies considerably from 21 ft to 44 ft. A summary of the depth to limestone, shale and refusal is presented in Table 3.3 and the detailed boring logs for this site can be found in Appendix A-3.

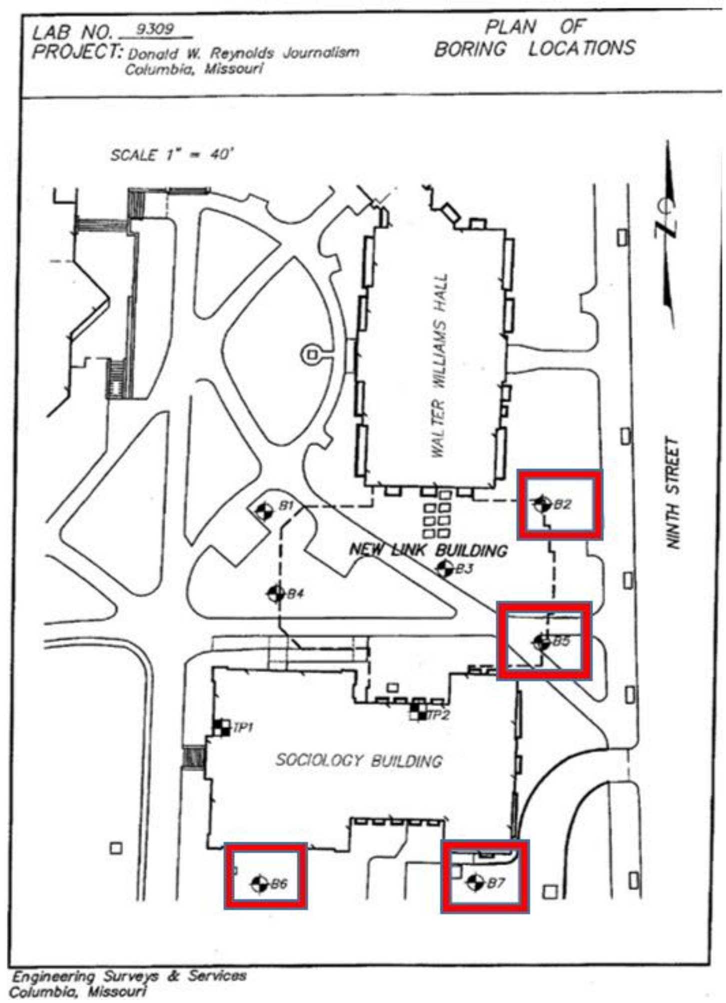


Figure 3. 4 Donald W. Reynolds Journalism Building boring plan (Aerial View), prepared by Engineering Surveys and Services. Red square indicates location of HVSR measurements for this study

Table 3. 3 Depth to rock summary for Donald W. Reynold Journalism Building boreholes

Borehole Name	Approximate Coordinate	Elevation (Boring) (2004)(ft)	Elevation (LiDAR) (2015)(ft)	Change in Elevation (ft)	Depth to Shale *(ft)	Depth to Limestone (ft)	Depth to Refusal (ft)
B-2	38°56'50.38"N, 92°19'39.90"W	740.6	744	-3.4	NP	24.4	24.5
B-5	38°56'49.96"N, 92°19'39.90"W	743.3	743.3	-0.1	25.0	26.1	26.2
B-6	38°56'48.83"N, 92°19'41.48"W	741.3	741.7	-0.4	27.0	43.9	43.9
B-7	38°56'48.82"N, 92°19'40.51"W	742.1	742.6	-0.5	26.0	38	38.1

*NP indicates not present

3.2.4: Lee's Hall

The site investigation of Lee's Hall was completed in 1992. A total of 18 boreholes were drilled and the HVSR measurements for this study were performed at 12 accessible borehole locations, as indicated with red boxes in Figure 3.5. The general subsurface profile at the Lee's Hall is fill over silty clay over shale and/or over limestone. The thickness of fill and silty clay ranges from 8 ft to 20 ft and the depth to rock varies considerably from 8 ft to 20 ft. The rocks are weathered shale and moderately weathered limestone. A summary of the depth to limestone, shale and refusal is presented in Table 3.4 and the detailed boring logs for this site can be found in Appendix A-4.

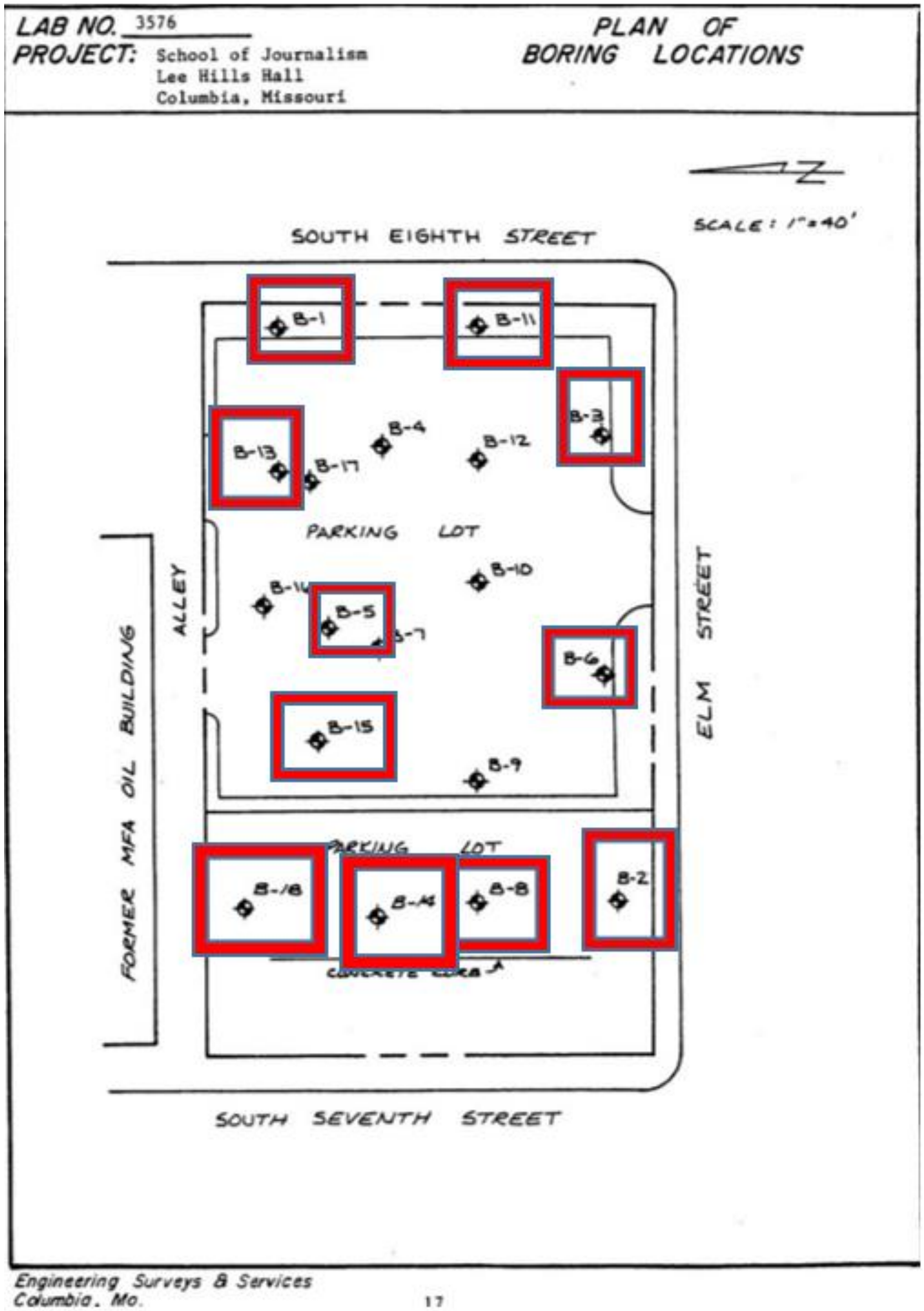


Figure 3. 5 Lee's Hall boring plan (Aerial View), prepared by Engineering Surveys and Services. Red square indicates location of HVSR measurements for this study

Table 3. 4 Depth to rock summary for Lee's Hall boreholes

Borehole Name	Approximate Coordinate	Elevation (Boring) (1992)(ft)	Elevation (LiDAR) (2015)(ft)	Change in Elevation (ft)	Depth to Shale *(ft)	Depth to Limestone (ft)	Depth to Refusal *(ft)
B-1	38°56'55.96"N, 92°19'43.89"W	729.9	729.2	0.7	14.3	15.3	18.5
B-2	38°56'54.97"N, 92°19'46.51"W	N/A	720.7	N/A	9	13	18.2
B-3	38°56'54.91"N, 92°19'44.74"W	725.6	724.5	1.1	13.9	18.9	21.8
B-5	38°56'55.90"N, 92°19'45.32"W	727	724.7	2.3	10.7	13.7	NP
B-6	38°56'54.94"N, 92°19'45.47"W	724.5	723	1.5	NP	12.5	NP
B-8	38°56'55.45"N, 92°19'46.76"W	N/A	718.7	N/A	8	16.5	16.7
B-11	38°56'55.48"N, 92°19'43.89"W	729.3	727.9	1.4	18.1	19.6	NP
B-13	38°56'56.03"N, 92°19'44.55"W	728.9	730.2	-1.3	15.3	24.8	NP
B-14	38°56'55.72"N, 92°19'46.68"W	720.4	718.4	2	6.5	8.2	NP
B-15	38°56'55.92"N, 92°19'45.73"W	726.4	720.3	6.1	7.9	13.4	NP
B-18	38°56'55.99"N, 92°19'46.52"W	719.6	N/A	N/A	8.5	10.2	15

*NP indicates not present

3.2.5: The State Historical Society of Missouri Center for Missouri Studies (SHSMO)

The site investigation of SHSMO was completed in 2016. A total of 17 boreholes were drilled and the HVSR measurements were performed at 9 accessible borehole locations, as indicated in Figure 3.6. The Google Earth Imagery showed no significant change in landscape from 2016 to 2022 so the ground elevation given in the borings were used without correction. The general subsurface profile at the SHSMO is fill over silty clay over shale and/or over limestone. The thickness of fill and silty clay ranges from 9 to 24 ft and the depth to rock ranges from 9 to 24 ft as well. The rocks are weathered shale and weathered limestone at this site. A summary of the depth to limestone, shale and refusal is presented in Table 3.5 and the detailed boring logs for this site can be found in Appendix A-5.

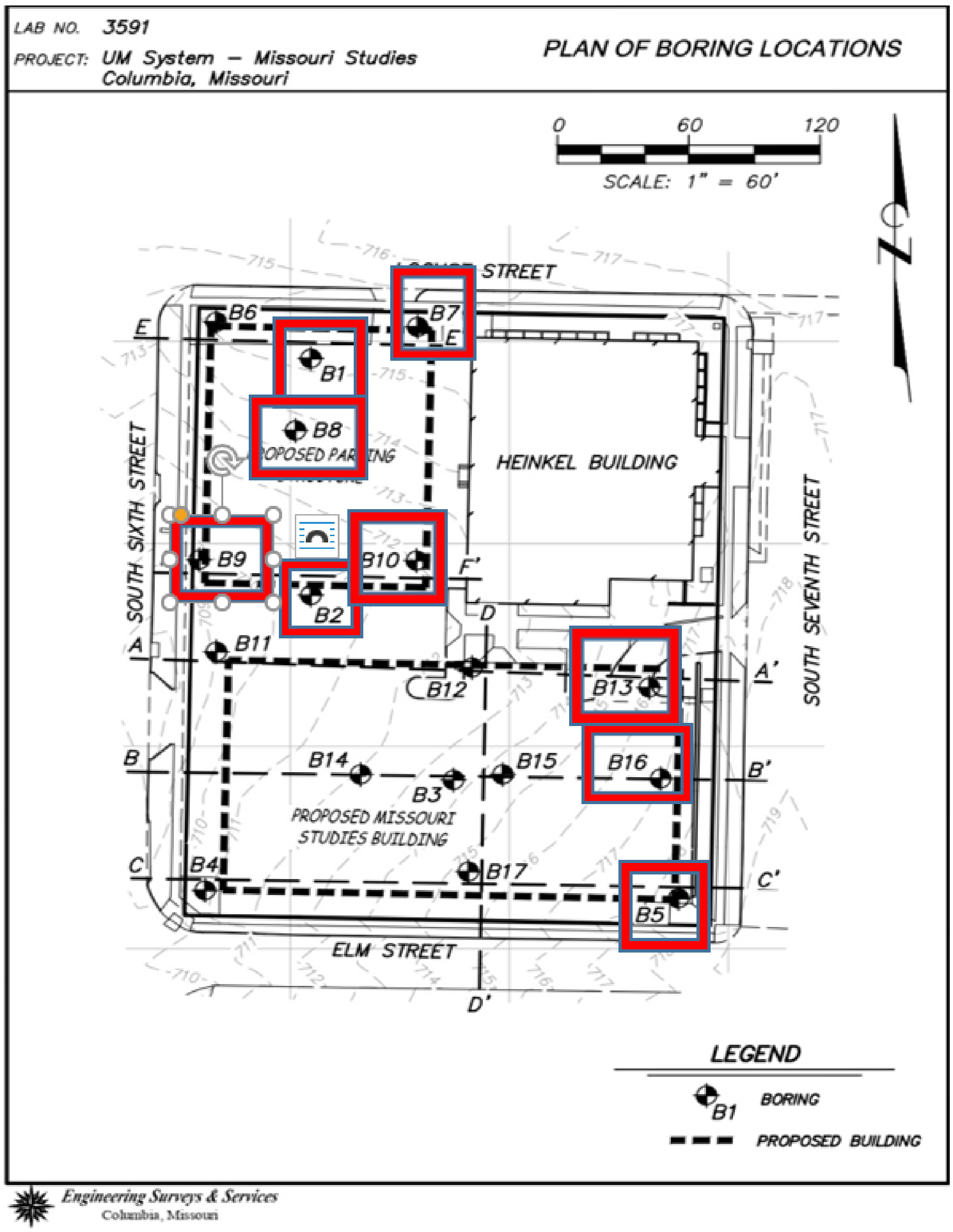


Figure 3. 6 The State Historical Society of Missouri Center for Missouri Studies (SHSMO) boring plan (Aerial View), prepared by Engineering Surveys and Services. Red square indicates location of HVSR measurements for this study

Table 3. 5 Depth to rock summary for The State Historical Society of Missouri Center for Missouri Studies (SHSMO) boreholes**

Borehole Name	Approximate Coordinate	Elevation (Boring) (2016)(ft)	Depth to Shale *(ft)	Depth to Limestone *(ft)	Depth to Refusal *(ft)
B-1	38°56'57.73"N, 92°19'50.01"W	715.3	11.5	16.0	18.0
B-2	38°56'56.53"N, 92°19'49.93"W	710.5	NP	11.0	19.5
B-5	38°56'55.17"N, 92°19'47.70"W	718.7	24.0	NP	NP
B-7	38°56'57.86"N, 92°19'49.67"W	715.5	9.5	17.5	18.0
B-8	38°56'57.19"N, 92°19'50.24"W	713.4	NP	10.5	11.0
B-9	38°56'56.68"N, 92°19'50.61"W	709.9	NP	11.5	12.2
B-10	38°56'56.68"N, 92°19'49.41"W	711.7	NP	11.0	11.5
B-13	38°56'56.15"N, 92°19'47.70"W	716.2	10.0	9.0	12.5
B-16	38°56'55.63"N, 92°19'47.66"W	717.5	10.0	16.0	16.0

*NP indicates not present

**No LiDAR data were available; Google Earth imagery showed no significance change in landscape from 2017 to 2022

3.2.6: Stewart Hall

The site investigation for Stewart Hall was completed in 2015. A total of five boreholes were drilled and three were accessible to perform the HVSR measurements, as marked with red squares in Figure 3.7. The general subsurface profile at Stewart Hall is fill over clay over shale and/or over limestone. The thickness of fill and clay ranges from 36 to 39 ft, while the depth to rock varies considerably from 36 to 51 ft. The rocks are shale and weathered limestone at this site. A summary of the depth to limestone, shale and refusal is presented in Table 3.6 and the detailed boring logs for this site can be found in Appendix A-6.

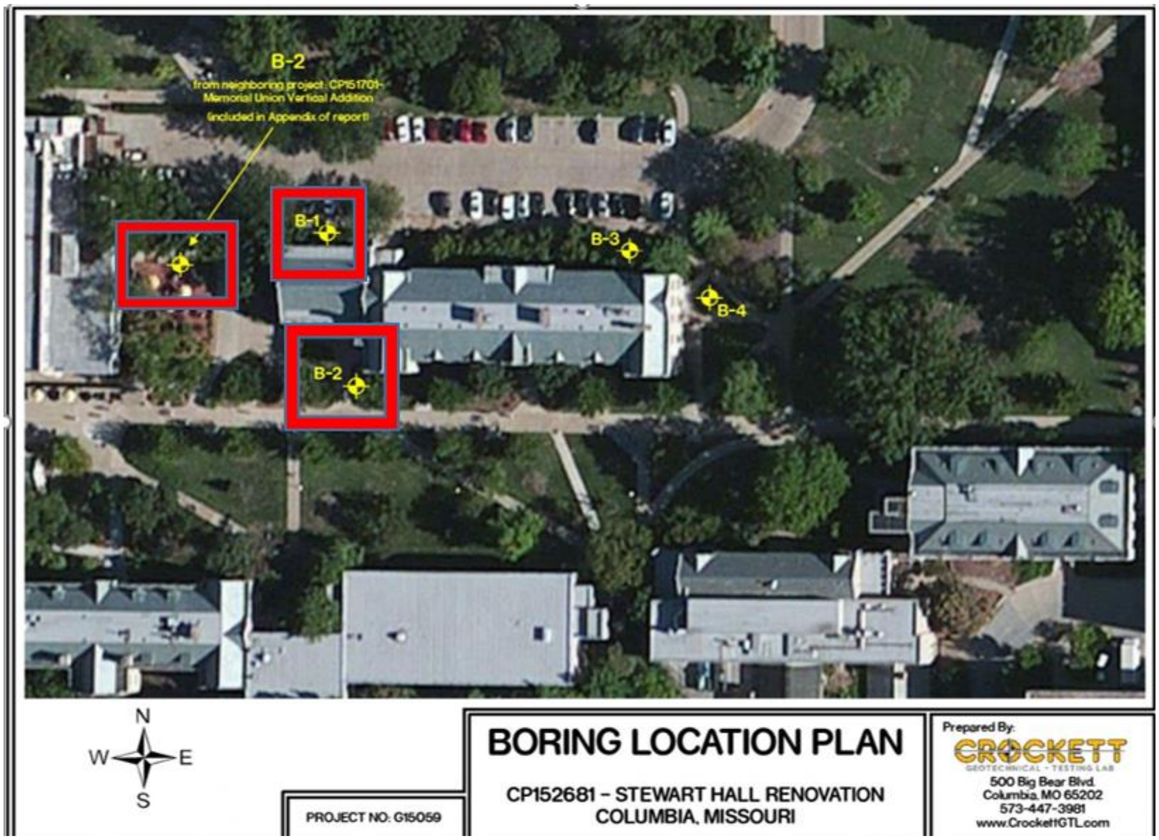


Figure 3. 7 Stewart Hall boring plan (Aerial View), prepared by Crockett. Red square indicates location of HVSR measurements for this study

Table 3. 6 Depth to rock summary for Stewart Hall boreholes

Borehole Name	Approximate Coordinate	Elevation (Boring) (2015)(ft)	Elevation (LiDAR) (2015)(ft)	Change in Elevation (ft)	Depth to Shale (ft)	Depth to Limestone *(ft)	Depth to Refusal *(ft)
B-1	38°56'43.05"N, 92°19'27.70"W	764	762.8	1.2	36.8	50.3	50.8
B-2	38°56'42.08"N, 92°19'27.60"W	762	762.9	-0.9	39.9	40.9	41.4
B-2*	38°56'42.87"N, 92°19'28.82"W	761	761	0	36.0	NP	NP

*NP indicates not present

3.2.7: MUHC East Pavilion

The site investigation of MUHC East Pavilion was completed in 2020. A total of 22 boreholes were drilled and HVSR measurements were performed at thirteen accessible locations, as indicated in Figure 3.8. The HVSR measurements were performed within ± 1 foot of borehole locations right after the site investigation where borehole locations were obvious. Therefore, no corrections to the ground elevations from the borings were necessary. The general subsurface profile at MUHC is fill over stiff clay over shale and/or over limestone with the thickness of fill and clay ranging from 27 to 38 ft and the depth to rock varying drastically from 27 ft to 54 ft. The rocks are severely weathered shale and fractured limestone. A summary of the depth to limestone, shale and refusal is presented in Table 3.7 and the detailed boring logs for this site can be found in Appendix A-7.

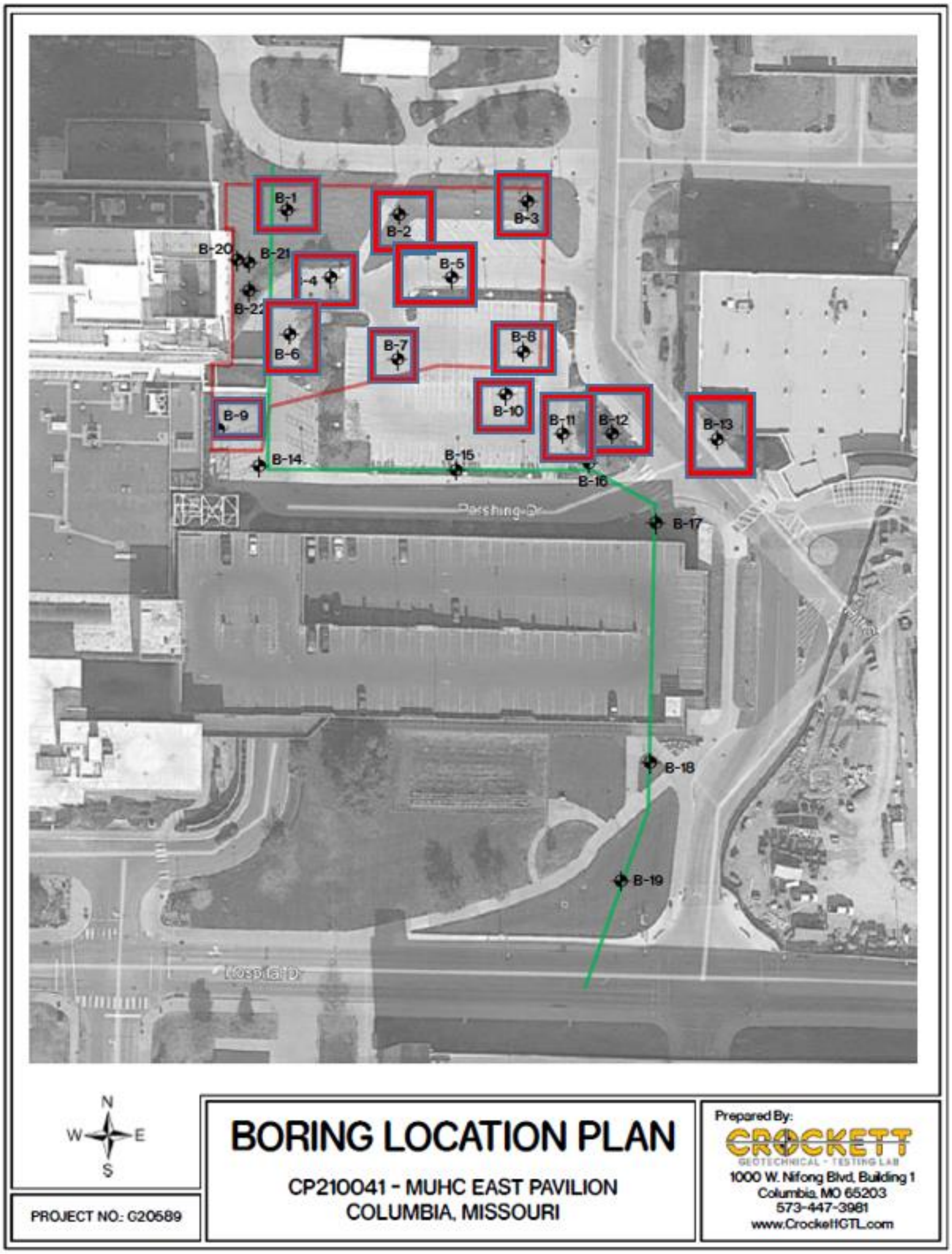


Figure 3. 8 MUHC East Pavilion boring plan (Aerial View), prepared by Crockett. Red square indicates location of HVSR measurements for this study

Table 3. 7 Depth to rock summary for MUHC East Pavilion boreholes**

Borehole Name	Approximate Coordinate	Depth to Shale (ft)	Depth to Limestone (ft)	Depth to Refusal (ft)
B-1	38°56'20.68"N, 92°19'34.64"W	33.0	39.0	39.0
B-2	38°56'20.58"N, 92°19'33.60"W	33.0	50.0	53.6
B-3	38°56'20.71"N, 92°19'32.23"W	27.0	53.6	53.6
B-4	38°56'20.12"N, 92°19'34.21"W	25.0	33.0	33.0
B-5	38°56'20.17"N, 92°19'33.13"W	24.0	47.5	47.5
B-6	38°56'19.77"N, 92°19'34.66"W	24.0	33.0	33.0
B-7	38°56'19.47"N, 92°19'33.62"W	33.0	39.0	39.0
B-8	38°56'19.53"N, 92°19'32.41"W	25.0	28.5	28.5
B-9	38°56'19.13"N, 92°19'35.19"W	25.5	49.6	48.6
B-10	38°56'19.32"N, 92°19'32.61"W	38.8	33.7	33.7
B-11	38°56'19.07"N, 92°19'32.24"W	28.0	35.0	40.0
B-12	38°56'19.01"N, 92°19'31.75"W	NP**	27.5	27.5
B-13	38°56'17.73"N, 92°19'26.65"W	NP**	18.5	18.8

**NP indicates not present

* No LiDAR data, HVSR measurements were performed right after drilling when borehole locations could be observed and ground elevations were unchanged

3.2.8: Roy Blunt NextGen Precision Health Building (NextGen)

The geotechnical investigation at NextGen was completed in 2018. A total of 22 boreholes were drilled and HVSR measurements were performed at thirteen accessible locations, as marked in Figure 3.9. The HVSR measurements were performed within $\pm$ 1 foot of borehole locations soon after the site investigation, where borehole location could be observed. Therefore, no corrections to the elevations in the boring logs were necessary. The general subsurface profile at the NextGen site is fill over stiff clay over shale and/or over limestone. The thickness of fill and clay ranges from 16 to 24 ft and the depth to rock varies drastically from 16 to 52 ft. The rocks are weathered shale and intact limestone at this site. A summary of the depth to limestone, shale and refusal is presented in Table 3.9 and the detailed boring logs for this site can be found in Appendix A-9.

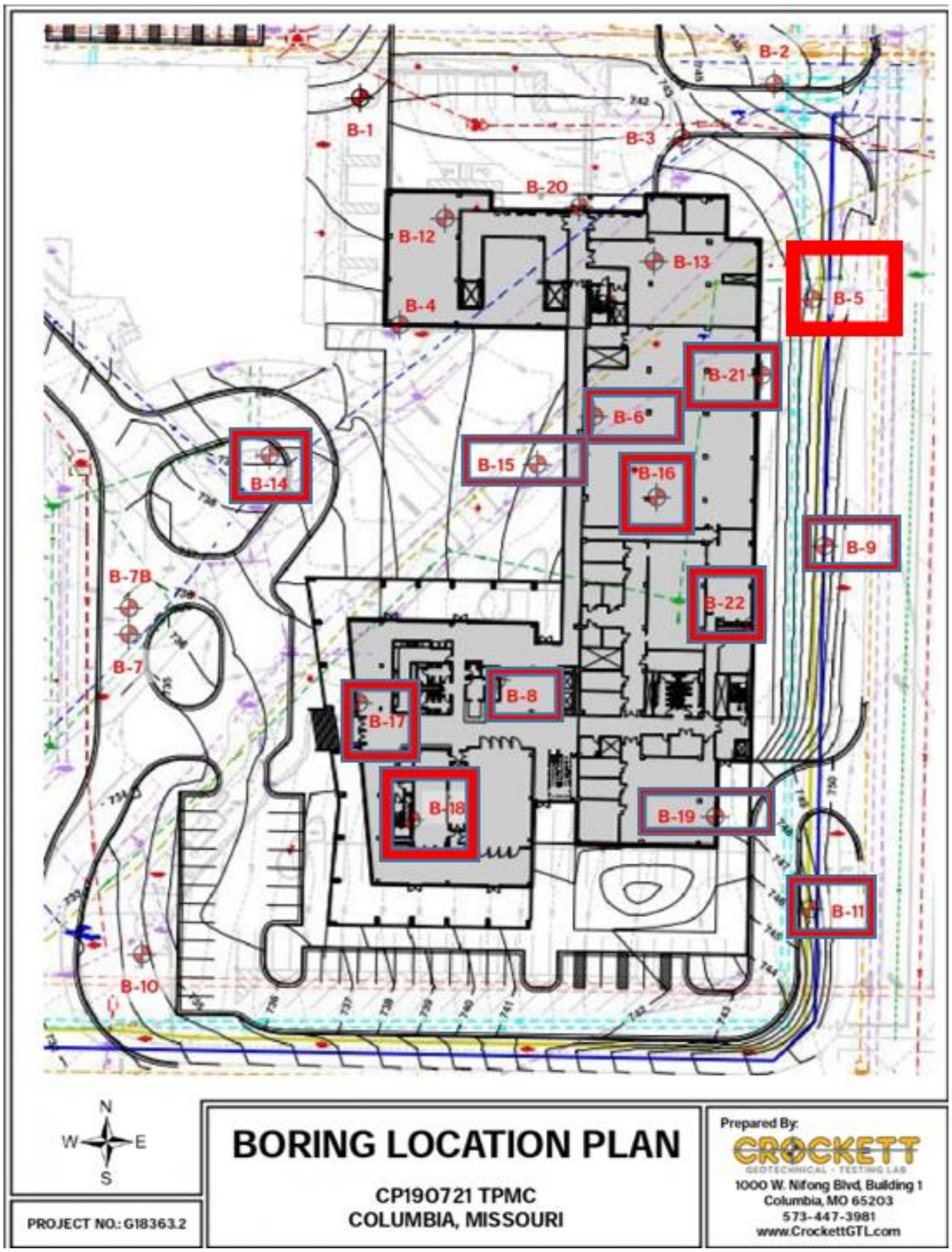


Figure 3. 9 Roy Blunt NextGen Precision Health Building (NextGen) boring plan (Aerial View), prepared by Crockett. Red square indicates location of HVSR measurements for this study

Table 3. 8 Depth to rock summary for Roy Blunt NextGen Precision Health Building (NextGen) boreholes**

Borehole Name	Approximate Coordinate	Depth to Shale *(ft)	Depth to Limestone *(ft)	Depth to Refusal *(ft)
B-5	38°93‘86.33"N, 92°32'38.72°W	23.5	NP	NP
B-6	38°93'84.94"N, 92°32'42.70"W	23	25.5	26.0
B-8	38°93'81.23"N, 92°32'44.30"W	NP	16.5	17.0
B-9	38°93'83.04"N, 92°32'38.75"W	25	NP	NP
B-11	38°93'78.02"N, 92°32'38.78"W	26	NP	NP
B-14	38°93'84.04"N, 92°32'47.92"W	16	20.5	21.0
B-15	38°93'84.01"N, 92°32'44.00"W	18.0	22.5	23.0
B-16	38°93'83.57"N, 92°32'42.03"W	21.0	32.5	33.0
B-17	38°93'80.58"N, 92°32'46.46"W	NP	17.0	18.6
B-18	38°93'79.43"N, 92°32'45.56"W	NP	17.5	18.7
B-19	38°93'79.34"N, 92°32'40.79"W	NP	24	24.5
B-21	38°93'85.06"N, 92°32'39.73"W	23.0	52.0	52.5
B-22	38°93'85.06"N, 92°32'39.73"W	23.0	52.0	52.5

*NP indicates not present

**No LiDAR data were available, HVSR measurements were performed right after drilling when borehole locations could be observed and ground elevations were unchanged

3.2.9: Virginia Housing and Dining

The geotechnical survey at Virginia Housing and Dining was completed in 2001. A total of 26 boreholes were drilled and the HVSR measurements were performed at 13 locations, only three locations encountered rock and they are indicated with red square in Figure 3.10. The Google Earth imagery showed no significance change in landscape from 2001 to 2022. The general subsurface profile is fill over clay over shale or limestone at the Virginia Housing and Dining. The depth to rock shows only small variations at the three locations with a range from 39 to 44 ft. The rocks are weathered shale or weathered limestone at this site. A depth to rock summary is presented in Table 3.9 and the detailed boring log can be found in the Appendix A-9.

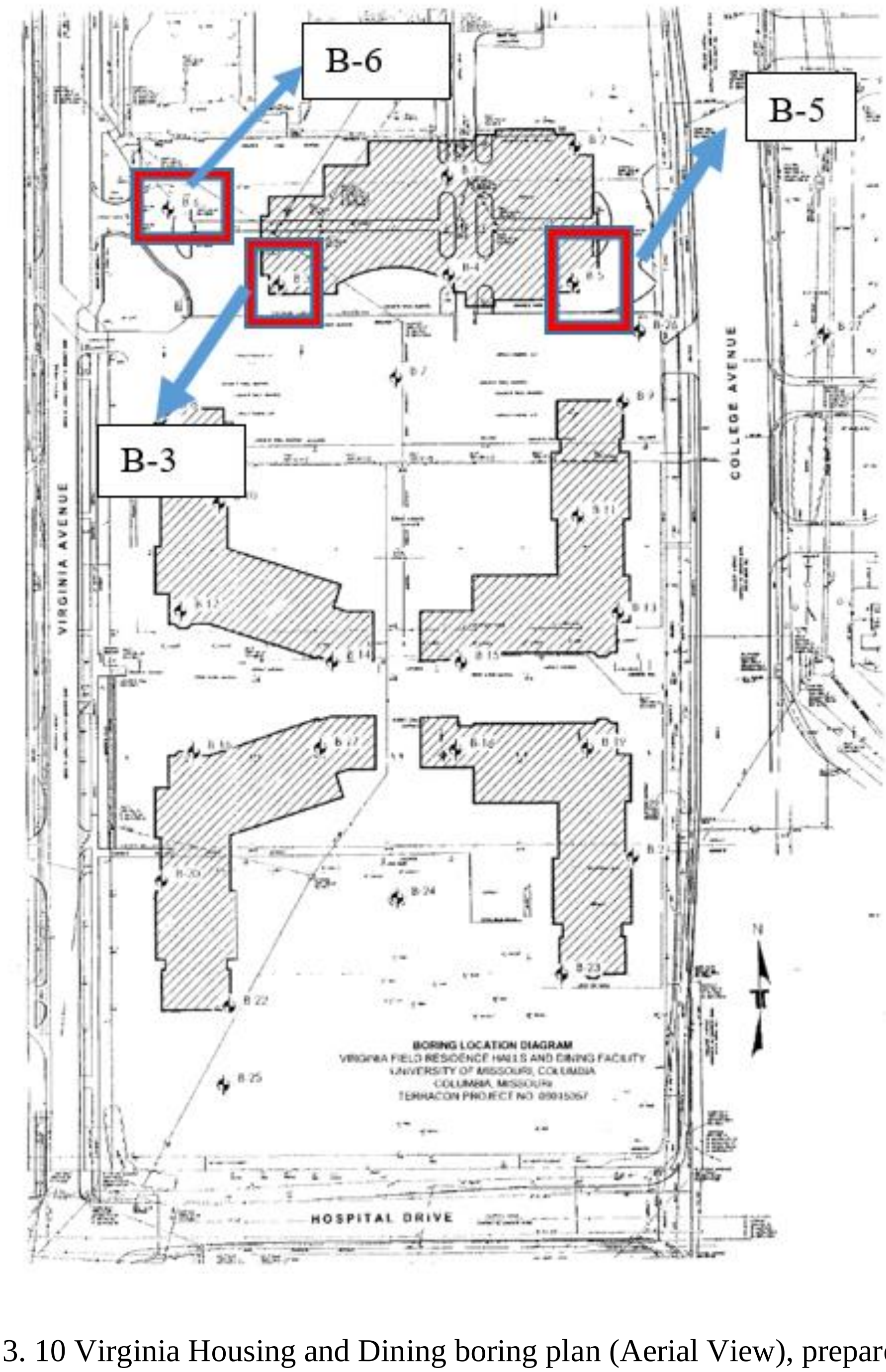


Figure 3. 10 Virginia Housing and Dining boring plan (Aerial View), prepared by Terracon (Red square indicates location of HVSR measurements)

Table 3. 9 Depth to rock summary for Virginia Housing and Dining boreholes

Borehole Name	Approximate Coordinate	Elevation (boring) (2001)(ft)	Elevation (LiDAR) (2015)(ft)	Change in Elevation (ft)	Depth to Shale (ft)	Depth to Limestone (ft)*	Depth to Refusal (ft)
B-3	38°56'26.60"N, 92°19'23.56"W	766	768	0	39	NP	42.2
B-5	38°56'26.63"N, 38°56'26.63"N	769	770	1	44.2	NP	44.2
B-6	38°56'26.95"N, 92°19'24.17"W	763	763	0	N/A	38.5	38.5

*NP indicates not present

3.3: Rocheport Bridge Approach Site – Field Verification Study

The project is located about 10 miles west of the University of Missouri campus. There was a need to estimate the depth to rock for a region located north-west of the existing I-70 route. Settlement calculations of the soil over the rock will be performed and the thickness of the soil is an important input. Limestone outcrops were evident and nearby borings showed shallow limestone with no shale. However, it was not clear how deep the limestone interface plunged below the surface at the locations off the I-70 alignment. Rough estimates of a few feet to several tens of feet were equally likely.

Drill rigs could not easily access the site due to the difficult terrain, so refraction measurements were performed by another contractor. The refraction measurements required cutting line through vegetation, deployment of numerous sensors and use of an active source. The HVSR measurements were performed in an afternoon to supplement the drilling and refraction information. No information was provided prior to the HVSR interpretation. A total of 6 HVSR measurements were performed along the line where the refraction measurements were performed. Figure 3.11 shows the approximate location where the HVSR measurements and refraction measurements were performed. The results of the HVSR measurements are discussed in Chapter 5.

Figure 3. 11 The approximate location where six HVSR measurements were performed (star) and the refraction measurement (red solid-line).

3.4: Summary

In this chapter, the general subsurface profile at each site was described briefly. The sites selected sample a variety of subsurface conditions and a wide range of depth to bedrock. A total of 81 HVSR measurements were performed at the accessible borehole locations, 65 measurements are used to develop the relationships for the University of Missouri campus that are presented in Chapter 5, The other six measurements were a verification study. In addition, a summary table of approximate borehole location, ground elevation, the depth to shale, limestone and refusal was presented for each site.

4. METHODS

4.1 Introduction

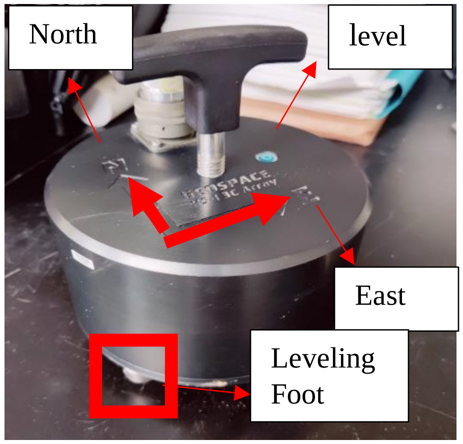
HVSR measurements were performed at the locations described in Chapter 3. In this chapter, the procedures used for the HVSR data collection, processing and interpretation are described. A summary of the data collection procedures, including equipment, location, measurement date, surface condition, and ambient noise environment are presented, followed by descriptions of the HVSR data processing procedures. Lastly, the procedures used to interpret the HVSR data, as well as the borehole data are described.

4.2 HVSR Data Collection Procedures

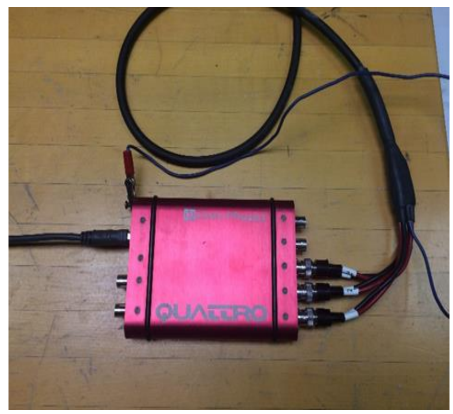
HVSR measurements were recorded using a three-component seismometer (Geospace Model type HS-1 3C Array), as shown in Figure 4.1a. This device consists of three geophones, each with a resonant frequency of 2 Hz (one vertical and two horizontal). To perform the measurement, the three-component seismometer was placed on the ground near each borehole location. For cases where the borehole location was still visible, the sensor was placed within 1 ft of the borehole location. For cases where the location was identified from a boring map, the sensor was placed as close as possible to the estimated borehole location, which is likely to be within about 3 ft in most cases. The sensor was either placed directly on asphalt pavement or on soil, as shown in Figure 4.1b and 4.1c, respectively. After placement, the device was carefully leveled by adjusting the feet of the sensor and monitoring a bubble level on the sensor. The two horizontal geophones were oriented in the north/south and east/west directions for all measurements. All measurements were recorded using a four-channel Data Physics "Quattro" dynamic signal analyzer (Figure 4.1d) and SignalCalc Ace 2.4 software. The

“Quattro” is powered directly from a laptop computer and the software was set-up to record ambient noise over a 10-minute period of time. The data collection set-up window used in the SignalCalc software is presented in Figure 4.2. In the figure, channels 1, 2, and 3 are marked, indicating the recordings from the Vertical, North, and East oriented geophones, respectively. The voltage (V) range for the ambient noise was set to the lowest setting of 0.1 Volts. The frequency range was set to 50 Hz, the sampling frequency was set to 128 Hz, and the measurement duration was set to 600 sec (10 mins) for all measurements. An example of an ambient noise record is presented in Figure 4.3. Table 4.1 summarizes the location name, date, surface condition, and ambient noise environment for each measurement.

It is important to note that the seismometer has a dimension of 6 in. by 6 in. by 3.5 in. and only weighs about 3.5 kg. Thus, it is very portable and can be carried by a single person and deployed rapidly with measurements collected within 15 mins. Also, it does not require an active source, which also contributes to the portability and efficiency of the technique.



(a) (b)



(c) (d)

Figure 4.1 The three-component seismometer (a), HVSR measurements collected on the top of soil (b) and pavement (c), the four-channel Data Physics “Quattro” dynamic signal analyzer (d).

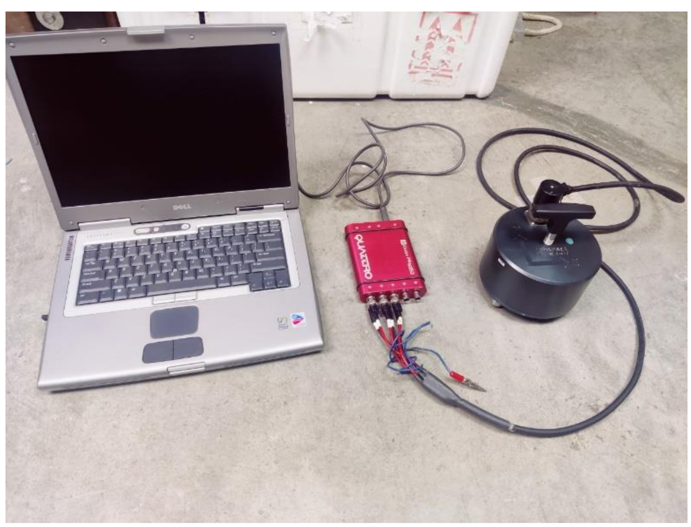


Figure 4.2 The testing equipment for HVSR measurement

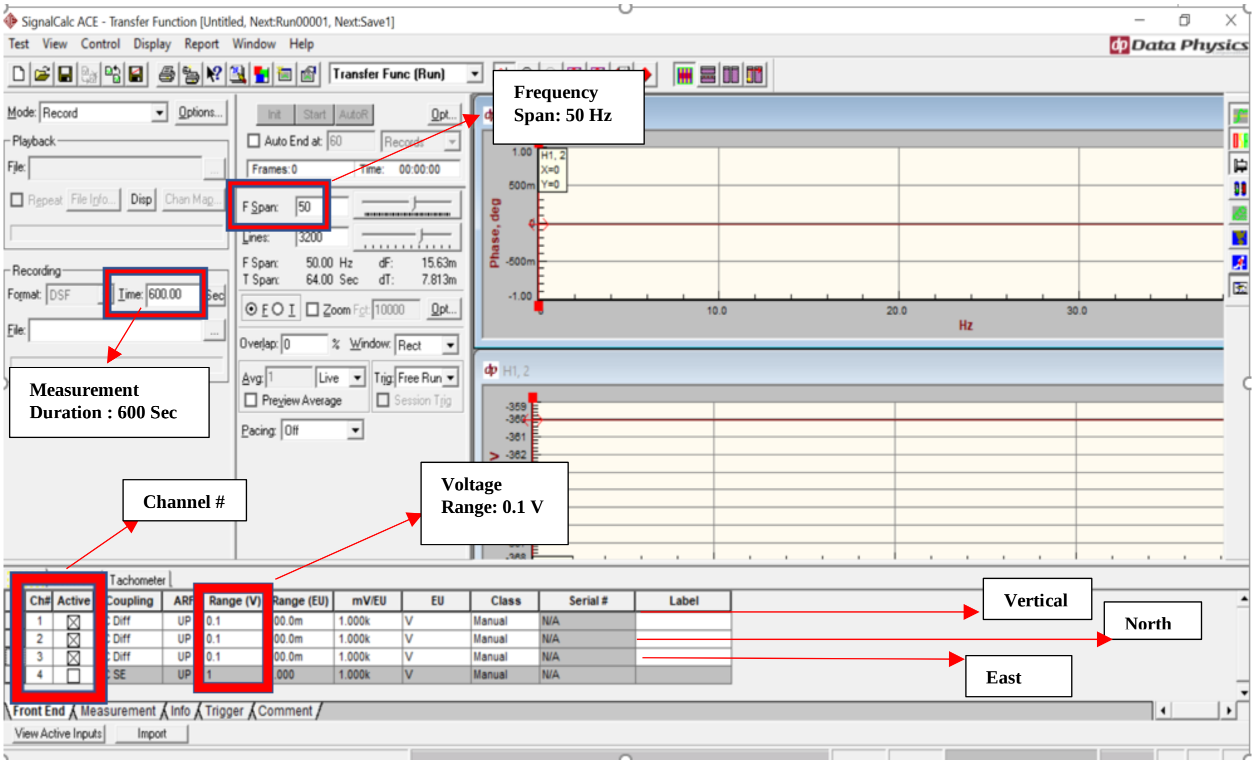


Figure 4. 3 The SignalCalc Ace 2.4 interface set-up window for ambient noise collection. All important parameters are squared.

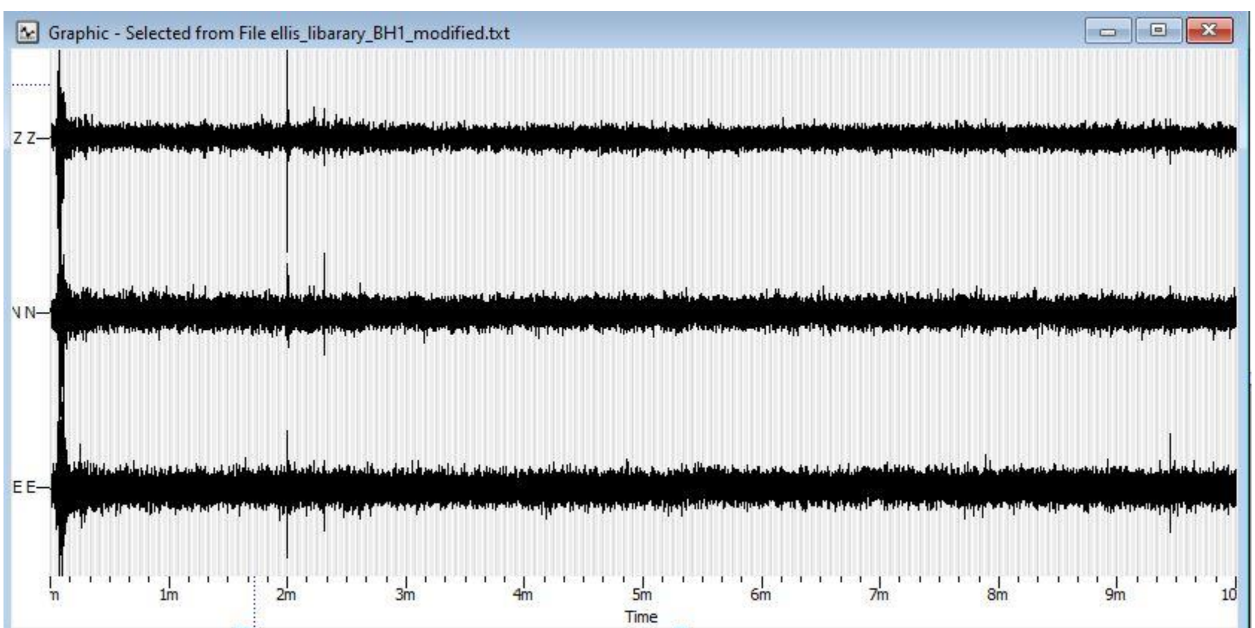


Figure 4. 4 An example of recorded ambient time record from the Vertical (Z), North (N) and East (E) directions at Ellis Library BH 1 location.

Table 4. 1 Summary of the date and conditions for all HVSR measurement locations.

Location Name	Measurement Date	Surface Condition	Noise Environment		Location Name	Measuremen t Date	Surface Condition	Noise Environment
Ellis BH-1	11/20/2020	Soil	No traffic		SHSMO BH-1	11/23/2022	Pavement	Light traffic
Ellis BH-2	11/20/2020	Pavement	No traffic		SHSMO BH-2	11/23/2022	Pavement	Light traffic
Ellis BH-3	11/20/2020	Soil	No traffic		SHSMO BH-5	11/23/2022	Pavement	Light traffic
Ellis BH-4	11/20/2020	Brick	No traffic		SHSMO BH-7	11/23/2022	Pavement	Light traffic
Gateway BH-1	11/21/2020	Pavement	Light traffic		SHSMO BH-8	11/23/2022	Pavement	Light traffic
Gateway BH-2	11/21/2020	Soil	Light traffic		SHSMO BH-9	11/23/2022	Pavement	Light traffic
Gateway BH-6	11/21/2020	Pavement	Light traffic		SHSMO BH-10	11/23/2022	Pavement	Light traffic
Gateway BH-7	11/21/2020	Pavement	No traffic		SHSMO BH-13	11/23/2022	Pavement	Light traffic
Gateway BH-11	11/21/2020	Soil	No traffic		SHSMO BH-16	11/23/2022	Pavement	Light traffic
Journalism BH-2	11/21/2020	Pavement	Light traffic		Stewart BH1	11/20/2020	Pavement	No traffic
Journalism BH-5	11/21/2020	Pavement	Light traffic		Stewart BH2	11/20/2020	Pavement	No traffic
Journalism BH-6	11/21/2020	Pavement	Light traffic		Stewart BH2'	11/20/2020	Brick	No traffic
Journalism BH-7	11/21/2020	Soil	Light traffic		MUHC BH-1	3/10/2021	Soil	Light traffic
Lee's Hall BH-1	11/22/2022	Pavement	High traffic		MUHC BH-2	3/10/2021	Soil	Light traffic
Lee's Hall BH-2	11/22/2022	Soil	Light traffic		MUHC BH-3	3/10/2021	Soil	Light traffic
Lee's Hall BH-3	11/22/2022	Pavement	High traffic		MUHC BH-4	3/10/2021	Pavement	Light traffic
Lee's Hall BH-5	11/22/2022	Pavement	No traffic		MUHC BH-5	3/10/2021	Pavement	Light traffic
Lee's Hall BH-6	11/22/2022	Pavement	Light traffic		MUHC BH-6	3/10/2021	Pavement	Light traffic
Lee's Hall BH-8	11/22/2022	Soil	Light traffic		MUHC BH-7	3/10/2021	Pavement	Light traffic
Lee's Hall BH-11	11/22/2022	Pavement	Light traffic		MUHC BH-8	3/10/2021	Pavement	Light traffic
Lee's Hall BH-13	11/22/2022	Pavement	No traffic		MUHC BH-9	3/10/2021	Pavement	Light traffic
Lee's Hall BH-14	11/22/2022	Pavement	No traffic		MUHC BH-10	3/10/2021	Pavement	Light traffic
Lee's Hall BH-15	11/22/2022	Pavement	No traffic		MUHC BH-11	3/10/2021	Pavement	Light traffic
Lee's Hall BH-18	11/22/2022	Pavement	No traffic		MUHC BH-12	3/10/2021	Pavement	Light traffic

Table 4.1 Continued.

Location Name	Measurement Date	Surface Condition	Noise Environment
MUHC BH-13	3/10/2021	Pavement	Light traffic
Nextgen BH-5	5/10/2019	Pavement	No traffic
Nextgen BH-6	5/10/2019	Pavement	No traffic
Nextgen BH-8	5/10/2019	Pavement	No traffic
Nextgen BH-9	5/10/2019	Pavement	No traffic
Nextgen BH11	5/10/2019	Pavement	No traffic
Nextgen BH14	5/10/2019	Pavement	No traffic
Nextgen BH15	5/10/2019	Pavement	No traffic
Nextgen BH16	5/10/2019	Pavement	No traffic
Nextgen BH17	5/10/2019	Pavement	No traffic
Nextgen BH18	5/10/2019	Pavement	No traffic
Nextgen BH19	5/10/2019	Pavement	No traffic
Nextgen BH21	5/10/2019	Pavement	No traffic
Nextgen BH22	5/10/2019	Pavement	No traffic
Virginia BH-3	11/23/2022	Pavement	No traffic
Virginia BH-5	11/23/2022	Pavement	No traffic
Virginia BH-6	11/23/2022	Pavement	No traffic

4.3 HVSR Data Processing Procedures

The HVSR data processing procedures involve dividing the ambient noise record into many short individual time windows (Fig. 4.5) and applying the Fast Fourier Transform (FFT) to each windowed time record. The FFT transforms the ambient noise record from the time domain into the frequency domain. For each window, two horizontal spectra are merged using the squared-average method, which is taken as the square root of the sum of the squared values from the horizontal spectra. This resulting squared-average horizontal spectrum is divided by the vertical spectrum, to produce the HVSR spectrum for each window. The multiple HVSR spectra from individual windows are then plotted together and an average HVSR value is calculated for each frequency, resulting in a single average HVSR plot, as shown in Fig 4.6.

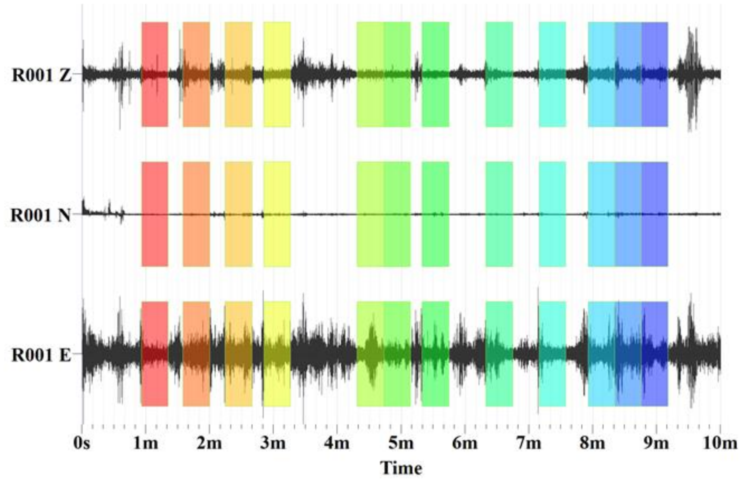


Figure 4. 5 The HVSR ambient noise record showing the auto selected number of windows (12 windows) for Roy Blunt NextGen Precision Health Building BH 14.

In this study, HVSR plot generation and data interpretation for all ambient noise records were performed using the Geopsy software v3.2.1, which was developed by the SESAME (**S**ite **E**ffect**S** assessment using **AM**bient **E**xcitation) Project. The Geopsy H/V toolbox (i.e. HVSR) has automated and manual windows selections, various parameters to process the ambient noise data, and a display of the processed results. All processing parameters were selected and used in accordance with the recommended values from the Geopsy User Guideline (2005). The parameters used in this study are presented in Table 4.2 and the explanations for choosing these parameters are provided below.

The window length in Table 4.2 refers to the time duration in seconds used to calculate individual HVSR curves. Geopsy guidelines recommend a window length of at least 5 seconds for recordings performed with a 2-Hz geophone. In Table 4.2, the terms STA (short term average) and LTA (long term average) refer to time durations used to calculate the average level of signal amplitude over a brief period of time and a long period of time, respectively. The ratio of STA/LTA is used in an anti-triggering algorithm to filter out transient noise such as pedestrian footsteps or close traffic, as shown in Figure 4.5. Geopsy guidelines recommend using STA values of around 0.5 to 2 s and LTA of several tens of seconds. Additionally, the Konno & Omachi smoothing algorithm was used to remove rapid fluctuations with a smoothing bandwidth constant of 40, as recommended in the Geopsy guidelines. Also, a cosine taper was used to overcome any unexpected discontinuities that may affect the Fourier spectrum. A frequency range of 3 to 30 Hz was selected for display, because 3 Hz is above the operating range of a 2 Hz geophone and 30 Hz is the upper bound of the expected site resonance frequencies. Once all the desired parameters were loaded into the H/V toolbox, the average, smoothed HVSR plot was calculated. An example of the smoothed HVSR spectrum is presented in Figure 4.6.

Table 4. 2 Default Values for Processing Parameters.

Chosen processing parameters	
Window Length	25 seconds
STA	1 second
LTA	30 seconds
Min STA/LTA	0.2
Max STA/LTA	2.5
Anti-triggering on Raw Signal	Yes
Smoothing	Konno & Omachi
Smoothing Bandwidth Constant	40
Tapering	Cosine
Horizontal Component Merge	Square Average
Display Frequency Range	3 to 30 Hz

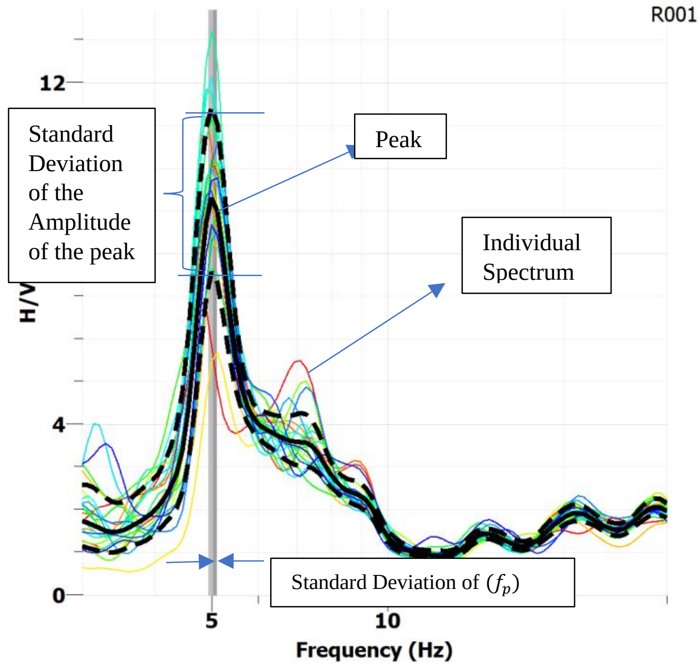


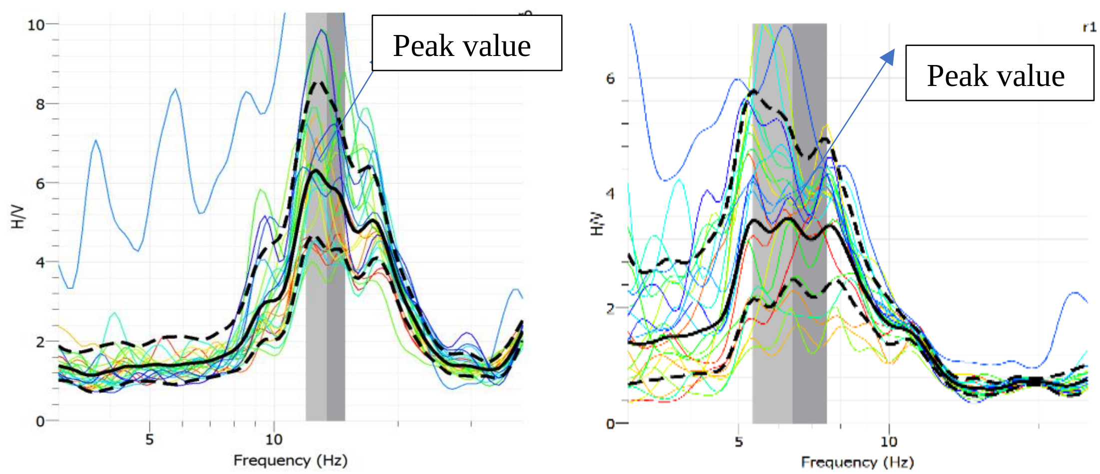
Figure 4. 6 Spectral HVSR ratio developed from the squared average method using 600 s (10 min) time window of ambient noise recorded at the Ellis Library BH1 location. The mean (black continuous line) and standard deviation are indicated (black dashed line). Each colored curve is the HVSR curve for an individual window. In addition, the standard deviation of peak frequency (f_p) is indicated (grey bar).

4.4 Data Interpretation Procedures

4.4.1 Interpretation of HVSR data

To meet the primary objective of this study, the data interpretation involved identifying the frequency of the peak value in all HVSR plots. These values were used to develop a local relationship between the measured frequency and depth to bedrock for the campus of the University of Missouri. These relationships are presented in Chapter 5.

In many cases, a clear, single peak is evident from HVSR measurements, as shown in Figure 4.6. For cases, where multiple peaks are observed the primary peak is chosen to be the highest value of the peaks, as shown in Figure 4. 7. The uncertainly of this peak is indicated by the standard deviation of the frequency of this peak, as indicated by the grey bands in Figure 4.7.



(a) (b)

Figure 4. 7 The HVSR plot with a narrow standard deviation from Lee's Hall BH 8, where two peak frequencies were observed (a). The HVSR plot with a wide standard deviation from Journalism Building BH 6, where three peak frequencies were observed (b).

A secondary interpretation of the data involved identifying various features of the HVSR plots apart from the peak, as shown in Figure 4.8. These attributes including the frequency of trough (f_z), the standard deviation of the amplitude of the trough (STD, A_z), the standard deviation of the amplitude of the peak (STD, A_p), the standard deviation of frequency of the peak (STD, f_p), the amplitude ratio between peak and trough (A_p/A_z), and the frequency ratio between peak and trough (f_p/f_z). These attributes were used to investigate if certain subsurface profile conditions could be identified from HVSR attributes, as shown for simple profiles in the work of Tuan (2009).

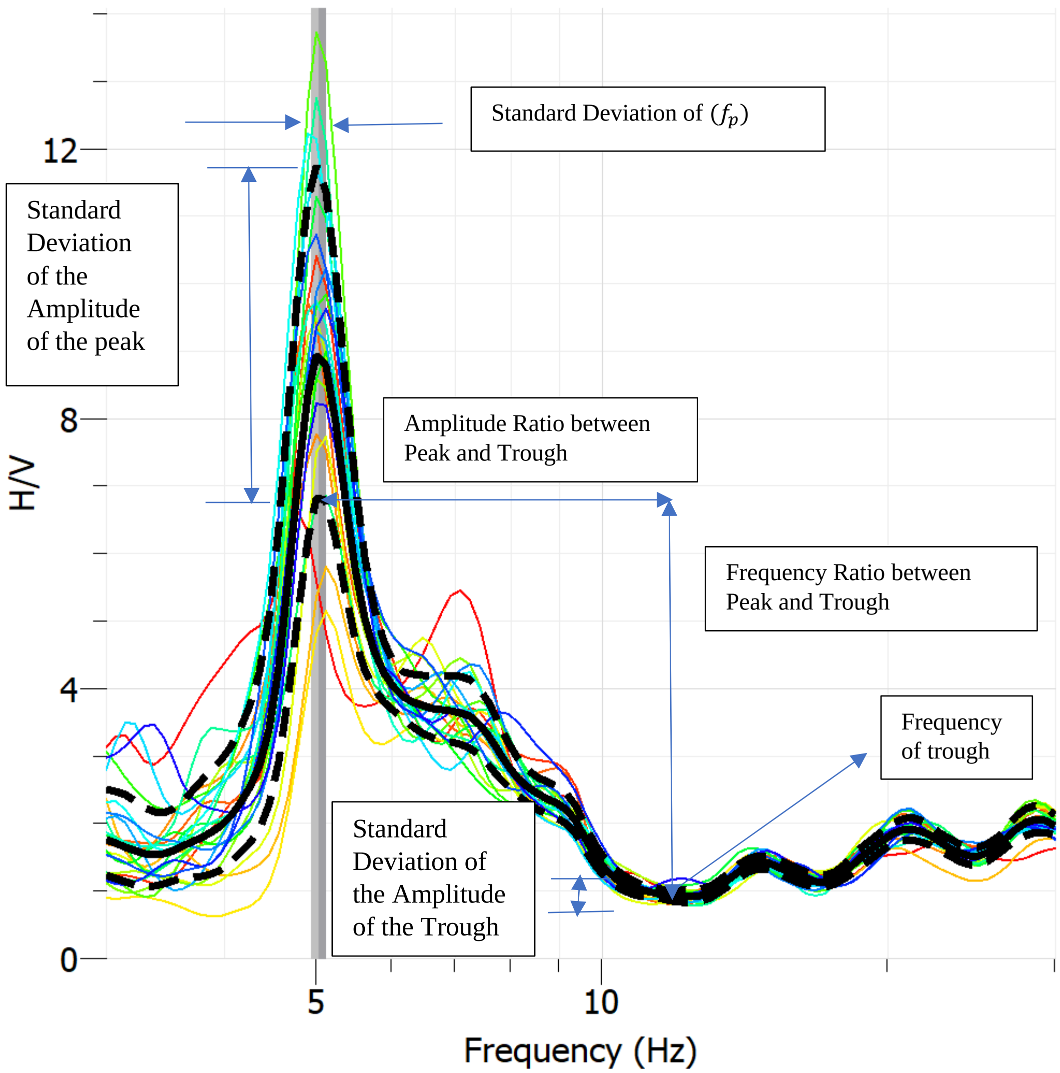


Figure 4. 8: The HVSR plot from The Ellis Library BH1. The trough (f_z), the standard deviation of the amplitude of the trough(STD, A_z), the standard deviation of the amplitude of the peak(STD, A_p), the standard deviation of frequency of the peak(STD, f_p), the amplitude ratio between peak and trough(A_p/A_z), and the frequency ratio between peak and trough(f_p/f_z) are labeled

4.4.2 Interpretation of Borehole Data

The depth to rock was determined from the ground elevation to the soil/rock interface, as identified from boring logs. It was not possible to perform elevation surveys at the HVSR locations at the time of measurement. Therefore, the ground elevation recorded in the boring log at the time of the boring was noted. The elevation from older logs were compared to a Digital Elevation Model (DEM) of the campus from 2015 LiDAR data to determine any changes in the ground elevation. The changes that were identified were applied to the elevation data and corrected. In addition, Google Earth imagery was used to visually confirm that no major changes in elevation occurred from 2015 to the date of the HVSR measurements. The depth to bedrock values are estimated to be within $\pm$ 1 ft of true value. For locations where the HVSR measurements were performed immediately after the borings (such that the boring location was still evident), the ground elevation was used directly from the boring log without correction.

4.5 Summary

This chapter covered the methods used to perform the HVSR data collection, processing, and interpretation. A summary of the HVSR equipment, deployment procedures, location name, measurement date, surface condition, and ambient noise environment were presented. In addition, interpretations of the HVSR peak value and additional attributes were discussed. Lastly, the interpretations of the borehole data were described in this chapter.

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5. RESULTS

5.1 Introduction

This chapter presents the relationships that were developed between the HVSR frequency values and depth to bedrock. First, a relationship was developed using all 65 HVSR measurements plotted versus the depth to where rock was first encountered (as identified from boring logs). Then, the data from this plot were separated based on subsurface conditions, namely: soil over limestone and soil over shale over limestone. Lastly, the soil over shale over limestone subsurface profile data were divided into categories based on the thickness of shale. Finally, results are presented to investigate if other attributes of HVSR plots can be used to identify subsurface conditions. In addition, a practical, real-world application of the HVSR relation developed in this study is presented.

5.2 Depth to Bedrock Relationship - All HVSR Measurements

A total of 65 HVSR plots were generated in this study, as presented in Appendix B. The frequency of the highest peak of each HVSR plot, as well as the standard deviation of the frequency of the peak value, were identified for each plot and are summarized in Table 5.1. A plot of the frequency versus the depth to first bedrock encountered was developed using the values in Table 5.1 and Tables 3.1 to 3.9 in Chapter 3 , as presented in Figure 5.1. The depth to first bedrock is defined as the depth at the first soil/rock interface, as identified by the descriptions in the boring log.

Table 5. 1: Frequency of HVSR peak and standard deviation for each measurement

Location Name	Frequency of HVSR peak (Hz)	Standard Deviation (Hz)		Location Name	Frequency of HVSR peak (Hz)	Standard Deviation (Hz)
Ellis BH-1	5.03	0.17		STEWART BH2'	6.20	0.91
Ellis BH-2	5.13	0.64		Stewart BH1	5.95	0.44
Ellis BH-3	6.58	1.87		Stewart BH2	6.20	0.84
Ellis BH-4	5.30	0.32		MUHC BH-1	8.13	2.11
Gateway BH-1	7.48	1.18		MUHC BH-2	6.21	0.22
Gateway BH-6	6.41	1.12		MUHC BH-3	6.67	0.78
Gateway BH-11	6.93	1.20		MUHC BH-5	6.42	0.64
Gateway BH-2	8.05	1.96		MUHC BH-6	7.21	2.03
Gateway BH-7	5.58	1.80		MUHC BH-7	6.54	0.27
Journalism BH-2	6.23	1.52		MUHC BH-8	6.58	0.42
Journalism BH-5	6.11	1.38		MUHC BH-9	6.97	2.27
Journalism BH-6	6.08	1.65		MUHC BH-10	6.61	0.77
Journalism BH-7	8.33	2.05		MUHC BH-11	6.56	3.77
Lee's Hall BH-1	7.98	0.55		MUHC BH-13	8.98	3.05
Lee's Hall BH-2	14.15	3.14		MUHC BH-4	6.33	0.70
Lee's Hall BH-3	7.73	0.31		MUHC BH-12	8.05	0.68
Lee's Hall BH-5	7.92	0.68		NextGen BH6	8.97	1.44
Lee's Hall BH-8	13.06	2.39		NextGen BH14	11.66	0.90
Lee's Hall BH-11	7.91	1.00		NextGen BH15	10.77	1.49
Lee's Hall BH-13	7.63	0.47		NextGen BH16	8.63	0.78
Lee's Hall BH-14	13.24	2.38		NextGen BH21	7.25	0.37
Lee's Hall BH-15	13.57	0.75		NextGen BH8	10.05	1.30
Lee's Hall BH-18	14.47	0.85		NextGen BH22	8.29	1.41
Lee's Hall BH-6	11.12	1.90		NextGen BH17	11.52	1.10
SHSMO BH-1	12.60	0.51		NextGen BH18	9.65	0.88
SHSMO BH-7	12.44	1.11		NextGen BH19	7.70	1.87
SHSMO BH-16	12.14	1.94		NextGen BH5	6.81	0.73
SHSMO BH-13	16.97	3.46		NextGen BH11	7.50	0.69
SHSMO BH-2	13.66	1.78		NextGen BH9	8.89	1.31
SHSMO BH-8	12.60	0.72		Virginia BH-6	5.70	0.25
SHSMO BH-10	13.61	3.93		Virginia BH-3	5.82	0.88
SHSMO BH-9	18.34	4.51		Virginia BH-5	4.82	0.84
SHSMO BH-5	9.14	1.65				

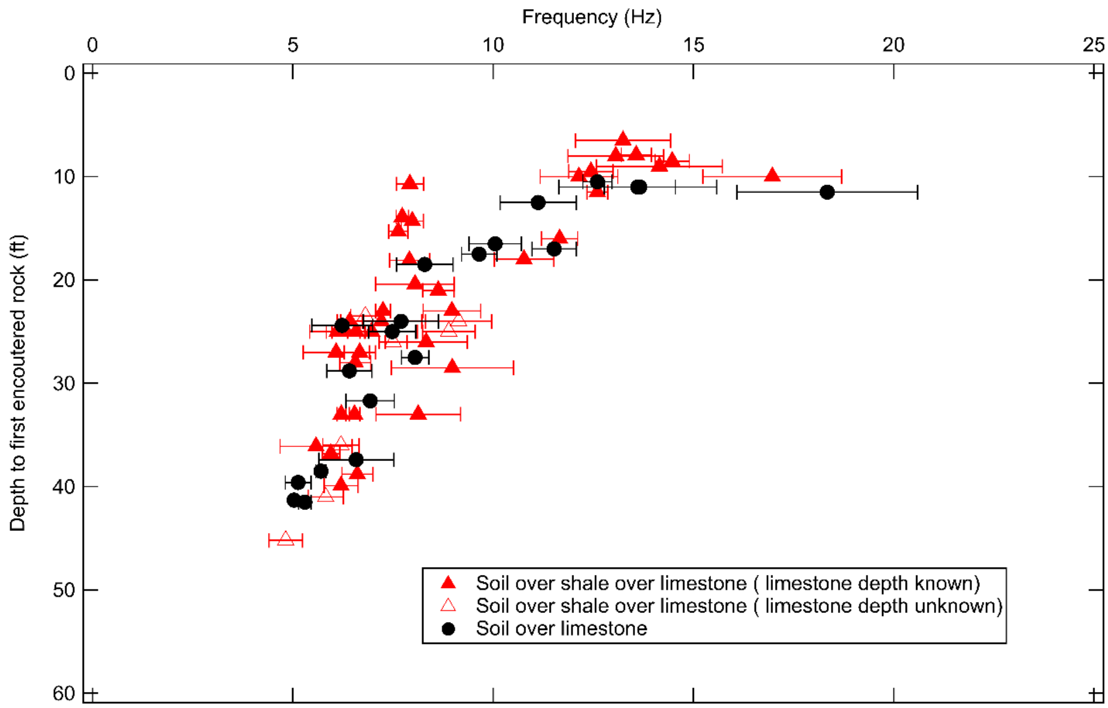


Figure 5. 1 HVSR frequency versus depth to first bedrock encountered from 65 HVSR measurements. The standard deviations of peak frequencies are indicated with error bars.

Equation 2.1 expresses the relationship between the resonant frequency of the site, the depth to rock, and shear wave velocity (V_s) for an ideal two-layer profile, consisting of uniform soil with constant velocity over rigid bedrock:

$$f_r = V_s/4H \quad \text{(Eq. 2.1)}$$

Where the f_r is the resonant frequency, V_s is the shear wave velocity and the H is sediment thickness.

This relationship can be rearranged into the power function form:

$$H = 0.25V_s * f_r^{-1} \quad \text{(Eq. 5.1)}$$

where the H is sediment thickness, V_s is shear wave velocity and f_r is the resonant frequency.

Equation 5.1 is only truly valid when the subsurface profile is a uniform soil over rigid bedrock. However, because the shear wave velocity of the top layer usually varies with the depth, the V_s is not a constant. In addition, in real cases, there is a finite impedance contrast between the soil and rock, so 0.25 is not always an accurate value. Therefore, the relationship of Eq. 5.1 can be expressed more generally, as:

$$H = a * f_r^{\ b} \qquad \text{(Eq. 5.2)}$$

where the H is sediment thickness, and a and b are unknown regression coefficients. This relationship between the frequency and the sediment thickness was first used by Ibs-Von Seht and Wohlenberg (1999), as described in Chapter 2. This form of the equation was used to fit a relationship to all 65 data points, as shown in Figure 5.2.

As shown in the Figure 5.1, a clear trend can be observed, where deep bedrock has lower frequency values relative to shallow bedrock. The power function fit, which is shown as a red line in Figure 5.2, has an a coefficient of 391 and exponent b of -1.379. In addition, the residual values, which is the difference between measured data points and the power function fit, were clearly a function of depth, as shown at the top of Figure 5.2. Much larger residuals were observed in the low frequency range of 5 to 10 Hz, while lesser residuals were observed at higher frequencies (i.e. above 10 Hz). The average error in the frequency range of 5 to 10 Hz is 18 % and above 10 Hz is 21%. Therefore, two 90% prediction bounds were calculated to capture this variability in the fit with frequency (and depth). The prediction bounds represent the expected range where the true bedrock depth will fall for an individual measurement with a certain probability. For example, if a HVSR measurement was performed with a measured peak frequency of 6 Hz, the predicted bedrock depth is 33 ft, with a 90% probability the true value falls in the range of 24 ft and 42 ft. At higher frequencies and shallower depths, the 90% prediction bounds showed a narrower range of about ± 5 ft. For example, for a measured

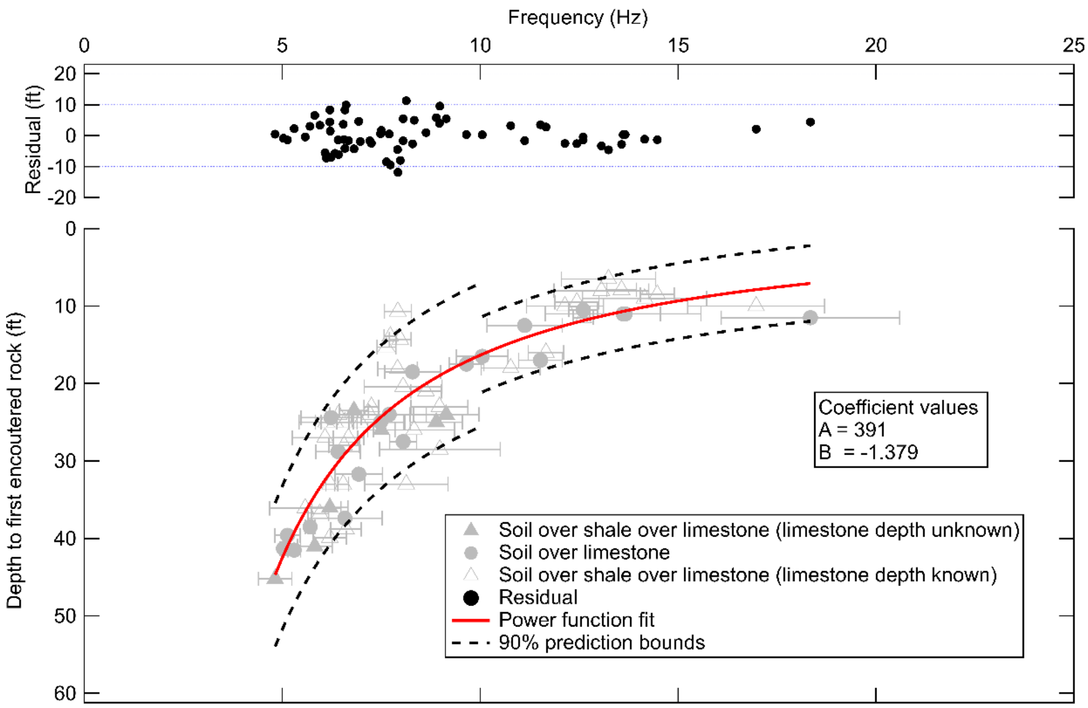


Figure 5. 2 The frequency versus depth to first bedrock encountered for 65 HVSR measurements. The power function fit is indicated with red solid-line. The 90% prediction bounds were labeled in black dash line.

peak frequency of 12 Hz, the predicted bedrock depth is 13 ft, with a 90% probability the true value falls in the range of 8 ft to 18 ft (i.e. ± 5 ft).

Another way to develop the relationship of frequency and depth to first bedrock relationship is to use the depth to refusal instead of the depth to rock identified in the borings. The depth to refusal is defined as the depth at which Standard Penetration Tests cannot penetrate 6 inches in 50 blows, as recorded on the boring logs. Of the 65 measured locations, 54 had a known refusal depth, as presented in Tables 3.1 to 3.9. The relationship of HVSR frequency versus depth to refusal is presented in Figure 5.3.

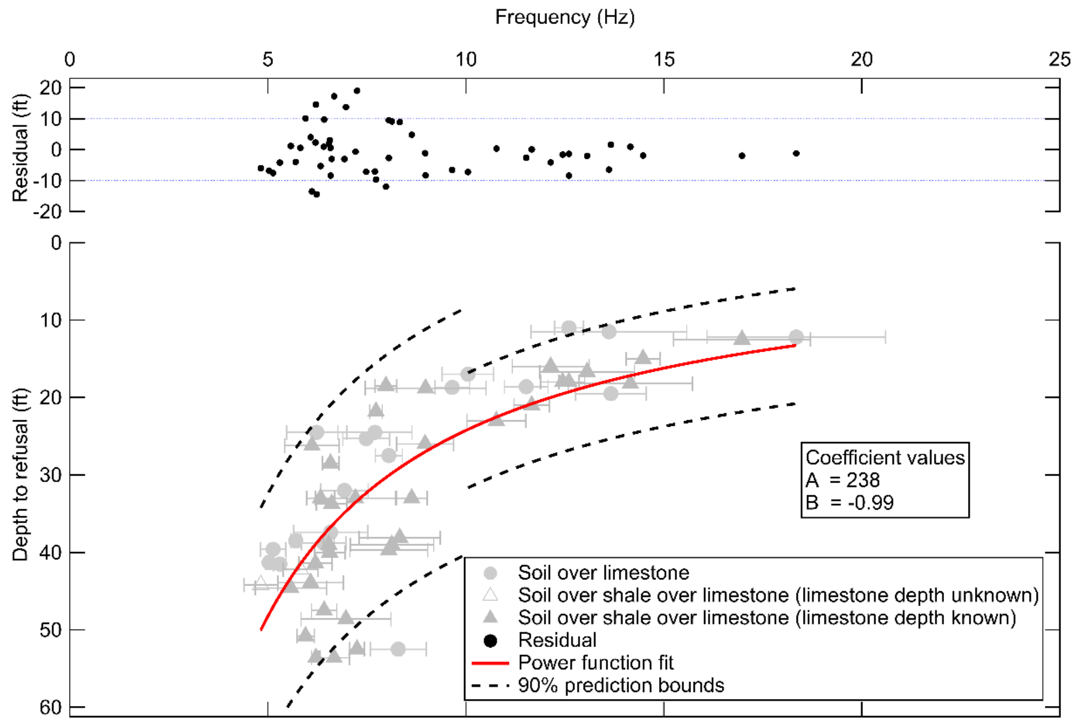


Figure 5. 3 The frequency versus depth to refusal for 54 HVSR measurements. The power function fit is indicated with red solid-line. The 90% prediction bounds were labeled in black dash line.

As shown in Figure 5.3, the power function fit has an a coefficient of 238 and an exponent b of -0.99. The residual values again showed a strong dependance with depth. The average error in the frequency range of 5 to 10 Hz is 21 % and above 10 Hz is 15%. The 90% prediction bounds were calculated independently for the low frequency (i.e. 5-10 Hz) and high frequency (above 10 Hz) regions. The relationship has 90% prediction bounds of $\pm$ 15 ft for the low frequency region and $\pm$ 7 ft for the high frequency region.

These large prediction errors at low frequencies in Figure 5.2 and 5.3 were unexpected and inconsistent with the errors published in other studies, as discussed in Chapter 2. To investigate this relationship further, the 65 data points were separated into different categories based on subsurface conditions, namely: (1) soil over limestone and (2) soil over shale over limestone, as presented in the following sections.

5.2.1 Depth to Bedrock Relationship - Soil over Limestone Profile

The relationship presented in this section was developed using only cases where soil was directly over limestone, with no shale present. A total of 20 of 65 measurements fit this category. The relationship developed using the power function fit is presented in Figure 5.3.

As shown in the Figure 5.3, the fit to this subset of the data yields an a coefficient of 339 and exponent b of -1.288. The 90% prediction bounds showed a narrower range than in Figure 5.2, indicating a better depth to bedrock prediction for this subsurface condition. For example, the 90% prediction bounds at frequencies below 10 Hz are $\pm$ 7 ft, where the 90% prediction bounds in Figure 5.2 are $\pm$ 10 ft. In other words, if this relationship was used to predict the bedrock depth with prior knowledge that no shale was present, there is a 90% chance that the depth of prediction will be within $\pm$ 7 ft for HVSR measured frequency of 5 to 10 Hz and $\pm$ 5 ft for above 10 Hz. The average error in the frequency range of 5 to 10 Hz is 10 % and above 10 Hz is 16%.

Therefore, if one wants to estimate the depth to bedrock on the University of Missouri campus, and the subsurface profile is known to be soil over limestone, this HVSR technique will provide a useful estimate of the depth to rock. A practical application of using the HVSR method to estimate depth to bedrock at a site near the University of Missouri campus is provided later in this chapter. In addition, more discussion regarding the depth to bedrock relationships will be provided in Chapter 6.

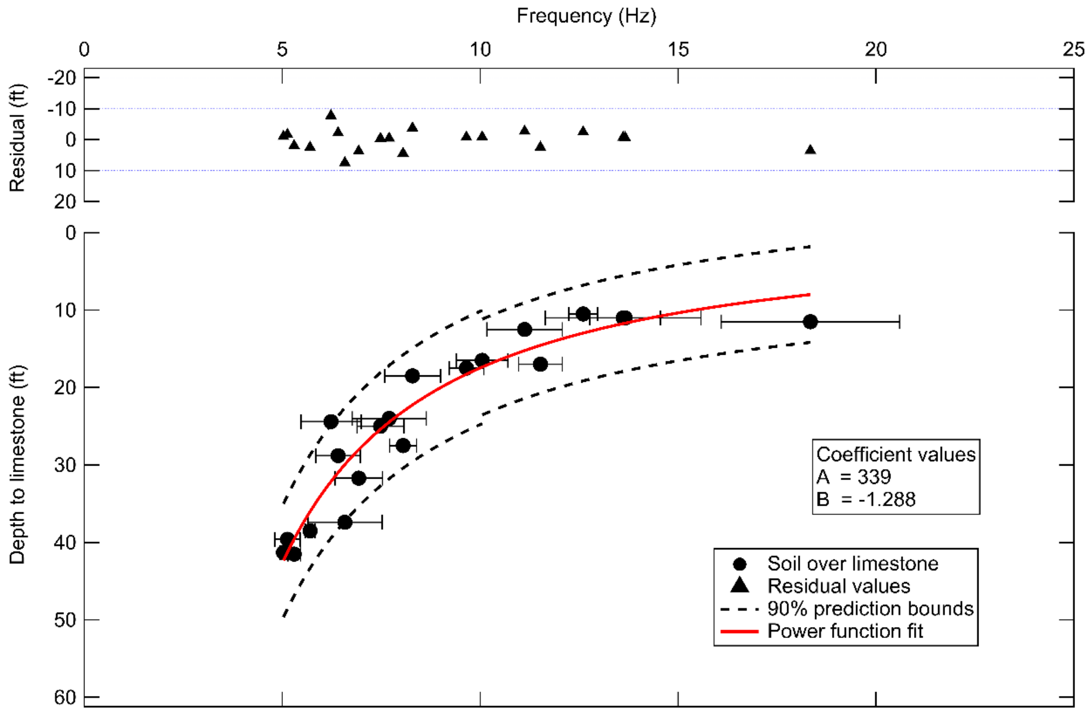


Figure 5. 4 The frequency versus depth to limestone bedrock for 20 HVSR measurements where no shale was present in the profile. The power function fit is indicated with the red solid-line. The standard deviations of peak frequencies are indicated with error bars. The 90% prediction bounds are indicated by the black dashed line.

5.2.2 Depth to Bedrock Relationship - Soil/Shale Interface

The remaining 45 profiles included a soil/shale interface. In this section, the relationship of soil over shale over limestone is examined using the depth of the soil/shale interface. This relationship is presented in Figure 5.5, where the depth to the soil/shale interface is plotted. The a coefficient is significantly higher with a value of 424 and the b exponent has a value of -1.427. There is significant scatter about the fit as indicated by the residual plots in Figure 5.5. The wide prediction bounds were influenced from the large variations observed in the frequency range of 5 to 10 Hz specifically. The 90% prediction bounds at frequencies below of 10 Hz are about $\pm$ 10 ft while the bounds above 10 Hz are about $\pm$5 ft.

A comparison of the power function fits of the relationship of soil over limestone and soil over shale interface is presented in Figure 5.6. As shown in Figure 5.6, the fits to these two relationships are similar. However, greater scatter of the data was observed for the case of the soil over shale. This would indicate that the V_S of the soil over shale is more variable than the V_S of the soil over limestone. This would seem to be an unlikely explanation as there is no reason that the soil should be more variable over the shale than over the limestone. Another possible explanation for the low frequency variability is that the impedance contrast between the soil and shale is not sufficient to generate a peak due to this soil/shale interface. Therefore, it is possible that the HVSR peak from soil over shale over limestone case was generated from the limestone interface. This explanation is investigated in the next section.

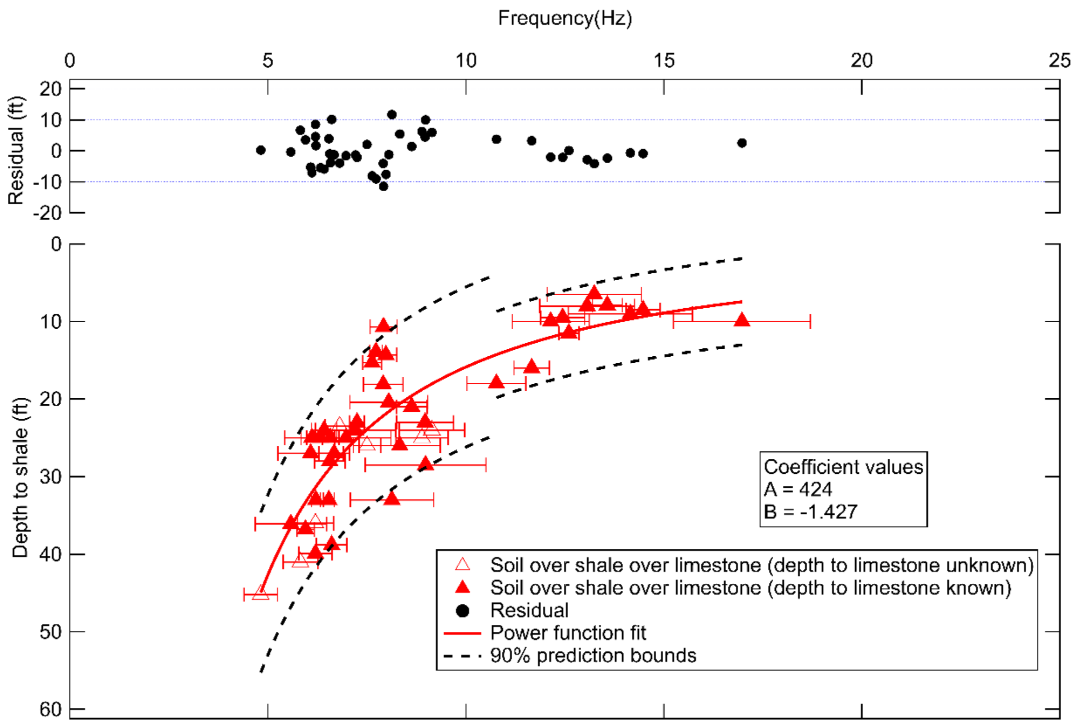


Figure 5. 5 The frequency versus depth to shale bedrock for 45 HVSR measurements. The power function fit is indicated with red solid-line. The standard deviations of peak frequencies are indicated with error bars. The 90% prediction bounds are labeled in black dash line.

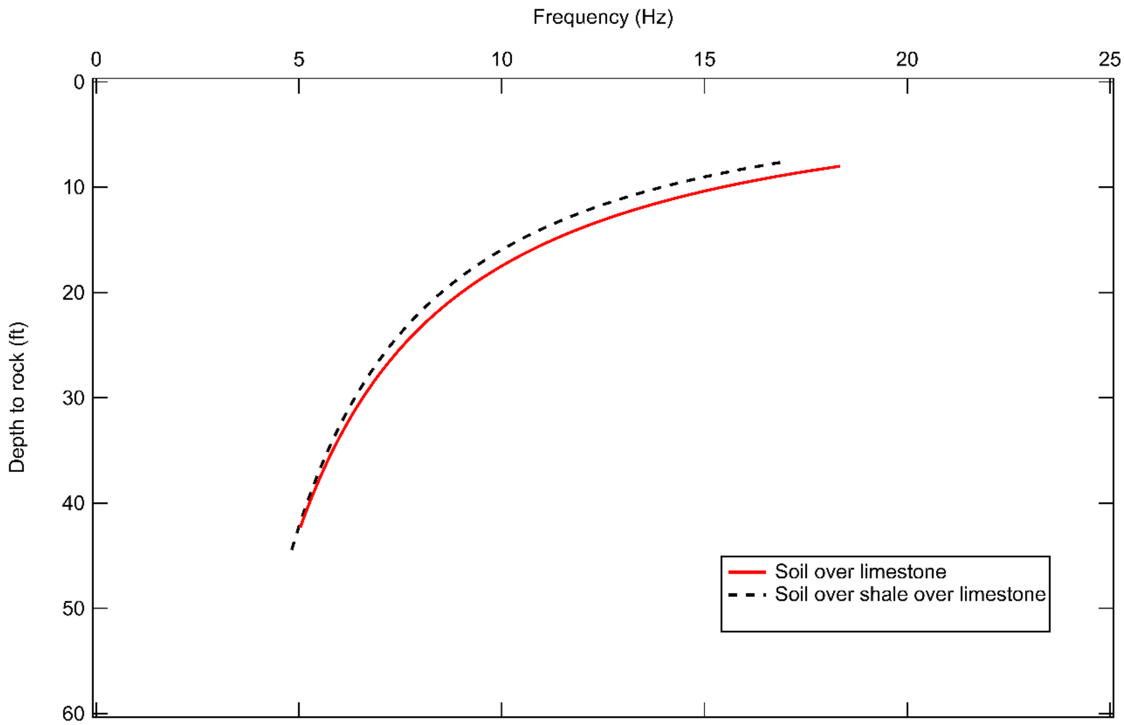


Figure 5.6 Power function fits of soil over limestone (red solid line) and soil over shale over limestone using depth to soil/shale interface (black dash line)

5.2.3 Depth to Limestone Relationship - Soil/Shale/Limestone Case

In this section, the frequency values are plotted versus the depth to limestone, as shown in Figure 5.7. Of the 45 data points shown in the previous section, 7 of the borings did not extend deep enough to identify limestone. Therefore, only 38 data points were used to develop the relationship presented in this section.

The power fit shown in Figure 5.7 has a very high “a” coefficient of 471 and an exponent ‘b’ of -1.334. The prediction bounds were the widest of all relationships developed so far. For example, in the frequency of 5 to 10 Hz, the depth prediction ranged from 12 to 52 ft with the 90% prediction bounds of ± 15 ft. However, for frequencies above 10 Hz, the prediction bounds showed a value of ± 5 ft, which is similar to the other relationships.

The shale thickness in these cases varied significantly from 0.5 ft for BH1 at Lee's Hall BH1 to 29 ft for BH21 at the NextGen site. The shale layer could have a large effect on the depth estimation due to large variations in its thickness. Therefore, the effect of the shale layer thickness was investigated by categorizing the data in Figure 5.7 based on shale layer thickness.

The 38 data points from Figure 5.7 were categorized into three different groups of shale thickness ranges: 0.5-5 ft, 5 to 10 ft, and greater than 10 ft of shale thickness. In addition, the 20 data points from Figure 5.3 were plotted as the "control group" with no shale layer (i.e. shale thickness is 0 ft.). All four power function fits are plotted in Figure 5.8.

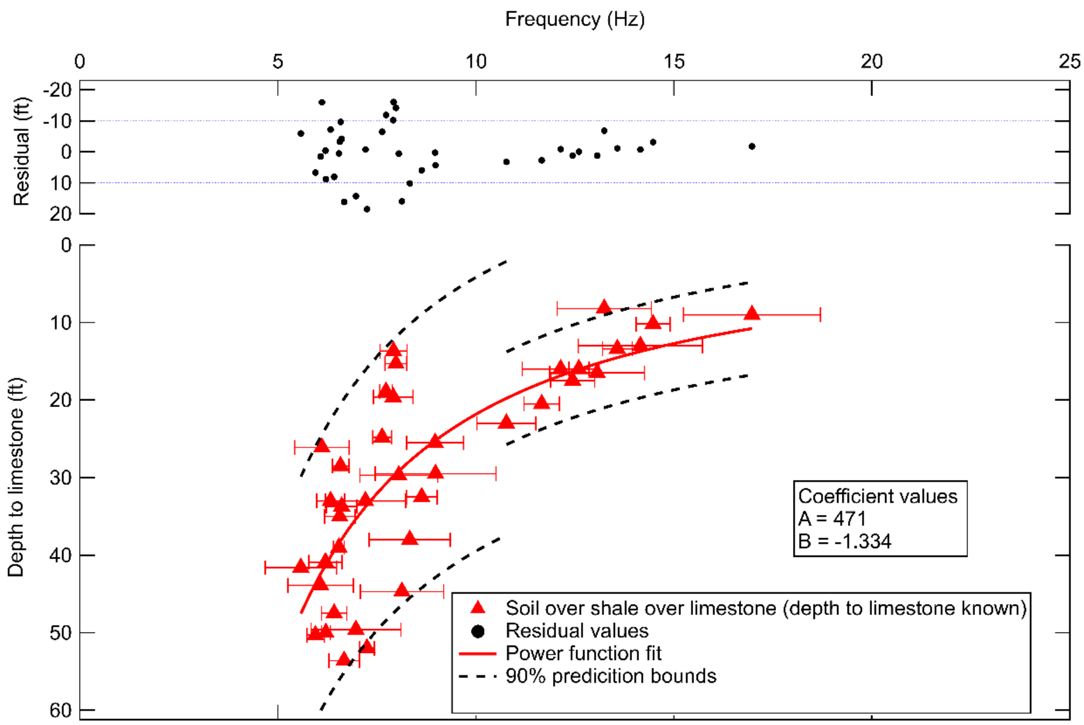


Figure 5. 7 The frequency versus depth to limestone bedrock for 38 HVSR measurements. The power function fit is indicated with red solid-line. The standard deviations of peak frequencies are indicated with error bars.

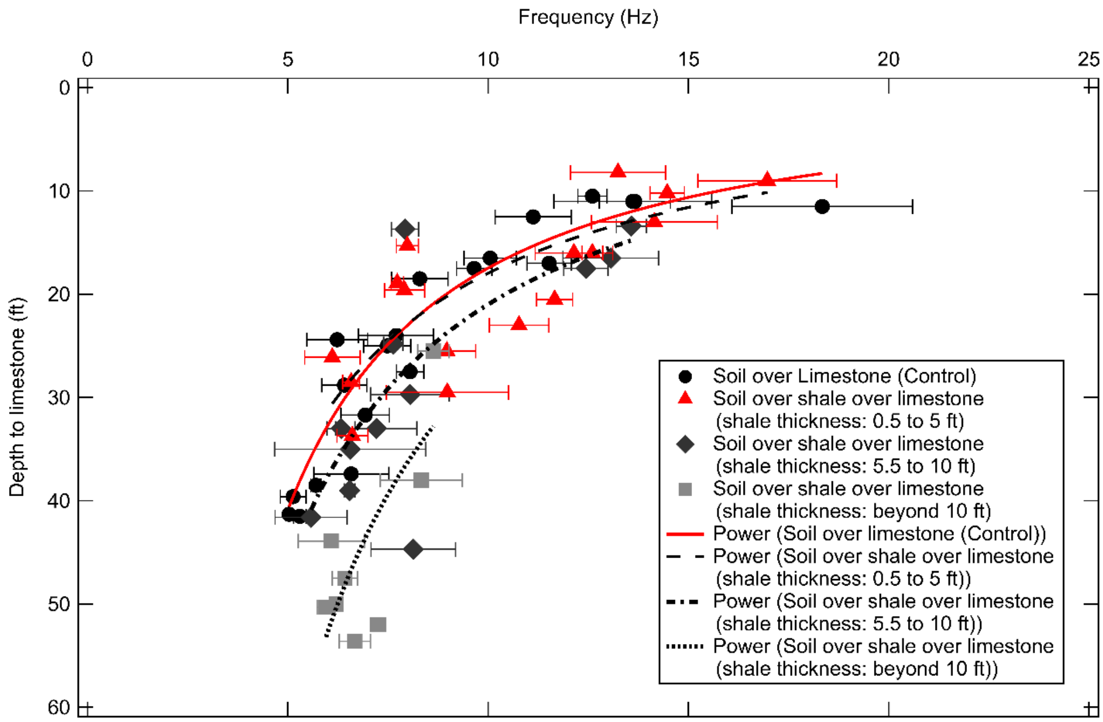


Figure 5. 8 The frequency versus depth to limestone bedrock for 58 HVSR measurements. The red solid line indicates the control group of no shale and three different dash-lines indicated different groups of shale thickness ranges. The standard deviations of peak frequencies are indicated with error bars for all measurements.

The curve fits presented in Figure 5.8 showed a trend of a shift to higher frequencies for thicker shale layers. When the shale layer is only 0.5 ft to 5 ft thick (grey dash-line), the fit is nearly the same as the soil over limestone relationship (red solid-line). However, as the shale thickness increases, the relationships deviate from the "control" group with the fit shifting to higher frequencies for thicker shale layers. This is consistent with what would be expected if the peak is due to the limestone interface, as the average shear velocity of the material above the limestone will increase due to the higher velocity shale layer. The thicker the shale layer, the larger the expected shift. This issue is discussed in greater detail in Chapter 6.

The a and b coefficients of the power function equations for all four relationships are presented in Table 5.2. More discussion regarding the a and b coefficient, with comparisons to other studies is provided in in Chapter 6.

Table 5. 2 The a and b coefficient of power function equation for each group.

Group Name	**"*a*" coefficient of the Power Function**	**"*b*" coefficient of the Power Function**
Soil over limestone (0 ft of shale) (Control)	339	-1.288
Soil over shale over limestone (Shale thickness: 0.5-5 ft)	216	-1.081
Soil over shale over limestone (Shale thickness: 5.5-10 ft)	291	-1.143
Soil over shale over limestone (Shale thickness: beyond 10 ft)	542	-1.302

Based on all the developed relationships, the relationship of soil over limestone provided a reliable and useful depth to rock estimations. Although, the prediction bounds are large, this relationship will still be of use in many practical situations. An example is presented at the end of this chapter. However, when shale is present, specifically when the thickness of the shale is 5 ft and greater, the predicted depth to rock relationship is different and has much larger uncertainties, such that it may be of little to no practical use. Therefore, it is important to identify if shale is present either from prior knowledge of the site, or possibly from attributes of the HVSR plot. The next section investigates whether other attributes of the HVSR plot may indicate the presence of a thick shale layer (i.e. lower impedance bedrock).

5.3 Identifying Shale from HVSR Attributes

The work by Tuan (2009) described in Chapter 2 showed that the impedance contrast between soil and rock affects attributes of the HVSR plot. Because the impedance contrast of soil/shale is lower than soil/limestone, it was hypothesized that it may be possible to detect the presence of shale from attributes of the HVSR plot. The attributes that were studied are: frequency ratio of the peak and trough, the standard deviation of the frequency of peak and trough, the amplitude ratio of the peak and trough, and the standard deviation of the amplitude of peak and trough. These attributes are described and illustrated in Chapter 2, Figure 2.10 and 2.11. The plots of these relationship are shown in Figures 5.9 to 5.11.

It was hypothesized that the soil/limestone and soil/thick shale data points would be clustered into distinct regions such that by measuring these features of the HVSR plots the presence or absence of a thick shale layer could be determined. However, as shown in Figure 5.9 to 5.11, no clear separation between groups was observed and it was concluded that subsurface conditions could not be inferred from the attribute plots.

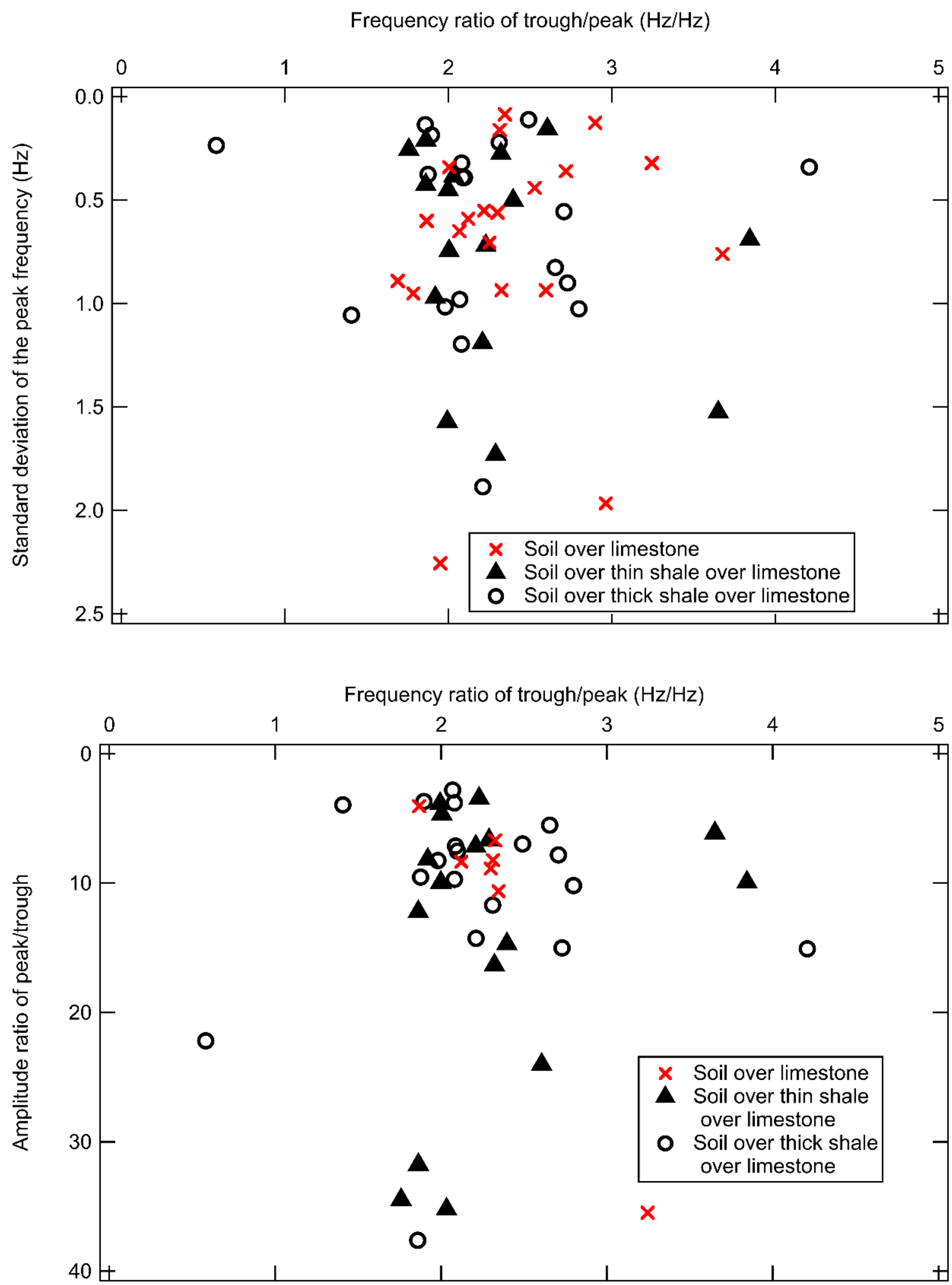
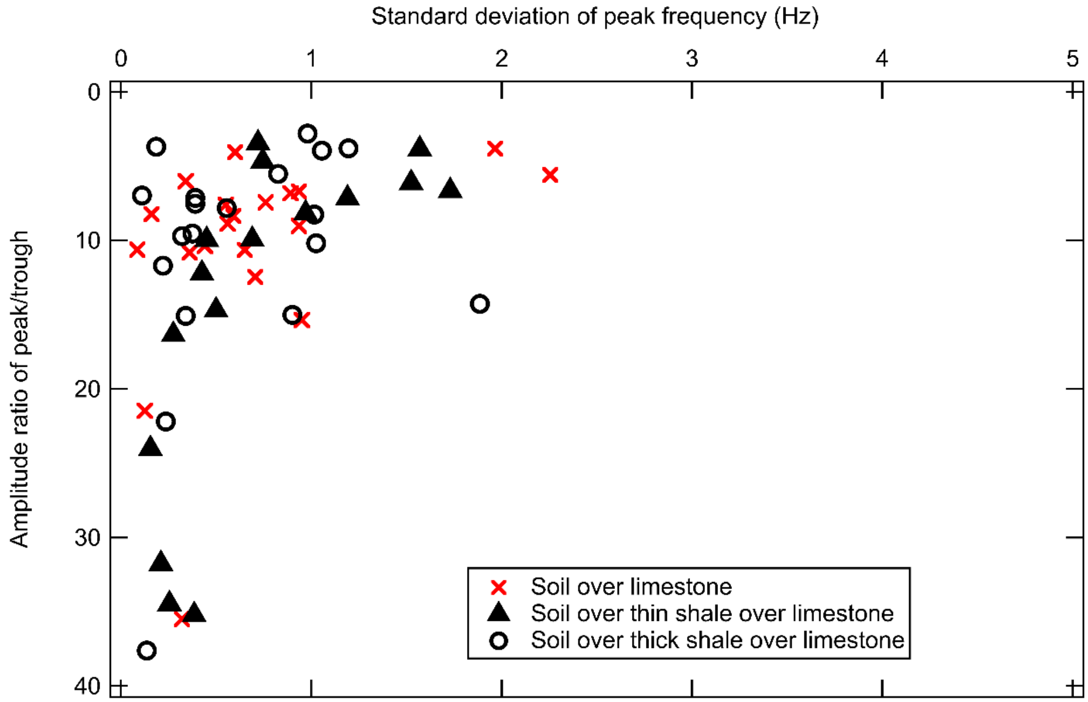


Figure 5. 9 Frequency ratio of trough/peak vs. standard deviation of the peak frequency (top) and frequency ratio of trough/peak vs. amplitude ratio of peak/trough (bottom)



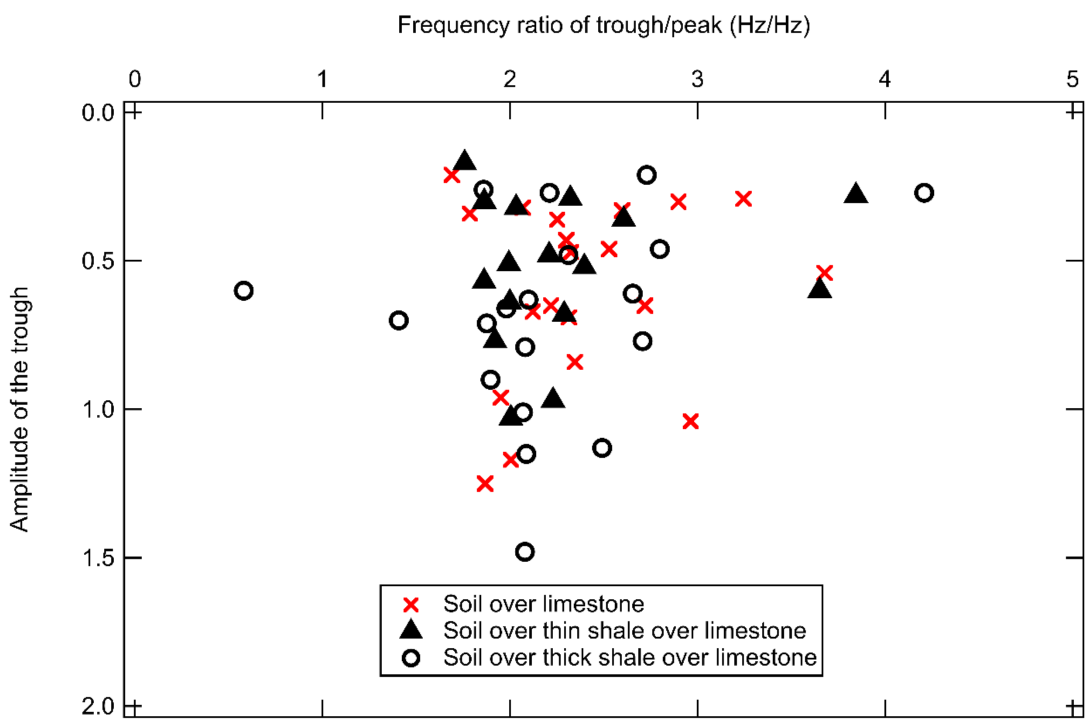


Figure 5. 10 Standard deviation of the peak frequency vs. amplitude of peak/trough (top) and frequency ratio of trough/peak vs. amplitude of the trough (bottom)

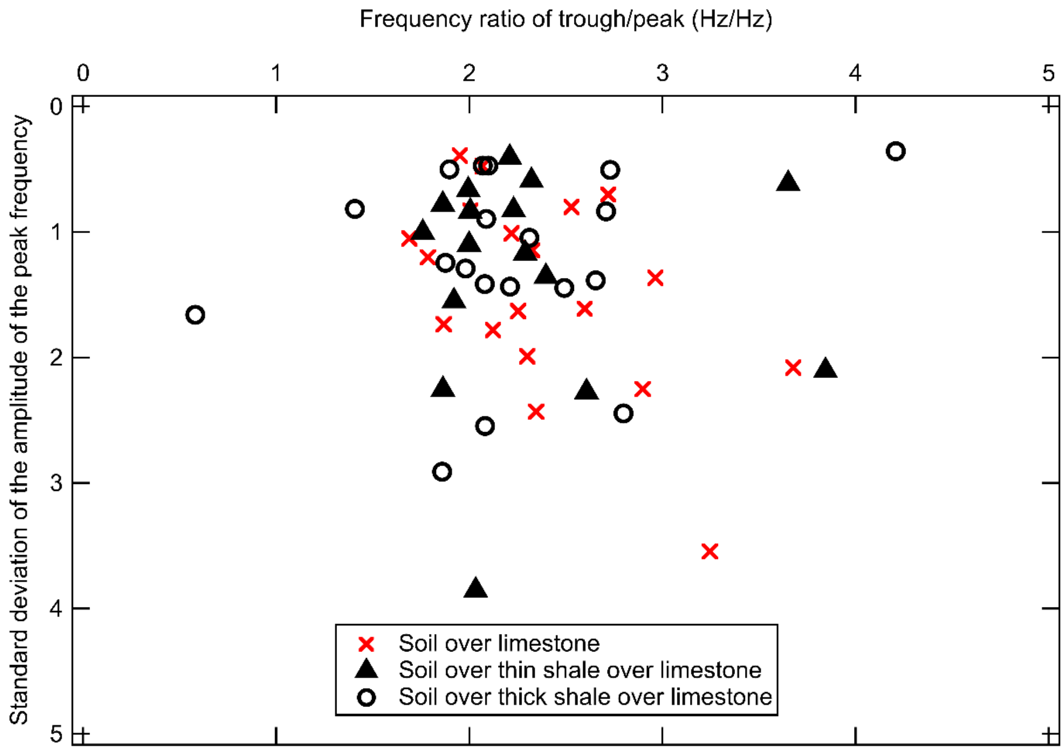


Figure 5. 11 Frequency ratio of trough/peak vs. standard deviation of the amplitude of the peak frequency

5.4 Example Application of the HVSR Method

HVSR measurements were performed at a site near the University of Missouri campus as described in Chapter 3, where nearby borings showed no shale was present. The objective was to estimate the depth of soil over rock for settlement predictions. Although the limestone outcrops were visible, it was not known if rock was a few feet below the surface or many tens of feet. In addition, it was not possible to mobilize a drilling rig due to irregular terrain. Refraction tests was performed by another company to estimate the depth to rock. A total of six HVSR measurements were performed as part of this work over a period of a few hours, and the relationship of soil over limestone developed in this study (Fig. 5.4) was used to predict the depth to rock. The depth to limestone estimates from the HVSR method are compared to the estimated rock depth based on the velocities obtained from the refraction results, as shown in Figure 5.12. It should be noted that the HVSR measurements were performed blind with no information from the refraction results used in the analysis. As shown in Figure 5.12, the depth estimation from the HVSR method agreed well with the refraction method, with differences of only a few feet in most cases. All of the rock depth estimates from the refraction tests fell within the 90% prediction range of the HVSR measurements.

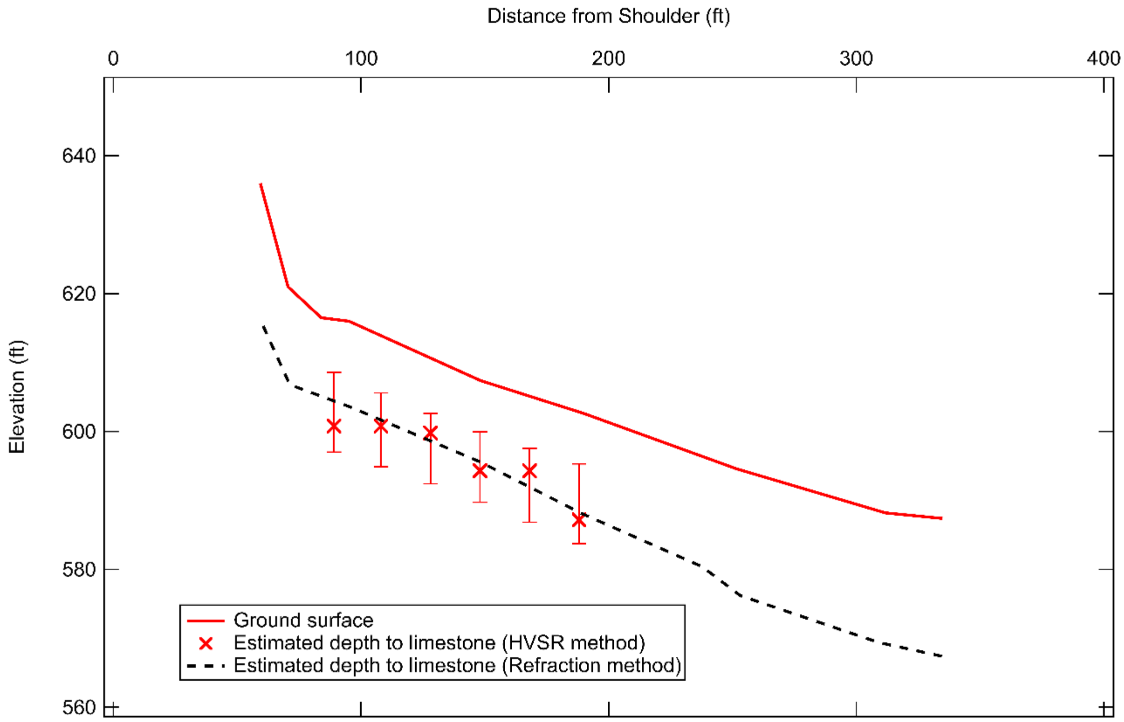


Figure 5. 12 The ground surface elevation (red solid line), the estimated depth to limestone using HVSR relationship for soil over limestone (red x marker), error bars indicating 90% prediction range, and the estimated depth to limestone refraction measurements (black dash line).

5.5 Summary

This chapter presented the frequency and depth to bedrock relationships developed from 65 HVSR data points. A regression using a power function fit was performed and prediction bounds of the fitted curve were determined. The data points were next categorized into separate plots based on the subsurface profiles and used to investigate the factors influencing the prediction bounds. It was determined that the shale layer has a large effect on scatter and uncertainty in the predicted depths. It was also observed in all cases that the scatter and uncertainty increased at lower frequencies (i.e larger depths). Other attributes of the HVSR plots were used to investigate if the existence of a thick shale layer could be identified. Lastly, the result of a practical application of the HVSR method was presented.

It was determined that a reliable relationship for the soil over limestone condition could be developed, with 90% prediction bounds of $\pm$7 ft over the frequency range of 5 to 10 Hz and $\pm$5 ft at frequencies above 10 Hz, the average error between the fit and measured data was 12%. A poor prediction was observed when thick shale was present in the subsurface profile, with prediction bounds of as much as $\pm$15 ft. The attempt to identify shale from attributes of the HVSR plots was not successful. Finally, a practical example of the successful application of the soil over limestone relationship was presented.

6. DISCUSSION

6.1 Introduction

The main objective of this thesis is to develop a relationship for the University of Missouri campus to predict the depth to rock from HVSR frequency measurements. In this chapter, the results presented from Chapter 5 are discussed and the findings are compared to similar past studies. Moreover, the consistency and reliability of HVSR measurements are discussed and evaluated based on limited repeat measurements performed in this study. Finally, results from the application of the HVSR soil limestone relationship presented in Chapter 5 are discussed.

6.2 Depth to Bedrock Relationships

As mentioned in Chapter 5, the relationship between the resonant frequency of the site (f_r), the depth to bedrock (H), and shear wave velocity (V_s) for a two-layer system can be expressed as:

$$H = 0.25V_s * f_r^{-1} \qquad \text{(Eq. 5.1)}$$

This equation can be rewritten into a more general term as:

$$H = a * f_r^{b} \qquad \text{(Eq. 5.2)}$$

where a and b are unknown regression coefficients.

In addition, the V_s profile for soil can also be modeled with a power function relationship that depends on the soil structure and composition (A) and effective stress (σ'_v):

$$V_s = A(\sigma'_v)^m \qquad \text{(Eq. 2.1)}$$

The exponent, m, can often be assumed to be about 0.25.

If the effective stress in Eq. 2.1 is replaced with the product of unit weight and depth, and the average shear wave velocity is calculated using the methods described in Chapter 2, the following relationship can be derived:

$$H = a * f_r^{-1.33} \qquad \text{(Eq. 6.1)}$$

This shows that the expected exponent should be around -1.33 for a soil with a velocity profile that follows Equation 2.1. Stokoe et al. (2014) present A values for reference profiles of stiff silt/clay and dense sand. Using these A values and the simple weighted averaging of Equation 2.3, it can be shown that the a coefficient in Equation 6.1 will be around 340 for clay and around 490 for dense sand, using units of ft/s for velocity. These values are presented to illustrate the expected range of values for typical soil profiles. The derivations of these relationships are presented in Appendix C.

When all data were plotted versus the depth to first bedrock encountered, as shown in Figure 5.2, the power fit had parameters of 391 for a and -1.379 for b. These values are consistent with the expected values derived above. However, very large prediction bounds at the low frequency range of 5 to 10 Hz were calculated with slightly narrower prediction bounds for frequencies above 10 Hz. The prediction errors at low frequencies were large enough that the relationship would be of limited use for many practical applications. The relationship developed using depth to refusal produced fitting parameters that were not as consistent with theoretical expectations and showed much more scatter (Fig. 5.3).

The data presented in Figure 5.2 were then divided into two categories based on bedrock conditions. The relationship developed for soil over limestone (Figure 5.4) produced a relationship with less scatter and a and b parameters (339 and -1.29 respectively) that were consistent with expected values. Although the prediction bounds were still relatively large, this relationship could certainly be used for many practical problems as a quick means to estimate the depth to bedrock, as shown for the practical example presented in Chapter 5. The values of the power function fit are compared to the values from other measurements in past studies in Table 6.1. The average percent error between the measured data and the fit was around 12 %, which is consistent with other studies.

Table 6. 1 Measured parameters “a" and “b” from this study and past studies

Fitting Parameters			**Relationship names & Reference**
***a* (ft)**	***a* (meters)**	***b***	
382	116	-1.367	Depth to first rock encountered relationship
339	103	-1.288	Depth to limestone relationship-soil/limestone
424	123	-1.404	Depth to shale-soil/shale/limestone profile
471	144	-1.334	Depth to limestone-soil/shale/limestone profile
-	96	-1.388	Ibs-von Seht and Wohlenberg,1999
-	108	-1.551	Parolai et al., 2002
-	137	-1.190	Hinzen et al.,2004
-	56	-1.268	Delgado et al.,2000

6.3 Influence of Shale on the HVSR Relationship

The presence of shale in the subsurface profile generally correlated with greater scatter in the HVSR relationships, as shown by comparing Figure 5.4 to Figure 5.5 and 5.7. When the data are plotted versus the soil/shale interface (Figure 5.5), a reasonable relationship is obtained, as shown in Table 6.1. However, large scatter was observed, specifically in the low frequency region of 5 to 10 Hz, where errors were as large as 58%. The greater scatter for the shale rock case as compared to the limestone case would indicate the shear velocity (V_s) of soil above shale is more variable than the V_s of soil above limestone, which is not a likely explanation. However, another explanation is that the impedance contrast at the soil/shale interface is not large enough to produce a reliable peak in the HVSR plot from the soil/shale interface. Instead, the measured peak is possibly due to the soil/limestone interface. Thus, the data were re-plotted versus depth to limestone, as shown in Figure 5.7.

Large scatter was also observed in Figure 5.7. However, in this case the scatter could be explained by the effect of the shale on the average shear wave velocity ($V_{s,AVG}$) above the limestone due to shale layer, where the higher-velocity shale layer will shift the $V_{s,AVG}$ to values that are greater than expected for a typical soil profile. The higher $V_{s,AVG}$ would tend to shift the curves to higher frequency, which was observed in Figure 5.8. It is expected that this effect would be most pronounced for thicker shale layers, which is what was observed in Figure 5.8 where the data were subdivided into shale thickness classes. Therefore, the more likely explanation of the poor performance of the HVSR results in soil/shale/limestone profiles is the large change in $V_{s,AVG}$ above the soil/rock interface due to shale layer. This change in $V_{s,AVG}$ can be observed in the fitting parameters presented in Table 5.2, where the "A" values generally increase with the shale thickness.

Due to the existence of two unknown variables: the V_S of shale and the thickness of shale, it is not possible to develop a useful and reliable relationship for the soil over shale over limestone condition. In addition, the HVSR technique does not measure either of these two variables. Therefore, unless one has performed velocity measurements to calibrate the “A” parameter to produce a more reliable relationship, this relationship of soil over shale over limestone cannot be effectively used without large prediction errors.

6.4 Variability of the HVSR Peak Frequency

In this section a few sources of additional uncertainty in the HVSR results are discussed. These factors were investigated to a limited degree in this work, but not incorporated into the relationships that were developed.

6.4.1 Directionality

As mentioned in Chapter 4, the HVSR technique measures one vertical channel and two horizontal channels. The approach taken in this study was to use the common method of taking the squared average of the two horizontal components to calculate the HVSR plot. However, one could also just use the north-south component, or the east-west component, or combine them to obtain any direction. Therefore, another way to present the HVSR frequency data is using a directionality plot, which shows the frequency peak as a function of wave direction. Directionality plots were generated for all 65 measurements and can be found in the Appendix D. Most directionality plots showed consistent peak frequency values with direction, as illustrated in Figure 6.1a. However, for a few measured locations, the deviations were as much as 40%. An example is shown in Figure 6.1b where the highest peak at an azimuth of 90 degrees is about 5.5 Hz, but at 20 degrees the highest peak is near 8 Hz. Therefore, this is a source of uncertainty that was not quantified in this study and should be included in future studies. However, this factor is expected to have a minor influence on the relationships because it was only observed at a few sites.

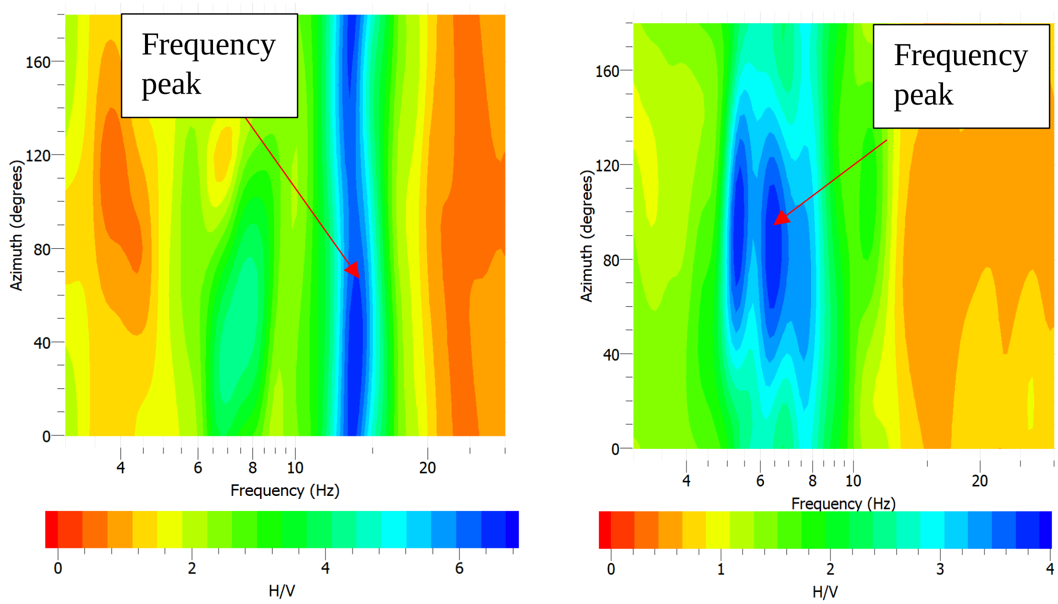


Figure 6. 1 Directionality plot for Lee's Hall BH 15 (left) and Journalism BH 6 (right), color indicated the amplitude of H/V ratio from different directions. 90 degrees are in the North direction, the 0 degree is in the East direction.

6.4.2 Repeat Measurement

In addition to investigating the consistency of HVSR peak frequency values for a single measurement from different directions, the HVSR measurements were repeated at a few sites to observe the variability in the peak frequency value for different dates and times of days. As can be seen Figure 6.2, some sites showed variations in the peak frequencies of as much as 18%. One explanation for this variability may have to do with different dominant propagation directions at different times of days (i.e. the dominant ambient noise source changes) producing different peaks due to the directionality effect presented above. It is also possible that the noise from a nearby building may dominate and affect the results at certain times of days. This variability was greater than expected and should be further investigated and quantified in future work.

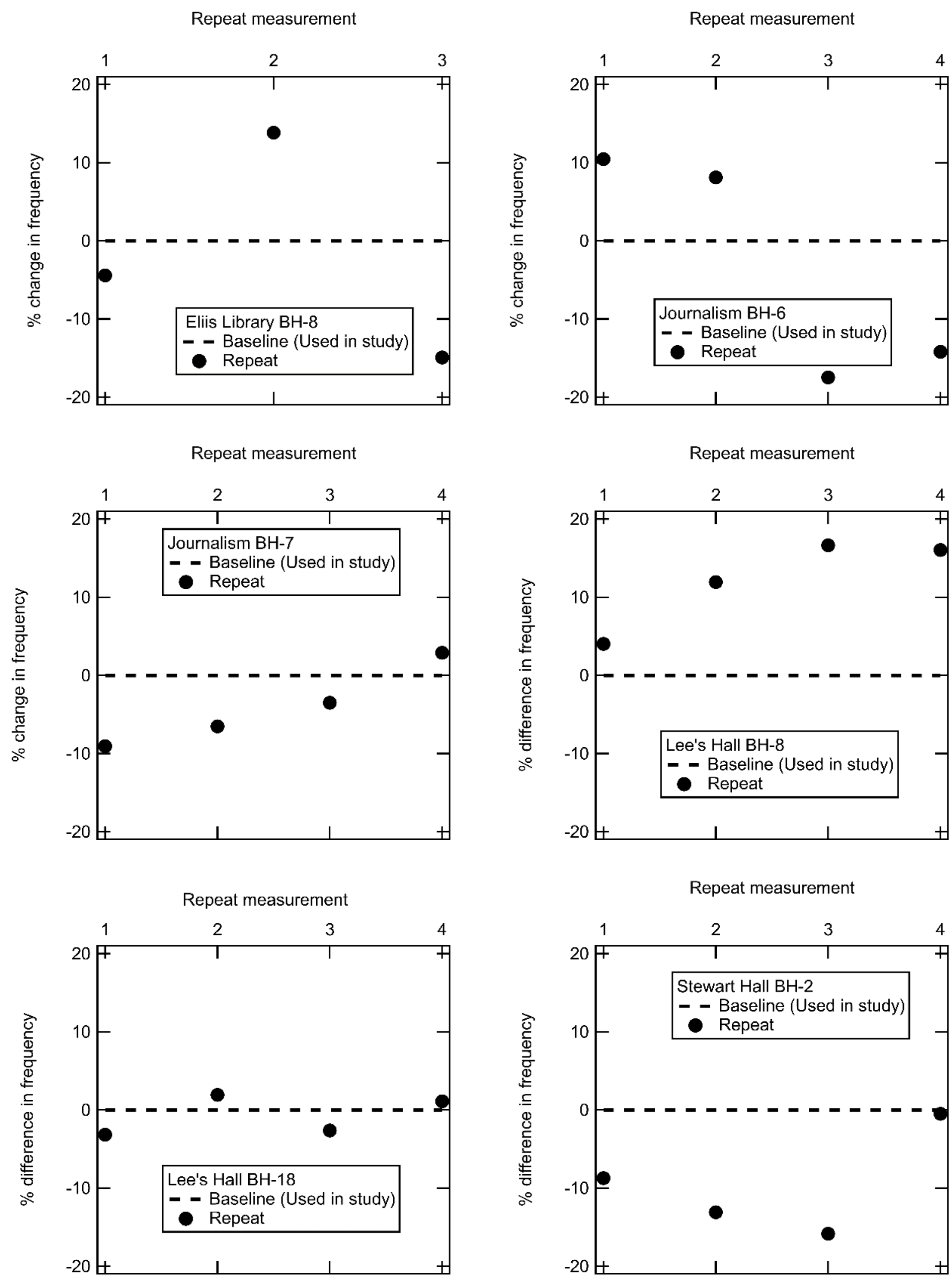


Figure 6. 2 The peak frequency used in this study (black dash line) and the percent difference in peak frequency from repeated measurements (black circle)

6.5 Application of the HVSR Method

Based on the findings from this study, a useful relationship was developed for cases where the profile is known to consist of soil over limestone. The results presented from a project in Central Missouri where that was the case showed errors in bedrock estimates were in the range of $\pm$ 0.5 ft to $\pm$ 3.2 ft. and demonstrated the applicability of this simple method when more robust methods are either too expensive or too difficult to deploy.

When shale is present, the uncertainties in the relationships were too large to be of practical use. Therefore, it would be helpful if the presence of shale could be identified from the HVSR data so it would be known that the relationship for that point is unreliable. In Chapter 5, several attributes of HVSR plots were identified and investigated as a means to detect the presence of shale. The study was conducted based on observations presented in Tuan (2009) for simple two-layer models (Figures 2.9 and 2.10). Unfortunately, the results from the study herein did not show any attributes of the HVSR plot for the soil/shale/limestone cases that differed consistently from the soil/limestone case. It is unclear why no trends were observed, but other unknown site factors likely dominated the expected effect.

In summary, the depth to bedrock can be found with great accuracy from various methods such as drilling and seismic refraction. However, the advantage of the HVSR method is that it is a single-station, economical, portable, non-intrusive and easily deployed technique that does not require an active source. It only takes approximately 15 minutes to collect a measurement and it does not require expertise to analyze the data or interpret the results. Although the relationship developed for soil over limestone provided a useful depth estimate from the findings of this study, the HVSR method is a crude tool that should not be used blindly. Because the existence of a shale layer in the profile cannot be detected by the HVSR measurements, this method cannot be applied broadly in Central Missouri unless the site is known to consist of soil over limestone. The measurement predictions could certainly be improved by performing surface wave measurements to obtain the V_S velocity profile. The combined use of surface waves and HVSR is now often done but suffers from the same drawbacks of extensive equipment deployment and expertise to perform the measurements. The study herein specifically focused on the use of the HVSR method alone as a site investigation method.

6.6 Summary

Discussions of the relationships developed between HVSR frequency and depth to bedrock were presented in this chapter. The relationships were separated into different plots based on the bedrock conditions to investigate the large scatter observed in the relationships. The relationship of soil over limestone produced a reliable depth to rock estimation while the other relationships developed for profiles containing a shale layer did not. The degree of scatter is likely influenced by the thickness and shear wave velocity of the shale, values that are not known without other supplemental measurements. The consistency and reliability of the HVSR peak frequency was also discussed in this chapter. In addition, a discussion on the practical application of the HVSR method in Central Missouri was presented. The results from this application showed that the HVSR method can be used to reliably estimate the depth to rock when shale is not present. However, the HVSR method should not be used blindly when the bedrock conditions are not known as a large error in the depth to rock prediction is possible.

7. CONCLUSION

7.1 Summary

Depth to bedrock determination is an important parameter in geotechnical site investigation. Numerous methods such as drilling, resistivity and seismic refraction can be used to determine the depth to bedrock. However, these methods can be expensive, labor intensive, time-consuming, and require expertise to perform. A more recent, simple geophysical method to determine the depth to rock is the Horizontal-to-Vertical Spectral Ratio (HVSR) method, which is a single-station method that requires only passive ambient noise, can be easily deployed by a single person quickly, and requires only minutes to collect data.

The central objective of this study was to use the HVSR method to develop a relationship for the depth to rock around the University of Missouri campus from the frequency measured from HVSR. Importantly, this approach can be performed without an independent shear wave velocity measurement. A total of 65 HVSR measurements were performed around the campus, where ground-truth data on bedrock depth were available from borings log. The ambient noise records were processed, analyzed, and interpreted using the open source Geopsy software. The relationship of depth to bedrock and frequency was developed using a power function fit for all data and the subsets of data that were developed based on the bedrock conditions.

Large 90% confidence bounds ($\pm$ 10 ft) in depth estimates were observed when all the data were considered. However, when the data were separated into subsets based on the geology, the relationship of soil over limestone provided a useful estimate of the bedrock depth, where the 90% confidence bounds were $\pm$ 6 to 7 ft. The average error in measured versus predicted values was 12%, with a range of 0.5 to 7.7 ft. This error is consistent with the errors reported from work of Delgado (2000), which is 15%. In addition, the values of the power function fit of this relationship agreed with measurements from past studies and expected values from theoretical considerations.

However, when shale was present in the subsurface profile, the relationship of depth to limestone showed very large confidence bounds (± 15 ft), which limit the usefulness for rock depth prediction applications. This poor performance in soil/shale/limestone profiles is likely due to the large change in the average shear wave velocity ($V_{s,AVG}$) above the soil/limestone interface due to the shale layer. Other attributes of HVSR measurements were investigated as a means to detect the presence of shale, and therefore identify measurements that were not reliable. However, these relationships did not provide enough evidence to support their use as a means of identifying shale in the subsurface.

The HVSR method was also performed at a major ongoing construction project near the University of Missouri. The results from this application showed that the HVSR method can be used to reliably estimate the depth to limestone when it is known beforehand that shale is not present. The HVSR results were in very good agreement with refraction measurements performed by another contractor, the average errors of depth prediction were within 12%.

7.2 Conclusions

Based on the results of this study, it was concluded that the HVSR method can be used to reliably estimate the depth to limestone around the University of Missouri campus when the subsurface profile is soil over limestone. The 90% confidence bounds were around 6 to 7 ft over a bedrock depth range of 10 to 50 ft. The average error in bedrock depth prediction was 12% for the 20 data points. However, when the subsurface profile included a shale layer the scatter was large with errors of as much as 58%. The large uncertainty is likely due to the variable thickness and higher shear wave velocity of the shale than soil, which will tend to shift the data points to higher frequencies for thicker shale layers. Neither the thickness nor shale velocity can be measured from HVSR alone. Also, the results showed the presence of shale was not indicated by other attributes of the HVSR plot. Therefore, it was concluded that the HVSR method can only be used reliably to estimate the depth to limestone when supplemental information (i.e. nearby borings) indicates that shale is not present or very thin. Bedrock depths predicted from HVSR measurements at a nearby construction site presented in this thesis support these conclusions.

7.3 Recommendations

It is recommended that the relationship of depth to limestone versus frequency developed in this study can be used on future site investigations for construction projects at the University of Missouri when the subsurface profile is known to not include shale layers. This may be beneficial, for example, when the contractor needs to relocate foundation locations to sites without boring information. In addition, the HVSR method could be performed prior to drilling operations to examine the variability of bedrock depth around the site and develop a more efficient and economical plan for the number and location of borings.

Based on the conclusions presented in this thesis, one recommendation for future work is to perform more HVSR measurements around Central Missouri to refine and improve the relationships and investigate and characterize the errors in depth to rock prediction when considering other factors. Also, there is a need to develop simple procedures to measure and incorporate shear wave velocity measurements to improve the accuracy of the predictions. In addition, more work should focus on the repeatability of the measurements and the impact of temporal and directional factors on measurement variability.

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APPENDIX A-1

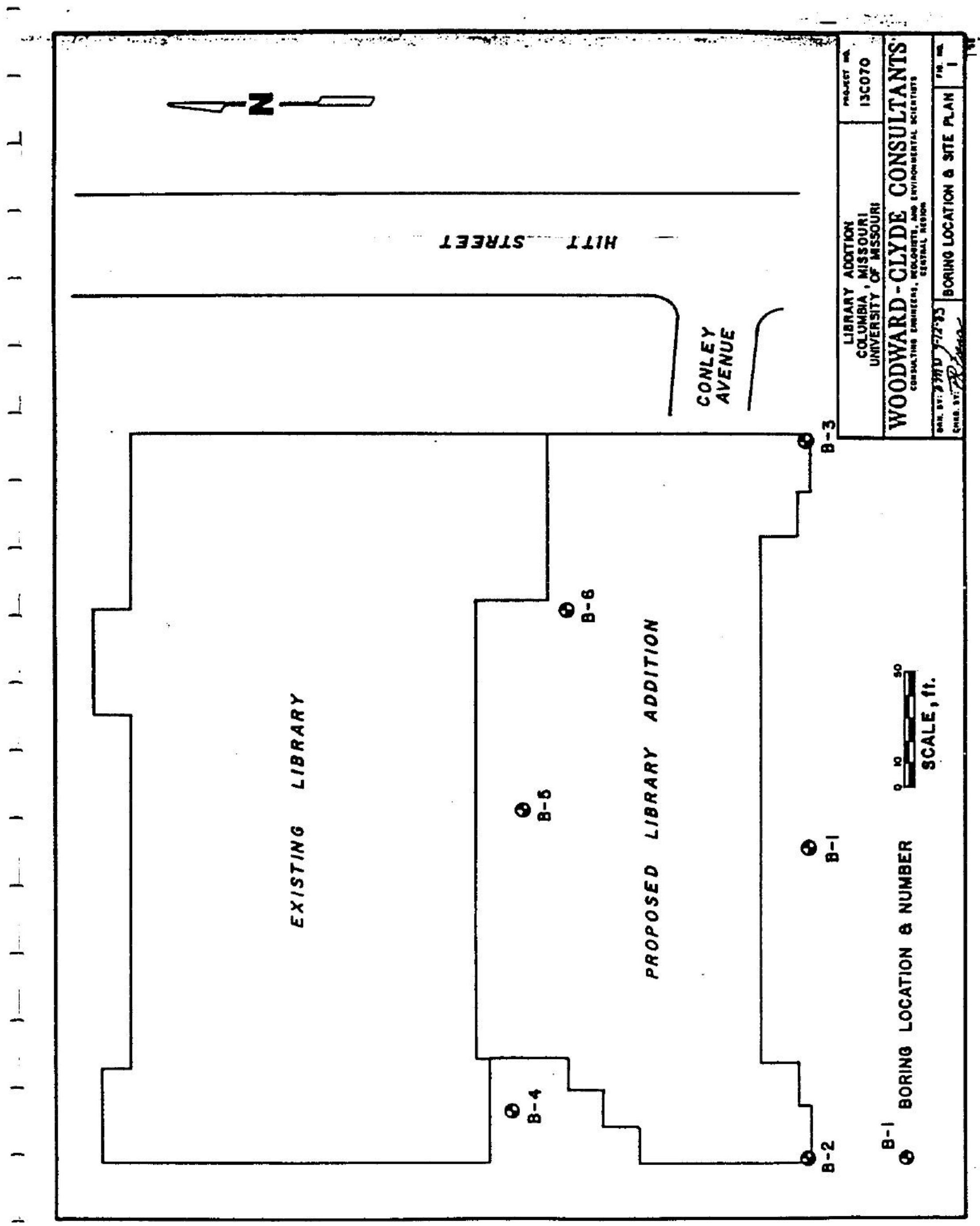

Figure 1: Gateway Residents Hall boring plan (Aerial View), prepared by Terracon Consulting Engineers & Scientists

BORING LOG

SHEET 1 OF 3

PROJECT NAME ELLIS LIBRARY - MU

PROJECT NO. 13C070

DATE 7-12-83

B-1

PROJECT LOCATION Columbia, MO

RIG CME-55

LOGGED BY C. Franks DRILLED BY R. Herber

WATER ENTERS El. 740 ATD

SURFACE ELEVATION 764 ELEVATION DATUM USC & GS

DEPTH	SAMPLE TYPE	SAMPLE REC	SAMPLE RESIST	DESCRIPTION	U.S.C.	SPECIAL NOTES AND FIELD OBSERVATIONS
0				Very stiff to hard, brown, highly plastic Silty CLAY with organics, blocky texture	CH	Boring advanced with 4" diameter CFA
	C	12/12	P			WC ≥ PL
				Hard yellowish-tan with gray, low plastic Silty CLAY with small nodules of limonite	CL	PP > 9.0 ksf
	C	12/12	P			WC > PL
5						PP = 4.5 ksf
				Stiff to very stiff, gray with rust, low plastic Sandy CLAY with rock fragments		
	C	12/12	P			
10				Very stiff to hard, reddish-brown mottled with brown and gray, medium plastic Sandy CLAY with rock fragments, zones of black staining with small pockets of gray, fine grained, Clayey SAND	W/ SC	WC > PL PP = 6.0 ksf
	C	12/12	P			WC > PL
15						PP > 9.0 ksf
				Becoming mixed with hard, gray, fine grained poorly graded SAND with clay silt and rock fragments	W/ SP	
				Very stiff, reddish-tan with gray, highly plastic CLAY with lenses of fine grained sand	CH W/ SP	
	C	12/12	P			WC > PL
20						PP > 9.0 ksf
				Dense, yellow-ochre, poorly graded, fine grained, Silty SAND with pockets of very stiff, reddish-brown, highly plastic CLAY	SM W/ CH	Water detected ATD
	C	4/4	P			
25						

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FIGURE NO. 4

Figure 2: Ellis Library Borehole 1

BORING LOG

SHEET 2 OF 3

PROJECT NAME ELLIS LIBRARY - MU

PROJECT NO. 13C070

DATE 7-12-83

B-1

PROJECT LOCATION Columbia, MO

RIG CME-55

LOGGED BY C. Franks DRILLED BY R. Herber

WATER ENTERS El. 740 ATD

SURFACE ELEVATION 764 ELEVATION DATUM USC & GS

DEPTH	SAMPLE TYPE	SAMPLE REC	SAMPLE RESIST	DESCRIPTION	U.S.C.	SPECIAL NOTES AND FIELD OBSERVATIONS
25				SAME: Dense, reddish brown to yellow-ochre and gray, poorly graded, fine grained Silty SAND with pockets of very stiff, highly plastic CLAY	SM W/ CH	
	C	6/8	P			
30						
	S	16/18	7 18 21			
35						
	S	18/18	8 17 20			Boring continued with NX double tube core barrel with diamond bit and water
40			RQD			
	NX RUN #1	35/48 73%	0/48 0%	LIMESTONE/CHERT: Gray, maroon, cream and dark gray, moderately weathered, to unweathered with zones of severely weathered material; micro-crystalline to finely crystalline; thin-bedded, jointed, very fractured, fossiliferous with very stiff, cream, highly plastic CLAY seams	LS W/ CH	NX RUN #1 Start: 41.5' Stop: 45.5' Run: 4.0' Rec: 2.9' Lost: 1.1'
45	NX RUN #2	60/72 83%	32/72 44%	Becoming less fractured, very fossiliferous zone; possibly sedimentary breccia		NX RUN #2 Start: 45.5' Stop: 51.5 Run: 6.0' Rec: 5.0' Lost: 1.0'
50						

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FIGURE NO 5

Figure 3: Ellis Library Borehole 1 (Continue)

BORING LOG

SHEET 3 OF 3

PROJECT NAME ELLIS LIBRARY - MU

PROJECT NO. 13C070

DATE 7-12-83

B-1

PROJECT LOCATION Columbia, MO

RIG CME-55

LOGGED BY C. Franks DRILLED BY R. Herber

WATER ENTERS El. 740 ATD

SURFACE ELEVATION 764 ELEVATION DATUM USC & GS

DEPTH	SAMPLE TYPE	REC	REQ RESIST	DESCRIPTION	U.S.C.	SPECIAL NOTES AND FIELD OBSERVATIONS
50	NX RUN #2 (Cont.)			LIMESTONE: Gray with green and some pink, lightly weathered to unweathered, micro-crystalline; with thin clay partings and crush zones, occasional chert layers; pockets of clay and stylolites	LS	NX RUN #2 (Cont.)
	NX RUN #3	4/12 33%	0/12 0%			NX RUN #3 Start: 51.5' Stop: 52.5' Run: 1.0' Rec: 0.3' Lost: 0.7'
55	NX RUN #4	53/60 88%	33/60 55%			NX RUN #4 Start: 52.5 Stop: 57.5' Run: 5.0' Rec: 4.4' Lost: 0.6' DWR 90%
						Bottom of boring 57.5'
60						
65						
70						
75						

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FIGURE NO. 6

Figure 4: Ellis Library Borehole 1 (Continue)

BORING LOG

SHEET 1 OF 3

PROJECT NAME ELLIS LIBRARY - MU

PROJECT NO. 13C070

DATE 7-13-83

B-2

PROJECT LOCATION Columbia, MO

RIG CME-55

LOGGED BY C. Franks DRILLED BY R. Herber

WATER ENTERS EL. 732 ATD

SURFACE ELEVATION 765 ELEVATION DATUM USC & GS

DEPTH	SAMPLE TYPE	SAMPLE REC	SAMPLE RESIST	DESCRIPTION	U.S.C.	SPECIAL NOTES AND FIELD OBSERVATIONS
0				ASPHALT	FILL	Boring advanced with 4" diameter CFA
				CRUSHED ROCK FILL		
				Stiff, dark brown, low plastic, Silty Clay FILL with some rock fragments		
				Very stiff, reddish-brown, low plastic, Silty CLAY	CL	WC > PL
	C	12/12	P	Becoming gray with reddish-brown, with trace of fine sand and small nodules of limonite		WC > PL
5						PP = 4.5 ksf
				Very stiff, mottled gray with rust, highly plastic CLAY with fine sand and small rock fragments	CH	
	U	0/12	P	Becoming yellow-ochre and gray with black zones		
10	U	24/12	P			WC > PL
						PP = 5.5 ksf
	C	12/12	P	Very stiff to hard, light olive-gray, highly plastic CLAY with thin partings; limonite, trace of fine sand and rock fragments		WC > PL
15						PP ≥ 8.5 ksf
				Becomes mixed and mottled reddish-brown and gray-olive with black increasing number of and size of rock fragments		
	C	12/12	P			WC > PL
20						PP > 9.0 ksf
				Becoming reddish-brown mottled with gray		
	C	12/12	P			WC > PL
25						PP > 9.0 ksf

WOODWARD-CLYDE CONSULTANTS

FIGURE NO. 7

Figure 5: Ellis Library Borehole 2

BORING LOG

SHEET 2 OF 3

PROJECT NAME ELLIS LIBRARY - MU

PROJECT NO. 13C070

DATE 7-14-83

B-2

PROJECT LOCATION Columbia, MO

RIG CME-55

LOGGED BY C. Franks DRILLED BY R. Herber

WATER ENTERS El. 732 ATD

SURFACE ELEVATION 765 ELEVATION DATUM USC & GS

DEPTH	SAMPLE TYPE	SAMPLE REC	SAMPLE RESIST	DESCRIPTION	U.S.C.	SPECIAL NOTES AND FIELD OBSERVATIONS
25				SAME: Very stiff to hard, reddish-brown, mottled with gray and yellow-ochre, highly plastic Sandy CLAY with dense, gray, fine grained poorly graded Silty SAND and occasional large gravel	CH W/ SM	WC > PL
	C	12/12	P			PP = 7.0-8.0 ksf
30				Dense, orange and gray, fine to medium grained, poorly graded SAND with silt and pockets of highly plastic CLAY	SP W/ CH	← Water detected ATD
	S	18/18	10 17 16			
35				Hard, orange, highly plastic CLAY with sand and rock fragments with layers of dense, orange, medium to finely grained poorly graded SAND with silt	CH W/ SP	WC < PL
	S	18/18	5 11 28			Boring continued with NX double tube core barrel with diamond bit and water
40				Hard, white-cream, highly plastic Silty CLAY	CH	
			RQD	LIMESTONE W/CHERT: Medium gray, very fractured; weathered to unweathered, micro-crystalline to finely crystalline, with fossils, pyrite, siliceous zones with layers of dark gray to black CHERT	LS W/ CHERT	NX RUN #1 Start 42.0' Stop: 51.5' Run: 9.5' Rec: 4.25' Lost: 5.25'
	NX RUN #1	51/114	10/114			
45				Becoming fine to medium crystalline		
		45%	9%			
50						

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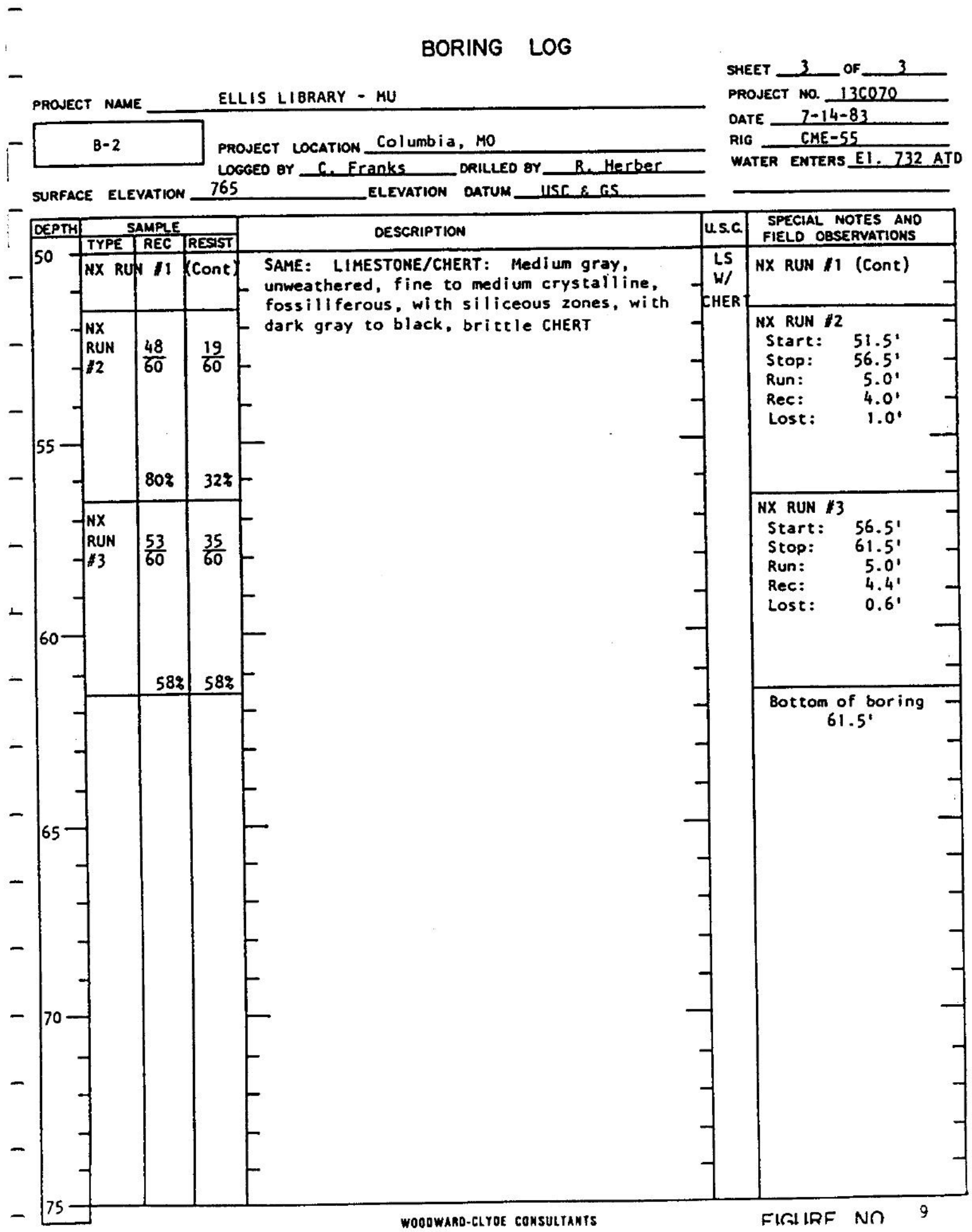
FIGURE NO. 8

Figure 5: Ellis Library Borehole 2 (Continue)



BORING LOG

SHEET 3 OF 3
PROJECT NO. 13C070
DATE 7-14-83
RIG CME-55
WATER ENTERS El. 732 ATD

PROJECT NAME ELLIS LIBRARY - MU

B-2

PROJECT LOCATION Columbia, MO
LOGGED BY C. Franks DRILLED BY R. Herber
SURFACE ELEVATION 765 ELEVATION DATUM USC & GS

DEPTH	SAMPLE TYPE	SAMPLE REC	SAMPLE RESIST	DESCRIPTION	U.S.C.	SPECIAL NOTES AND FIELD OBSERVATIONS
50	NX RUN #1		(Cont)	SAME: LIMESTONE/CHERT: Medium gray, unweathered, fine to medium crystalline, fossiliferous, with siliceous zones, with dark gray to black, brittle CHERT	LS W/ CHERT	NX RUN #1 (Cont)
	NX RUN #2	48/60	19/60			NX RUN #2 Start: 51.5' Stop: 56.5' Run: 5.0' Rec: 4.0' Lost: 1.0'
55		80%	32%			
	NX RUN #3	53/60	35/60			NX RUN #3 Start: 56.5' Stop: 61.5' Run: 5.0' Rec: 4.4' Lost: 0.6'
60		58%	58%			Bottom of boring 61.5'
65						
70						
75						

WOODWARD-CLYDE CONSULTANTS

FIGURE NO. 9

Figure 6: Ellis Library Borehole 2 (Continue)

BORING LOG

SHEET 1 OF 2

PROJECT NAME ELLIS LIBRARY - MU

PROJECT NO. 13C070

DATE 7-15-83

RIG CME-55

WATER ENTERS El. 743 ATD

B-3

PROJECT LOCATION Columbia, MO

LOGGED BY C. Franks DRILLED BY R. Herber

SURFACE ELEVATION 761 ELEVATION DATUM USC & GS

DEPTH	SAMPLE TYPE	SAMPLE REC	SAMPLE RESIST	DESCRIPTION	U.S.C.	SPECIAL NOTES AND FIELD OBSERVATIONS
0				ASPHALT		Boring advanced with 4" diameter CFA
				CRUSHED ROCK FILL	FILL	
				Stiff to very stiff, olive-tan, low plastic Silty CLAY	CL	WC > PL
				Becoming gray with dark reddish-brown, with heavy iron staining		WC > PL
5	U	12/12	P			PP = 4.0 ksf
				Very stiff to hard, gray and reddish-brown, highly plastic CLAY with sand and rock fragments and black staining	CH	
10	C	12/12	P			WC > PL PP 6.0 ksf
				Becoming hard and fissured		WC > PL
15	C	12/12	P			PP ≥ 9.0 ksf
20	C	12/12	P			WC > PL PP ≥ 9.0 ksf
				Becomes very sandy		← Water detected ATD
25	C	12/12	P			

WOODWARD-CLYDE CONSULTANTS

FIGURE NO. 10

Figure 7: Ellis Library Borehole 3

BORING LOG

SHEET 2 OF 2
PROJECT NO. 13C070
DATE 7-15-83
RIG CME-55
WATER ENTERS El. 743 ATD

PROJECT NAME ELLIS LIBRARY - MU

B-3

PROJECT LOCATION Columbia, MO
LOGGED BY C. Franks DRILLED BY R. Herber
SURFACE ELEVATION 761 ELEVATION DATUM USC & GS

DEPTH	SAMPLE TYPE	SAMPLE REC	SAMPLE RESIST	DESCRIPTION	U.S.C.	SPECIAL NOTES AND FIELD OBSERVATIONS
25				SAME: Very stiff to hard, gray and reddish brown, highly plastic CLAY very sandy with rock fragments and black staining	CH	
				Dense, orange and gray, fine to medium grained, poorly graded Clayey SAND to hard, orange, highly plastic, Sandy CLAY with occasional gravel	SC | CH	
30	S	18/18	16 13 21			
				Becoming mixed gray, reddish brown and cream		
35	S	17/17	10 18 50/5"	Hard, cream, highly plastic Silty CLAY	CH	WC < PL
				LIMESTONE W/CHERT: Gray & cream white, fractured	LS W/ CHERT	Bottom of boring 37.0'
40						
45						
50						

WOODWARD-CLYDE CONSULTANTS

FIGURE NO. 11

Figure 8: Ellis Library Borehole 3 (Continue)

BORING LOG

SHEET 1 OF 2

PROJECT NAME ELLIS LIBRARY - MU

PROJECT NO. 13C070

DATE 7-15-83

B-4

PROJECT LOCATION Columbia, MO

RIG CME-55

LOGGED BY C. Franks DRILLED BY R. Herber

WATER ENTERS El. 737 ATD

SURFACE ELEVATION 765 ELEVATION DATUM USC & GS

DEPTH	SAMPLE TYPE	SAMPLE REC	SAMPLE RESIST	DESCRIPTION	U.S.C.	SPECIAL NOTES AND FIELD OBSERVATIONS
0				Stiff to very stiff, reddish-tan, low plastic Silty CLAY	CL	Boring advanced with 4" diameter CFA; WC ≤ PL
				Becoming mixed with gray with blocky texture and limonite		
5	C	12/12	P	Very stiff, light gray with light brown, highly plastic CLAY with silt and iron stains	CH	WC ≥ PL; PP > 9.0 ksf
10	U	12/12	P	Becoming hard and fissured, with some fine sand and rock fragments		WC ≥ PL; PP > 9.0 ksf
15	C	12/12	P	Hard, gray and reddish-brown, highly plastic CLAY with silt and sand, occasional rock fragments, limonite and black stains		WC ≥ PL; PP > 9.0 ksf
20	C	4/4	P	Very dense, yellow-ochre, fine grained, poorly graded Silty SAND	SM	Poorly cemented
25	S	18/18	9 15 28	Becomes medium grained, mixed with SILT and CLAY stratification	W/ CH & ML	

WOODWARD-CLYDE CONSULTANTS

FIGURE NO 12

Figure 9: Ellis Library Borehole 4

BORING LOG

SHEET 2 OF 2

PROJECT NAME ELLIS LIBRARY - MU

PROJECT NO. 13C070

DATE 7-15-83

B-4

PROJECT LOCATION Columbia, MO

RIG CME-55

LOGGED BY C. Franks DRILLED BY R. Herber

WATER ENTERS El. 737 ATD

SURFACE ELEVATION 765 ELEVATION DATUM " USC & GS

DEPTH	SAMPLE TYPE	SAMPLE REC	SAMPLE RESIST	DESCRIPTION	U.S.C.	SPECIAL NOTES AND FIELD OBSERVATIONS
25				SAME: Very dense, yellow-ochre, medium grained, poorly graded, Silty SAND stratified with SILT and CLAY	SM W/ CH & ML	Moist ← Water detected ATD
30	S	18/18	9 11 18	Becoming medium dense and stratified		
35	S	18/18	10 22 31	Becoming very dense		
40	S	12/12	8 53	LIMESTONE/CHERT: Gray, fractured, thin bedded	LS W/ CHERT	Bottom of boring 42.0'
45						
50						

WOODWARD-CLYDE CONSULTANTS

FIGURE NO. 13

Figure 10: Ellis Library Borehole 4 (Continue)

APPENDIX A-2

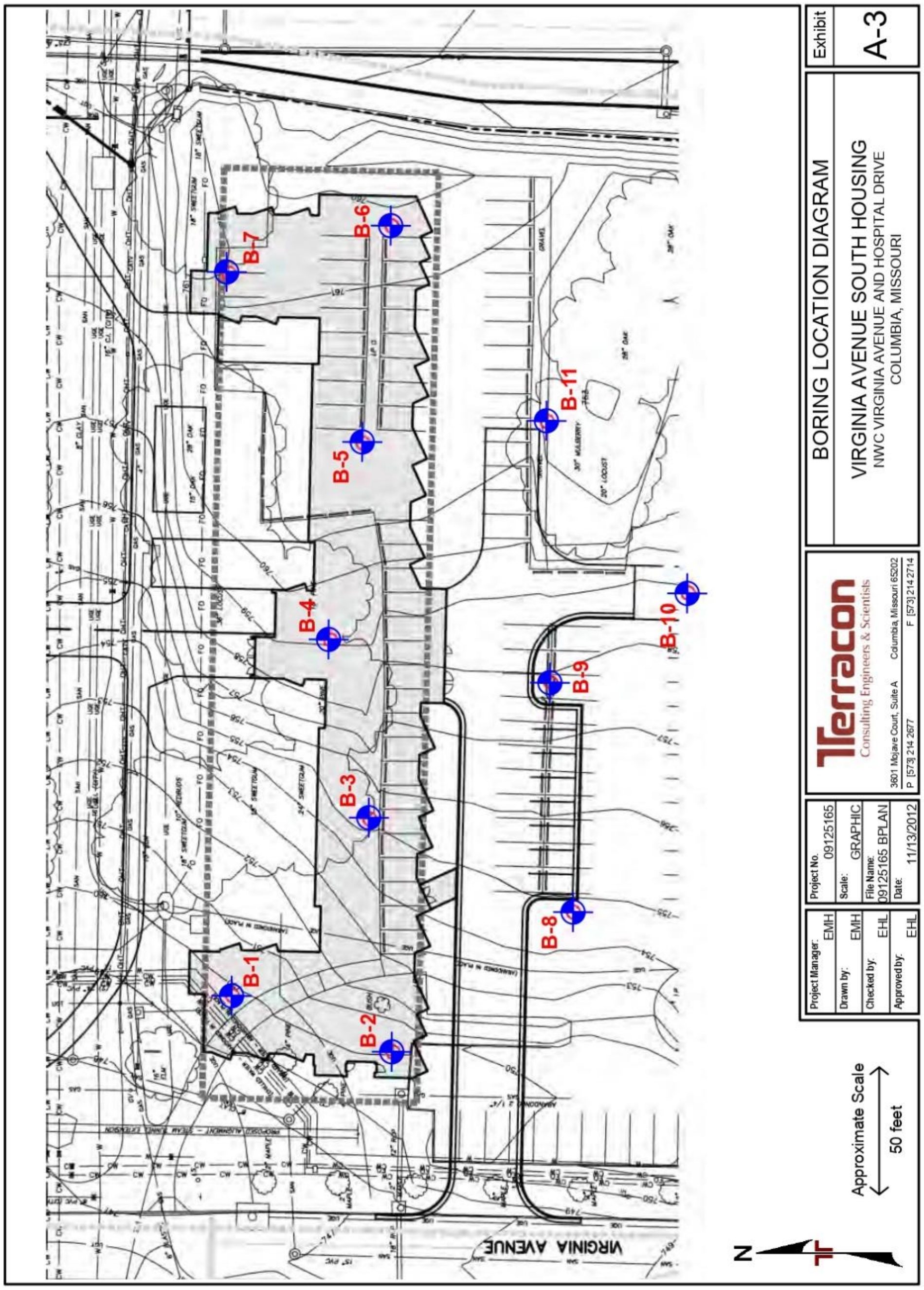


Figure 1: Gateway Residents Hall boring plan (Aerial View), prepared by Terracon Consulting Engineers & Scientists

THIS BORING LOG IS NOT VALID IF SEPARATED FROM ORIGINAL REPORT. TERRACON SMART LOG-NO WELL 09125165.GPJ ODOT TEST.GPJ 11/12/12

BORING LOG NO. B-1

Page 1 of 1

PROJECT: Virginia Avenue South Housing

CLIENT: University of Missouri Columbia, Missouri

SITE: Virginia Avenue Columbia, Missouri

LOCATION See Exhibit A-3

Approximate Surface Elev: 750 (Ft.) +/-

DEPTH	Material description	ELEVATION (Ft.)
0.2	**TOPSOIL**, 2"	750+/-
3.0	**FAT CLAY (CH)**, trace sand, brown, with reddish brown and black, hard	747+/-
18.0	**FAT CLAY (CH)**, with sand, gray, with brown, stiff to very stiff (Glacial Drift) -- trace gravel	732+/-
23.0	**CLAYEY SAND (SC)**, brown, medium dense (Glacial Drift)	727+/-
24.0		726+/-
26.0	**FAT CLAY (CH)**, with sand, gravel, and cobbles, brown, hard (Glacial Drift)	724+/-
26.3	**SHALEY FAT CLAY (CH)**, gray, hard	723.5+/-
	LIMESTONE, white, slightly weathered, hard ***Auger Refusal at 26.3 Feet***	

RECOVERY (In.)	FIELD TEST RESULTS	SAMPLE NUMBER	SWELL (%)	UNCONFINED COMPRESSIVE STRENGTH (psf)	WATER CONTENT (%)	DRY UNIT WEIGHT (pcf)	ATTERBERG LIMITS LL-PL-PI
10	9000 (HP)	1			12		
22	6000 (HP)	2	1.8		17		47-13-34
19	3500 (HP)	3		3850	18	113	
24	8000 (HP)	4			20		
24		5			19		
5	50/5" N=50/5"	6			17		

DEPTH (Ft.): 5, 10, 15, 20, 25

Stratification lines are approximate. In-situ, the transition may be gradual.

Classifications and stratigraphic boundaries estimated from disturbed samples. Core samples and petrographic analysis may reveal other rock types and stratigraphic classifications.

Hammer Type: Automatic SPT Hammer

Advancement Method:
Solid-stem augers

Abandonment Method:
Backfilled with soil cuttings after obtaining 24-hour groundwater readings.

See Exhibit A-15 for description of field procedures

See Appendix B for description of laboratory procedures and additional data, (if any).

See Appendix C for explanation of symbols and abbreviations.

Elevations were interpolated from a topographic site plan.

Notes:

WATER LEVEL OBSERVATIONS

22 feet while sampling

19 feet at completion of drilling

15 feet at 24 hours after completion of drilling

Terracon
3601 Mojave Court, Suite A
Columbia, Missouri

Boring Started: 10/29/2012	Boring Completed: 10/29/2012
Drill Rig: CME-75	Driller: JBW
Project No.: 09125165	Exhibit: A-4

Figure 2: Gateway Residents Hall Borehole 1

BORING LOG NO. B-2

Page 1 of 1

PROJECT: Virginia Avenue South Housing

CLIENT: University of Missouri, Columbia, Missouri

SITE: Virginia Avenue, Columbia, Missouri

LOCATION See Exhibit A-3

Approximate Surface Elev. 750 (Ft.) +/-

DEPTH	DESCRIPTION	ELEVATION (Ft.)
0.3	**TOPSOIL**, 4"	749.5+/-
1.0	**AGGREGATE BASE COURSE (GW)**, 8" base rock fill	749+/-
3.0	**UNCONTROLLED FILL**, with sand and gravel, dark gray	747+/-
	FAT CLAY (CH), with sand, trace gravel, gray, with tan and brown, stiff to very stiff (Glacial Drift)	
	-- sandy, with gravel, reddish brown, with tan and brown	
	-- with sand, gray	
	-- with brown	
23.5		726.5+/-
	SHALE, gray, severely weathered, medium hard	
32.8		717+/-
	LIMESTONE, white and gray, with chert and shale, highly fractured, moderately weathered, hard	
39.3		710.5+/-
	LIMESTONE, gray, slightly weathered, hard	
42.8		707+/-
	Boring Terminated at 42.8 Feet	

RECOVERY (In.)	FIELD TEST RESULTS	SAMPLE NUMBER	SWELL (%)	UNCONFINED COMPRESSIVE STRENGTH (psf)	WATER CONTENT (%)	DRY UNIT WEIGHT (pcf)	ATTERBERG LIMITS LL-PL-PI
15	2000 (HP)	1			14		
18	4000 (HP)	2		1540	22	102	
24	6000 (HP)	3			27		
22	6000 (HP)	4		7890	17	115	
18	4-6-10 N=16 6000 (HP)	5			16		
18	20-27-50 N=77 9000 (HP)	6			9		
5	50/5" N=50/5"	7			7		
43	RQD = 0%	R1					
83	RQD = 0%	R2					
71	RQD = 10%	R3					

Stratification lines are approximate. In-situ, the transition may be gradual.
Classifications and stratigraphic boundaries estimated from visual observations of samples.
Petrographic and fossil analysis may reveal other rock types and stratigraphic classifications.

Hammer Type: Automatic SPT Hammer

Advancement Method:
Solid-stem augers

Abandonment Method:
Backfilled with soil cuttings after obtaining 24-hour groundwater readings.

See Exhibit A-15 for description of field procedures

See Appendix B for description of laboratory procedures and additional data, (if any).

See Appendix C for explanation of symbols and abbreviations.

Elevations were interpolated from a topographic site plan.

Notes:

Note 1: A meaningful groundwater reading was not able to be obtained at completion of drilling due to the introduction of drilling fluid to facilitate rock coring at a depth of approximatley 32.8 feet.

WATER LEVEL OBSERVATIONS

24 feet while sampling

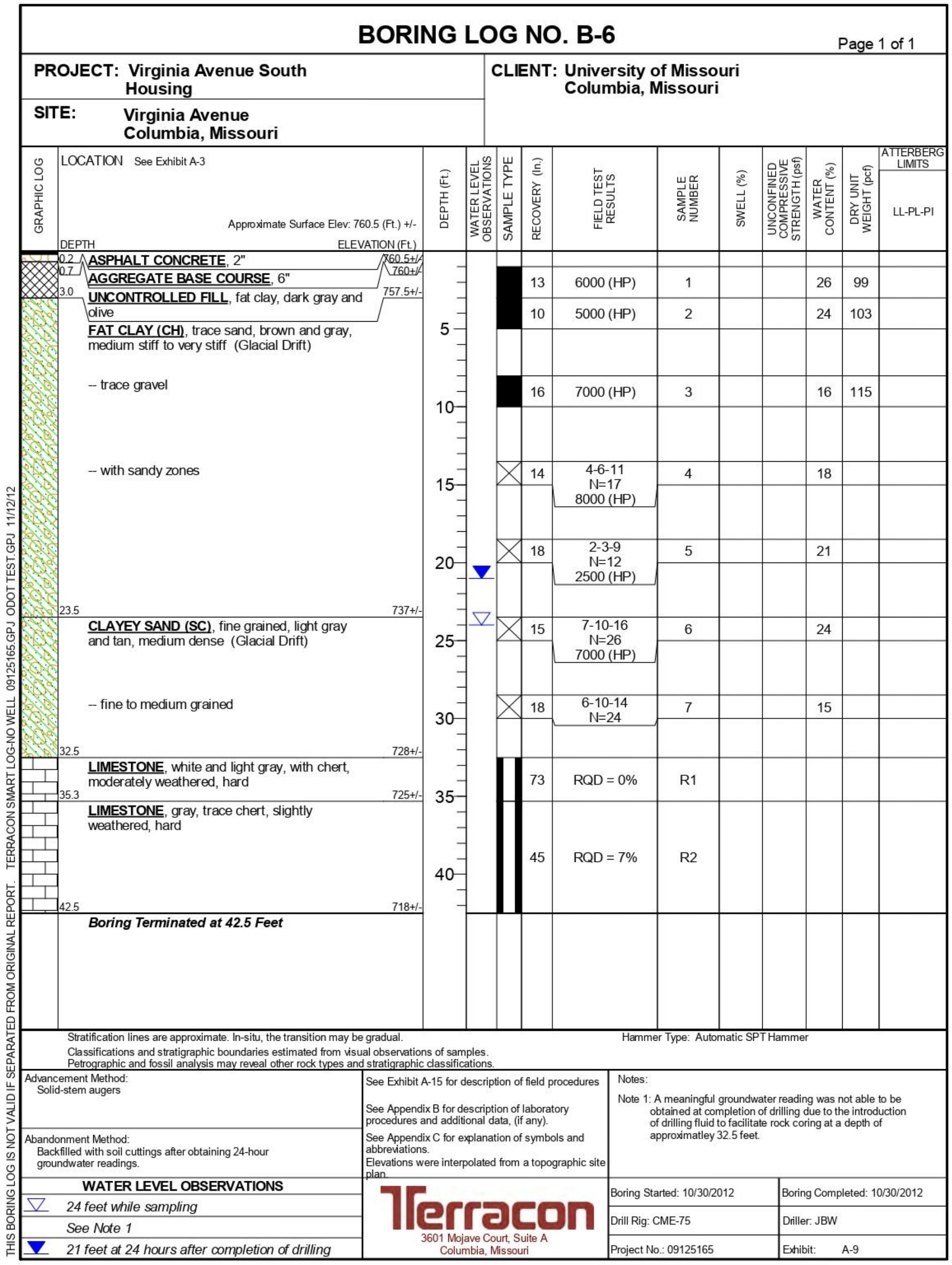
See Note 1

13 feet at 24 hours after completion of drilling

Terracon
3601 Mojave Court, Suite A
Columbia, Missouri

Boring Started: 10/31/2012	Boring Completed: 10/31/2012
Drill Rig: CME-75	Driller: JBW
Project No.: 09125165	Exhibit: A-5

Figure 3: Gateway Residents Hall Borehole 2



BORING LOG NO. B-6

Page 1 of 1

PROJECT: Virginia Avenue South Housing

CLIENT: University of Missouri, Columbia, Missouri

SITE: Virginia Avenue, Columbia, Missouri

LOCATION See Exhibit A-3

Approximate Surface Elev: 760.5 (Ft.) +/-

DEPTH	Description	ELEVATION (Ft.)	DEPTH (Ft.)	RECOVERY (In.)	FIELD TEST RESULTS	SAMPLE NUMBER	SWELL (%)	UNCONFINED COMPRESSIVE STRENGTH (psf)	WATER CONTENT (%)	DRY UNIT WEIGHT (pcf)	ATTERBERG LIMITS LL-PL-PI
0.2	**ASPHALT CONCRETE**, 2"	760.5+/-									
0.7	**AGGREGATE BASE COURSE**, 6"	760+/-									
3.0	**UNCONTROLLED FILL**, fat clay, dark gray and olive	757.5+/-		13	6000 (HP)	1			26	99	
	FAT CLAY (CH), trace sand, brown and gray, medium stiff to very stiff (Glacial Drift)		5	10	5000 (HP)	2			24	103	
	-- trace gravel		10	16	7000 (HP)	3			16	115	
	-- with sandy zones		15	14	4-6-11 N=17 8000 (HP)	4			18		
			20	18	2-3-9 N=12 2500 (HP)	5			21		
23.5	**CLAYEY SAND (SC)**, fine grained, light gray and tan, medium dense (Glacial Drift)	737+/-	25	15	7-10-16 N=26 7000 (HP)	6			24		
	-- fine to medium grained		30	18	6-10-14 N=24	7			15		
32.5	**LIMESTONE**, white and light gray, with chert, moderately weathered, hard	728+/-		73	RQD = 0%	R1					
35.3	**LIMESTONE**, gray, trace chert, slightly weathered, hard	725+/-	35, 40	45	RQD = 7%	R2					
42.5	***Boring Terminated at 42.5 Feet***	718+/-									

Stratification lines are approximate. In-situ, the transition may be gradual.
Classifications and stratigraphic boundaries estimated from visual observations of samples.
Petrographic and fossil analysis may reveal other rock types and stratigraphic classifications.

Hammer Type: Automatic SPT Hammer

Advancement Method: Solid-stem augers

Abandonment Method: Backfilled with soil cuttings after obtaining 24-hour groundwater readings.

See Exhibit A-15 for description of field procedures

See Appendix B for description of laboratory procedures and additional data, (if any).

See Appendix C for explanation of symbols and abbreviations.

Elevations were interpolated from a topographic site plan.

Notes:

Note 1: A meaningful groundwater reading was not able to be obtained at completion of drilling due to the introduction of drilling fluid to facilitate rock coring at a depth of approximatley 32.5 feet.

WATER LEVEL OBSERVATIONS

- 24 feet while sampling
- See Note 1
- 21 feet at 24 hours after completion of drilling

Terracon, 3601 Mojave Court, Suite A, Columbia, Missouri

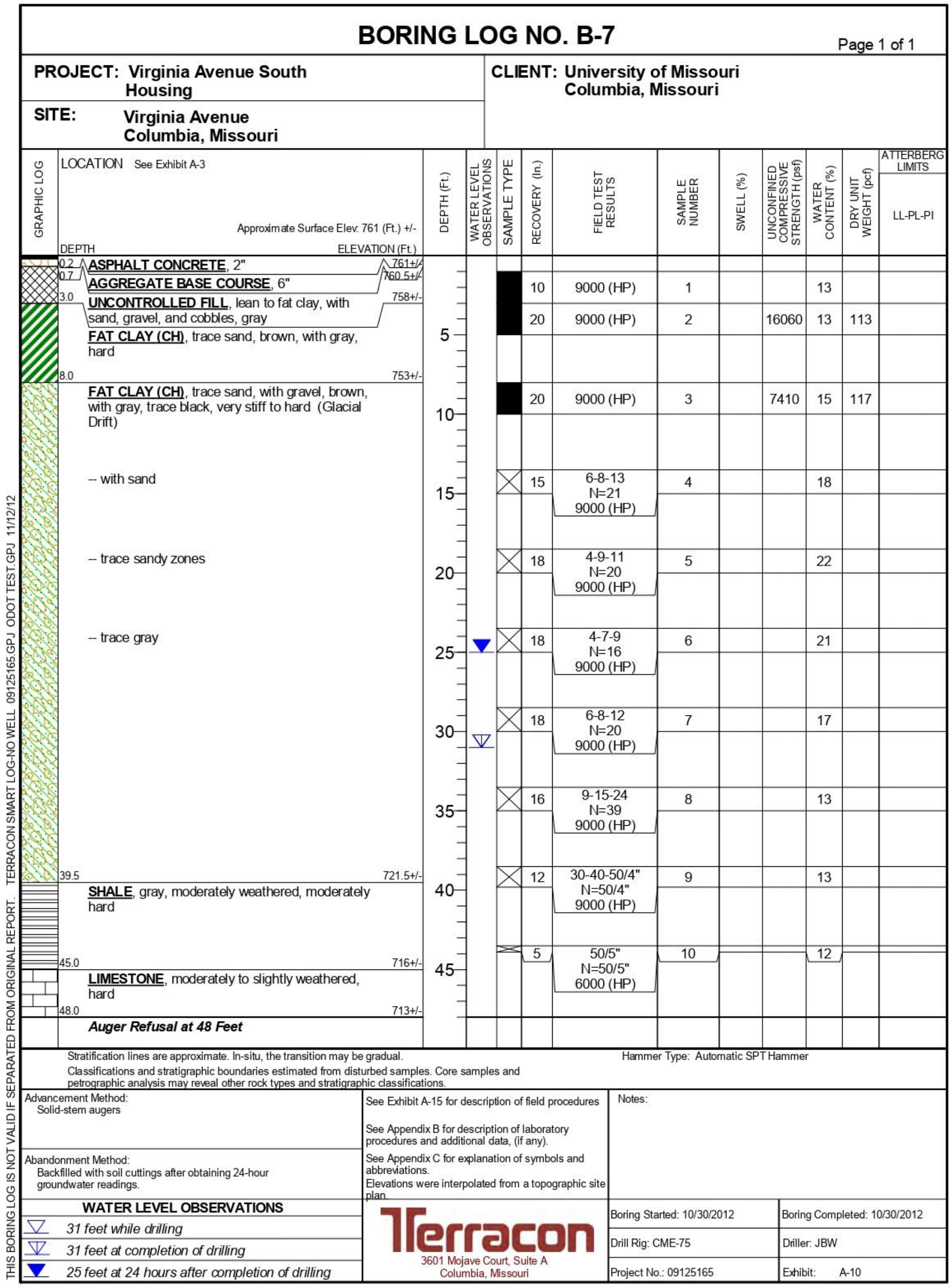
Boring Started: 10/30/2012 | Boring Completed: 10/30/2012

Drill Rig: CME-75 | Driller: JBW

Project No.: 09125165 | Exhibit: A-9

THIS BORING LOG IS NOT VALID IF SEPARATED FROM ORIGINAL REPORT. TERRACON SMART LOG-NO WELL 09125165.GPJ ODOT TEST.GPJ 11/12/12

Figure 4: Gateway Residents Hall Borehole



BORING LOG NO. B-7

Page 1 of 1

PROJECT: Virginia Avenue South Housing

CLIENT: University of Missouri Columbia, Missouri

SITE: Virginia Avenue Columbia, Missouri

LOCATION See Exhibit A-3

Approximate Surface Elev: 761 (Ft.) +/-

DEPTH	Description	ELEVATION (Ft.)
0.2	**ASPHALT CONCRETE**, 2"	761+/-
0.7	**AGGREGATE BASE COURSE**, 6"	760.5+/-
3.0	**UNCONTROLLED FILL**, lean to fat clay, with sand, gravel, and cobbles, gray	758+/-
8.0	**FAT CLAY (CH)**, trace sand, brown, with gray, hard	753+/-
39.5	**FAT CLAY (CH)**, trace sand, with gravel, brown, with gray, trace black, very stiff to hard (Glacial Drift) -- with sand -- trace sandy zones -- trace gray	721.5+/-
45.0	**SHALE**, gray, moderately weathered, moderately hard	716+/-
48.0	**LIMESTONE**, moderately to slightly weathered, hard	713+/-
	Auger Refusal at 48 Feet	

RECOVERY (In.)	FIELD TEST RESULTS	SAMPLE NUMBER	SWELL (%)	UNCONFINED COMPRESSIVE STRENGTH (psf)	WATER CONTENT (%)	DRY UNIT WEIGHT (pcf)	ATTERBERG LIMITS LL-PL-PI
10	9000 (HP)	1			13		
20	9000 (HP)	2		16060	13	113	
20	9000 (HP)	3		7410	15	117	
15	6-8-13 N=21 9000 (HP)	4			18		
18	4-9-11 N=20 9000 (HP)	5			22		
18	4-7-9 N=16 9000 (HP)	6			21		
18	6-8-12 N=20 9000 (HP)	7			17		
16	9-15-24 N=39 9000 (HP)	8			13		
12	30-40-50/4" N=50/4" 9000 (HP)	9			13		
5	50/5" N=50/5" 6000 (HP)	10			12		

Stratification lines are approximate. In-situ, the transition may be gradual.

Classifications and stratigraphic boundaries estimated from disturbed samples. Core samples and petrographic analysis may reveal other rock types and stratigraphic classifications.

Hammer Type: Automatic SPT Hammer

Advancement Method: Solid-stem augers

Abandonment Method: Backfilled with soil cuttings after obtaining 24-hour groundwater readings.

See Exhibit A-15 for description of field procedures

See Appendix B for description of laboratory procedures and additional data, (if any).

See Appendix C for explanation of symbols and abbreviations.

Elevations were interpolated from a topographic site plan.

Notes:

WATER LEVEL OBSERVATIONS

- *31 feet while drilling*
- *31 feet at completion of drilling*
- *25 feet at 24 hours after completion of drilling*

Terracon, 3601 Mojave Court, Suite A, Columbia, Missouri

Boring Started: 10/30/2012 | Boring Completed: 10/30/2012

Drill Rig: CME-75 | Driller: JBW

Project No.: 09125165 | Exhibit: A-10

THIS BORING LOG IS NOT VALID IF SEPARATED FROM ORIGINAL REPORT. TERRACON SMART LOG-NO WELL 09125165.GPJ ODOT TEST.GPJ 11/12/12

Figure 5: Gateway Residents Hall Borehole 7

BORING LOG NO. B-11

Page 1 of 1

PROJECT: Virginia Avenue South Housing

CLIENT: University of Missouri Columbia, Missouri

SITE: Virginia Avenue Columbia, Missouri

LOCATION See Exhibit A-3

Approximate Surface Elev: 762 (Ft.) +/-

DEPTH	Description	ELEVATION (Ft.)	RECOVERY (In.)	FIELD TEST RESULTS	SAMPLE NUMBER	SWELL (%)	UNCONFINED COMPRESSIVE STRENGTH (psf)	WATER CONTENT (%)	DRY UNIT WEIGHT (pcf)	ATTERBERG LIMITS LL-PL-PI
0.2	**TOPSOIL**, 2"	762+/-								
	FAT CLAY (CH), trace sand and gravel, brown, trace gray, hard		23	9000 (HP)	1			12		
			24	9000 (HP)	2		6590	20	103	
8.0		754+/-								
	FAT CLAY (CH), with sand and gravel, brown, with gray, trace black, very stiff to hard (Glacial Drift)		8	9000 (HP)	3			13	115	
	-- possible cobbles		14	8-10-14 N=24 9000 (HP)	4			15		
			18	5-8-9 N=17 9000 (HP)	5			16		
			18	6-7-9 N=16 9000 (HP)	6			20		
			18	5-6-8 N=14 7000 (HP)	7			17		
33.0		729+/-								
33.3	**LIMESTONE**, slightly weathered, hard	728.5+/-								
	Auger Refusal at 33.3 Feet									

Stratification lines are approximate. In-situ, the transition may be gradual.

Classifications and stratigraphic boundaries estimated from disturbed samples. Core samples and petrographic analysis may reveal other rock types and stratigraphic classifications.

Hammer Type: Automatic SPT Hammer

Advancement Method:
Solid-stem augers

Abandonment Method:
Backfilled with soil cuttings after obtaining 24-hour groundwater readings.

See Exhibit A-15 for description of field procedures

See Appendix B for description of laboratory procedures and additional data, (if any).

See Appendix C for explanation of symbols and abbreviations.

Elevations were interpolated from a topographic site plan.

Notes:

WATER LEVEL OBSERVATIONS

- *32 feet while drilling*
- *26 feet at completion of drilling*
- *24.5 feet at 24 hours after completion of drilling*

Terracon
3601 Mojave Court, Suite A
Columbia, Missouri

Boring Started: 10/29/2012	Boring Completed: 10/29/2012
Drill Rig: CME-75	Driller: JBW
Project No.: 09125165	Exhibit: A-14

THIS BORING LOG IS NOT VALID IF SEPARATED FROM ORIGINAL REPORT. TERRACON SMART LOG-NO WELL 09125165.GPJ ODOT TEST.GPJ 11/12/12

Figure 6: Gateway Residents Hall Borehole 11

APPENDIX A-3

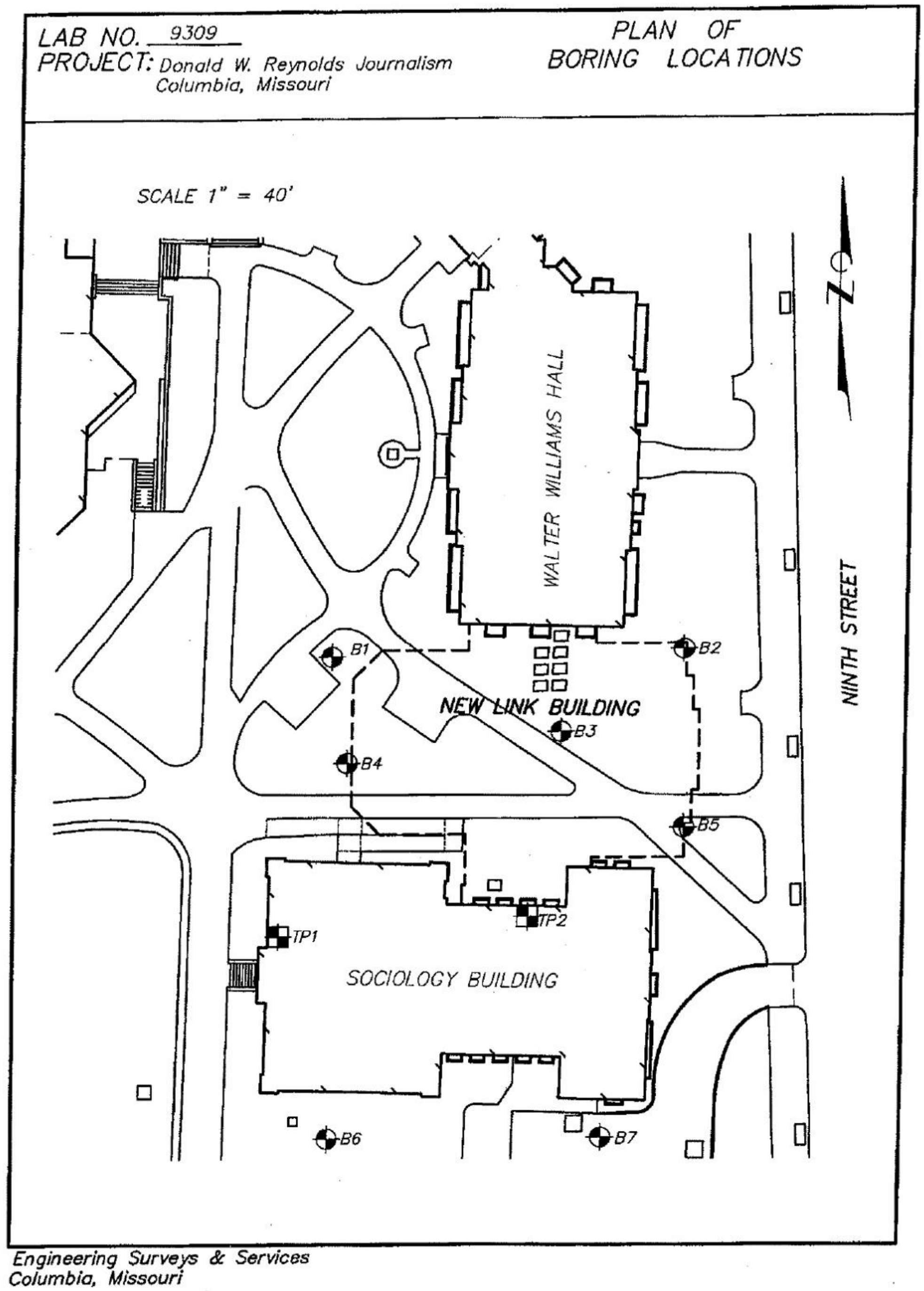


Figure 1: Donald W. Reynolds Journalism boring plan (Aerial View), prepared by Engineering Surveys and Services

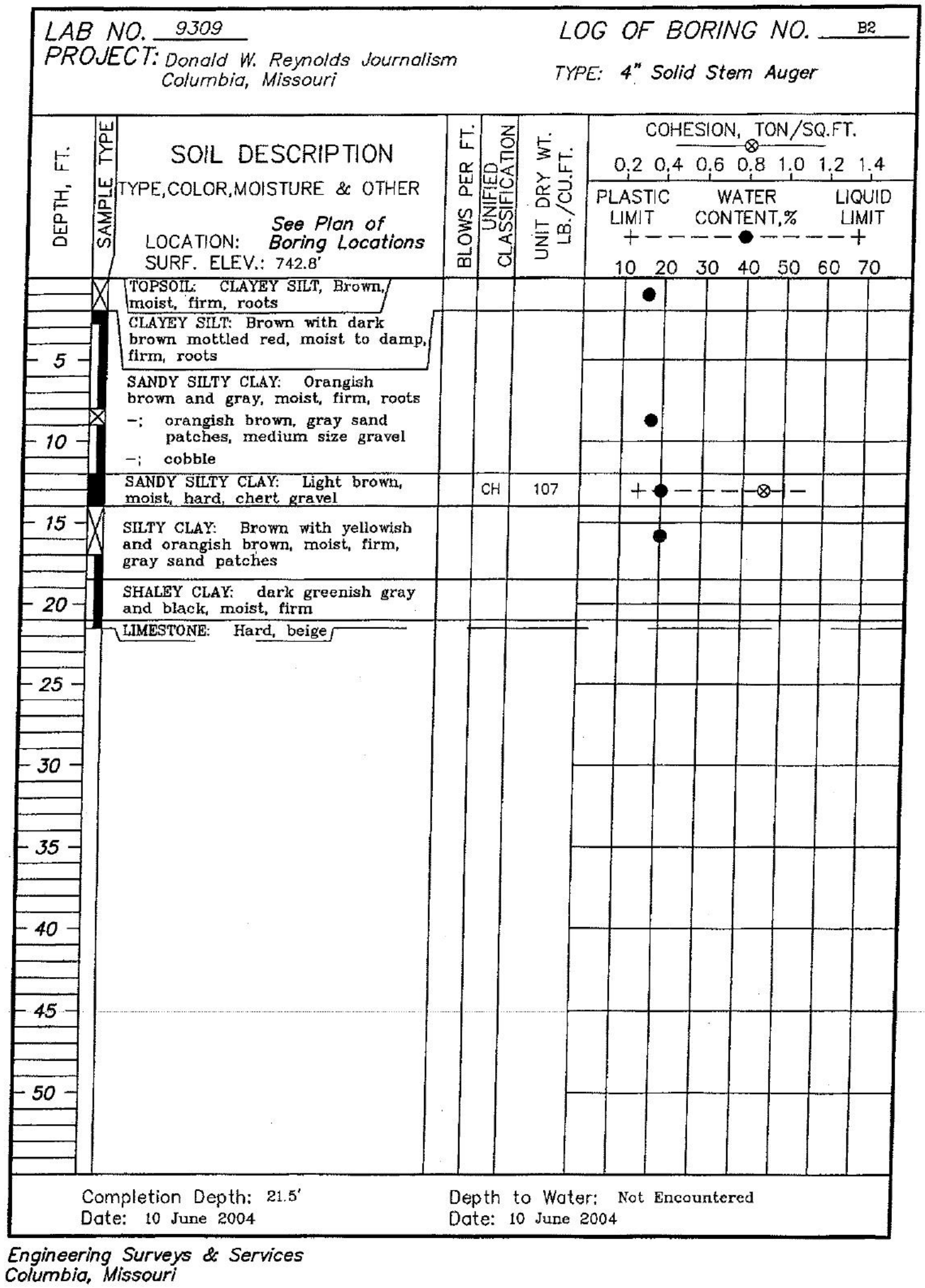


Figure 2: Donald W. Reynolds Journalism Borehole 2

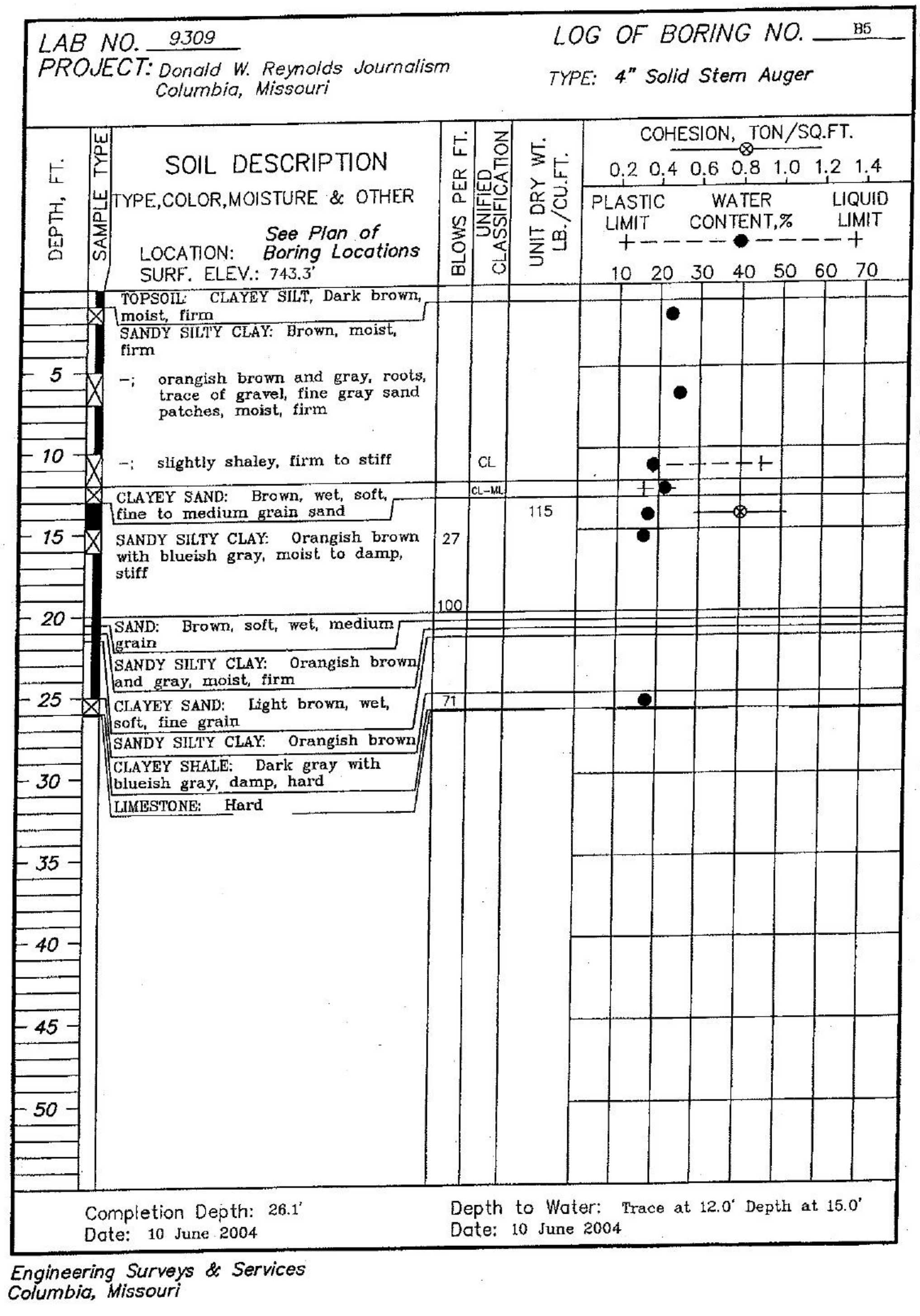


Figure 3: Donald W. Reynolds Journalism Borehole 5

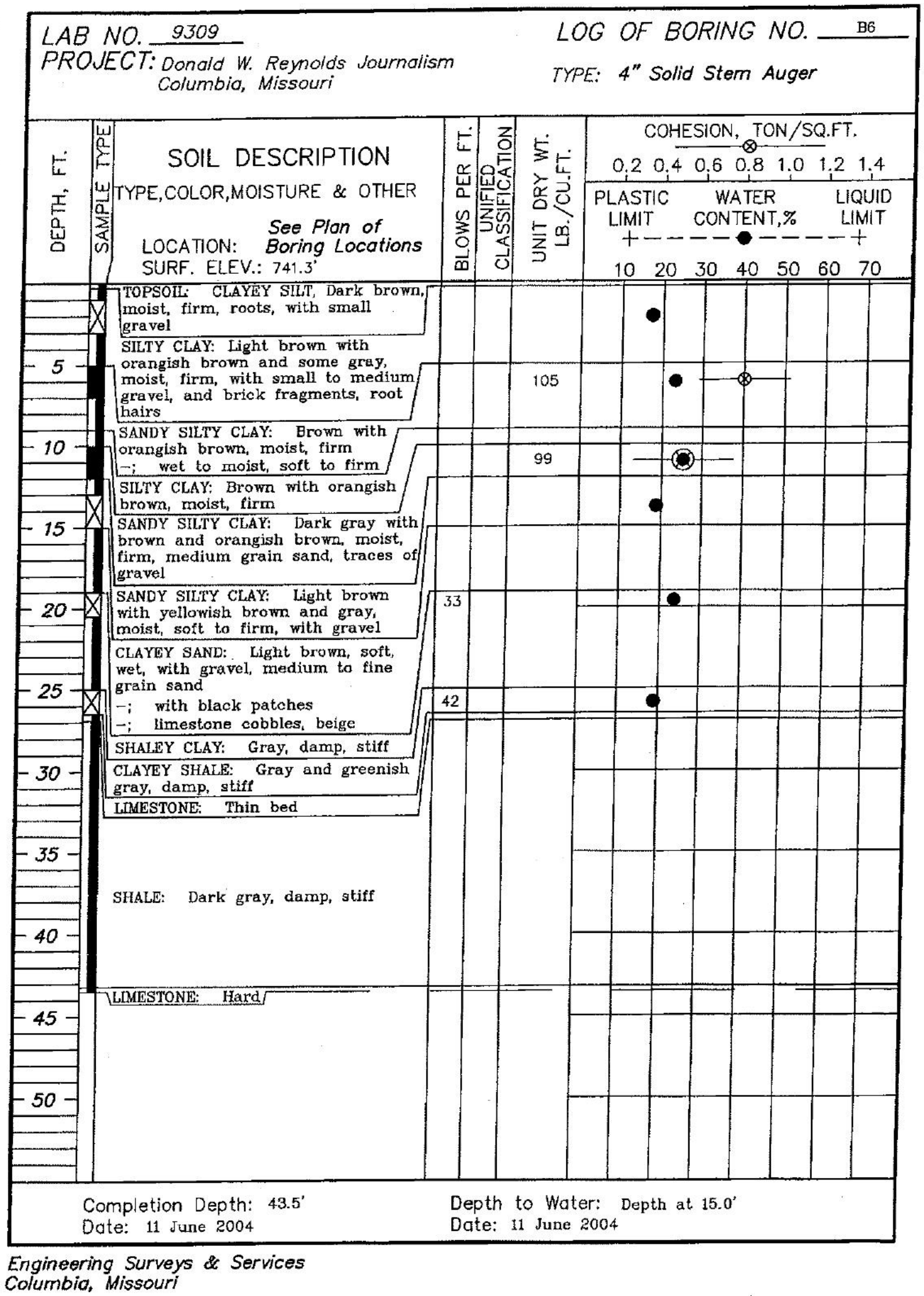


Figure 4: Donald W. Reynolds Journalism Borehole 6

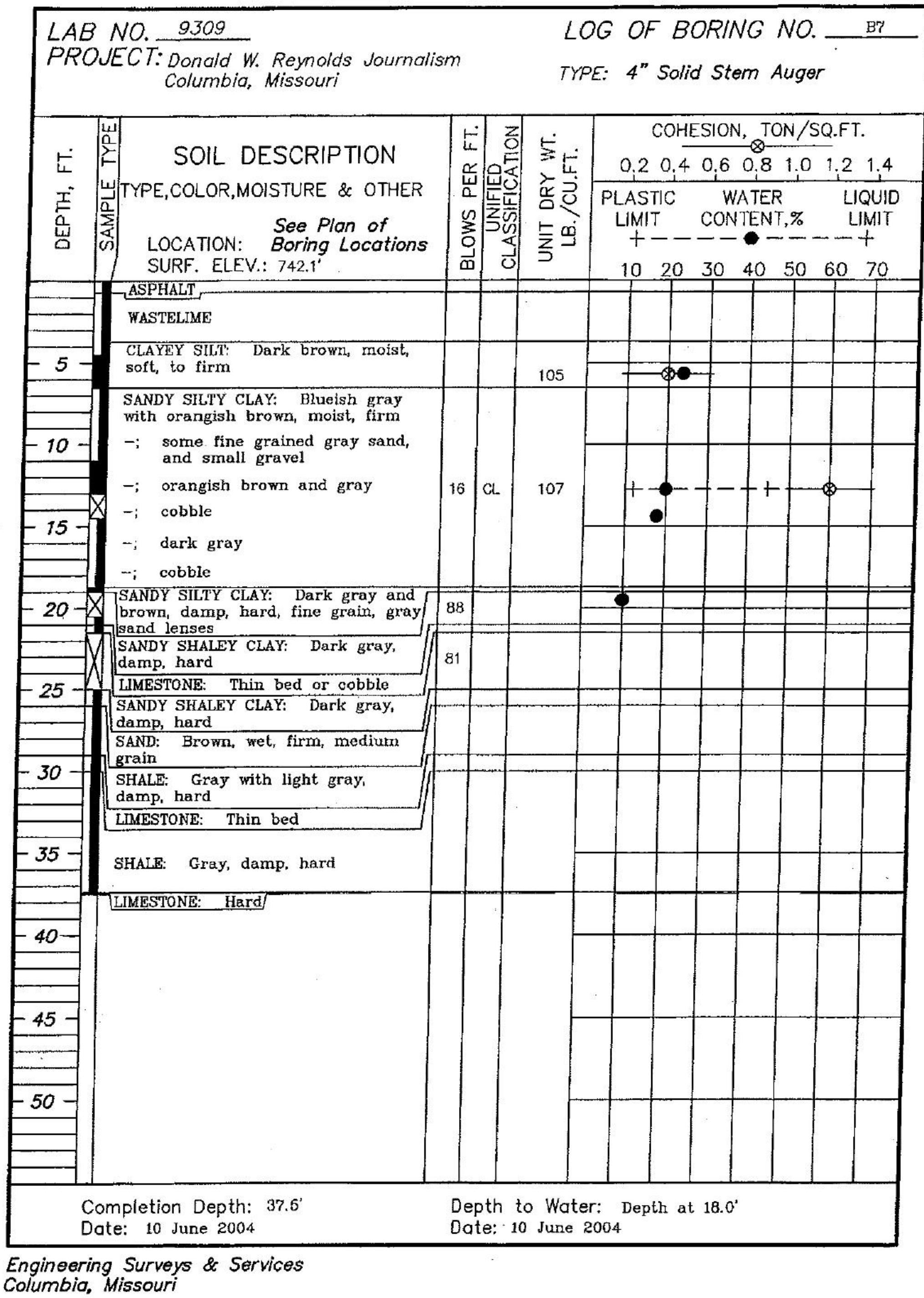


Figure 5: Donald W. Reynolds Journalism Borehole 7

APPENDIX A-4

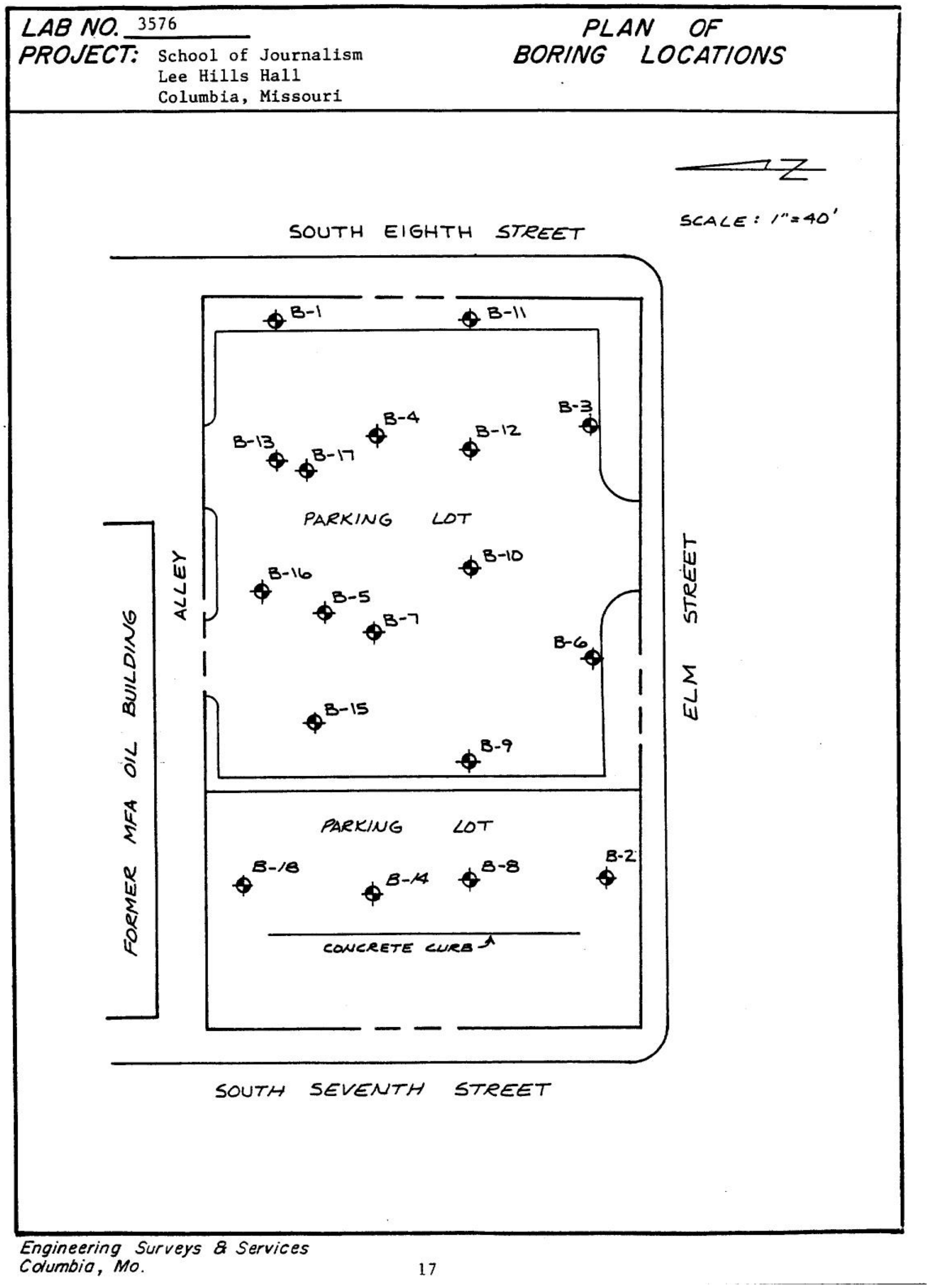


Figure 1: Lee Hills Hall boring plan (Aerial View), prepared by Engineering Surveys and Services

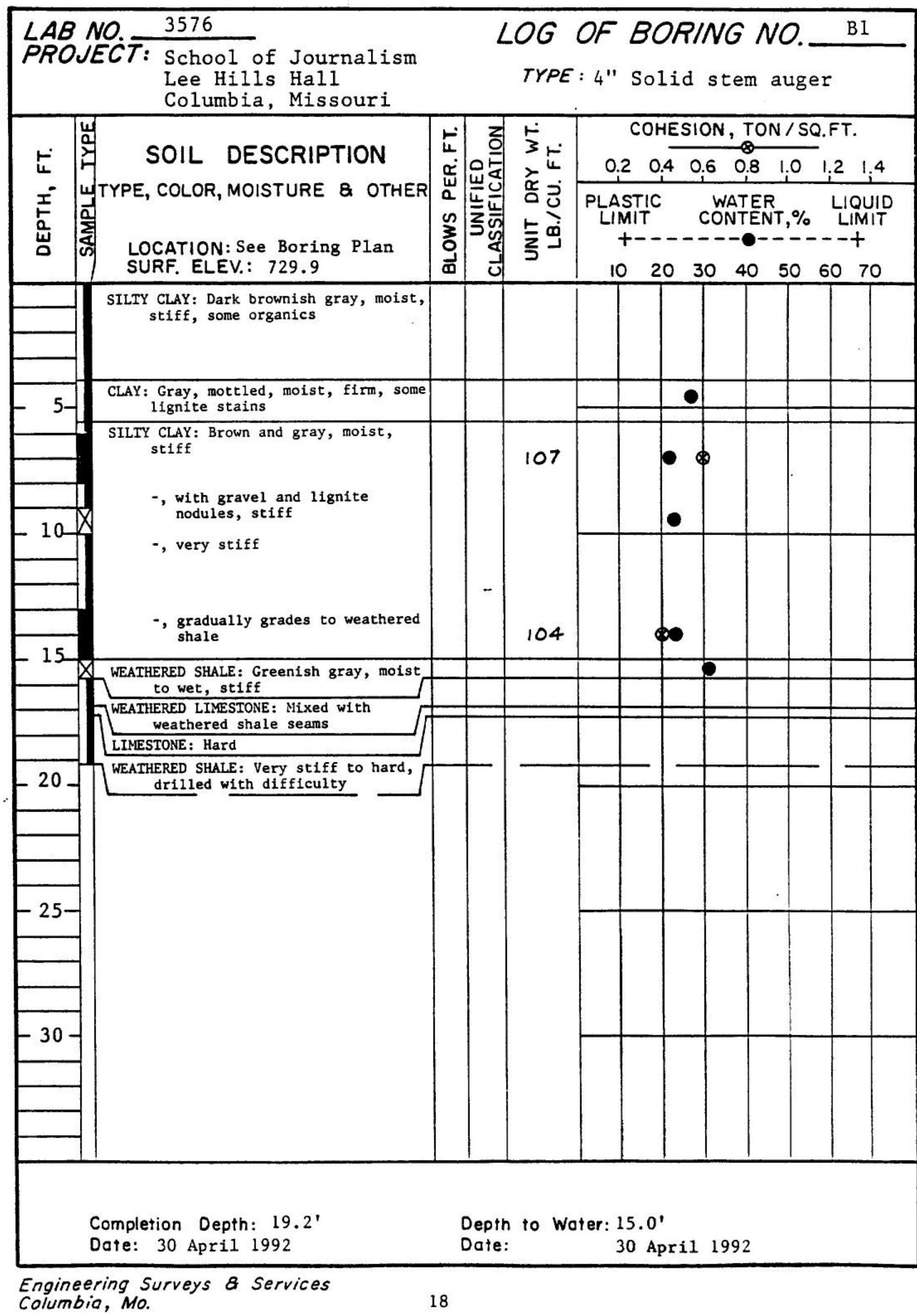
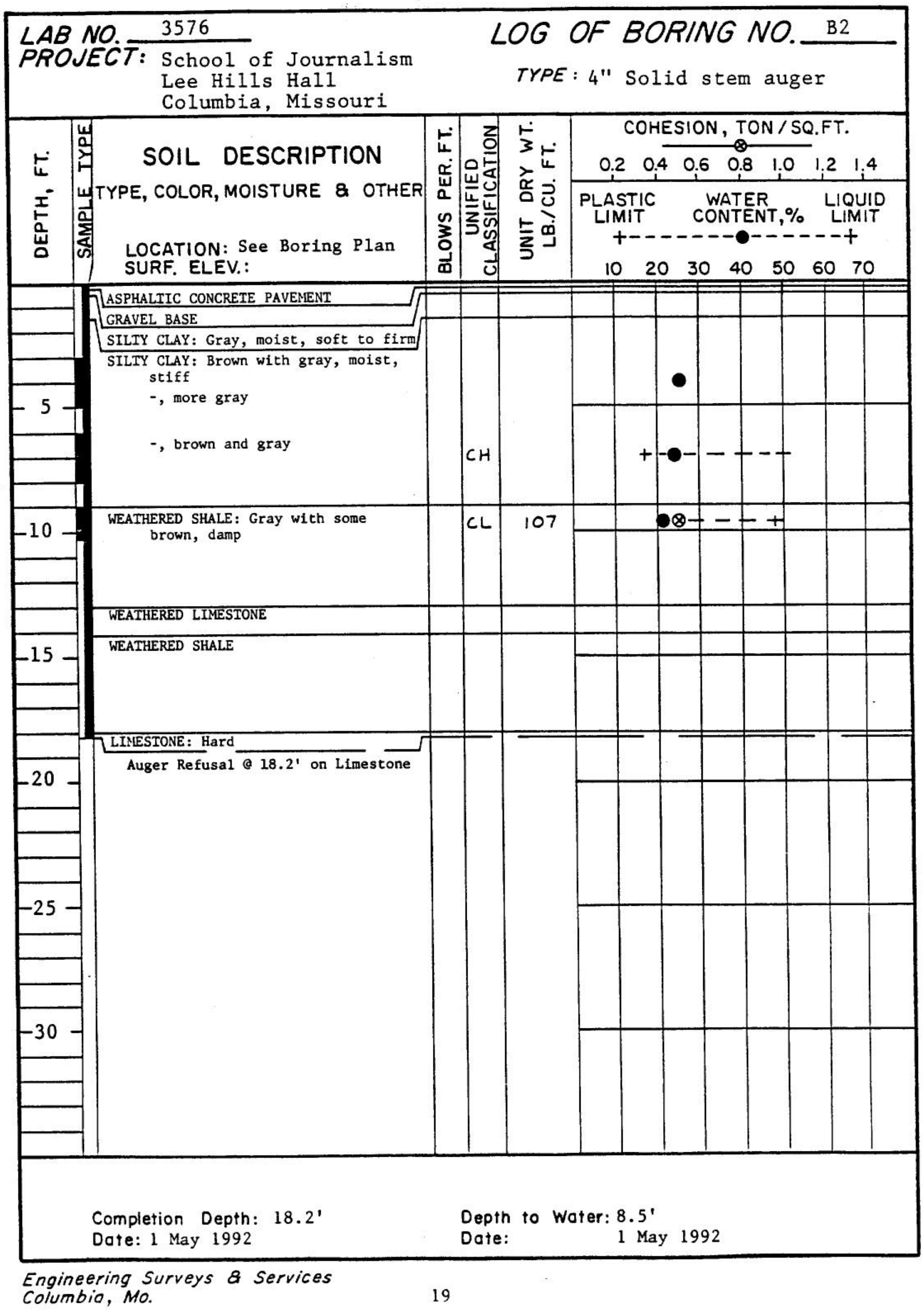


Figure 2: Lee Hills Hall Borehole 1



LAB NO. 3576

LOG OF BORING NO. B2

PROJECT: School of Journalism
Lee Hills Hall
Columbia, Missouri

TYPE: 4" Solid stem auger

DEPTH, FT.	SAMPLE TYPE	SOIL DESCRIPTION TYPE, COLOR, MOISTURE & OTHER (LOCATION: See Boring Plan; SURF. ELEV.:)	BLOWS PER. FT.	UNIFIED CLASSIFICATION	UNIT DRY WT. LB./CU. FT.
		ASPHALTIC CONCRETE PAVEMENT			
		GRAVEL BASE			
		SILTY CLAY: Gray, moist, soft to firm			
		SILTY CLAY: Brown with gray, moist, stiff			
5		-, more gray			
		-, brown and gray		CH	
10		WEATHERED SHALE: Gray with some brown, damp		CL	107
		WEATHERED LIMESTONE			
15		WEATHERED SHALE			
		LIMESTONE: Hard			
20		Auger Refusal @ 18.2' on Limestone			
25					
30					

COHESION, TON/SQ.FT. 0.2 0.4 0.6 0.8 1.0 1.2 1.4

PLASTIC LIMIT — WATER CONTENT,% — LIQUID LIMIT: 10 20 30 40 50 60 70

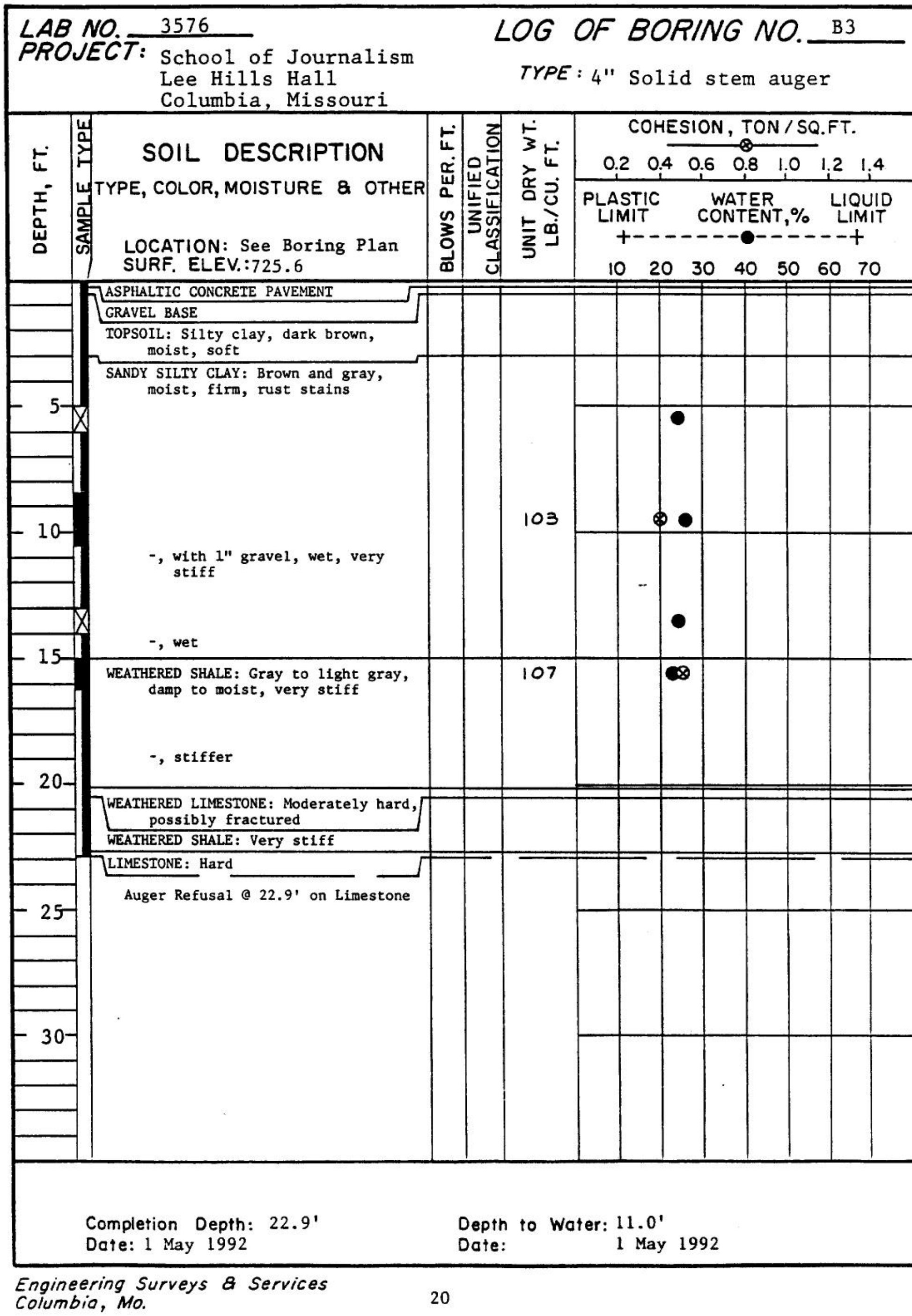
Completion Depth: 18.2'
Date: 1 May 1992

Depth to Water: 8.5'
Date: 1 May 1992

Engineering Surveys & Services
Columbia, Mo.

19

Figure 3: Lee Hills Hall Borehole 2



LAB NO. 3576

PROJECT: School of Journalism
Lee Hills Hall
Columbia, Missouri

LOG OF BORING NO. B3

TYPE: 4" Solid stem auger

DEPTH, FT.	SAMPLE TYPE	SOIL DESCRIPTION TYPE, COLOR, MOISTURE & OTHER (LOCATION: See Boring Plan; SURF. ELEV.: 725.6)	BLOWS PER. FT.	UNIFIED CLASSIFICATION	UNIT DRY WT. LB./CU. FT.
		ASPHALTIC CONCRETE PAVEMENT			
		GRAVEL BASE			
		TOPSOIL: Silty clay, dark brown, moist, soft			
		SANDY SILTY CLAY: Brown and gray, moist, firm, rust stains			
5					
10					103
		-, with 1" gravel, wet, very stiff			
15		-, wet			
		WEATHERED SHALE: Gray to light gray, damp to moist, very stiff			107
		-, stiffer			
20					
		WEATHERED LIMESTONE: Moderately hard, possibly fractured			
		WEATHERED SHALE: Very stiff			
		LIMESTONE: Hard			
		Auger Refusal @ 22.9' on Limestone			
25					
30					

COHESION, TON/SQ.FT.: 0.2 0.4 0.6 0.8 1.0 1.2 1.4

PLASTIC LIMIT — WATER CONTENT, % — LIQUID LIMIT: 10 20 30 40 50 60 70

Completion Depth: 22.9'
Date: 1 May 1992

Depth to Water: 11.0'
Date: 1 May 1992

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Columbia, Mo.

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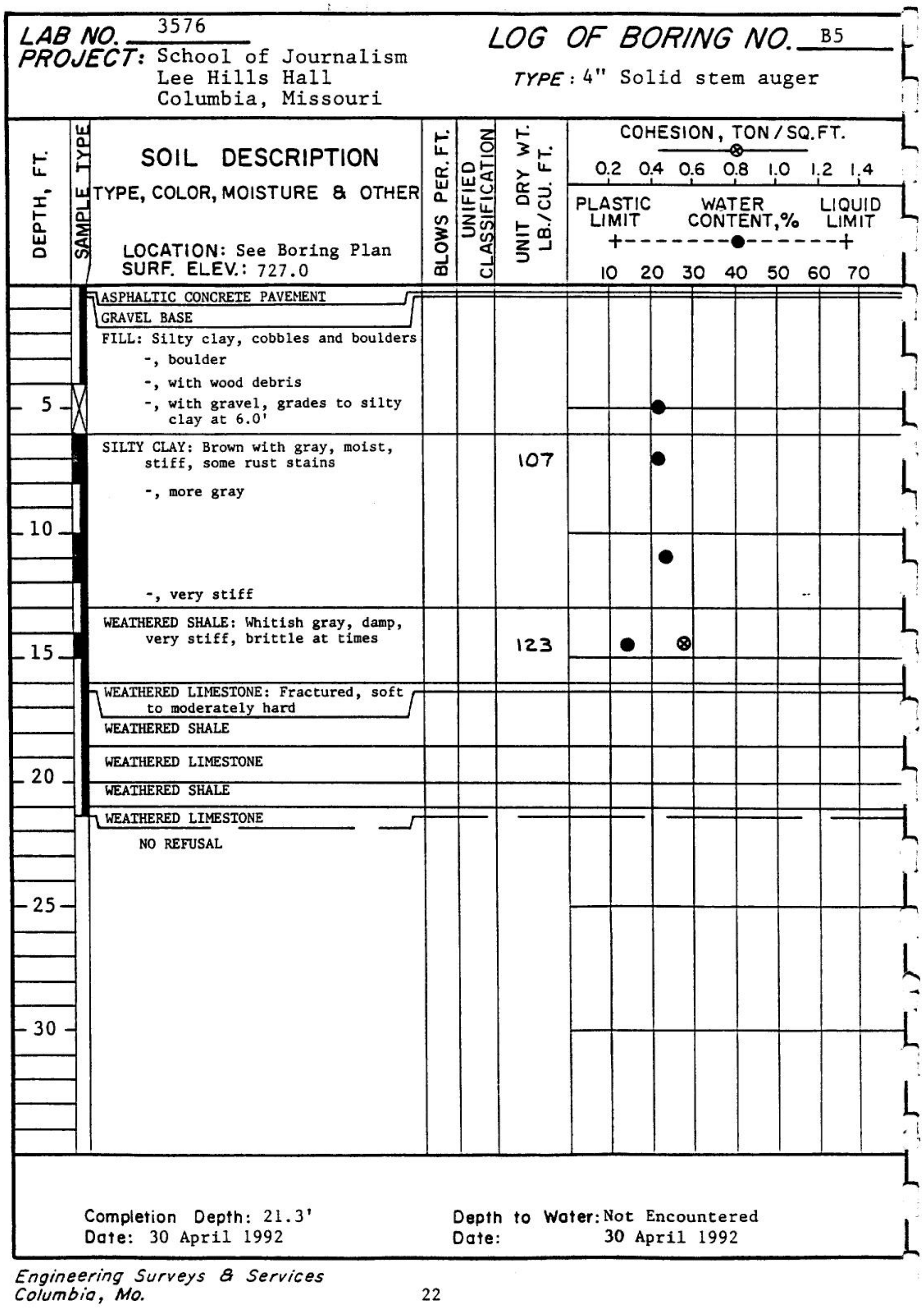
Figure 4: Lee Hills Hall Borehole 3


LAB NO. 3576
PROJECT: School of Journalism
Lee Hills Hall
Columbia, Missouri

LOG OF BORING NO. B5
TYPE: 4" Solid stem auger

DEPTH, FT. | SAMPLE TYPE | SOIL DESCRIPTION — TYPE, COLOR, MOISTURE & OTHER | BLOWS PER. FT. | UNIFIED CLASSIFICATION | UNIT DRY WT. LB./CU. FT. | COHESION, TON / SQ. FT. 0.2 0.4 0.6 0.8 1.0 1.2 1.4 | PLASTIC LIMIT — WATER CONTENT, % — LIQUID LIMIT 10 20 30 40 50 60 70

LOCATION: See Boring Plan
SURF. ELEV.: 727.0

ASPHALTIC CONCRETE PAVEMENT
GRAVEL BASE
FILL: Silty clay, cobbles and boulders
-, boulder
-, with wood debris
-, with gravel, grades to silty clay at 6.0'
SILTY CLAY: Brown with gray, moist, stiff, some rust stains — 107
-, more gray
-, very stiff
WEATHERED SHALE: Whitish gray, damp, very stiff, brittle at times — 123
WEATHERED LIMESTONE: Fractured, soft to moderately hard
WEATHERED SHALE
WEATHERED LIMESTONE
WEATHERED SHALE
WEATHERED LIMESTONE
NO REFUSAL

5
10
15
20
25
30

Completion Depth: 21.3'
Date: 30 April 1992
Depth to Water: Not Encountered
Date: 30 April 1992

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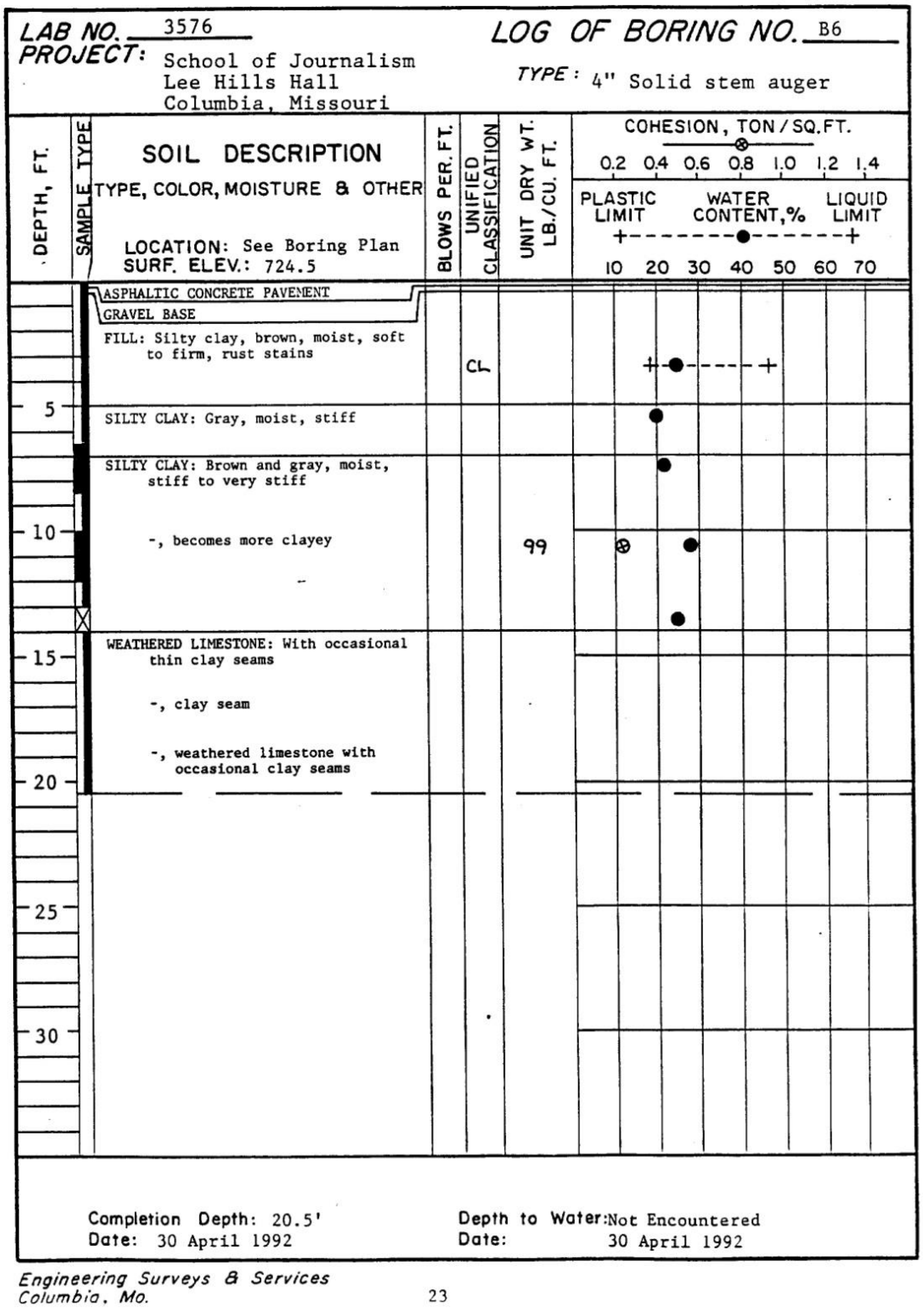
22

Figure 5: Lee Hills Hall Borehole 5



LAB NO. 3576

LOG OF BORING NO. B6

PROJECT: School of Journalism
Lee Hills Hall
Columbia, Missouri

TYPE: 4" Solid stem auger

DEPTH, FT.	SAMPLE TYPE	SOIL DESCRIPTION TYPE, COLOR, MOISTURE & OTHER LOCATION: See Boring Plan SURF. ELEV.: 724.5	BLOWS PER. FT.	UNIFIED CLASSIFICATION	UNIT DRY WT. LB./CU. FT.	COHESION, TON / SQ.FT. (0.2 0.4 0.6 0.8 1.0 1.2 1.4) PLASTIC LIMIT — WATER CONTENT, % — LIQUID LIMIT (10 20 30 40 50 60 70)
		ASPHALTIC CONCRETE PAVEMENT				
		GRAVEL BASE				
		FILL: Silty clay, brown, moist, soft to firm, rust stains		CL		
5		SILTY CLAY: Gray, moist, stiff				
		SILTY CLAY: Brown and gray, moist, stiff to very stiff				
10		-, becomes more clayey			99	
15		WEATHERED LIMESTONE: With occasional thin clay seams				
		-, clay seam				
20		-, weathered limestone with occasional clay seams				
25						
30						

Completion Depth: 20.5'
Date: 30 April 1992

Depth to Water: Not Encountered
Date: 30 April 1992

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Columbia, Mo.

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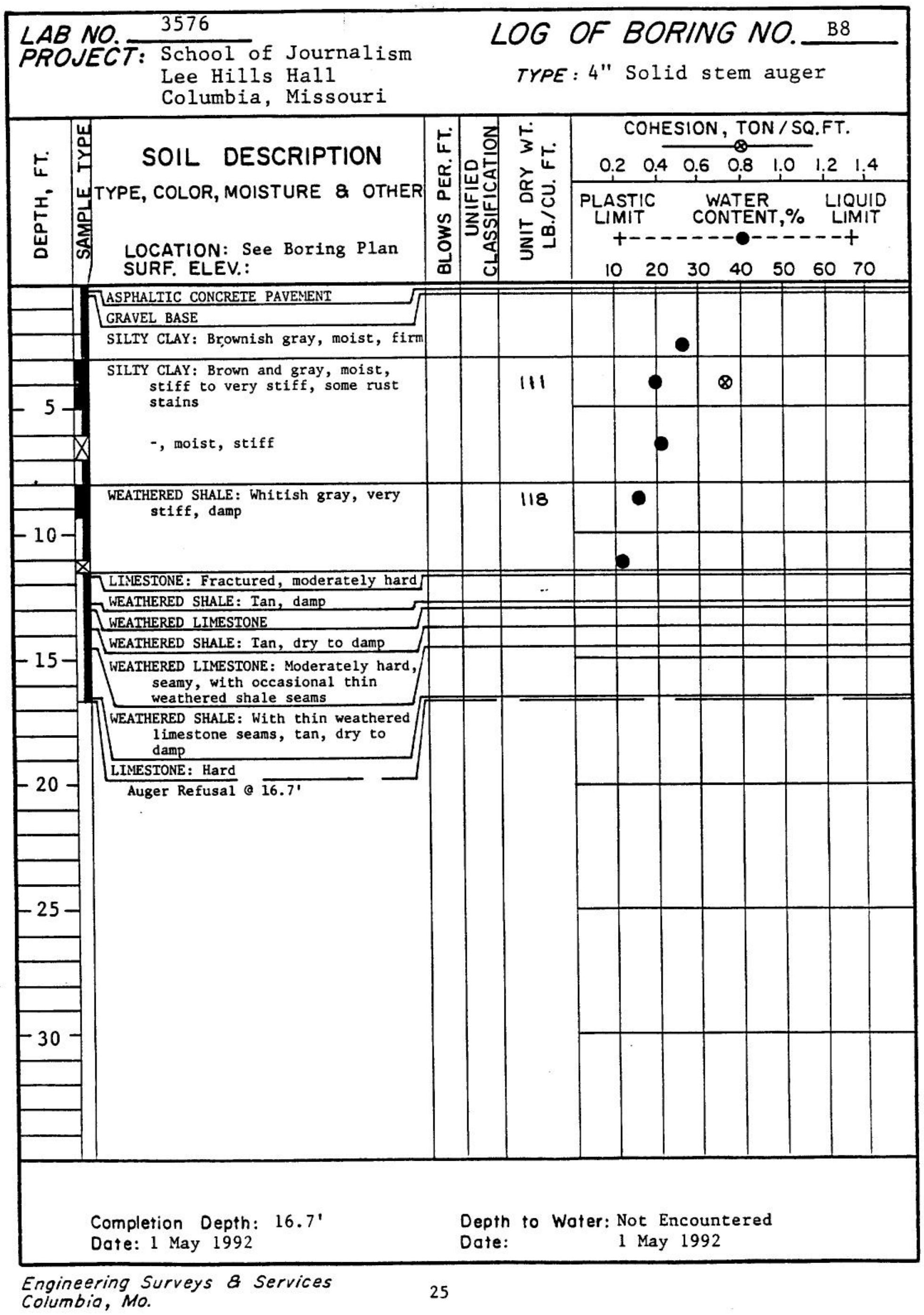
Figure 6: Lee Hills Hall Borehole 6



LAB NO. 3576
PROJECT: School of Journalism
Lee Hills Hall
Columbia, Missouri

LOG OF BORING NO. B8
TYPE: 4" Solid stem auger

DEPTH, FT. | SAMPLE TYPE | SOIL DESCRIPTION — TYPE, COLOR, MOISTURE & OTHER | BLOWS PER FT. | UNIFIED CLASSIFICATION | UNIT DRY WT. LB./CU. FT. | COHESION, TON/SQ.FT. (0.2 0.4 0.6 0.8 1.0 1.2 1.4) — PLASTIC LIMIT, WATER CONTENT, %, LIQUID LIMIT (10 20 30 40 50 60 70)

LOCATION: See Boring Plan
SURF. ELEV.:

ASPHALTIC CONCRETE PAVEMENT
GRAVEL BASE
SILTY CLAY: Brownish gray, moist, firm
SILTY CLAY: Brown and gray, moist, stiff to very stiff, some rust stains — 111
-, moist, stiff
WEATHERED SHALE: Whitish gray, very stiff, damp — 118
LIMESTONE: Fractured, moderately hard
WEATHERED SHALE: Tan, damp
WEATHERED LIMESTONE
WEATHERED SHALE: Tan, dry to damp
WEATHERED LIMESTONE: Moderately hard, seamy, with occasional thin weathered shale seams
WEATHERED SHALE: With thin weathered limestone seams, tan, dry to damp
LIMESTONE: Hard
Auger Refusal @ 16.7'

5
10
15
20
25
30

Completion Depth: 16.7'
Date: 1 May 1992

Depth to Water: Not Encountered
Date: 1 May 1992

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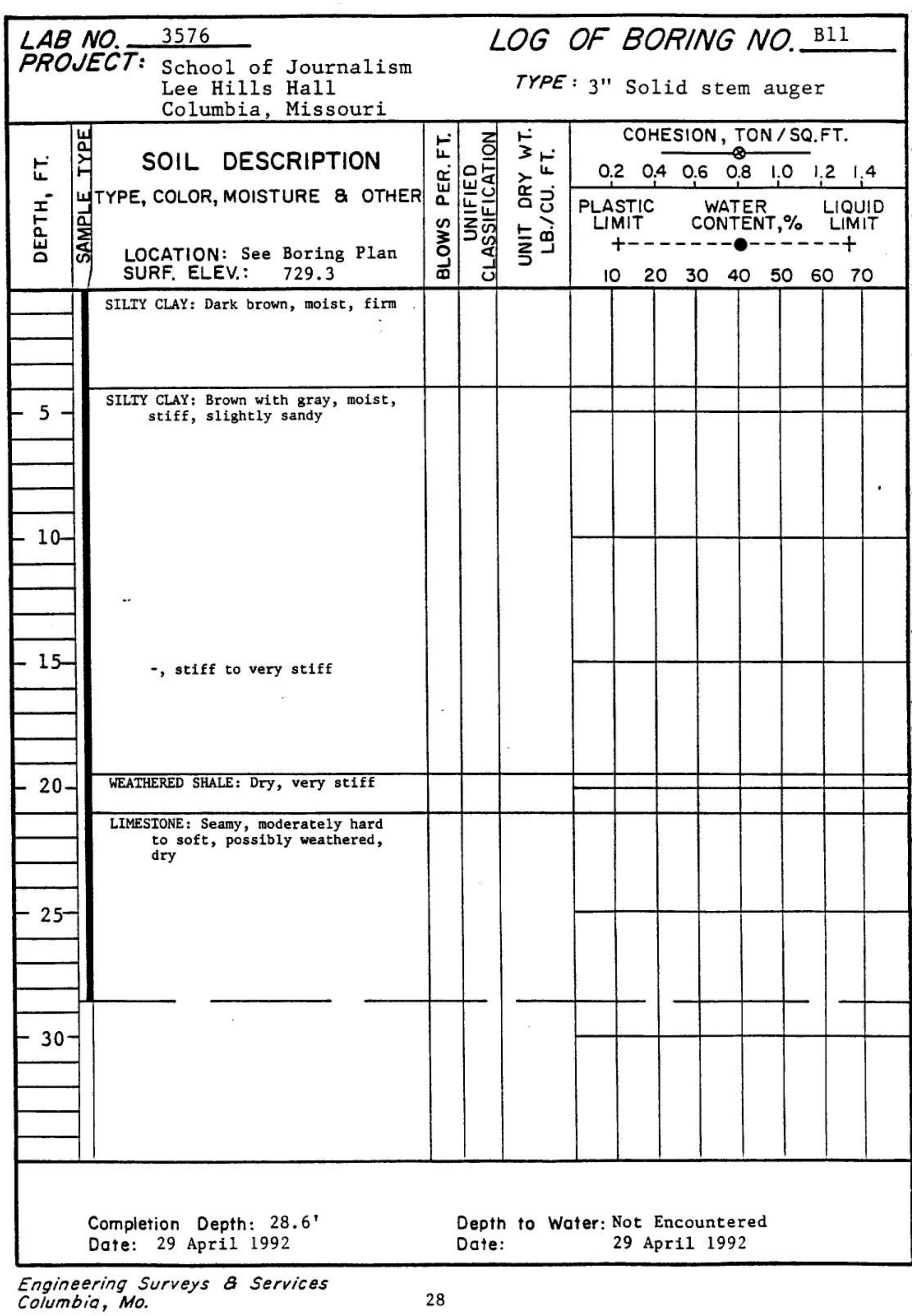
Columbia, Mo.

25

Figure 7: Lee Hills Hall Borehole 8



LAB NO. 3576

PROJECT: School of Journalism
Lee Hills Hall
Columbia, Missouri

LOG OF BORING NO. B11

TYPE: 3" Solid stem auger

DEPTH, FT.	SAMPLE TYPE	SOIL DESCRIPTION TYPE, COLOR, MOISTURE & OTHER LOCATION: See Boring Plan SURF. ELEV.: 729.3	BLOWS PER. FT.	UNIFIED CLASSIFICATION	UNIT DRY WT. LB./CU. FT.	COHESION, TON / SQ.FT. (0.2 0.4 0.6 0.8 1.0 1.2 1.4) PLASTIC LIMIT + - - - WATER CONTENT, % ● - - - LIQUID LIMIT + (10 20 30 40 50 60 70)
0		SILTY CLAY: Dark brown, moist, firm				
5		SILTY CLAY: Brown with gray, moist, stiff, slightly sandy				
10						
15		-, stiff to very stiff				
20		WEATHERED SHALE: Dry, very stiff				
		LIMESTONE: Seamy, moderately hard to soft, possibly weathered, dry				
25						
30						

Completion Depth: 28.6'
Date: 29 April 1992

Depth to Water: Not Encountered
Date: 29 April 1992

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Figure 8: Lee Hills Hall Borehole 11

LAB NO. 3576

PROJECT: School of Journalism
Lee Hills Hall
Columbia, Missouri

LOG OF BORING NO. B13

TYPE: 3" Solid stem auger

DEPTH, FT.	SAMPLE TYPE	SOIL DESCRIPTION TYPE, COLOR, MOISTURE & OTHER LOCATION: See Boring Plan SURF. ELEV.: 728.9	BLOWS PER. FT.	UNIFIED CLASSIFICATION	UNIT DRY WT. LB./CU. FT.	COHESION, TON/SQ.FT. (0.2 0.4 0.6 0.8 1.0 1.2 1.4) PLASTIC LIMIT — WATER CONTENT, % — LIQUID LIMIT (10 20 30 40 50 60 70)
		ASPHALTIC CONCRETE PAVEMENT				
		GRAVEL BASE				
		FILL COBBLES & BOULDERS: Loose				
5						
		SILTY CLAY: Brown with gray, moist, stiff, slightly sandy				
10						
		WEATHERED SHALE: Tan and gray, very stiff, dry				
15						
20						
		LIMESTONE: Moderately hard				
25		Trace water @ 14.0', Dry @ 14.5' depth.				
30						

Completion Depth: 24.3'
Date: 29 April 1992

Depth to Water: 14.0'
Date: 29 April 1992

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Figure 9: Lee Hills Hall Borehole 13

LAB NO. 3576

PROJECT: School of Journalism
Lee Hills Hall
Columbia, Missouri

LOG OF BORING NO. B14

TYPE: 3" Solid stem auger

DEPTH, FT.	SAMPLE TYPE	SOIL DESCRIPTION TYPE, COLOR, MOISTURE & OTHER LOCATION: See Boring Plan SURF. ELEV.: 720.4	BLOWS PER. FT.	UNIFIED CLASSIFICATION	UNIT DRY WT. LB./CU. FT.	COHESION, TON/SQ.FT. 0.2 0.4 0.6 0.8 1.0 1.2 1.4 PLASTIC LIMIT — WATER CONTENT,% — LIQUID LIMIT 10 20 30 40 50 60 70
		ASPHALTIC CONCRETE PAVEMENT				
		GRAVEL BASE				
		SILTY CLAY: Dark brown, firm, moist				
		SILTY CLAY: Brown and gray, moist, stiff, some sand				
5						
		WEATHERED SHALE: Gray and tan, dry, very stiff				
10		WEATHERED LIMESTONE: Some clay seams				
		LIMESTONE: Possibly jointed				
15		LIMESTONE: Hard				
		CLAY				
		LIMESTONE: Hard, possibly fractured				
20						
25						
30						

Completion Depth: 16.3'
Date: 29 April 1992

Depth to Water: Not Encountered
Date: 29 April 1992

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Figure 10: Lee Hills Hall Borehole 14

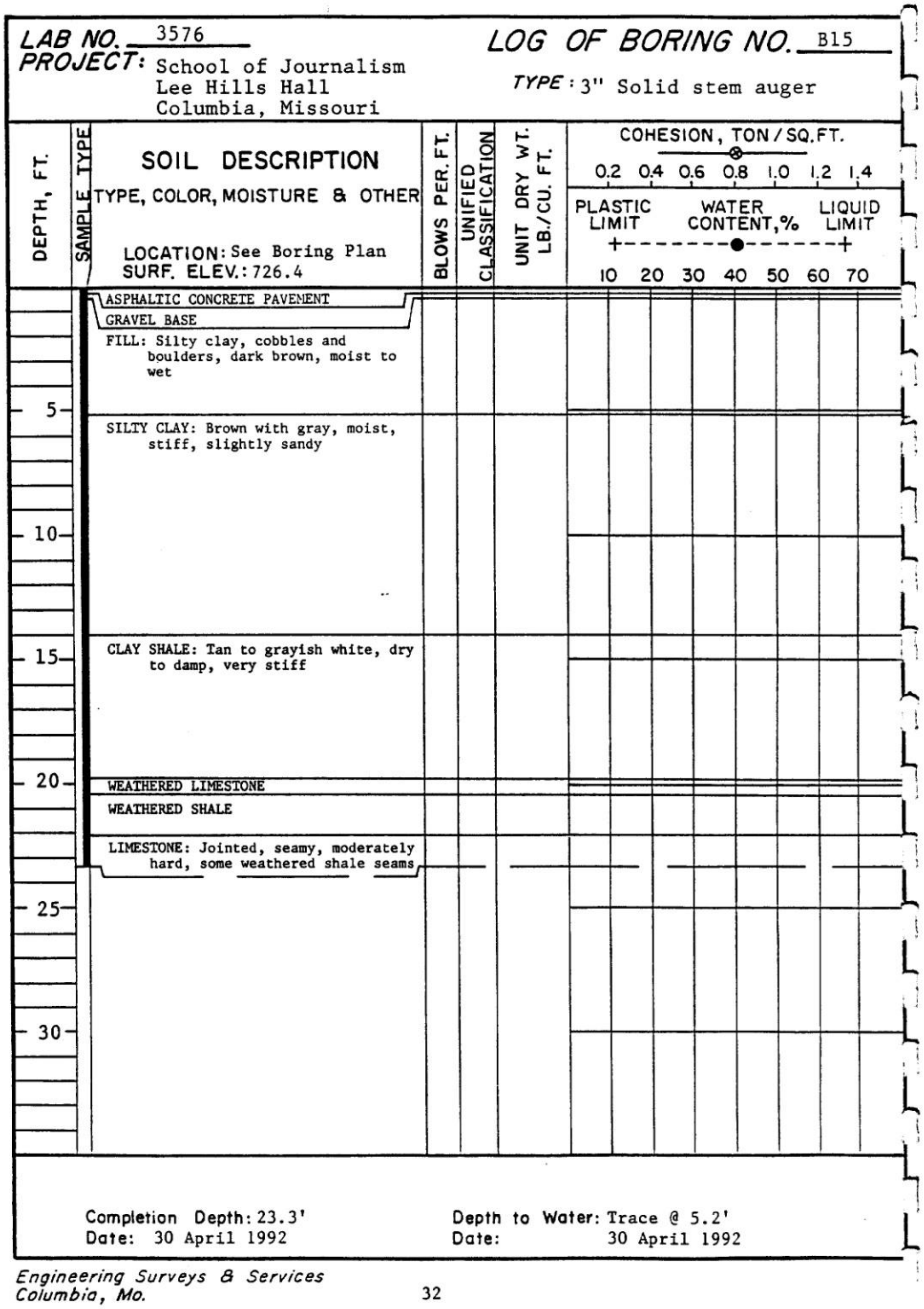
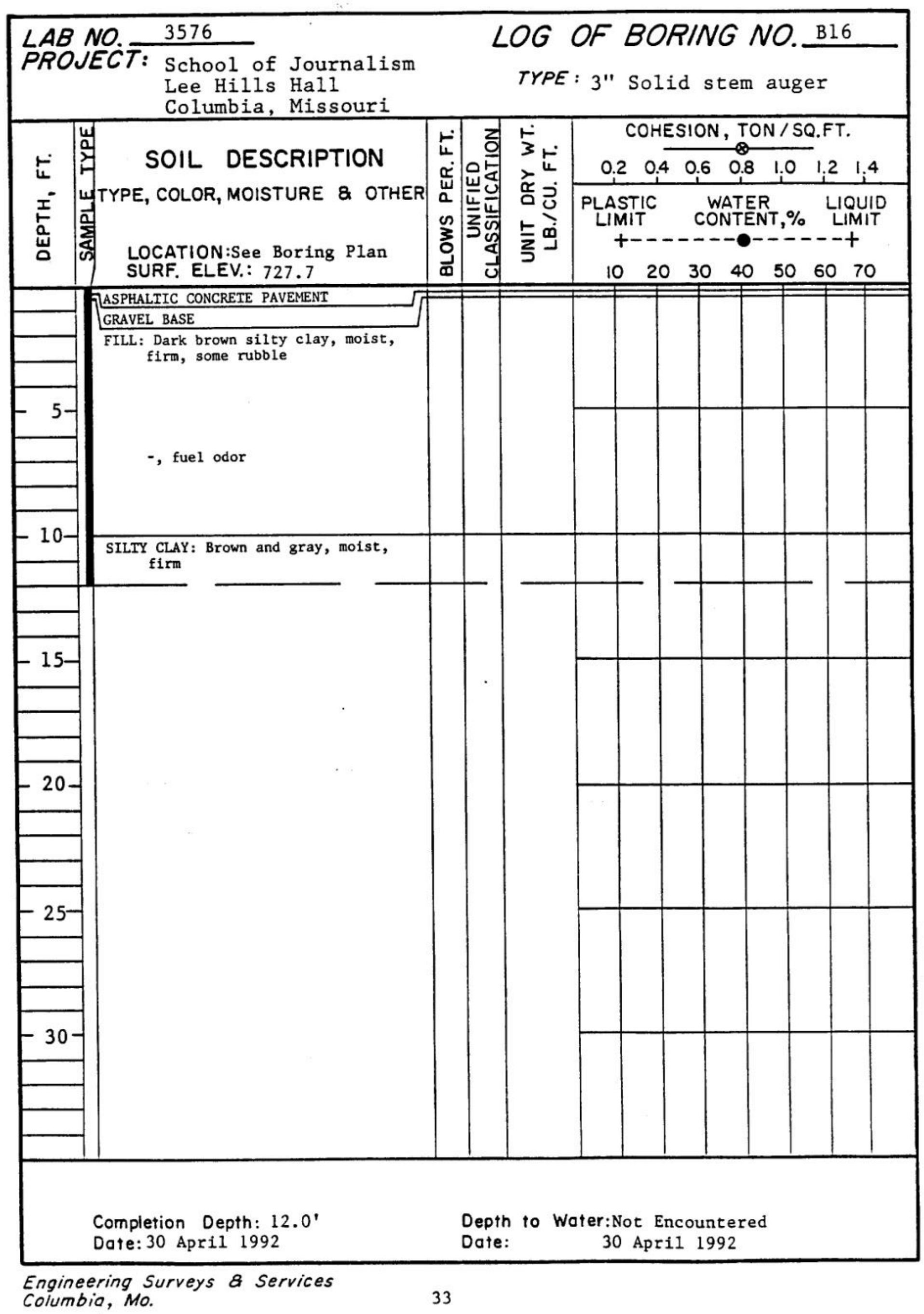


Figure 11: Lee Hills Hall Borehole 15



LAB NO. 3576

LOG OF BORING NO. B16

PROJECT: School of Journalism
Lee Hills Hall
Columbia, Missouri

TYPE: 3" Solid stem auger

DEPTH, FT.	SAMPLE TYPE	SOIL DESCRIPTION TYPE, COLOR, MOISTURE & OTHER LOCATION: See Boring Plan SURF. ELEV.: 727.7	BLOWS PER FT.	UNIFIED CLASSIFICATION	UNIT DRY WT. LB./CU. FT.	COHESION, TON/SQ.FT. 0.2 0.4 0.6 0.8 1.0 1.2 1.4 / PLASTIC LIMIT — WATER CONTENT, % — LIQUID LIMIT 10 20 30 40 50 60 70
		ASPHALTIC CONCRETE PAVEMENT				
		GRAVEL BASE				
		FILL: Dark brown silty clay, moist, firm, some rubble				
5						
		-, fuel odor				
10		SILTY CLAY: Brown and gray, moist, firm				
15						
20						
25						
30						

Completion Depth: 12.0'
Date: 30 April 1992

Depth to Water: Not Encountered
Date: 30 April 1992

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Columbia, Mo.

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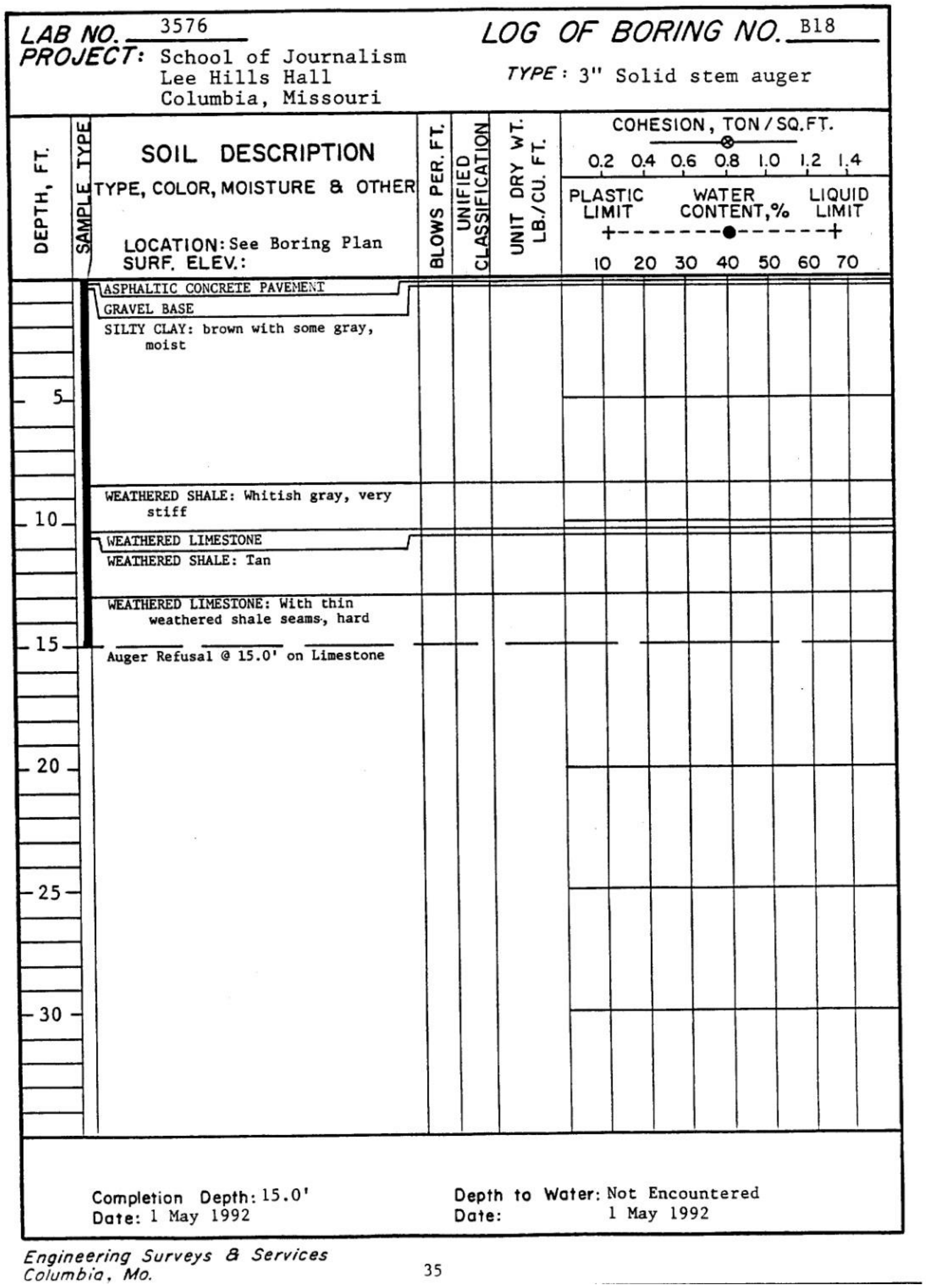
Figure 12: Lee Hills Hall Borehole 16



LAB NO. 3576

LOG OF BORING NO. B18

PROJECT: School of Journalism
Lee Hills Hall
Columbia, Missouri

TYPE: 3" Solid stem auger

DEPTH, FT.	SAMPLE TYPE	SOIL DESCRIPTION TYPE, COLOR, MOISTURE & OTHER LOCATION: See Boring Plan SURF. ELEV.:	BLOWS PER. FT.	UNIFIED CLASSIFICATION	UNIT DRY WT. LB./CU. FT.	COHESION, TON / SQ.FT. 0.2 0.4 0.6 0.8 1.0 1.2 1.4 PLASTIC LIMIT — WATER CONTENT,% — LIQUID LIMIT 10 20 30 40 50 60 70
		ASPHALTIC CONCRETE PAVEMENT				
		GRAVEL BASE				
		SILTY CLAY: brown with some gray, moist				
5						
		WEATHERED SHALE: Whitish gray, very stiff				
10						
		WEATHERED LIMESTONE				
		WEATHERED SHALE: Tan				
		WEATHERED LIMESTONE: With thin weathered shale seams, hard				
15		Auger Refusal @ 15.0' on Limestone				
20						
25						
30						

Completion Depth: 15.0'
Date: 1 May 1992

Depth to Water: Not Encountered
Date: 1 May 1992

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Figure 13: Lee Hills Hall Borehole 18

APPENDIX A-5

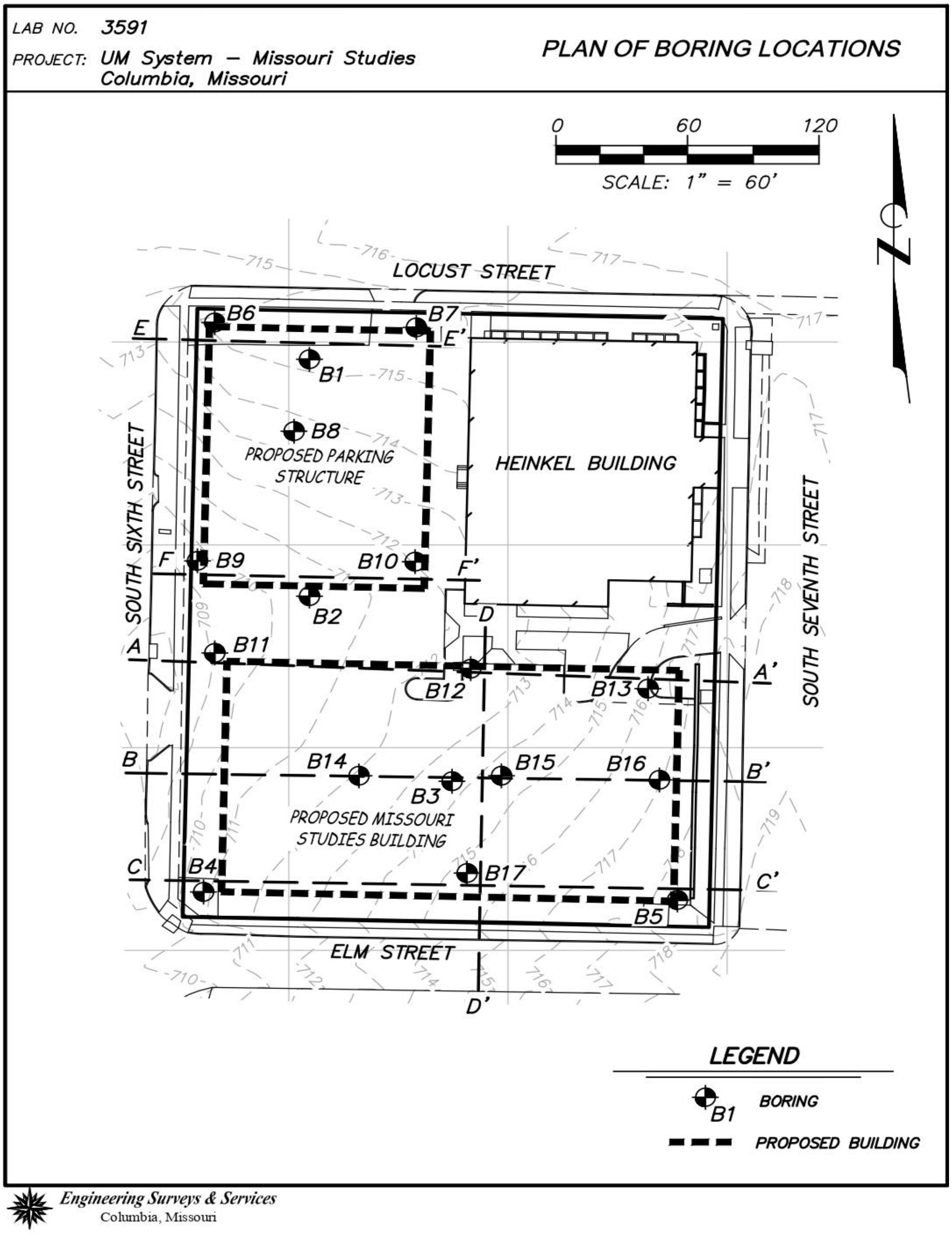


Figure 1: Missouri Studies and State Historic Building boring plan (Aerial View), prepared by Engineering Surveys and Services

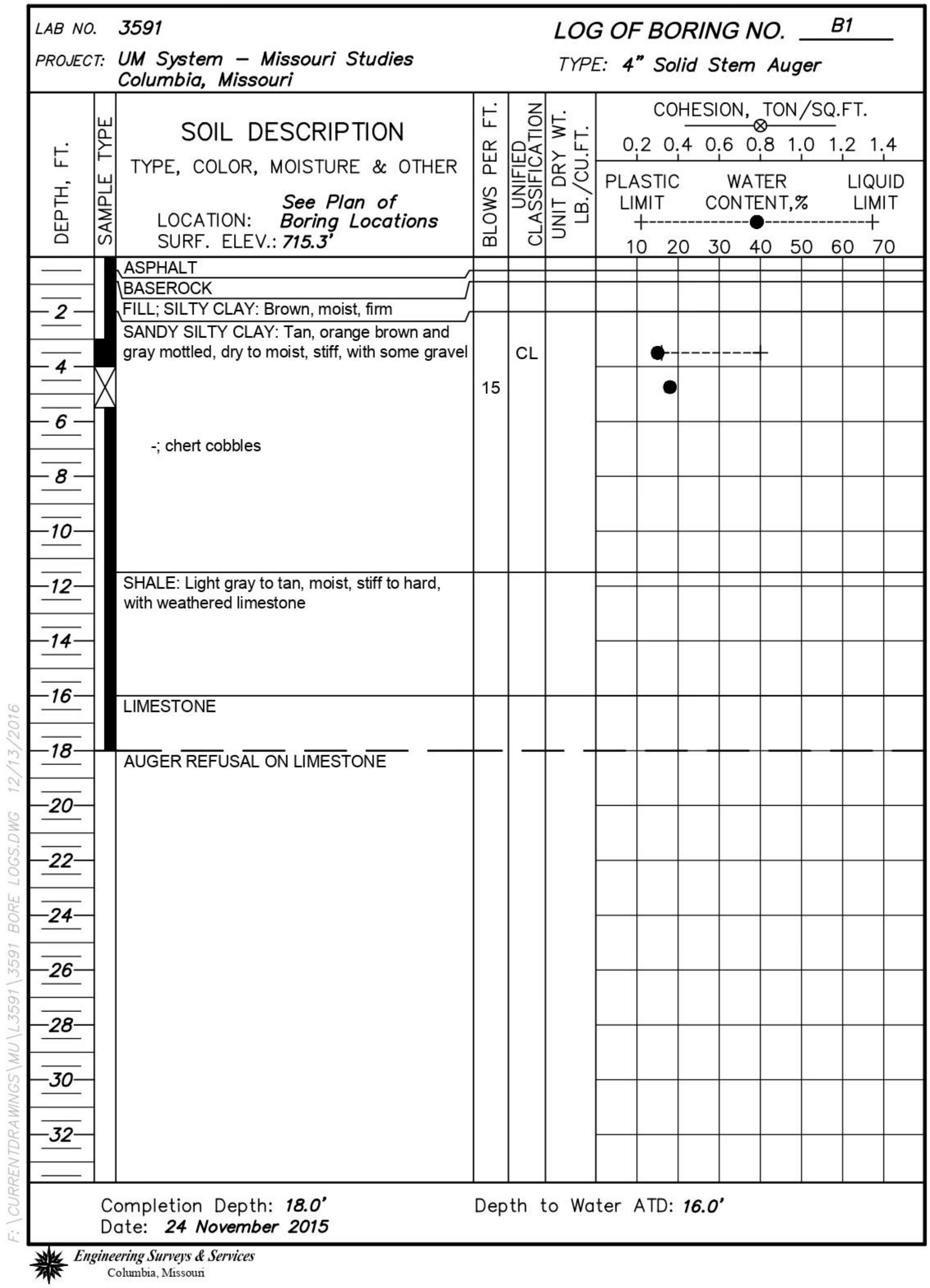


Figure 2: Missouri Studies and State Historic Building Borehole 1

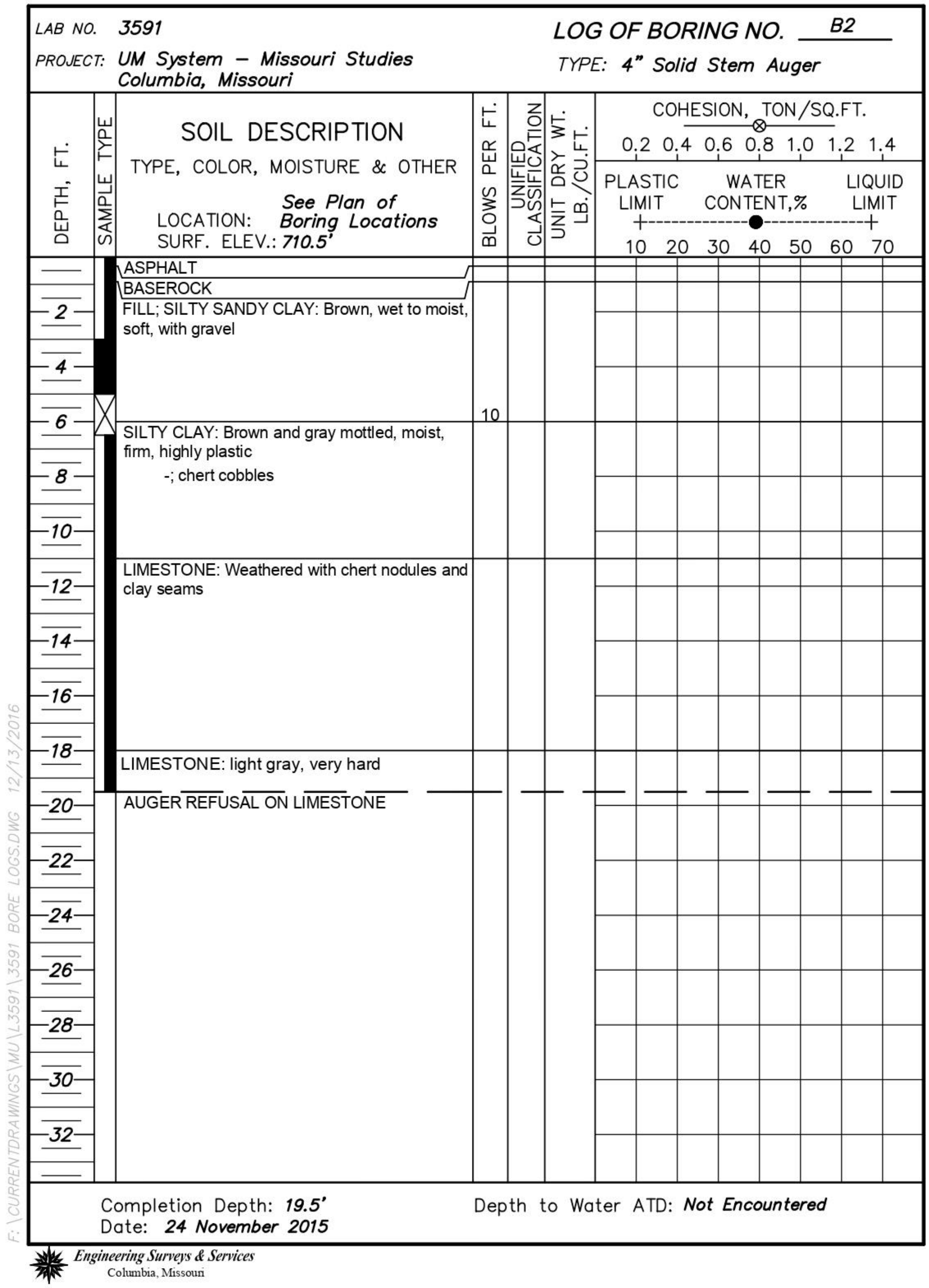


Figure 3: Missouri Studies and State Historic Building Borehole 2

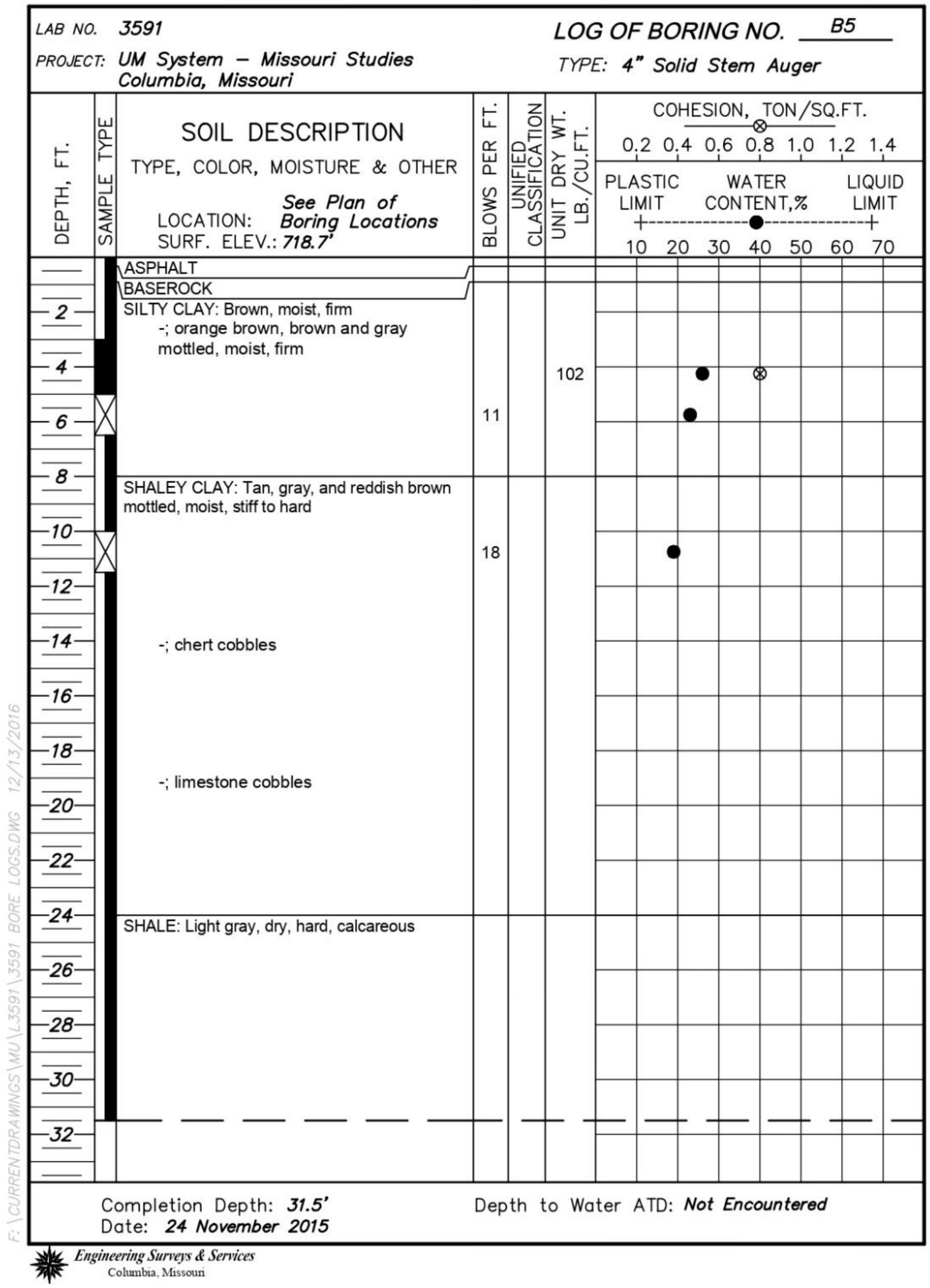


Figure 4: Missouri Studies and State Historic Building Borehole 5

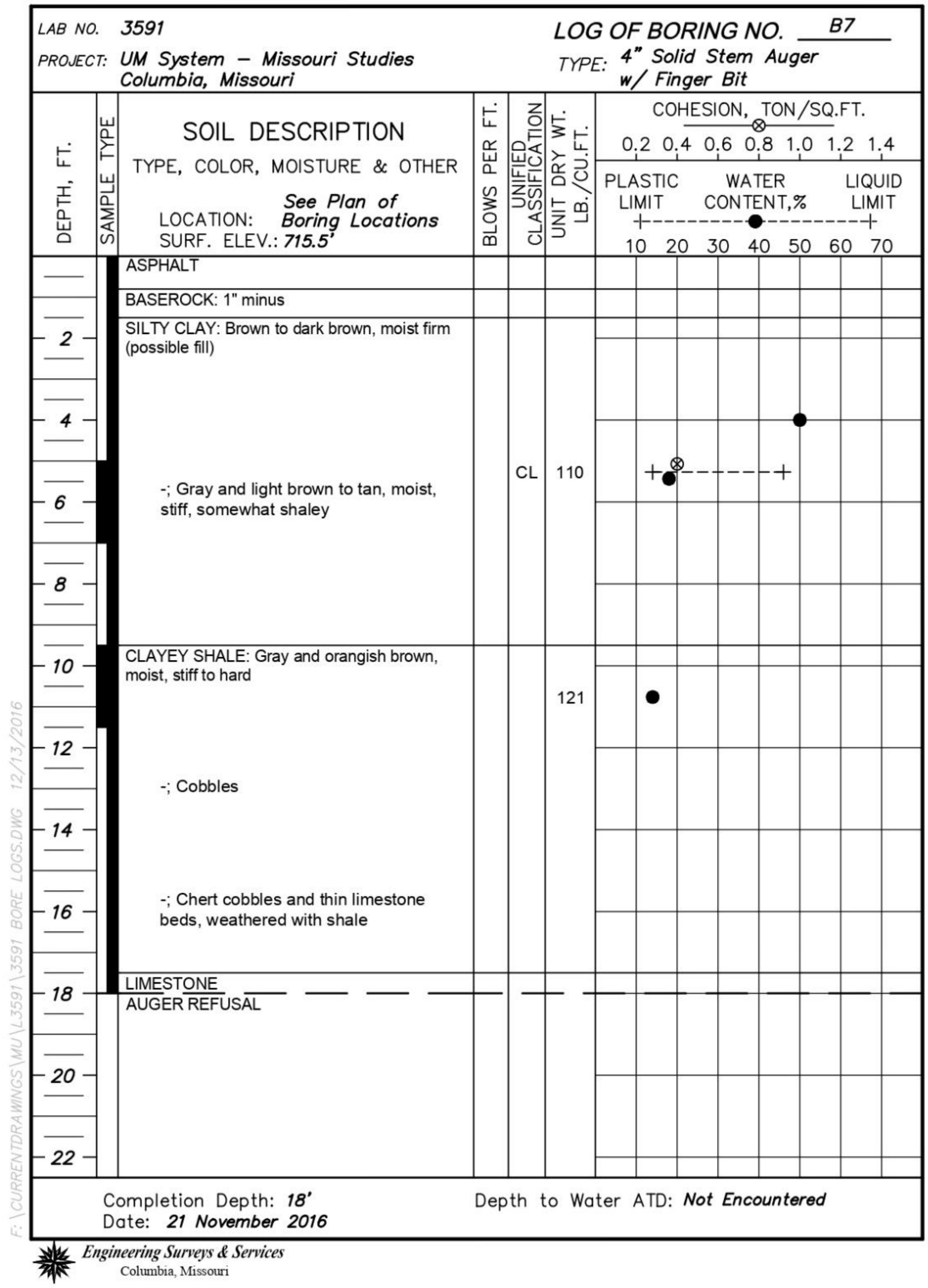


Figure 5: Missouri Studies and State Historic Building Borehole 7

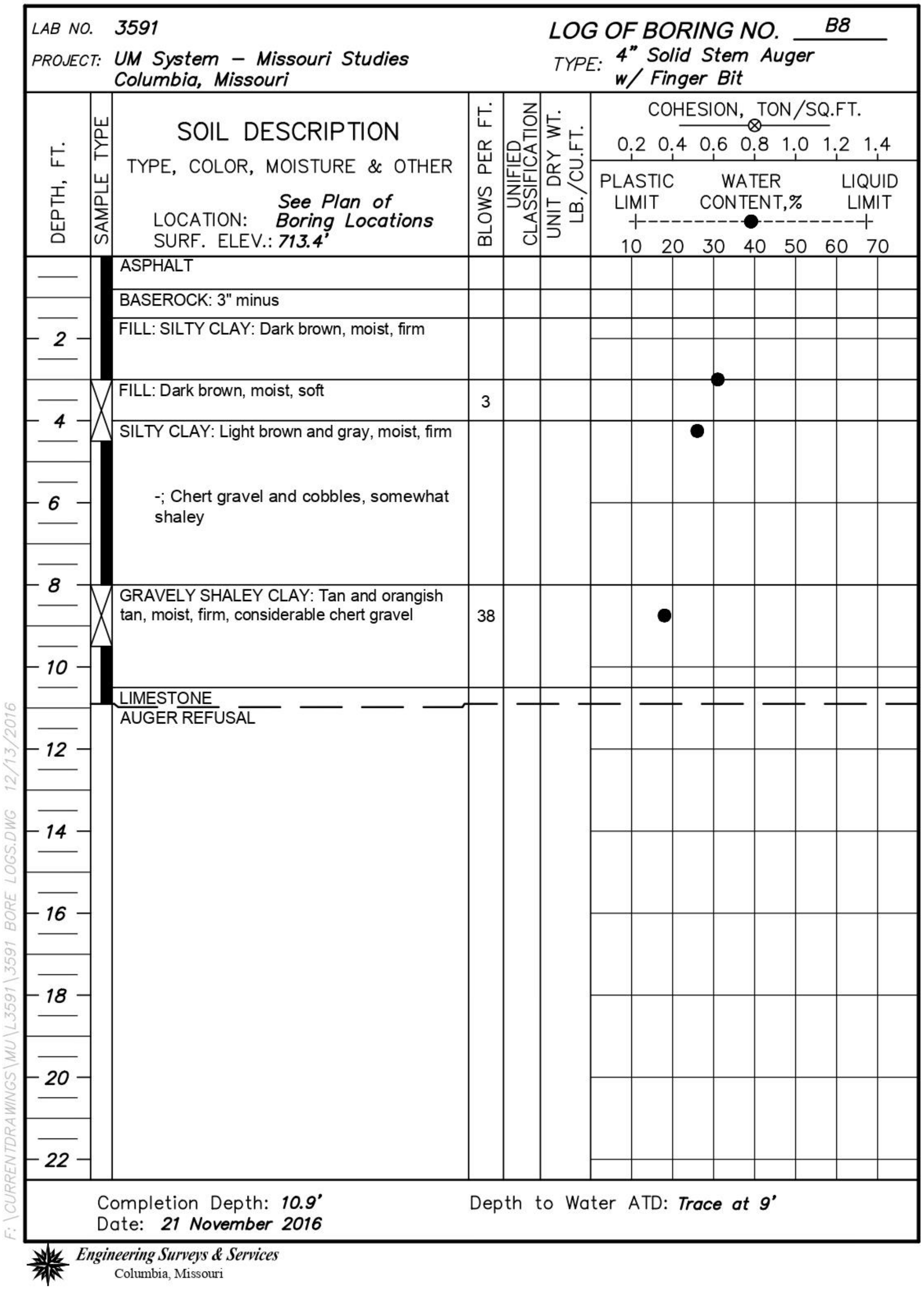


Figure 6: Missouri Studies and State Historic Building Borehole 8

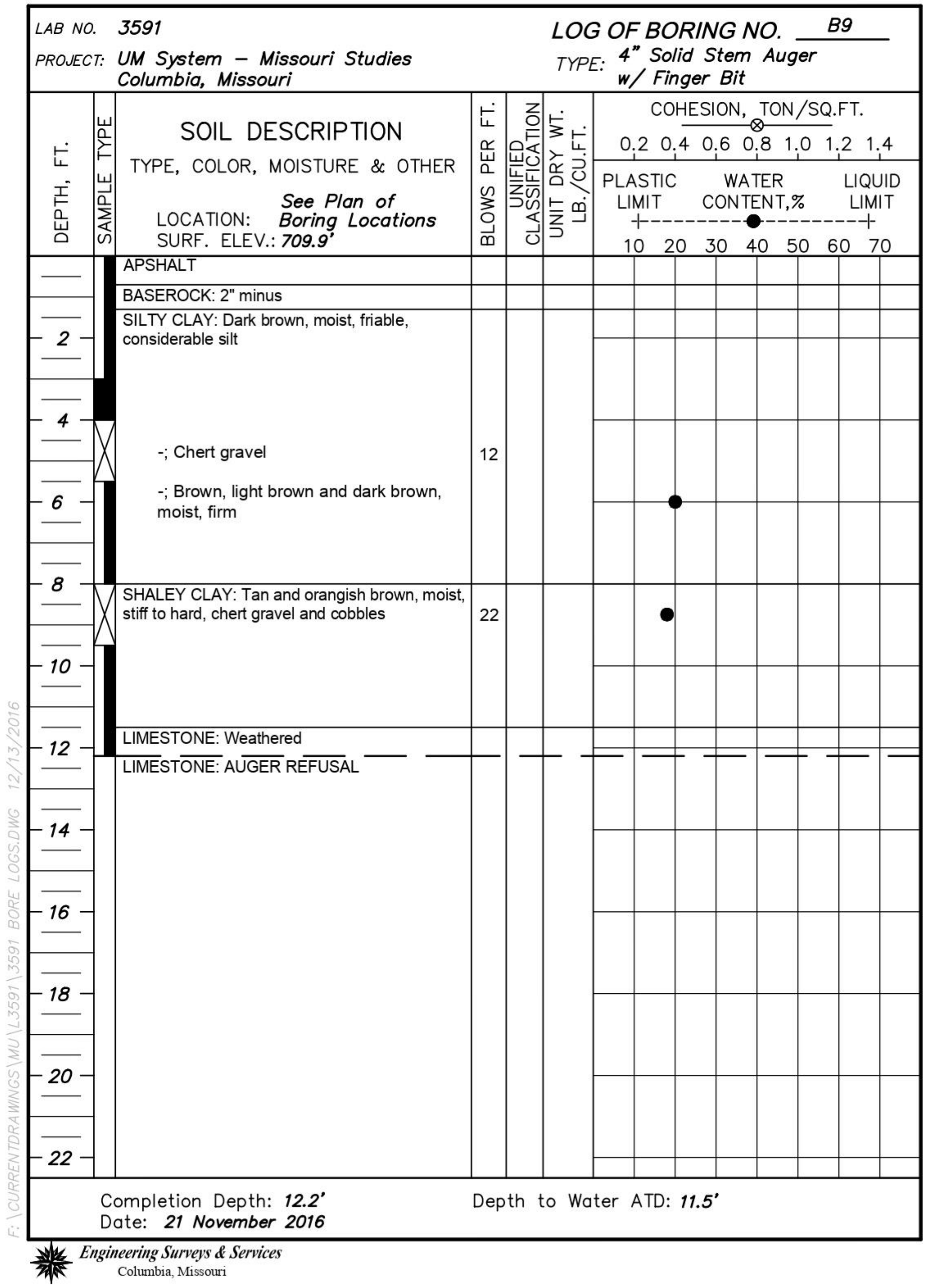


Figure 7: Missouri Studies and State Historic Building Borehole 9

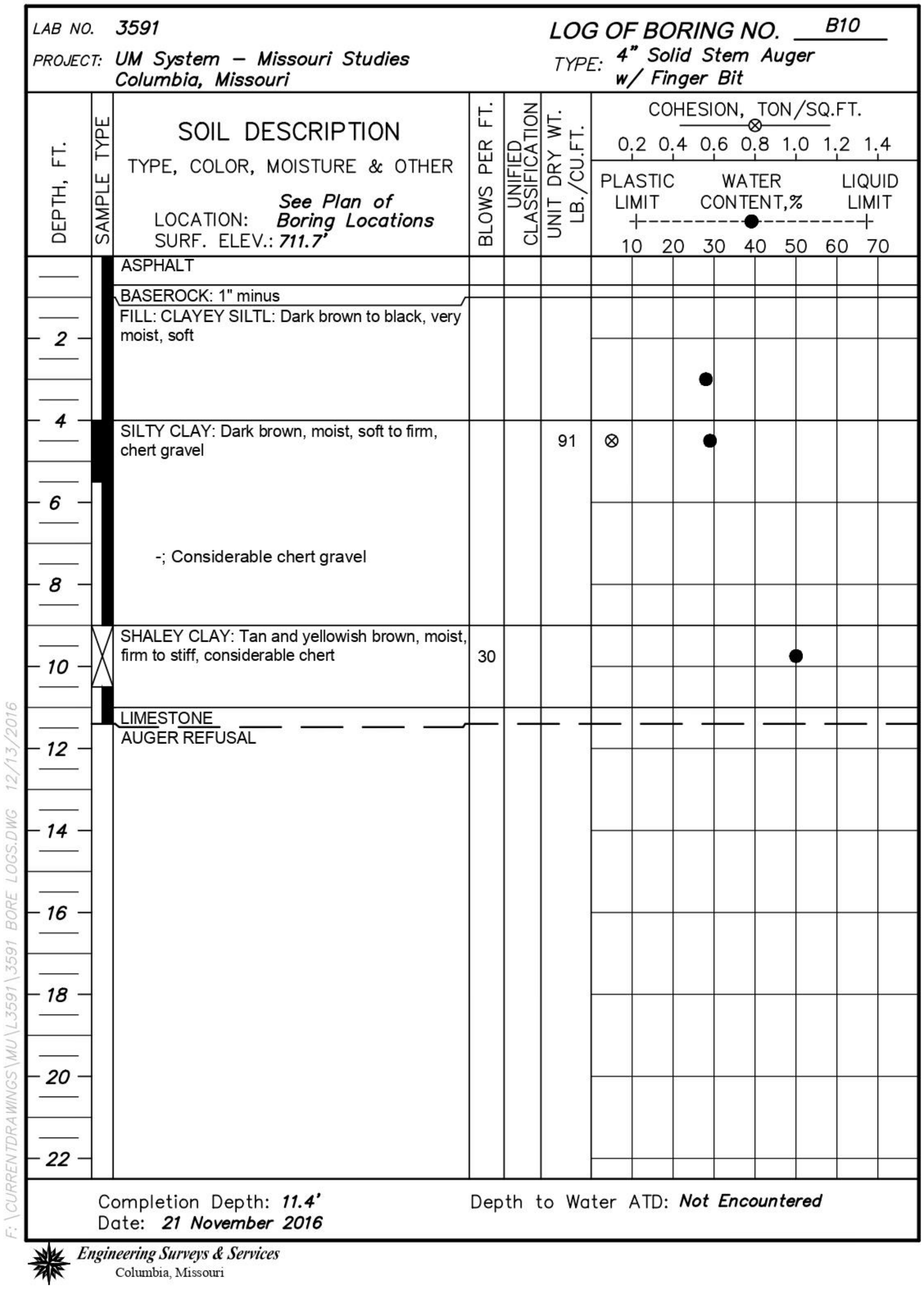


Figure 8: Missouri Studies and State Historic Building Borehole 10

LAB NO. 3591

PROJECT: UM System – Missouri Studies
Columbia, Missouri

LOG OF BORING NO. B13

TYPE: 4" Solid Stem Auger w/ Finger Bit

DEPTH, FT.	SAMPLE TYPE	SOIL DESCRIPTION TYPE, COLOR, MOISTURE & OTHER LOCATION: See Plan of Boring Locations SURF. ELEV.: 716.2'	BLOWS PER FT.	UNIFIED CLASSIFICATION	UNIT DRY WT. LB./CU.FT.	COHESION, TON/SQ.FT. 0.2 0.4 0.6 0.8 1.0 1.2 1.4 PLASTIC LIMIT — WATER CONTENT,% — LIQUID LIMIT 10 20 30 40 50 60 70
0–1.5		ASPHALT, BASEROCK				
1.5–7.5		FILL: SILTY CLAY: Dark brown -; Brown to dark brown, moist, firm, some brick	8			
7.5–9		SHALEY CLAY: Gray, trace of tan, moist, firm to stiff				
9–10		LIMESTONE: Weathered				
10–12		CLAYEY SHALE: Tan and gray, damp, stiff to hard				
12–12.5		LIMESTONE				
12.5		AUGER REFUSAL				

Completion Depth: 12.5'
Date: 21 November 2016

Depth to Water ATD: Not Encountered

Engineering Surveys & Services
Columbia, Missouri

F:\CURRENTDRAWINGS\MU\L3591\3591 BORE LOGS.DWG 12/13/2016

Figure 9: Missouri Studies and State Historic Building Borehole 13

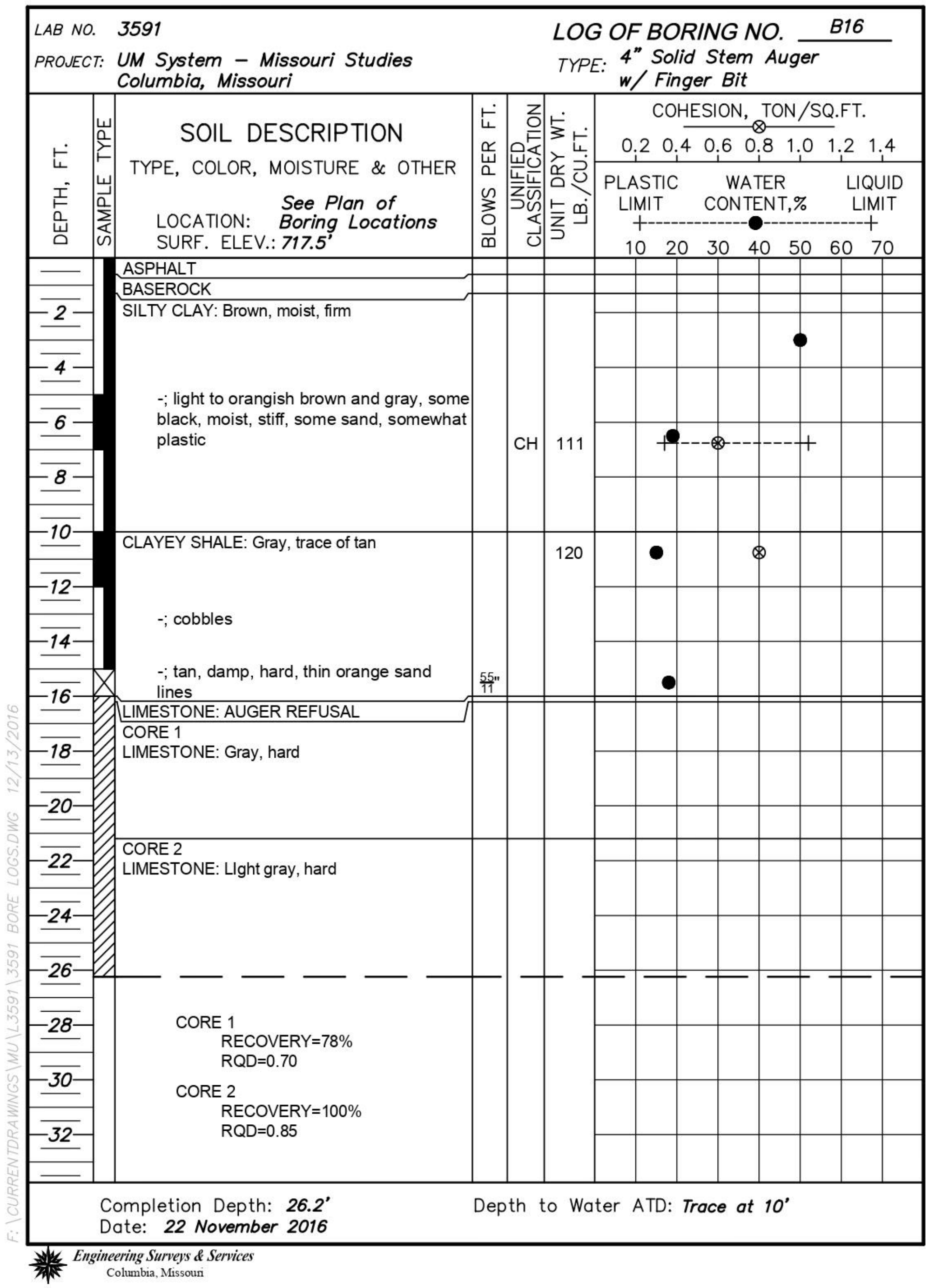


Figure 10: Missouri Studies and State Historic Building Borehole 16

APPENDIX A-6

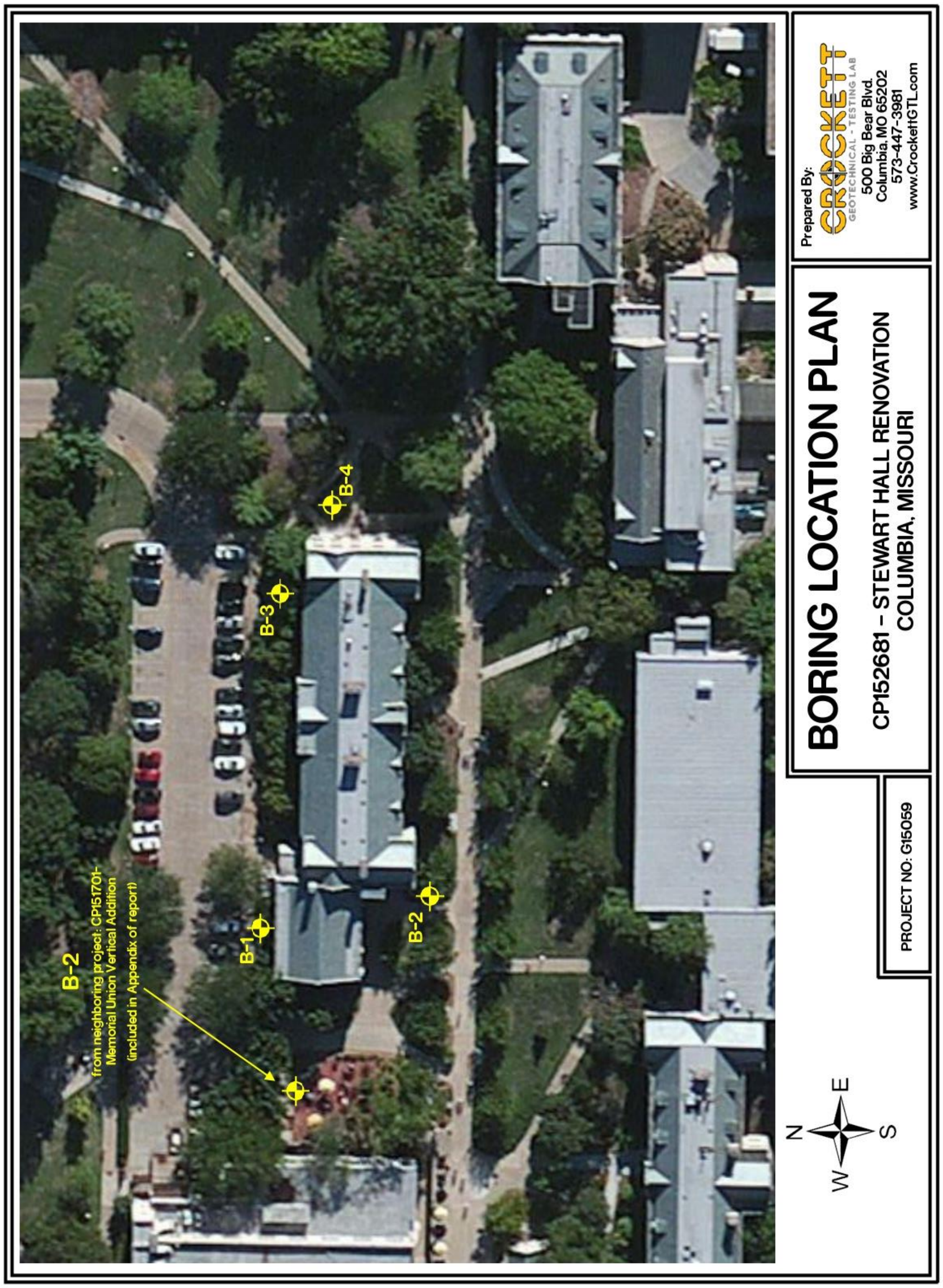


Figure 1: Stewart Hall boring plan (Aerial View), prepared by Crockett

SAMPLE LENGTH REPORT - LAT-LONG TEMPLATE.GDT - 8/26/15 16:32 - C:\SERVER FILES\GEOTECH GENERAL\===PROJECTS===\GEOT PROJECTS\2015\G15059 - CP152681-STEWART HALL- RENOVATION\G15059.GPJ

Crockett Geotechnical - Testing Lab
500 Big Bear Boulevard
Columbia, MO 65202
Telephone: 573-447-3981

CROCKETT GEOTECHNICAL - TESTING LAB

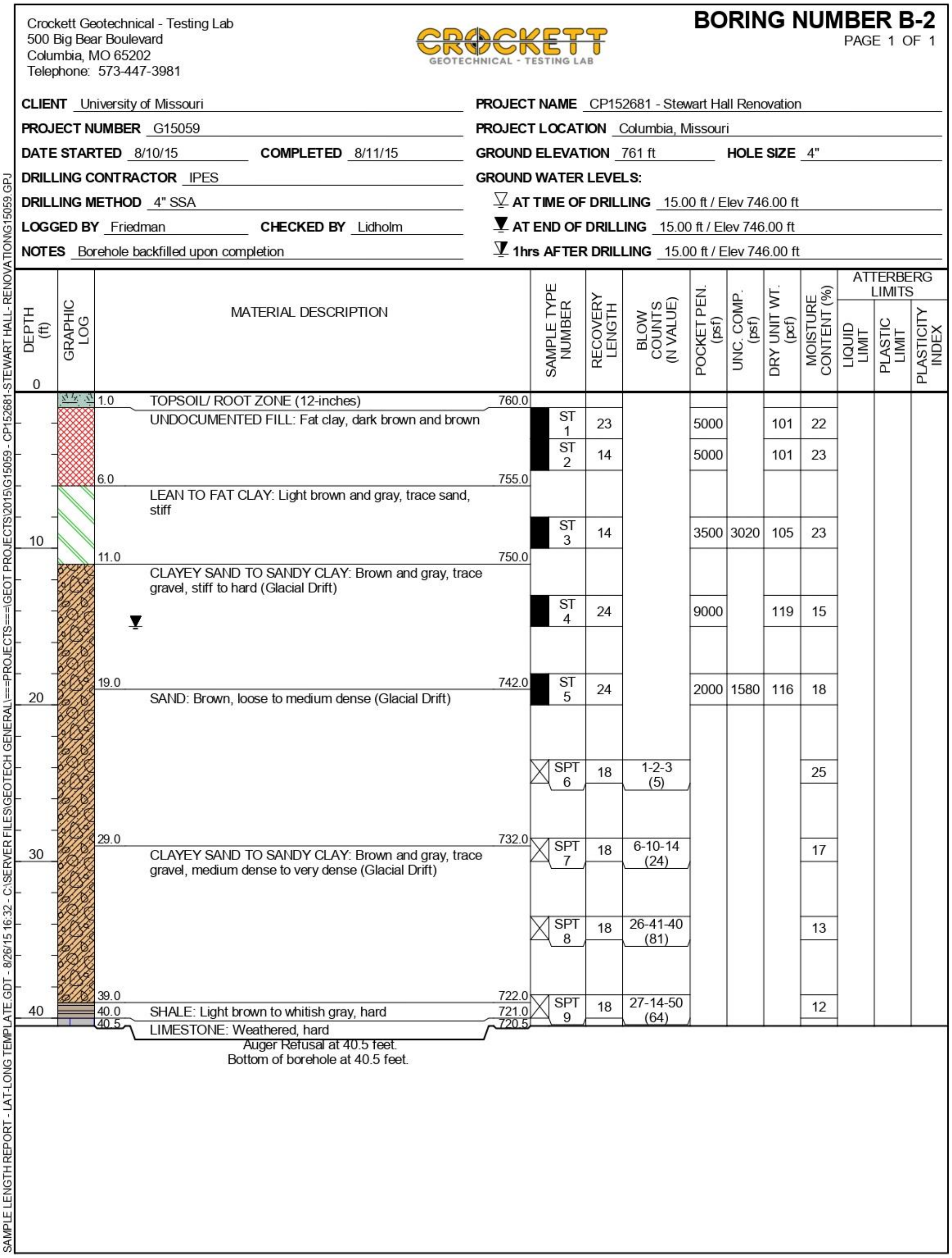
BORING NUMBER B-1
PAGE 1 OF 1

CLIENT University of Missouri
PROJECT NAME CP152681 - Stewart Hall Renovation
PROJECT NUMBER G15059
PROJECT LOCATION Columbia, Missouri
DATE STARTED 8/10/15 **COMPLETED** 8/11/15
GROUND ELEVATION 762 ft **HOLE SIZE** 4"
DRILLING CONTRACTOR IPES
GROUND WATER LEVELS:
DRILLING METHOD 4" SSA
▽ **AT TIME OF DRILLING** 19.00 ft / Elev 743.00 ft
LOGGED BY Friedman **CHECKED BY** Lidholm
▼ **AT END OF DRILLING** 19.00 ft / Elev 743.00 ft
NOTES Borehole backfilled upon completion
▼ **2hrs AFTER DRILLING** 17.00 ft / Elev 745.00 ft

DEPTH (ft)	MATERIAL DESCRIPTION	Elev.	SAMPLE TYPE NUMBER	RECOVERY LENGTH	BLOW COUNTS (N VALUE)	POCKET PEN. (psf)	UNC. COMP. (psf)	DRY UNIT WT. (pcf)	MOISTURE CONTENT (%)	ATTERBERG LIMITS: LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX
0.5	MULCH (6-inches)	761.5										
2.0	UNDOCUMENTED FILL: Fat clay, dark brown and brown	760.0	ST 1	21		5500		114	16			
	LEAN TO FAT CLAY: Light brown and gray, trace sand, stiff to hard		ST 2	17		5000		108	20			
	--: becomes gray to dark brown											
			ST 3	24		9000	3030	106	21			
11.0	LEAN TO FAT CLAY: Brown and gray, trace sand, trace gravel, trace lignite, occasional sand pockets, very stiff to hard (Glacial Drift)	751.0	ST 4	15		9000		115	16			
19.0	CLAYEY SAND TO SANDY CLAY: Brown and gray, trace gravel, very stiff (Glacial Drift)	743.0	ST 5	23		5000		93	48			
24.0	LEAN TO FAT CLAY: Brown and gray, trace sand, trace gravel, trace lignite, occasional sand pockets, very stiff to hard (Glacial Drift)	738.0	SPT 6	18	7-7-6 (13)	6500			16			
			SPT 7	17	6-10-11 (21)	9000			16			
	--: becomes dark gray, trace sand and gravel, very stiff to hard		SPT 8	18	14-29-38 (67)	9000			14			
38.0	CLAYEY SHALE: Dark gray, trace gravel, very stiff, with occassional cobbles and possible boulders	724.0	SPT 9	5	50/5"	5000			17			
			SPT 10	14	10-17-22 (39)	6500			16			
	--: cobbles and possible boulders from 46.0 to 51.5 feet, possible weathered rock											
51.5	LIMESTONE: Weathered, hard	710.5										
52.0		710.0										

Auger Refusal at 52.0 feet
Bottom of borehole at 52.0 feet.

Figure 2: Stewart Hall Borehole 1



Crockett Geotechnical - Testing Lab
500 Big Bear Boulevard
Columbia, MO 65202
Telephone: 573-447-3981

CROCKETT GEOTECHNICAL - TESTING LAB

BORING NUMBER B-2
PAGE 1 OF 1

CLIENT University of Missouri
PROJECT NAME CP152681 - Stewart Hall Renovation
PROJECT NUMBER G15059
PROJECT LOCATION Columbia, Missouri
DATE STARTED 8/10/15 **COMPLETED** 8/11/15
GROUND ELEVATION 761 ft **HOLE SIZE** 4"
DRILLING CONTRACTOR IPES
GROUND WATER LEVELS:
DRILLING METHOD 4" SSA
AT TIME OF DRILLING 15.00 ft / Elev 746.00 ft
LOGGED BY Friedman **CHECKED BY** Lidholm
AT END OF DRILLING 15.00 ft / Elev 746.00 ft
NOTES Borehole backfilled upon completion
1hrs AFTER DRILLING 15.00 ft / Elev 746.00 ft

DEPTH (ft)	MATERIAL DESCRIPTION	Elev.	SAMPLE TYPE NUMBER	RECOVERY LENGTH	BLOW COUNTS (N VALUE)	POCKET PEN. (psf)	UNC. COMP. (psf)	DRY UNIT WT. (pcf)	MOISTURE CONTENT (%)	ATTERBERG LIMITS: LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX
1.0	TOPSOIL/ ROOT ZONE (12-inches)	760.0										
	UNDOCUMENTED FILL: Fat clay, dark brown and brown		ST 1	23		5000		101	22			
			ST 2	14		5000		101	23			
6.0	LEAN TO FAT CLAY: Light brown and gray, trace sand, stiff	755.0	ST 3	14		3500	3020	105	23			
11.0	CLAYEY SAND TO SANDY CLAY: Brown and gray, trace gravel, stiff to hard (Glacial Drift)	750.0	ST 4	24		9000		119	15			
19.0	SAND: Brown, loose to medium dense (Glacial Drift)	742.0	ST 5	24		2000	1580	116	18			
			SPT 6	18	1-2-3 (5)				25			
29.0	CLAYEY SAND TO SANDY CLAY: Brown and gray, trace gravel, medium dense to very dense (Glacial Drift)	732.0	SPT 7	18	6-10-14 (24)				17			
			SPT 8	18	26-41-40 (81)				13			
39.0		722.0										
40.0	SHALE: Light brown to whitish gray, hard	721.0	SPT 9	18	27-14-50 (64)				12			
40.5	LIMESTONE: Weathered, hard	720.5										

Auger Refusal at 40.5 feet.
Bottom of borehole at 40.5 feet.

SAMPLE LENGTH REPORT - LAT-LONG TEMPLATE.GDT - 8/26/15 16:32 - C:\SERVER FILES\GEOTECH GENERAL\==PROJECTS==\GEOT PROJECTS\2015\G15059 - CP152681-STEWART HALL- RENOVATION\G15059.GPJ

Figure 3: Stewart Hall Borehole 2

Crockett Geotechnical - Testing Lab
500 Big Bear Boulevard
Columbia, MO 65202
Telephone: 573-447-3981

CROCKETT GEOTECHNICAL - TESTING LAB

BORING NUMBER B-2

CLIENT University of Missouri	**PROJECT NAME** Memorial Union Vertical Addition
PROJECT NUMBER G15023	**PROJECT LOCATION** Columbia, Missouri
DATE STARTED 3/26/15 **COMPLETED** 3/26/15	**GROUND ELEVATION** 764 ft **HOLE SIZE** 4"
DRILLING CONTRACTOR IPES	**GROUND WATER LEVELS:**
DRILLING METHOD 4" SSA	**AT TIME OF DRILLING** 23.00 ft / Elev 741.00 ft
LOGGED BY Friedman **CHECKED BY** Lidholm	**AT END OF DRILLING** 23.00 ft / Elev 741.00 ft
NOTES Borehole backfilled upon completion	**0.5hrs AFTER DRILLING** 23.00 ft / Elev 741.00 ft

DEPTH (ft)	MATERIAL DESCRIPTION	Elevation
0.5	MULCH (6-inches)	763.5
	UNDOCUMENTD FILL: Fat clay, dark brown and brown, trace gravel, trace rust stains	
6.5		757.5
	LEAN TO FAT CLAY: Light brown and gray, trace sand, very stiff	
11.0		753.0
	LEAN TO FAT CLAY: Brown and gray, trace sand and gravel, trace lignite, possible cobbles, occassional sand pockets, stiff to very stiff (Glacial Drift)	
23.0		741.0
	CLAYEY SAND TO A SANDY CLAY: Brown and gray, trace gravel, possible cobbles, stiff when clayey (Glacial Drift)	
31.0		733.0
	LEAN TO FAT CLAY: Dark gray and brown, trace gravel, possible cobbles, hard (Glacial Drift)	
36.0		728.0
	WEATHERED SHALE: Light gray to gray, with gravel, cobbles, and possible boulders, very stiff	
44.7		719.3
	Bottom of borehole at 44.7 feet.	

SAMPLE TYPE NUMBER	RECOVERY LENGTH	BLOW COUNTS (N VALUE)	POCKET PEN. (psf)	UNC. COMP. (psf)	DRY UNIT WT. (pcf)	MOISTURE CONTENT (%)	ATTERBERG LIMITS LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX
ST 1	17		5000		105	22			
ST 2	23		4500	2940	91	32			
ST 3	24		5500		104	22			
ST 4	24		7500		109	18	43	14	29
ST 5	24		4500		110	16	33	15	18
ST 6	24		4000		108	18	35	14	21
ST 7	15		3500	660	112	18			
SPT 8	18	5-8-11 (19)	9000			15			
SPT 9	18	13-17-23 (40)	9000			12			
SPT 10	7	12-50/1"	9000			16			
SPT 11	6	27-22-50/2"	9000			20			

Figure 4: Stewart Hall Borehole 2' (From Memorial Union Vertical Addition Project)

APPENDIX A-7

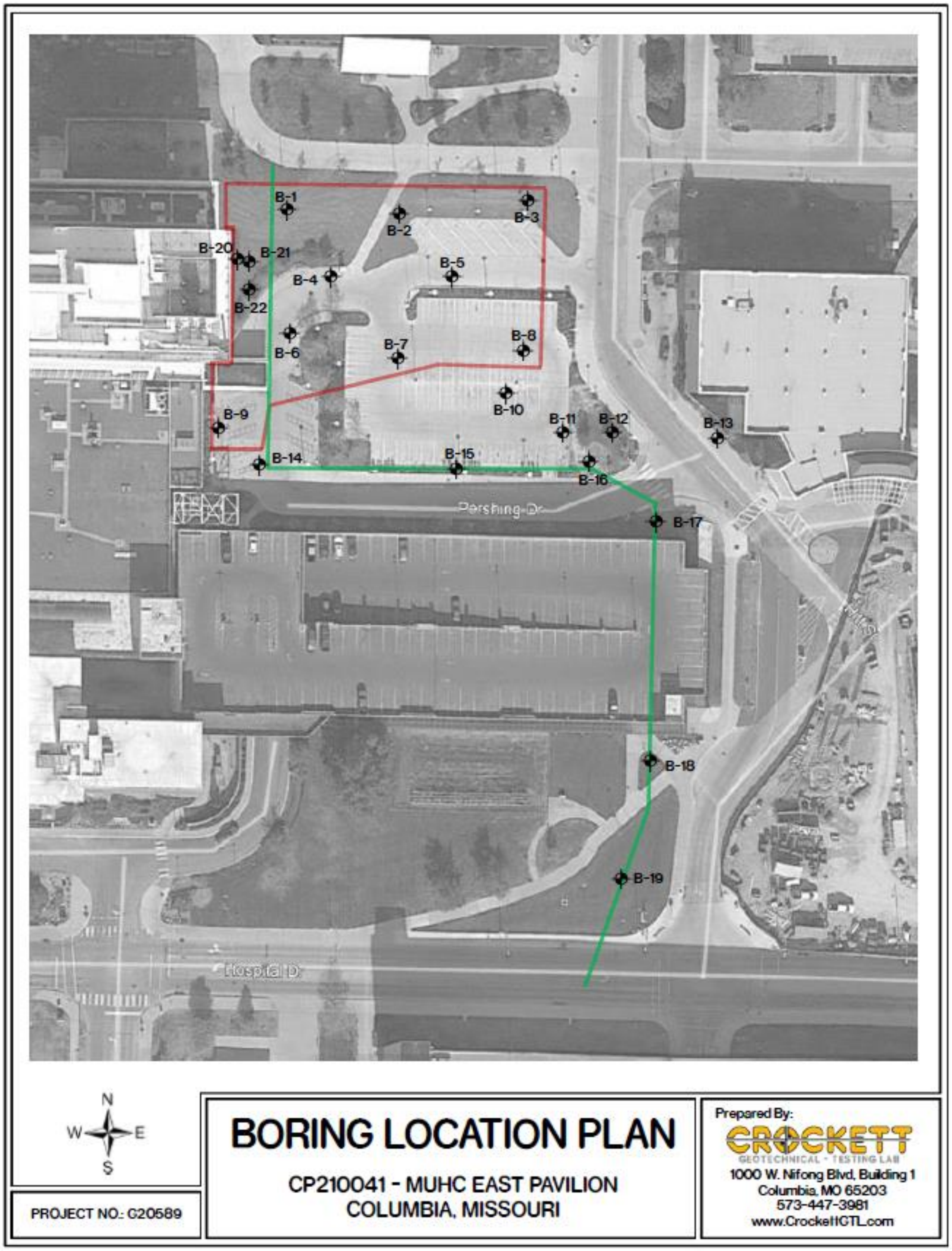


Figure 1: MUHC East Pavilion boring plan (Aerial View), prepared by Crockett

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BORING NUMBER B-1

PAGE 1 OF 1

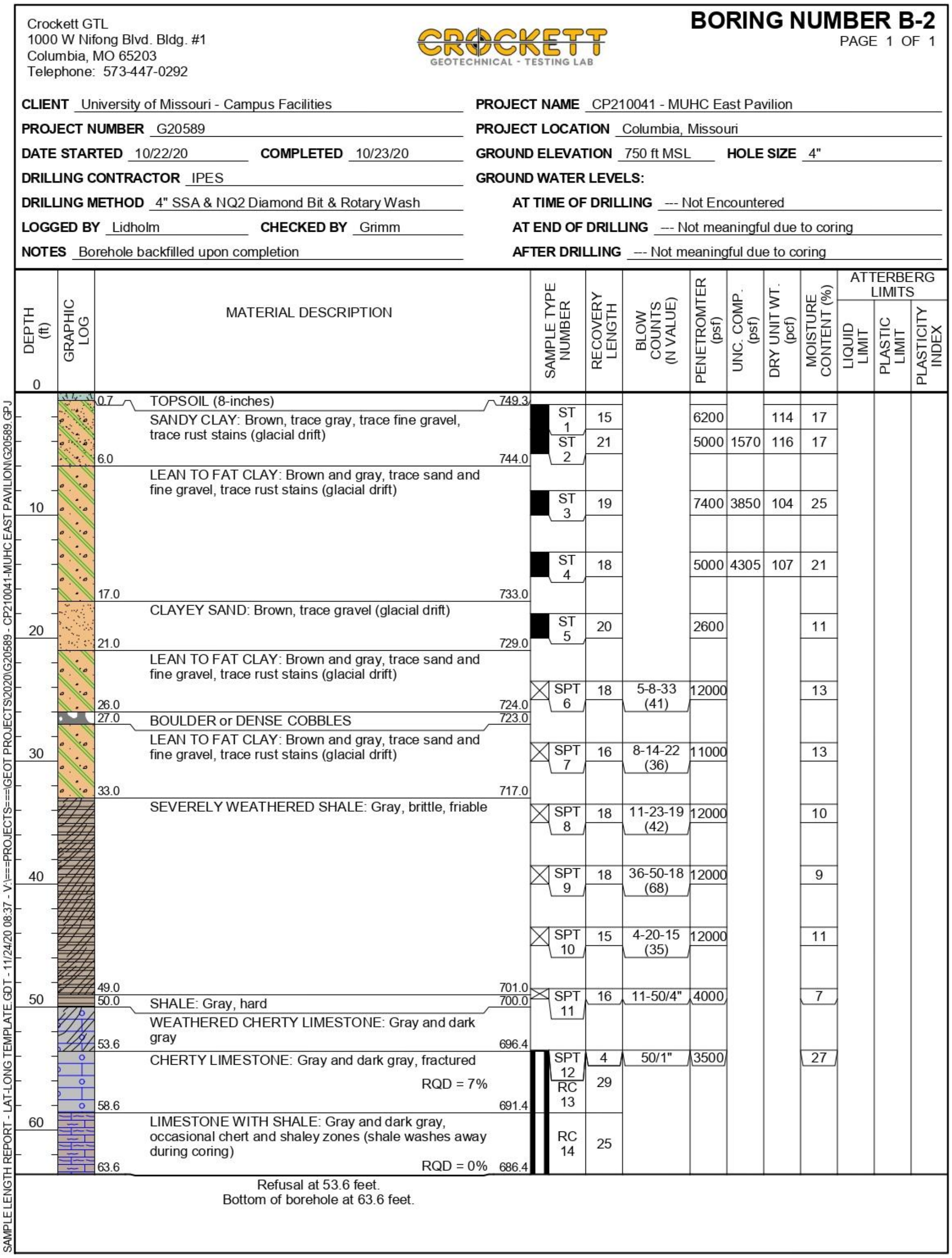
CLIENT University of Missouri - Campus Facilities	**PROJECT NAME** CP210041 - MUHC East Pavilion
PROJECT NUMBER G20589	**PROJECT LOCATION** Columbia, Missouri
DATE STARTED 10/29/20 **COMPLETED** 10/29/20	**GROUND ELEVATION** 752 ft MSL **HOLE SIZE** 4"
DRILLING CONTRACTOR IPES	**GROUND WATER LEVELS:**
DRILLING METHOD 4" SSA & NQ2 Diamond Bit & Rotary Wash	**AT TIME OF DRILLING** --- Not Encountered
LOGGED BY Lidholm **CHECKED BY** Grimm	**AT END OF DRILLING** --- Not meaningful due to coring
NOTES Borehole backfilled upon completion	**AFTER DRILLING** --- Not meaningful due to coring

DEPTH (ft)	MATERIAL DESCRIPTION	ELEV.	SAMPLE TYPE NUMBER	RECOVERY LENGTH	BLOW COUNTS (N VALUE)	PENETROMTER (psf)	UNC. COMP. (psf)	DRY UNIT WT. (pcf)	MOISTURE CONTENT (%)	ATTERBERG LIMITS: LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX
0.5	TOPSOIL (6-inches)	751.5										
	UNDOCUMENTED FILL: Clay, brown and light brown, with gravel to gravelly		ST 1	19		3400			12			
			ST 2	15		3000		116	16			
7.0	LEAN TO FAT CLAY: Brown and gray, with sand to sandy, trace fine gravel, trace rust stains (glacial drift)	745.0	ST 3	18		4500	3385	110	20			
	--: trace sand		ST 4	22		5500	4850	107	22			
	--: with gravel to gravelly zones		SPT 5	17	7-4-6 (10)	7000			20			
			SPT 6	17	3-5-31 (36)	6200			19			
	--: occasional gravelly zones		SPT 7	17	5-13-17 (30)	8000			15			
33.0	CLAYEY SHALE: Gray	719.0	SPT 8	18	2-14-25 (39)	12000			13			
37.0	SEVERELY WEATHERED SHALE: Gray, brittle, friable	715.0										
39.0	LIMESTONE WITH SHALE: Gray, interbedded (shale washes away during coring) RQD = 0%	713.0	SPT 9	4	50/4"				7			
			RC 10	12								
44.7	LIMESTONE: Gray to whitish gray, occassional weathered zones, occasional shale partings RQD = 38%	707.3	RC 11	38								
	RQD = 52%		RC 12	58								
52.1	SHALE: Gray	699.9										
52.9	LIMESTONE: Gray to whitish gray	699.1										
54.0		698.0										

Refusal at 39.0 feet.
Bottom of borehole at 54.0 feet.

SAMPLE LENGTH REPORT - LAT-LONG TEMPLATE.GDT - 11/24/20 08:37 - V:\==PROJECTS==\GEOT PROJECTS\2020\G20589 - CP210041-MUHC EAST PAVILION\G20589.GPJ

Figure 2: MUHC Borehole 1



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BORING NUMBER B-2
PAGE 1 OF 1

CLIENT University of Missouri - Campus Facilities
PROJECT NAME CP210041 - MUHC East Pavilion
PROJECT NUMBER G20589
PROJECT LOCATION Columbia, Missouri
DATE STARTED 10/22/20 **COMPLETED** 10/23/20
GROUND ELEVATION 750 ft MSL **HOLE SIZE** 4"
DRILLING CONTRACTOR IPES
GROUND WATER LEVELS:
DRILLING METHOD 4" SSA & NQ2 Diamond Bit & Rotary Wash
AT TIME OF DRILLING --- Not Encountered
LOGGED BY Lidholm **CHECKED BY** Grimm
AT END OF DRILLING --- Not meaningful due to coring
NOTES Borehole backfilled upon completion
AFTER DRILLING --- Not meaningful due to coring

DEPTH (ft)	MATERIAL DESCRIPTION	Elevation
0.7	TOPSOIL (8-inches)	749.3
6.0	SANDY CLAY: Brown, trace gray, trace fine gravel, trace rust stains (glacial drift)	744.0
17.0	LEAN TO FAT CLAY: Brown and gray, trace sand and fine gravel, trace rust stains (glacial drift)	733.0
21.0	CLAYEY SAND: Brown, trace gravel (glacial drift)	729.0
26.0	LEAN TO FAT CLAY: Brown and gray, trace sand and fine gravel, trace rust stains (glacial drift)	724.0
27.0	BOULDER or DENSE COBBLES	723.0
33.0	LEAN TO FAT CLAY: Brown and gray, trace sand and fine gravel, trace rust stains (glacial drift)	717.0
49.0	SEVERELY WEATHERED SHALE: Gray, brittle, friable	701.0
50.0	SHALE: Gray, hard	700.0
53.6	WEATHERED CHERTY LIMESTONE: Gray and dark gray	696.4
58.6	CHERTY LIMESTONE: Gray and dark gray, fractured RQD = 7%	691.4
63.6	LIMESTONE WITH SHALE: Gray and dark gray, occasional chert and shaley zones (shale washes away during coring) RQD = 0%	686.4

Refusal at 53.6 feet.
Bottom of borehole at 63.6 feet.

SAMPLE TYPE NUMBER	RECOVERY LENGTH	BLOW COUNTS (N VALUE)	PENETROMTER (psf)	UNC. COMP. (psf)	DRY UNIT WT. (pcf)	MOISTURE CONTENT (%)	ATTERBERG LIMITS LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX
ST 1	15		6200		114	17			
ST 2	21		5000	1570	116	17			
ST 3	19		7400	3850	104	25			
ST 4	18		5000	4305	107	21			
ST 5	20		2600			11			
SPT 6	18	5-8-33 (41)	12000			13			
SPT 7	16	8-14-22 (36)	11000			13			
SPT 8	18	11-23-19 (42)	12000			10			
SPT 9	18	36-50-18 (68)	12000			9			
SPT 10	15	4-20-15 (35)	12000			11			
SPT 11	16	11-50/4"	4000			7			
SPT 12	4	50/1"	3500			27			
RC 13	29								
RC 14	25								

SAMPLE LENGTH REPORT - LAT-LONG TEMPLATE.GDT - 11/24/20 08:37 - V:\===PROJECTS===\GEOT PROJECTS\2020\G20589 - CP210041-MUHC EAST PAVILION\G20589.GPJ

Figure 3: MUHC Borehole 2

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BORING NUMBER B-3

PAGE 1 OF 1

CLIENT University of Missouri - Campus Facilities
PROJECT NAME CP210041 - MUHC East Pavilion
PROJECT NUMBER G20589
PROJECT LOCATION Columbia, Missouri
DATE STARTED 10/30/20 **COMPLETED** 10/30/20
GROUND ELEVATION 749 ft MSL **HOLE SIZE** 4"
DRILLING CONTRACTOR IPES
GROUND WATER LEVELS:
DRILLING METHOD 4" SSA & NQ2 Diamond Bit & Rotary Wash
AT TIME OF DRILLING --- Not Encountered
LOGGED BY Lidholm **CHECKED BY** Grimm
AT END OF DRILLING --- Not meaningful due to coring
NOTES Borehole backfilled upon completion
AFTER DRILLING --- Not meaningful due to coring

DEPTH (ft)	MATERIAL DESCRIPTION	ELEV.	SAMPLE TYPE NUMBER	RECOVERY LENGTH	BLOW COUNTS (N VALUE)	PENETROMTER (psf)	UNC. COMP. (psf)	DRY UNIT WT. (pcf)	MOISTURE CONTENT (%)	ATTERBERG LIMITS: LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX
0.6	TOPSOIL (7-inches)	748.4										
3.0	SANDY CLAY: Brown, trace gray, trace fine gravel, trace rust stains (glacial drift)	746.0	ST 1	21		9000		122	13			
	LEAN TO FAT CLAY: Brown and gray, trace sand and fine gravel, trace rust stains (glacial drift)		ST 2	18		7500	5850	120	14			
			ST 3	24		4600	4195	111	18			
			ST 4	24		4000	6540	1110	21			
	--: occasional sandy zones		ST 5	24		5000	4880	116	16	30	11	19
			SPT 6	12	9-14-16 (30)	8400			13			
27.0	CLAYEY SHALE: Gray	722.0										
			SPT 7	17	8-14-25 (39)	12000			11			
33.0	SEVERELY WEATHERED TO WEATHERED SHALE: Gray, brittle, friable	716.0	SPT 8	18	7-22-27 (49)	12000			12			
			SPT 9	15	2-15-42 (57)	9600			11			
			SPT 10	16	5-27-50/5"	12000			10			
			SPT 11	18	2-17-46 (63)	3000			12			
53.6	LIMESTONE WITH SHALE: Gray and dark gray, occasional chert and shaley zones (shale washes away during coring)	695.4	SPT 12	1	50/1"				8			
58.6	RQD = 0%	690.4	RC 13	5								

NOTE: The diamond bit broke apart in the borehole during the first core run. The borehole had to be abandoned because of this.
Refusal at 53.6 feet.
Bottom of borehole at 58.6 feet.

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Figure 4: MUHC Borehole 3

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BORING NUMBER B-4
PAGE 1 OF 1

CLIENT University of Missouri - Campus Facilities
PROJECT NAME CP210041 - MUHC East Pavilion
PROJECT NUMBER G20589
PROJECT LOCATION Columbia, Missouri
DATE STARTED 10/25/20 **COMPLETED** 10/31/20
GROUND ELEVATION 746 ft MSL **HOLE SIZE** 4"
DRILLING CONTRACTOR IPES
GROUND WATER LEVELS:
DRILLING METHOD 4" SSA & NQ2 Diamond Bit & Rotary Wash
AT TIME OF DRILLING --- Not Encountered
LOGGED BY Lidholm **CHECKED BY** Grimm
AT END OF DRILLING --- Not Encountered
NOTES Borehole backfilled upon completion
3hrs AFTER DRILLING --- Not Encountered

Depth (ft)	MATERIAL DESCRIPTION	Elevation
0.7	CONCRETE (8-inches)	745.3
1.0	GRAVEL (4-inches)	745.0
7.0	SANDY CLAY: Light brown and brown, trace gray, trace fine gravel, trace rust stains (glacial drift)	739.0
25.0	LEAN TO FAT CLAY: Brown and gray, trace sand and fine gravel, trace rust stains (glacial drift); --: with sand to sandy zones	721.0
31.0	WEATHERED SHALE: Gray	715.0
33.0	BOULDER or DENSE COBBLES: Possible weathered rock	713.0
36.2	LIMESTONE WITH SHALE: Gray, interbedded (shale washes away during coring) RQD = 26%	709.8
38.2	LIMESTONE: Gray to whitish gray	707.8
39.4	RQD = 55%	706.6
42.1	SHALE: Gray to light gray, limey zones	703.9
44.0	LIMESTONE: Gray to whitish gray	702.0
	LIMESTONE WITH SHALE: Gray, interbedded RQD = 79%	

SAMPLE TYPE NUMBER	RECOVERY LENGTH	BLOW COUNTS (N VALUE)	PENETROMTER (psf)	UNC. COMP. (psf)	DRY UNIT WT. (pcf)	MOISTURE CONTENT (%)	ATTERBERG LIMITS: LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX
ST 1	13		7500		118	12			
ST 2	24		8500	3015	120	14			
ST 3	24		5600	3935	102	23			
ST 4	24		5000	4130	109	21			
ST 5	24		2800	2660	107	21	41	12	29
ST 6	15		12000			11			
SPT 7	18	16-45-49 (94)	7000			11			
RC 8	21								
RC 9	51								
RC 10	32								

Refusal at 33.0 feet.
Bottom of borehole at 44.0 feet.

Figure 5: MUHC Borehole 4

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BORING NUMBER B-5

PAGE 1 OF 1

CLIENT University of Missouri - Campus Facilities
PROJECT NAME CP210041 - MUHC East Pavilion
PROJECT NUMBER G20589
PROJECT LOCATION Columbia, Missouri
DATE STARTED 10/25/20 **COMPLETED** 10/25/20
GROUND ELEVATION 747 ft MSL **HOLE SIZE** 4"
DRILLING CONTRACTOR IPES
GROUND WATER LEVELS:
DRILLING METHOD 4" SSA & NQ2 Diamond Bit & Rotary Wash
AT TIME OF DRILLING --- Not Encountered
LOGGED BY Lidholm **CHECKED BY** Grimm
AT END OF DRILLING --- Not meaningful due to coring
NOTES Borehole backfilled upon completion
AFTER DRILLING --- Not meaningful due to coring

Depth (ft)	Material Description	Elevation
0.7	CONCRETE (8-inches)	746.3
0.9	GRAVEL (3-inches)	746.1
6.0	SANDY CLAY: Brown, trace gray, trace fine gravel, trace rust stains (glacial drift)	741.0
24.0	LEAN TO FAT CLAY: Brown and gray, trace sand and fine gravel, trace rust stains (glacial drift)	723.0
43.5	SEVERELY WEATHERED TO WEATHERED SHALE: Gray, brittle, friable	703.5
47.5	SHALE: Gray, hard	699.5
52.5	CHERTY LIMESTONE: Gray and dark gray, fractured RQD = 11%	694.5
53.6	LIMESTONE: Gray to whitish gray RQD = 28%	693.4
62.5	LIMESTONE WITH SHALE: Gray, interbedded, occasional chert (shale washes away during coring) RQD = 6%	684.5

Sample Type Number	Recovery Length	Blow Counts (N Value)	Penetromter (psf)	Unc. Comp. (psf)	Dry Unit Wt. (pcf)	Moisture Content (%)	Liquid Limit	Plastic Limit	Plasticity Index
ST 1	23		6000		115	16			
ST 2	23		3600	2080	116	16			
ST 3	23		9000	7495	113	19			
ST 4	24		6400	4430	109	19			
ST 5	24		4800	1640	114	17	30	12	18
SPT 6	16	1-5-28 (33)	8000			17			
SPT 7	17	13-36-50/5"	12000			12			
SPT 8	16	26-45-46 (91)	12000			15			
SPT 9	7	49-50/1"	7600			13			
SPT 10	1	50/1"	10200			13			
RC 11	21								
RC 12	40								
RC 13	29								

Refusal at 47.5 feet.
Bottom of borehole at 62.5 feet.

SAMPLE LENGTH REPORT - LAT-LONG TEMPLATE.GDT - 11/24/20 08:37 - V:\==PROJECTS==\GEOT PROJECTS\2020\G20589 - CP210041-MUHC EAST PAVILION\G20589.GPJ

Figure 6: MUHC Borehole 5

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BORING NUMBER B-6

- **CLIENT** University of Missouri - Campus Facilities
- **PROJECT NAME** CP210041 - MUHC East Pavilion
- **PROJECT NUMBER** G20589
- **PROJECT LOCATION** Columbia, Missouri
- **DATE STARTED** 10/25/20 **COMPLETED** 10/31/20
- **GROUND ELEVATION** 744 ft MSL **HOLE SIZE** 4"
- **DRILLING CONTRACTOR** IPES
- **GROUND WATER LEVELS:**
  - **AT TIME OF DRILLING** --- Not Encountered
  - **AT END OF DRILLING** --- Not Encountered
  - **2.5hrs AFTER DRILLING** --- Not Encountered
- **DRILLING METHOD** 4" SSA & NQ2 Diamond Bit & Rotary Wash
- **LOGGED BY** Lidholm **CHECKED BY** Grimm
- **NOTES** Borehole backfilled upon completion

DEPTH (ft)	MATERIAL DESCRIPTION		SAMPLE TYPE NUMBER	RECOVERY LENGTH	BLOW COUNTS (N VALUE)	PENETROMTER (psf)	UNC. COMP. (psf)	DRY UNIT WT. (pcf)	MOISTURE CONTENT (%)	ATTERBERG LIMITS: LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX
0.8	CONCRETE (9.5-inches)	743.3										
3.0	SANDY CLAY: Brown, trace gray, trace fine gravel, trace rust stains (glacial drift)	741.0	ST 1	15		2000		115	17			
	LEAN TO FAT CLAY: Brown and gray, trace sand and fine gravel, trace rust stains (glacial drift)		ST 2	13		2400	2030	108	19			
10	--: gray		ST 3	20		6800	4880	103	24			
			ST 4	23		8000	6305	111	18	33	12	21
20	--: with sand zones		SPT 5	18	4-4-7 (11)	5400			18			
24.0	SEVERELY WEATHERED SHALE: Gray, brittle, friable	720.0	SPT 6	18	22-47-50/4"	12000			7			
30			SPT 7	18	20-34-50/5"	12000			8			
33.0	WEATHERED CHERTY LIMESTONE: Gray and dark gray, fractured	711.0										
37.0	CHERTY LIMESTONE: Gray and dark gray, fractured RQD = 16%	707.0	RC 8	22								
42.8	LIMESTONE WITH SHALE: Gray, interbedded, occasional chert (shale washes away during coring) RQD = 30%	701.2	RC 9	42								
50	RQD = 81%		RC 10	55								
51.8		692.2										

Refusal at 33.0 feet.
Bottom of borehole at 51.8 feet.

Figure 7: MUHC Borehole 6

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CROCKETT GEOTECHNICAL - TESTING LAB

BORING NUMBER B-7
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CLIENT University of Missouri - Campus Facilities
PROJECT NAME CP210041 - MUHC East Pavilion
PROJECT NUMBER G20589
PROJECT LOCATION Columbia, Missouri
DATE STARTED 11/15/20 **COMPLETED** 11/15/20
GROUND ELEVATION 746 ft MSL **HOLE SIZE** 4"
DRILLING CONTRACTOR IPES
GROUND WATER LEVELS:
DRILLING METHOD 4" SSA & NQ2 Diamond Bit & Rotary Wash
▽ **AT TIME OF DRILLING** 22.00 ft / Elev 724.00 ft
LOGGED BY Lidholm **CHECKED BY** Grimm
AT END OF DRILLING --- Not meaningful due to coring
NOTES Borehole backfilled upon completion
AFTER DRILLING --- Not meaningful due to coring

DEPTH (ft)	MATERIAL DESCRIPTION	Elev.	SAMPLE TYPE NUMBER	RECOVERY LENGTH	BLOW COUNTS (N VALUE)	PENETROMTER (psf)	UNC. COMP. (psf)	DRY UNIT WT. (pcf)	MOISTURE CONTENT (%)	ATTERBERG LIMITS: LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX
0.5	TOPSOIL (6-inches)	745.5										
2.0	UNDOCUMENTED FILL: Gravel and clay, brown	744.0	ST 1A	9		4200			12			
				9		3000		111	18			
	LEAN TO FAT CLAY: Brown, trace gray, trace to with sand and gravel (glacial drift)		ST 1B	14		1000	1030	106	22			
			ST 2									
10	--: becomes sandy, occasional clayey sand zones		ST 3	24		4500	1695	116	13			
	--: zones of fat clay		ST 4	20		4000	4155	102	24			
20			ST 5	24		11600	8180	115	17	34	13	21
	▽											
	--: trace to with sand and silt		SPT 6	10	1-10-11 (21)	3000			19			
30	--: trace to with sand and gravel		SPT 7	17	3-5-10 (15)	6600			17			
33.0	CLAYEY SHALE to SEVERELY WEATHERED SHALE: Gray, softens when wet	713.0	SPT 8	17	15-27-50/5"	7200			18			
39.0	WEATHERED CHERTY LIMESTONE: Gray and dark gray, fractured, with mineralization, occasional shale seams from 39' - 41.5'	707.0	SPT 9	6	50/3"	5000			16			
	RQD = 0%		RC 10	14								
	RQD = 0%		RC 11	21								
49.0	LIMESTONE: Gray to whitish gray, fractured, poor recovery RQD = 0%	697.0	RC 12	26								
53.0		693.0										

Refusal at 39.0 feet.
Bottom of borehole at 53.0 feet.

Figure 8: MUHC Borehole 7

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BORING NUMBER B-8

PAGE 1 OF 1

CLIENT University of Missouri - Campus Facilities
PROJECT NAME CP210041 - MUHC East Pavilion
PROJECT NUMBER G20589
PROJECT LOCATION Columbia, Missouri
DATE STARTED 11/8/20 **COMPLETED** 11/15/20
GROUND ELEVATION 745 ft MSL **HOLE SIZE** 4"
DRILLING CONTRACTOR IPES
GROUND WATER LEVELS:
DRILLING METHOD 4" SSA & NQ2 Diamond Bit & Rotary Wash
▽ **AT TIME OF DRILLING** 25.00 ft / Elev 720.00 ft
LOGGED BY Lidholm **CHECKED BY** Grimm
AT END OF DRILLING --- Not meaningful due to coring
NOTES Borehole backfilled upon completion
AFTER DRILLING --- Not meaningful due to coring

DEPTH (ft)	MATERIAL DESCRIPTION	ELEV.
0.5	CONCRETE (6-inches)	744.5
0.8	GRAVEL (4-inches)	744.2
	LEAN TO FAT CLAY: Brown and gray, trace sand and fine gravel, trace rust stains (glacial drift)	
24.0	--: becomes gravelly to clayey gravel, with sand to sandy	721.0
25.0 ▽	BOULDER or DENSE COBBLES	720.0
28.5	SEVERELY WEATHERED SHALE: Gray, with gravel to gravelly	716.5
	CHERTY LIMESTONE: Gray and dark gray, fractured RQD = 7%	
33.5	LIMESTONE: Gray to whitish gray RQD = 80%	711.5
38.5		706.5

SAMPLE TYPE NUMBER	RECOVERY LENGTH	BLOW COUNTS (N VALUE)	PENETROMTER (psf)	UNC. COMP. (psf)	DRY UNIT WT. (pcf)	MOISTURE CONTENT (%)	ATTERBERG LIMITS: LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX
ST 1	14		6200		113	18			
ST 2	18		5400	3190	105	22			
ST 3	18		7400	3760	108	22			
ST 4	19		6400	7560	110	20			
ST 5	19		6200	6445	107	17	36	13	23
SPT 6	12	9-19-50/3"				13			
RC 8	22								
RC 9	60								

Refusal at 28.5 feet.
Bottom of borehole at 38.5 feet.

Figure 9: MUHC Borehole 8

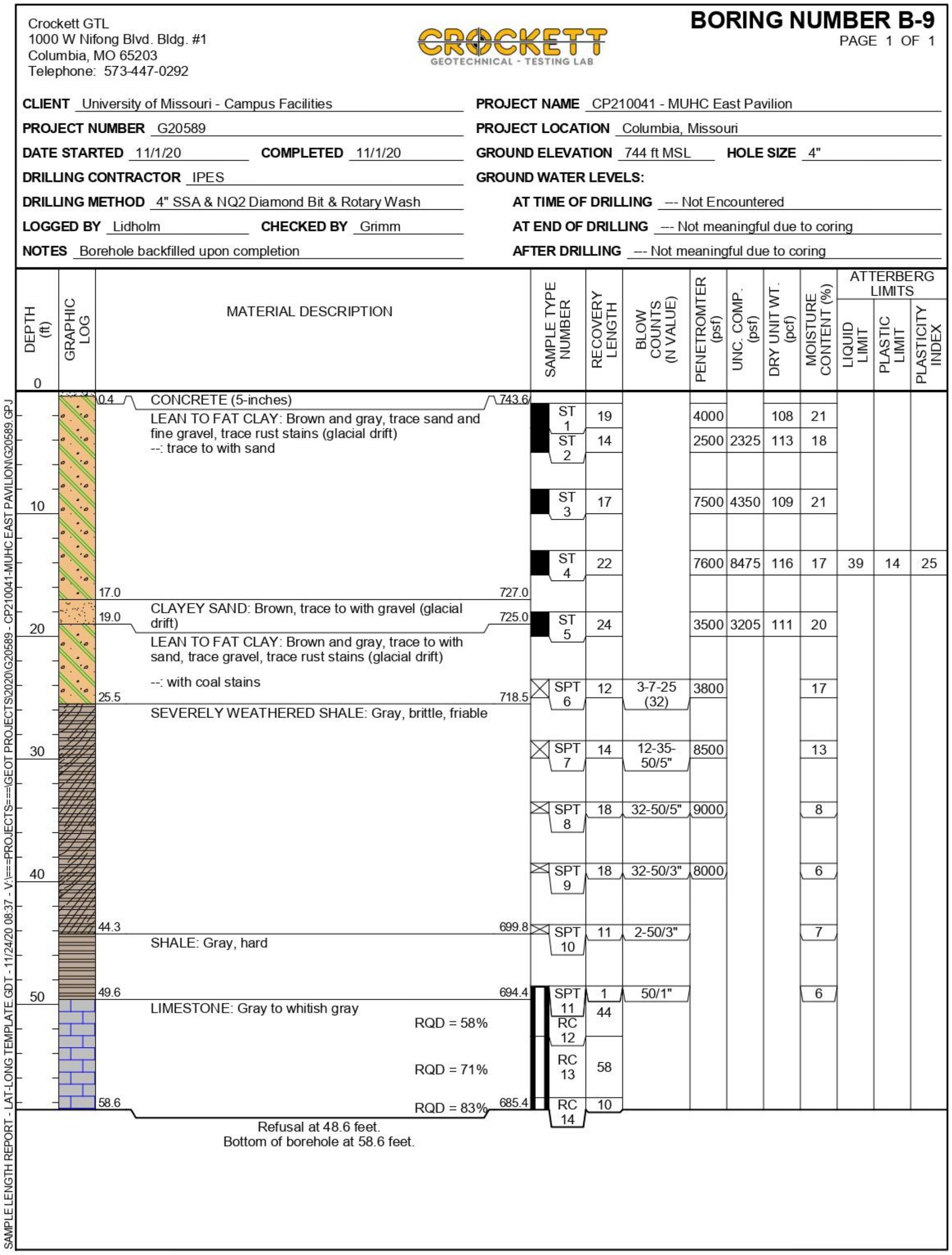

Figure 10: MUHC Borehole 9

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BORING NUMBER B-10

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CLIENT University of Missouri - Campus Facilities
PROJECT NAME CP210041 - MUHC East Pavilion
PROJECT NUMBER G20589
PROJECT LOCATION Columbia, Missouri
DATE STARTED 11/7/20 **COMPLETED** 11/7/20
GROUND ELEVATION 745 ft MSL **HOLE SIZE** 4"
DRILLING CONTRACTOR IPES
GROUND WATER LEVELS:
DRILLING METHOD 4" SSA & NQ2 Diamond Bit & Rotary Wash
▽ **AT TIME OF DRILLING** 22.00 ft / Elev 723.00 ft
LOGGED BY Lidholm **CHECKED BY** Grimm
AT END OF DRILLING --- Not meaningful due to coring
NOTES Borehole backfilled upon completion
AFTER DRILLING --- Not meaningful due to coring

DEPTH (ft)	MATERIAL DESCRIPTION	Elev.	SAMPLE TYPE NUMBER	RECOVERY LENGTH	BLOW COUNTS (N VALUE)	PENETROMTER (psf)	UNC. COMP. (psf)	DRY UNIT WT. (pcf)	MOISTURE CONTENT (%)	ATTERBERG LIMITS: LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX
0.5	CONCRETE (6-inches)	744.5										
0.8	GRAVEL (3-inches)	744.3	ST 1	15		5000		110	19			
	LEAN TO FAT CLAY: Brown and gray, trace sand and fine gravel, trace rust stains (glacial drift) --: occasional sandy zones		ST 2	12		5600		110	19			
10			ST 3	21		3000	2260	105	22			
			ST 4	19		7200	5995	112	18			
17.0		728.0										
20	SANDY CLAY: Gray, trace brown, trace fine gravel, trace rust stains (glacial drift)		ST 5	22		2600			12			
23.0 ▽		722.0										
	CLAYEY SAND: Brown, trace to with gravel		SPT 6	18	7-5-6 (11)				18			
28.5		716.5										
30	SHALEY FAT CLAY: Gray, trace to with gravel, occasional possible cobbles and boulders		SPT 7	11	15-25-30 (55)	10000			12			
33.7		711.3										
	CHERTY LIMESTONE: Gray and light gray, occasional shale, fractured RQD = 37%		SPT 8	2	50/2"				12			
			RC 9	36								
38.8		706.3										
40	WEATHERED SHALE: Gray (washed away during coring) RQD = 0%		RC 10	5								
43.3		701.7										
	LIMESTONE: Gray to whitish gray, trace shale RQD = 71%		RC 11	59								
48.7		696.3										

Refusal at 33.7 feet.
Bottom of borehole at 48.7 feet.

Figure 11: MUHC Borehole 10

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CROCKETT GEOTECHNICAL - TESTING LAB

BORING NUMBER B-11

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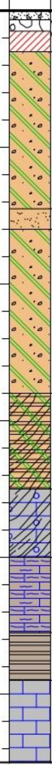
CLIENT University of Missouri - Campus Facilities
PROJECT NAME CP210041 - MUHC East Pavilion
PROJECT NUMBER G20589
PROJECT LOCATION Columbia, Missouri
DATE STARTED 10/24/20 **COMPLETED** 10/24/20
GROUND ELEVATION 743.5 ft MSL **HOLE SIZE** 4"
DRILLING CONTRACTOR IPES
GROUND WATER LEVELS:
DRILLING METHOD 4" SSA & NQ2 Diamond Bit & Rotary Wash
▽ **AT TIME OF DRILLING** 20.00 ft / Elev 723.50 ft
LOGGED BY Lidholm **CHECKED BY** Grimm
AT END OF DRILLING --- Not meaningful due to coring
NOTES Borehole backfilled upon completion
AFTER DRILLING --- Not meaningful due to coring



DEPTH (ft)	MATERIAL DESCRIPTION	ELEV.
0.7	CONCRETE (8-inches)	742.8
1.5	GRAVEL (10-inches), with sand	742.0
3.0	FAT CLAY: Grayish brown and gray, trace to with sand (possible undocumented fill)	740.5
14.5	LEAN TO FAT CLAY: Brown and gray, trace sand and fine gravel, trace rust stains (glacial drift)	729.0
16.0	CLAYEY SAND: Brown, trace gravel (glacial drift)	727.5
28.0	LEAN TO FAT CLAY: Brown and gray, trace sand and fine gravel, trace rust stains (glacial drift) ▽ (20 ft)	715.5
35.0	CLAYEY SHALE: Light brown and light gray	708.5
40.0	WEATHERED CHERTY LIMESTONE: Gray and dark gray, with shale	703.5
45.5	LIMESTONE WITH SHALE: Gray and dark gray, occasional chert and shaley zones (shale washes away during coring) RQD = 6%	698.0
49.0	SHALE: Gray RQD = 7%	694.5
55.0	LIMESTONE: Gray to whitish gray, occassional weathered zones, occasional shale partings RQD = 56%	688.5

SAMPLE TYPE NUMBER	RECOVERY LENGTH	BLOW COUNTS (N VALUE)	PENETROMTER (psf)	UNC. COMP. (psf)	DRY UNIT WT. (pcf)	MOISTURE CONTENT (%)	ATTERBERG LIMITS: LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX
ST 1	14		6000		111	18			
ST 2	14		2500	4445	107	22			
ST 3	21		7000	4105	107	22			
ST 4	17		9600	7660	118	17			
ST 5	20		9000	4745	113	18			
SPT 6	12	7-9-13 (22)	8000			16			
SPT 7	17	13-21-27 (48)	12000			15			
SPT 8	6	50/1"	8600			13			
RC 9	17								
RC 10	27								
RC 11	60								

Refusal at 40.0 feet.
Bottom of borehole at 55.0 feet.

Figure 12: MUHC Borehole 11

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BORING NUMBER B-12

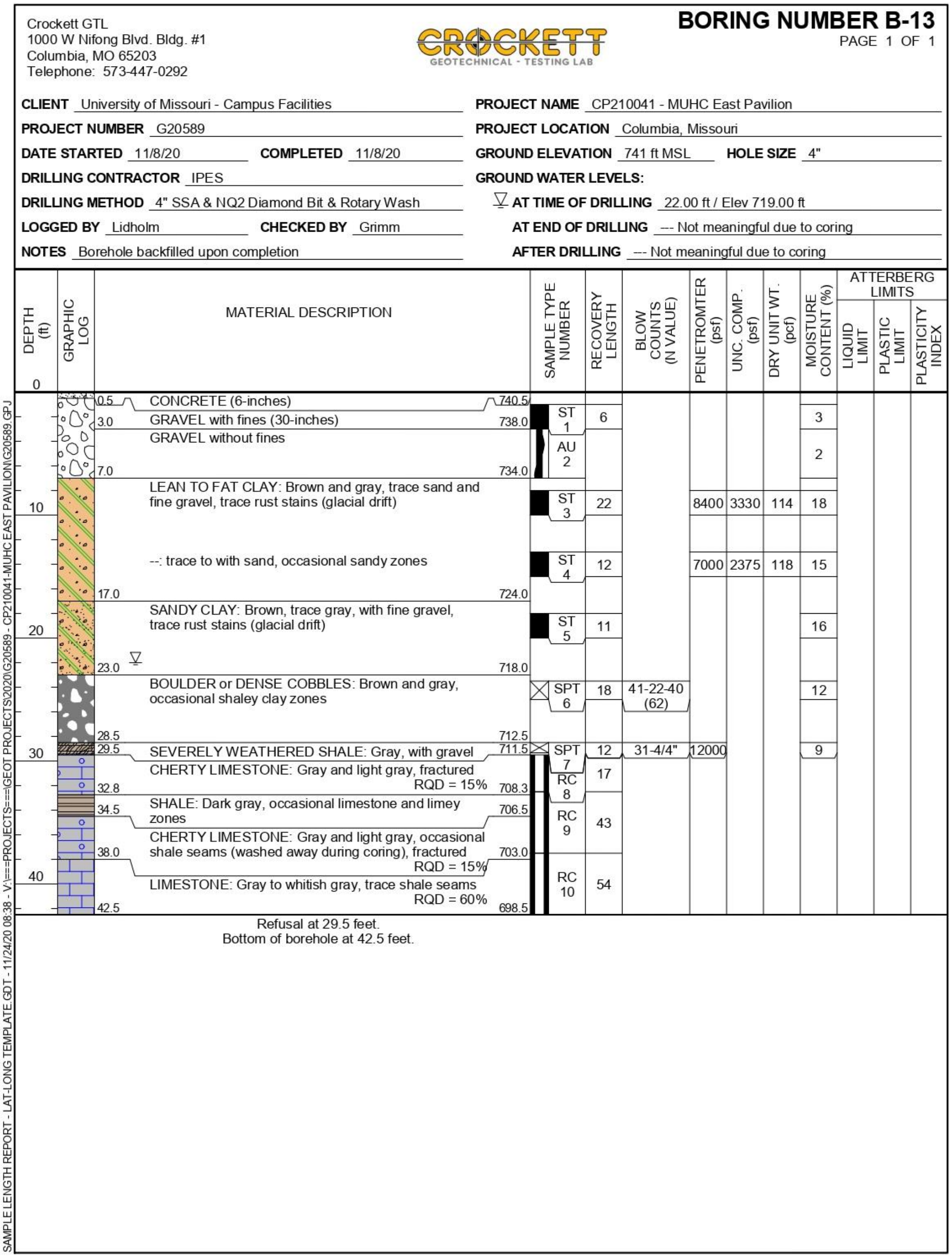
CLIENT University of Missouri - Campus Facilities
PROJECT NAME CP210041 - MUHC East Pavilion
PROJECT NUMBER G20589
PROJECT LOCATION Columbia, Missouri
DATE STARTED 11/2/20 **COMPLETED** 11/2/20
GROUND ELEVATION 742 ft MSL **HOLE SIZE** 4"
DRILLING CONTRACTOR IPES
GROUND WATER LEVELS:
DRILLING METHOD 4" SSA & NQ2 Diamond Bit & Rotary Wash
AT TIME OF DRILLING --- Not Encountered
LOGGED BY Lidholm **CHECKED BY** Grimm
AT END OF DRILLING --- Not meaningful due to coring
NOTES Borehole backfilled upon completion
AFTER DRILLING --- Not meaningful due to coring

DEPTH (ft)	GRAPHIC LOG	MATERIAL DESCRIPTION	Elev.	SAMPLE TYPE NUMBER	RECOVERY LENGTH	BLOW COUNTS (N VALUE)	PENETROMTER (psf)	UNC. COMP. (psf)	DRY UNIT WT. (pcf)	MOISTURE CONTENT (%)	ATTERBERG LIMITS: LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX
0													
0.5		TOPSOIL (6-inches)	741.5										
2.0		UNDOCUMENTED FILL: Gravelly clay fill, gray, with root hairs	740.0	ST 1	24		9000		117	11			
		UNDOCUMENTED FILL: Clay, brown		ST 2	15		7500		114	12			
8.0			734.0										
10		LEAN TO FAT CLAY: Brown and gray, trace sand and fine gravel, trace rust stains (glacial drift)		ST 3	17		8200	7620	112	19			
				ST 4	24		4000	2925	111	18			
20		--: with shaley zones, possible cobbles and boulders		SPT 5	13	5-28-23 (51)	10400			14			
23.0		BOULDER or DENSE COBBLES: some clayey zones	719.0	SPT 6	10	39-15-50/3"	5400			14			
27.5		LIMESTONE WITH SHALE: Gray and dark gray, occasional chert and shaley zones (shale washes away during coring)	714.5										
30		RQD = 0%		RC 7	8								
		RQD = 0%		RC 8	9								
36.5		LIMESTONE: Gray to whitish gray	705.5										
40		RQD = 77%		RC 9	57								
41.5			700.5										

Refusal at 27.5 feet.
Bottom of borehole at 41.5 feet.

SAMPLE LENGTH REPORT - LAT-LONG TEMPLATE.GDT - 11/24/20 08:38 - V:\==PROJECTS==\GEOT PROJECTS\2020\G20589 - CP210041-MUHC EAST PAVILION\G20589.GPJ

Figure 13: MUHC Borehole 12



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CROCKETT GEOTECHNICAL - TESTING LAB

BORING NUMBER B-13
PAGE 1 OF 1

CLIENT University of Missouri - Campus Facilities
PROJECT NAME CP210041 - MUHC East Pavilion
PROJECT NUMBER G20589
PROJECT LOCATION Columbia, Missouri
DATE STARTED 11/8/20 **COMPLETED** 11/8/20
GROUND ELEVATION 741 ft MSL **HOLE SIZE** 4"
DRILLING CONTRACTOR IPES
GROUND WATER LEVELS:
DRILLING METHOD 4" SSA & NQ2 Diamond Bit & Rotary Wash
∇ **AT TIME OF DRILLING** 22.00 ft / Elev 719.00 ft
LOGGED BY Lidholm **CHECKED BY** Grimm
AT END OF DRILLING --- Not meaningful due to coring
NOTES Borehole backfilled upon completion
AFTER DRILLING --- Not meaningful due to coring

Depth to bottom (ft)	MATERIAL DESCRIPTION	Elevation (ft)
0.5	CONCRETE (6-inches)	740.5
3.0	GRAVEL with fines (30-inches)	738.0
7.0	GRAVEL without fines	734.0
17.0	LEAN TO FAT CLAY: Brown and gray, trace sand and fine gravel, trace rust stains (glacial drift) --: trace to with sand, occasional sandy zones	724.0
23.0	SANDY CLAY: Brown, trace gray, with fine gravel, trace rust stains (glacial drift) ∇	718.0
28.5	BOULDER or DENSE COBBLES: Brown and gray, occasional shaley clay zones	712.5
29.5	SEVERELY WEATHERED SHALE: Gray, with gravel	711.5
32.8	CHERTY LIMESTONE: Gray and light gray, fractured RQD = 15%	708.3
34.5	SHALE: Dark gray, occasional limestone and limey zones	706.5
38.0	CHERTY LIMESTONE: Gray and light gray, occasional shale seams (washed away during coring), fractured RQD = 15%	703.0
42.5	LIMESTONE: Gray to whitish gray, trace shale seams RQD = 60%	698.5

Refusal at 29.5 feet.
Bottom of borehole at 42.5 feet.

SAMPLE TYPE NUMBER	RECOVERY LENGTH	BLOW COUNTS (N VALUE)	PENETROMTER (psf)	UNC. COMP. (psf)	DRY UNIT WT. (pcf)	MOISTURE CONTENT (%)	LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX
ST 1	6					3			
AU 2						2			
ST 3	22		8400	3330	114	18			
ST 4	12		7000	2375	118	15			
ST 5	11					16			
SPT 6	18	41-22-40 (62)				12			
SPT 7	12	31-4/4"	12000			9			
RC 8	17								
RC 9	43								
RC 10	54								

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Figure 14: MUHC Borehole 13

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BORING NUMBER B-14

PAGE 1 OF 1

CLIENT University of Missouri - Campus Facilities
PROJECT NAME CP210041 - MUHC East Pavilion
PROJECT NUMBER G20589
PROJECT LOCATION Columbia, Missouri
DATE STARTED 10/25/20 **COMPLETED** 10/25/20
GROUND ELEVATION 745 ft MSL **HOLE SIZE** 4"
DRILLING CONTRACTOR IPES
GROUND WATER LEVELS:
DRILLING METHOD 4" SSA
AT TIME OF DRILLING --- Not Encountered
LOGGED BY Lidholm **CHECKED BY** Grimm
AT END OF DRILLING --- Not Encountered
NOTES Borehole backfilled upon completion
0.25hrs AFTER DRILLING --- Not Encountered

DEPTH (ft)	MATERIAL DESCRIPTION	Elev.
0.8	CONCRETE (10-inches)	744.2
3.0	UNDOCUMENTED FILL: Lean to fat clay, brown and light brown, trace to with sand	742.0
7.0	LEAN TO FAT CLAY: Brown and gray, trace sand and fine gravel, trace rust stains (glacial drift)	738.0
13.0	SANDY CLAY: Brown, trace gray, trace fine gravel, trace rust stains (glacial drift)	732.0
20.0	CLAYEY SAND: Brown, trace gravel (glacial drift)	725.0

Bottom of borehole at 20.0 feet.

SAMPLE TYPE NUMBER	RECOVERY LENGTH	BLOW COUNTS (N VALUE)	PENETROMTER (psf)	UNC. COMP. (psf)	DRY UNIT WT. (pcf)	MOISTURE CONTENT (%)	ATTERBERG LIMITS: LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX
ST 1	21		4200		109	20			
ST 2	20		7400	2285	113	17			
ST 3	18		9000	8235	117	15			
ST 4	10					12			
ST 5	14					9			

Figure 15: MUHC Borehole 14

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BORING NUMBER B-15

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CLIENT University of Missouri - Campus Facilities
PROJECT NAME CP210041 - MUHC East Pavilion
PROJECT NUMBER G20589
PROJECT LOCATION Columbia, Missouri
DATE STARTED 11/7/20 **COMPLETED** 11/7/20
GROUND ELEVATION 745 ft MSL **HOLE SIZE** 4"
DRILLING CONTRACTOR IPES
GROUND WATER LEVELS:
DRILLING METHOD 4" SSA
AT TIME OF DRILLING --- Not Encountered
LOGGED BY Lidholm **CHECKED BY** Grimm
AT END OF DRILLING --- Not Encountered
NOTES Borehole backfilled upon completion
0.25hrs AFTER DRILLING --- Not Encountered

DEPTH (ft)	GRAPHIC LOG	MATERIAL DESCRIPTION	SAMPLE TYPE NUMBER	RECOVERY LENGTH	BLOW COUNTS (N VALUE)	PENETROMTER (psf)	UNC. COMP. (psf)	DRY UNIT WT. (pcf)	MOISTURE CONTENT (%)	ATTERBERG LIMITS: LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX
0		0.5 CONCRETE (6-inches) 744.5										
		0.8 GRAVEL (4-inches) 744.2	ST 1	15		4600	3390	110	19			
		LEAN TO FAT CLAY: Brown and gray, trace sand and fine gravel, trace rust stains (glacial drift)	ST 2	21		3500	2010	108	20			
10			ST 3	22		6000	1740	95	29			
		--: gray, trace to with sand	ST 4	24		5600	2945	116	17			
		18.0 727.0										
20		20.0 SANDY CLAY: Brown, trace gray, with fine gravel, trace rust stains (glacial drift) 725.0	ST 5	14		7600			12			

Bottom of borehole at 20.0 feet.

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Figure 16: MUHC Borehole 15

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BORING NUMBER B-16

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CLIENT University of Missouri - Campus Facilities
PROJECT NAME CP210041 - MUHC East Pavilion
PROJECT NUMBER G20589
PROJECT LOCATION Columbia, Missouri
DATE STARTED 10/27/20 **COMPLETED** 10/27/20
GROUND ELEVATION 743 ft MSL **HOLE SIZE** 4"
DRILLING CONTRACTOR IPES
GROUND WATER LEVELS:
DRILLING METHOD 4" SSA
▽ **AT TIME OF DRILLING** 18.00 ft / Elev 725.00 ft
LOGGED BY Lidholm **CHECKED BY** Grimm
▼ **AT END OF DRILLING** 18.00 ft / Elev 725.00 ft
NOTES Borehole backfilled upon completion
▼ **0.25hrs AFTER DRILLING** 18.00 ft / Elev 725.00 ft

DEPTH (ft)	GRAPHIC LOG	MATERIAL DESCRIPTION		SAMPLE TYPE NUMBER	RECOVERY LENGTH	BLOW COUNTS (N VALUE)	PENETROMTER (psf)	UNC. COMP. (psf)	DRY UNIT WT. (pcf)	MOISTURE CONTENT (%)	ATTERBERG LIMITS: LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX
0	0.5	TOPSOIL (6-inches)	742.5										
	3.0	UNDOCUMENTED FILL: Lean to fat clay, dark brown anad brown, with gravel to gravelly	740.0	ST 1	12		9000			17			
		LEAN TO FAT CLAY: Brown and gray, trace sand and fine gravel, trace rust stains (glacial drift)		ST 2	17		5000	4165	105	23			
10				ST 3	24		6000	6100	117	17			
				ST 4	24		5600	3215	110	19			
20	20.0	--: becomes gravelly	723.0	SPT 5	13	9-10-11 (21)	6500			14			

Bottom of borehole at 20.0 feet.

SAMPLE LENGTH REPORT - LAT-LONG TEMPLATE.GDT - 11/24/20 08:38 - V:\==PROJECTS==\GEOT PROJECTS\2020\G20589 - CP210041-MUHC EAST PAVILION\G20589.GPJ

Figure 17: MUHC Borehole 16

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BORING NUMBER B-18

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CLIENT University of Missouri - Campus Facilities
PROJECT NAME CP210041 - MUHC East Pavilion
PROJECT NUMBER G20589
PROJECT LOCATION Columbia, Missouri
DATE STARTED 10/28/20 **COMPLETED** 10/28/20
GROUND ELEVATION 732.5 ft MSL **HOLE SIZE** 4"
DRILLING CONTRACTOR IPES
GROUND WATER LEVELS:
DRILLING METHOD 4" SSA
AT TIME OF DRILLING --- Not Encountered
LOGGED BY Lidholm **CHECKED BY** Grimm
AT END OF DRILLING --- Not Encountered
NOTES Borehole backfilled upon completion
0.25hrs AFTER DRILLING --- Not Encountered

DEPTH (ft)	MATERIAL DESCRIPTION	Elev.	SAMPLE TYPE NUMBER	RECOVERY LENGTH	BLOW COUNTS (N VALUE)	PENETROMTER (psf)	UNC. COMP. (psf)	DRY UNIT WT. (pcf)	MOISTURE CONTENT (%)	ATTERBERG LIMITS LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX
0												
0.5	TOPSOIL (6-inches)	732.0										
3.0	UNDOCUMENTED FILL: Fat clay, dark brown and brown	729.5	ST 1	15		3400		100	27			
	LEAN TO FAT CLAY: Brown and gray, trace sand and fine gravel, trace rust stains (glacial drift)		ST 2	19		6600	2790	109	21			
10			ST 3	15		4800	2740	105	23			
13.5		719.0										
15.0	SHALEY FAT CLAY: Tan and gray	717.5	SPT 4	15	5-7-10 (17)	11600			22			

Bottom of borehole at 15.0 feet.

SAMPLE LENGTH REPORT - LAT-LONG TEMPLATE.GDT - 11/24/20 08:38 - V:\==PROJECTS==\GEOT PROJECTS\2020\G20589 - CP210041-MUHC EAST PAVILION\G20589.GPJ

Figure 18: MUHC Borehole 18

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BORING NUMBER B-19
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CLIENT University of Missouri - Campus Facilities
PROJECT NAME CP210041 - MUHC East Pavilion
PROJECT NUMBER G20589
PROJECT LOCATION Columbia, Missouri
DATE STARTED 10/28/20 **COMPLETED** 10/28/20
GROUND ELEVATION 731 ft MSL **HOLE SIZE** 4"
DRILLING CONTRACTOR IPES
GROUND WATER LEVELS:
DRILLING METHOD 4" SSA
AT TIME OF DRILLING --- Not Encountered
LOGGED BY Lidholm **CHECKED BY** Grimm
AT END OF DRILLING --- Not Encountered
NOTES Borehole backfilled upon completion
0.25hrs AFTER DRILLING --- Not Encountered

DEPTH (ft)	MATERIAL DESCRIPTION	Elev.	SAMPLE TYPE NUMBER	RECOVERY LENGTH	BLOW COUNTS (N VALUE)	PENETROMTER (psf)	UNC. COMP. (psf)	DRY UNIT WT. (pcf)	MOISTURE CONTENT (%)	ATTERBERG LIMITS: LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX
0.5	TOPSOIL (6-inches)	730.5										
3.0	UNDOCUMENTED FILL: Lean to fat clay, dark brown and brown, with sand and gravel	728.0	ST 1	15		6600		112	16			
6.0	LEAN TO FAT CLAY: Brown (possible undocumented fill)	725.0	ST 2	16		4200	2115	96	24			
10	LEAN TO FAT CLAY: Brown and gray, trace sand and fine gravel, trace rust stains (glacial drift)		ST 3	24		7000	2195	108	21			
15.0	--: becomes gravelly, with sand	716.0	SPT 4	11	4-4-9 (13)	4000			17			

Bottom of borehole at 15.0 feet.

SAMPLE LENGTH REPORT - LAT-LONG TEMPLATE.GDT - 11/24/20 08:38 - V:\==PROJECTS==\GEOT PROJECTS\2020\G20589 - CP210041-MUHC EAST PAVILION\G20589.GPJ

Figure 19: MUHC Borehole 19

APPENDIX A-8

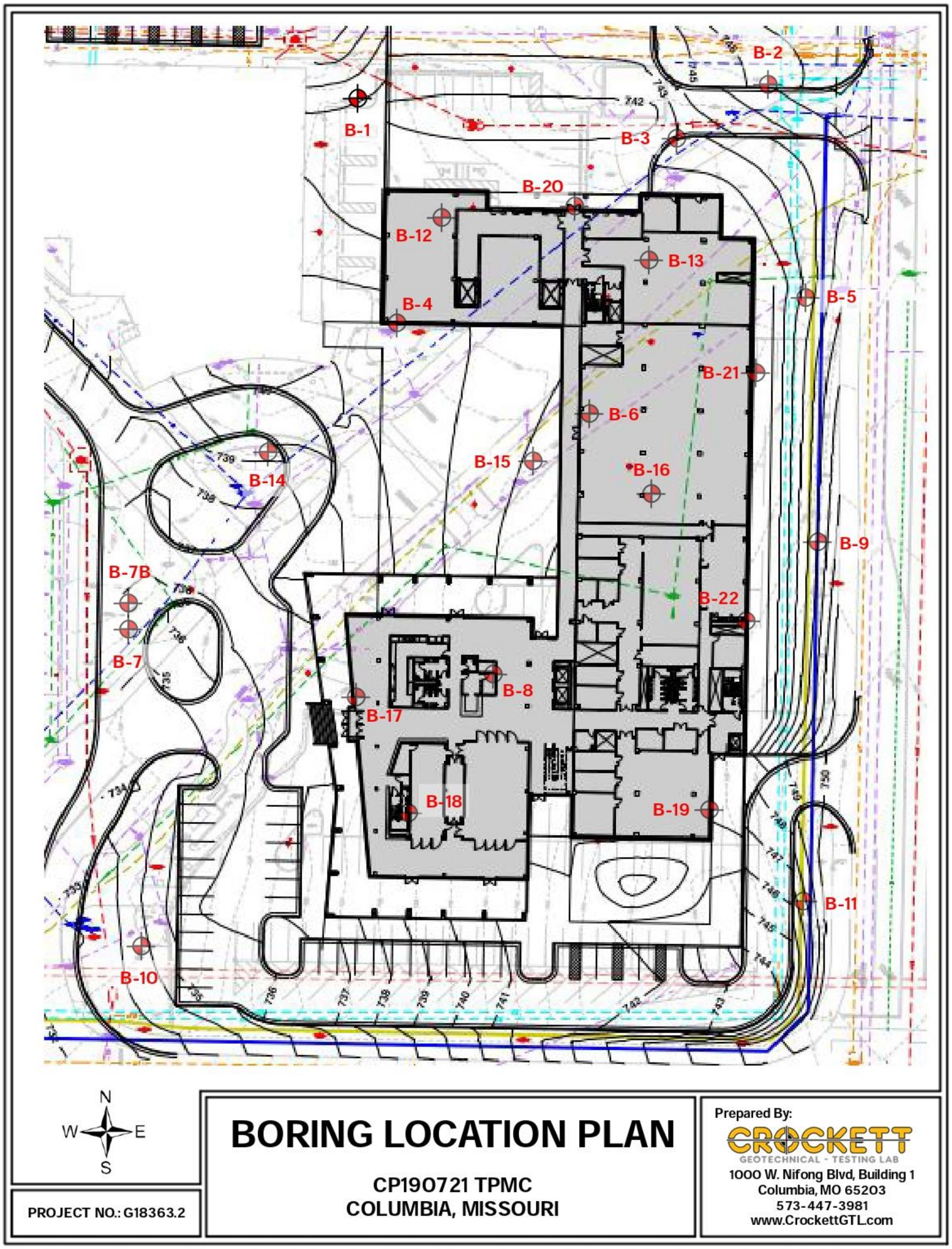

Figure 1: Roy Blunt NextGen Precision Health Building (NextGen) boring plan (Aerial View), prepared by Crockett

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CROCKETT GEOTECHNICAL - TESTING LAB

BORING NUMBER B-5

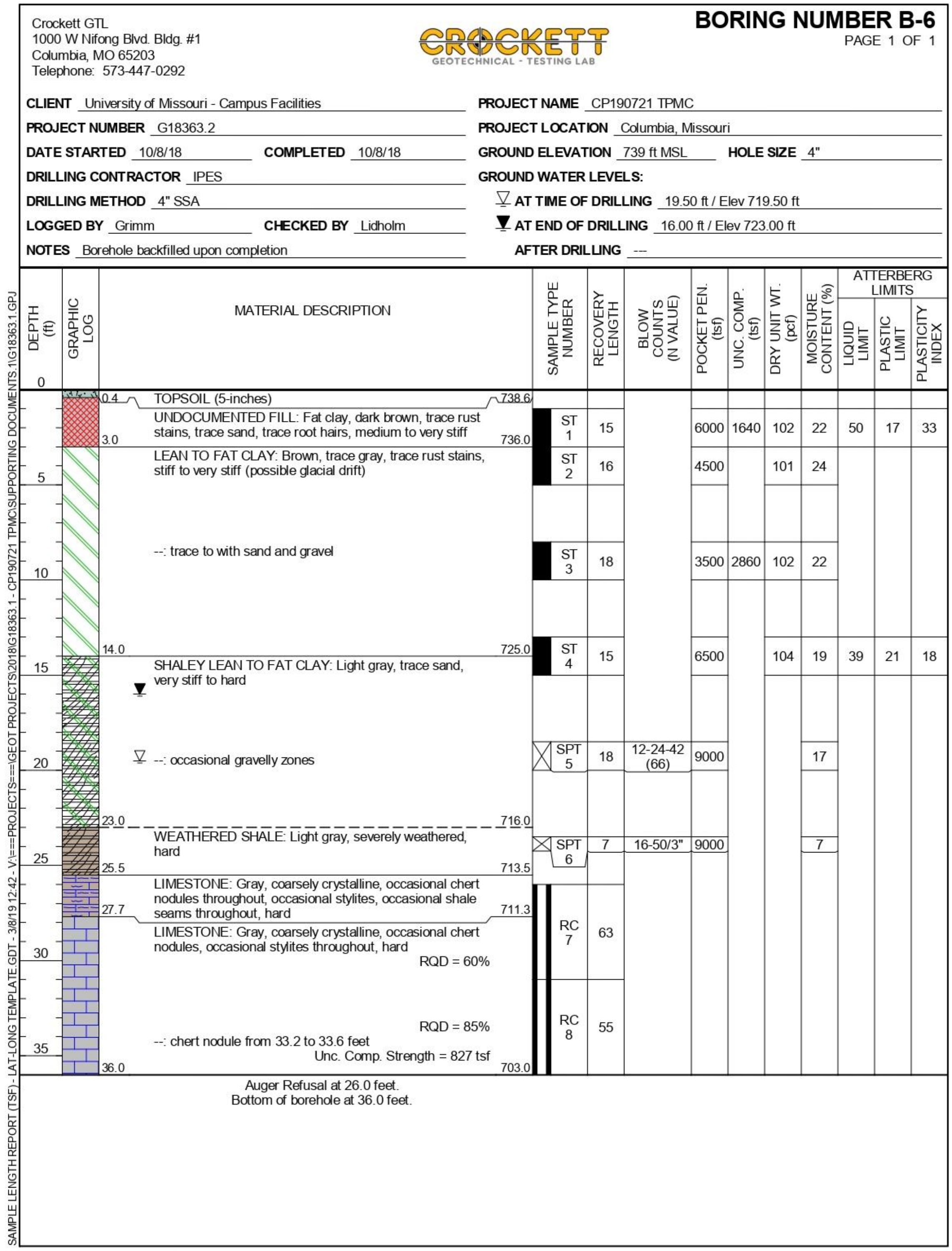
PAGE 1 OF 1

CLIENT University of Missouri - Campus Facilities
PROJECT NAME CP190721 TPMC
PROJECT NUMBER G18363.2
PROJECT LOCATION Columbia, Missouri
DATE STARTED 10/8/18 **COMPLETED** 10/8/18
GROUND ELEVATION 745 ft MSL **HOLE SIZE** 4"
DRILLING CONTRACTOR IPES
GROUND WATER LEVELS:
DRILLING METHOD 4" SSA
∇ **AT TIME OF DRILLING** 16.00 ft / Elev 729.00 ft
LOGGED BY Grimm **CHECKED BY** Lidholm
▼ **AT END OF DRILLING** 18.00 ft / Elev 727.00 ft
NOTES Borehole backfilled upon completion
▼ **0.25hrs AFTER DRILLING** 18.00 ft / Elev 727.00 ft

DEPTH (ft)	MATERIAL DESCRIPTION	Elev.	SAMPLE TYPE NUMBER	RECOVERY LENGTH	BLOW COUNTS (N VALUE)	POCKET PEN. (tsf)	UNC. COMP. (tsf)	DRY UNIT WT. (pcf)	MOISTURE CONTENT (%)	ATTERBERG LIMITS: LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX
0.3	TOPSOIL (4-inches)	744.7										
3.0	UNDOCUMENTED FILL: Gravelly lean to fat clay, brown, trace rust stains, trace sand, trace root hairs, hard	742.0	ST 1	14		9000			15			
	LEAN TO FAT CLAY: Light brown, trace gray, trace rust stains, trace sand and gravel, soft to hard (glacial drift)		ST 2	15		9000		115	14			
	--: silty zones, dark gray and brown		ST 3	18		4000	930	100	22			
			ST 4	24		8000	3580	112	17	42	14	28
17.0	∇ ▼ SHALEY LEAN CLAY: Light brown and gray, trace rust stains, trace sand, occasional gravelly zones, very soft to hard	728.0	SPT 5	10	12-28-50/5"	500			23	34	18	16
23.5	WEATHERED SHALE: Gray, moderately to severely weathered, hard	721.5	SPT 6	10	6-13-18 (31)	9000			17			
			SPT 7	8	27-50/3"	9000			18			
34.2		710.8	SPT 8	12	23-50/2"	9000			9			

Bottom of borehole at 34.2 feet.

Figure 2: NextGen Borehole 5



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BORING NUMBER B-6
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CLIENT University of Missouri - Campus Facilities
PROJECT NAME CP190721 TPMC
PROJECT NUMBER G18363.2
PROJECT LOCATION Columbia, Missouri
DATE STARTED 10/8/18 **COMPLETED** 10/8/18
GROUND ELEVATION 739 ft MSL **HOLE SIZE** 4"
DRILLING CONTRACTOR IPES
GROUND WATER LEVELS:
DRILLING METHOD 4" SSA
▽ **AT TIME OF DRILLING** 19.50 ft / Elev 719.50 ft
LOGGED BY Grimm **CHECKED BY** Lidholm
▼ **AT END OF DRILLING** 16.00 ft / Elev 723.00 ft
NOTES Borehole backfilled upon completion
AFTER DRILLING ---

DEPTH (ft)	MATERIAL DESCRIPTION	Elev.
0.4	TOPSOIL (5-inches)	738.6
3.0	UNDOCUMENTED FILL: Fat clay, dark brown, trace rust stains, trace sand, trace root hairs, medium to very stiff	736.0
14.0	LEAN TO FAT CLAY: Brown, trace gray, trace rust stains, stiff to very stiff (possible glacial drift) --: trace to with sand and gravel	725.0
23.0	SHALEY LEAN TO FAT CLAY: Light gray, trace sand, very stiff to hard ▼ ▽ --: occasional gravelly zones	716.0
25.5	WEATHERED SHALE: Light gray, severely weathered, hard	713.5
27.7	LIMESTONE: Gray, coarsely crystalline, occasional chert nodules throughout, occasional stylites, occasional shale seams throughout, hard	711.3
36.0	LIMESTONE: Gray, coarsely crystalline, occasional chert nodules, occasional stylites throughout, hard RQD = 60% RQD = 85% --: chert nodule from 33.2 to 33.6 feet Unc. Comp. Strength = 827 tsf	703.0

SAMPLE TYPE NUMBER	RECOVERY LENGTH	BLOW COUNTS (N VALUE)	POCKET PEN. (tsf)	UNC. COMP. (tsf)	DRY UNIT WT. (pcf)	MOISTURE CONTENT (%)	ATTERBERG LIMITS: LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX
ST 1	15		6000	1640	102	22	50	17	33
ST 2	16		4500		101	24			
ST 3	18		3500	2860	102	22			
ST 4	15		6500		104	19	39	21	18
SPT 5	18	12-24-42 (66)	9000			17			
SPT 6	7	16-50/3"	9000			7			
RC 7	63								
RC 8	55								

Auger Refusal at 26.0 feet.
Bottom of borehole at 36.0 feet.

SAMPLE LENGTH REPORT (TSF) - LAT-LONG TEMPLATE.GDT - 3/8/19 12:42 - V:\==PROJECTS==\GEOT PROJECTS\2018\G18363.1 - CP190721 TPMC\SUPPORTING DOCUMENTS.1\G18363.1.GPJ

Figure 3: NextGen Borehole 6

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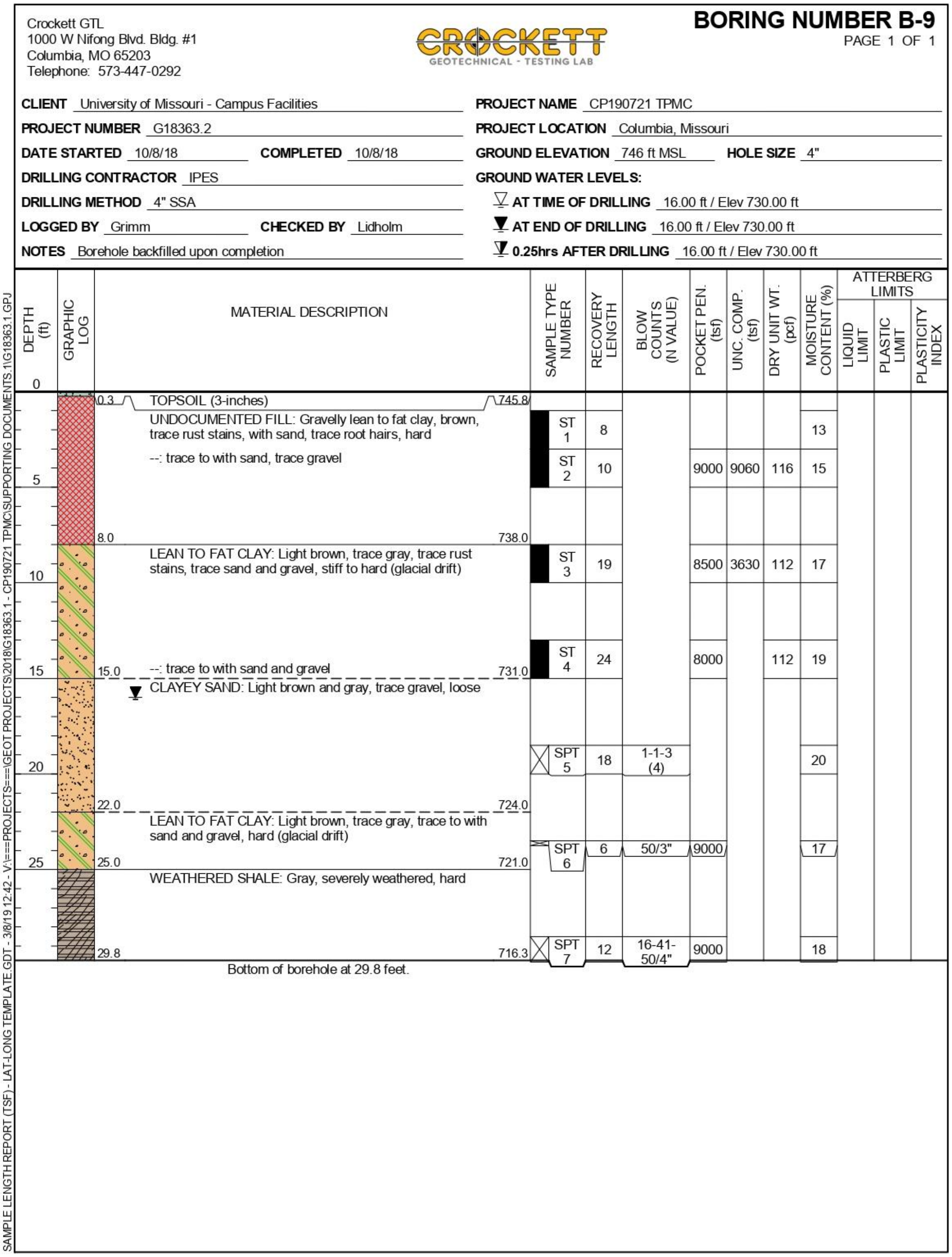
BORING NUMBER B-8

CLIENT University of Missouri - Campus Facilities
PROJECT NAME CP190721 TPMC
PROJECT NUMBER G18363.2
PROJECT LOCATION Columbia, Missouri
DATE STARTED 10/13/18 **COMPLETED** 10/13/18
GROUND ELEVATION 739 ft MSL **HOLE SIZE** 4"
DRILLING CONTRACTOR IPES
GROUND WATER LEVELS:
DRILLING METHOD 4" SSA
▽ **AT TIME OF DRILLING** 7.00 ft / Elev 732.00 ft
LOGGED BY Grimm **CHECKED BY** Lidholm
AT END OF DRILLING --- Not Encountered
NOTES Borehole backfilled upon completion
0.25hrs AFTER DRILLING --- Not Encountered

DEPTH (ft)	MATERIAL DESCRIPTION	Elev.	SAMPLE TYPE NUMBER	RECOVERY LENGTH	BLOW COUNTS (N VALUE)	POCKET PEN. (tsf)	UNC. COMP. (tsf)	DRY UNIT WT. (pcf)	MOISTURE CONTENT (%)	ATTERBERG LIMITS: LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX
0.3	ASPHALT (3-inches)	738.8										
0.4	BASE ROCK (2-inches)	738.6	ST 1	15		4000			17			
3.0	UNDOCUMENTED FILL: Lean to fat clay, brown and gray, trace rust stains, trace sand, with gravel to gravelly, stiff	736.0										
	FAT CLAY: Gray and brown, trace rust stains, trace sand and gravel, stiff (possible glacial drift)		ST 2	20		4000	3700	101	26			
7.0 ▽	LEAN TO FAT CLAY: Brown, trace gray, trace rust stains, trace sand and gravel, very stiff (glacial drift)	732.0	ST 3	20		7500		112	19			
	--: occasional sandy and gravelly zones		ST 4	17		5000			19			
16.5	LIMESTONE: Hard	722.5										
17.0		722.0										

Auger Refusal at 17.0 feet.
Bottom of borehole at 17.0 feet.

Figure 4: NextGen Borehole 8



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BORING NUMBER B-9
PAGE 1 OF 1

CLIENT University of Missouri - Campus Facilities
PROJECT NAME CP190721 TPMC
PROJECT NUMBER G18363.2
PROJECT LOCATION Columbia, Missouri
DATE STARTED 10/8/18 **COMPLETED** 10/8/18
GROUND ELEVATION 746 ft MSL **HOLE SIZE** 4"
DRILLING CONTRACTOR IPES
GROUND WATER LEVELS:
DRILLING METHOD 4" SSA
AT TIME OF DRILLING 16.00 ft / Elev 730.00 ft
LOGGED BY Grimm **CHECKED BY** Lidholm
AT END OF DRILLING 16.00 ft / Elev 730.00 ft
NOTES Borehole backfilled upon completion
0.25hrs AFTER DRILLING 16.00 ft / Elev 730.00 ft

Depth (ft)	Material Description	Elev. (ft)
0.3	TOPSOIL (3-inches)	745.8
8.0	UNDOCUMENTED FILL: Gravelly lean to fat clay, brown, trace rust stains, with sand, trace root hairs, hard --: trace to with sand, trace gravel	738.0
15.0	LEAN TO FAT CLAY: Light brown, trace gray, trace rust stains, trace sand and gravel, stiff to hard (glacial drift) --: trace to with sand and gravel	731.0
22.0	CLAYEY SAND: Light brown and gray, trace gravel, loose	724.0
25.0	LEAN TO FAT CLAY: Light brown, trace gray, trace to with sand and gravel, hard (glacial drift)	721.0
29.8	WEATHERED SHALE: Gray, severely weathered, hard	716.3

Bottom of borehole at 29.8 feet.

Sample Type Number	Recovery Length	Blow Counts (N Value)	Pocket Pen. (tsf)	Unc. Comp. (tsf)	Dry Unit Wt. (pcf)	Moisture Content (%)	Liquid Limit	Plastic Limit	Plasticity Index
ST 1	8					13			
ST 2	10		9000	9060	116	15			
ST 3	19		8500	3630	112	17			
ST 4	24		8000		112	19			
SPT 5	18	1-1-3 (4)				20			
SPT 6	6	50/3"	9000			17			
SPT 7	12	16-41-50/4"	9000			18			

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Figure 5: NextGen Borehole 9

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CROCKETT GEOTECHNICAL - TESTING LAB

BORING NUMBER B-11
PAGE 1 OF 1

CLIENT University of Missouri - Campus Facilities
PROJECT NAME CP190721 TPMC
PROJECT NUMBER G18363.2
PROJECT LOCATION Columbia, Missouri
DATE STARTED 10/9/18 **COMPLETED** 10/9/18
GROUND ELEVATION 750 ft MSL **HOLE SIZE** 4"
DRILLING CONTRACTOR IPES
GROUND WATER LEVELS:
DRILLING METHOD 4" SSA
▽ **AT TIME OF DRILLING** 17.00 ft / Elev 733.00 ft
LOGGED BY Grimm **CHECKED BY** Lidholm
▼ **AT END OF DRILLING** 30.00 ft / Elev 720.00 ft
NOTES Borehole backfilled upon completion
▼ **0.25hrs AFTER DRILLING** 30.00 ft / Elev 720.00 ft

DEPTH (ft)	MATERIAL DESCRIPTION	ELEV.	SAMPLE TYPE NUMBER	RECOVERY LENGTH	BLOW COUNTS (N VALUE)	POCKET PEN. (tsf)	UNC. COMP. (tsf)	DRY UNIT WT. (pcf)	MOISTURE CONTENT (%)	ATTERBERG LIMITS: LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX
0.3	TOPSOIL (4-inches)	749.7										
	UNDOCUMENTED FILL: Gravelly lean to fat clay, brown, trace gray, trace rust stains, trace to with sand, trace root hairs, very stiff to hard		ST 1	13		6000			14			
			ST 2	10		9000			7			
6.0	LEAN TO FAT CLAY: Light brown with gray, trace rust stains, trace to with sand and gravel, very stiff (glacial drift)	744.0										
			ST 3	15		7500	4320	106	22	43	17	26
13.0	SAND: Light brown, occasional clayey zones, loose	737.0	SPT 4	13	4-5-3 (8)				6			
18.0	LEAN CLAY: Light brown with gray, trace rust stains, with sand and gravel, very stiff to hard (glacial drift)	732.0	SPT 5	13	4-4-5 (9)	9000			18			
			SPT 6	16	3-6-6 (12)	8000			16	29	15	14
26.0	CLAYEY SHALE: Gray, moderately to severely weathered, hard	724.0	SPT 7	12	12-23-41 (64)	9000			12			
			SPT 8	13	22-30-50/3"	9000			16			
37.0	WEATHERED SHALE: Gray, moderately weathered, hard	713.0										
39.2		710.8	SPT 9	7	42-50/2"	9000			14			

Bottom of borehole at 39.2 feet.

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Figure 6: NextGen Borehole 11

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BORING NUMBER B-14

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CLIENT University of Missouri - Campus Facilities
PROJECT NAME CP190721 TPMC
PROJECT NUMBER G18363.2
PROJECT LOCATION Columbia, Missouri
DATE STARTED 1/21/19 **COMPLETED** 1/21/19
GROUND ELEVATION 737 ft MSL **HOLE SIZE** 4"
DRILLING CONTRACTOR IPES
GROUND WATER LEVELS:
DRILLING METHOD 4" SSA
AT TIME OF DRILLING --- Not Encountered
LOGGED BY Grimm **CHECKED BY** Lidholm
AT END OF DRILLING --- Not Encountered
NOTES Borehole backfilled upon completion
0.25hrs AFTER DRILLING --- Not Encountered

DEPTH (ft)	MATERIAL DESCRIPTION	Elev.
0.4	TOPSOIL (5-inches)	736.6
8.0	UNDOCUMENTED FILL: Brown and light brown, trace to with rust stains, trace sand, with gravel, stiff to very stiff	729.0
12.0	LEAN TO FAT CLAY: Brown and gray, trace rust stains, trace sand and gravel, very stiff (possible glacial drift)	725.0
16.0	CLAYEY GRAVEL: light brown, possible cobbles and boulders, dense	721.0
20.5	GRAVELLY WEATHERED SHALE: Light gray, moderately to severely weathered, possible cobbles and boulders, hard	716.5
21.0	LIMESTONE: Hard	716.0

Auger Refusal at 21.0 feet.
Bottom of borehole at 21.0 feet.

SAMPLE TYPE NUMBER	RECOVERY LENGTH	BLOW COUNTS (N VALUE)	POCKET PEN. (tsf)	UNC. COMP. (tsf)	DRY UNIT WT. (pcf)	MOISTURE CONTENT (%)	ATTERBERG LIMITS: LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX
ST 1	16				112	15			
ST 2	12		6500	3520	112	16			
ST 3	15		5500	5250	105	24			
SPT 4	11	16-18-16 (34)				10			
SPT 5	11	25-37-34 (71)	9000			10			

SAMPLE LENGTH REPORT (TSF) - LAT-LONG TEMPLATE.GDT - 3/8/19 12:42 - V:\==PROJECTS==\GEOT PROJECTS\2018\G18363.1 - CP190721 TPMC\SUPPORTING DOCUMENTS.1\G18363.1.GPJ

Figure 7: NextGen Borehole 14

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CROCKETT GEOTECHNICAL - TESTING LAB

BORING NUMBER B-15

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CLIENT University of Missouri - Campus Facilities
PROJECT NAME CP190721 TPMC
PROJECT NUMBER G18363.2
PROJECT LOCATION Columbia, Missouri
DATE STARTED 1/21/19 **COMPLETED** 1/21/19
GROUND ELEVATION 738 ft MSL **HOLE SIZE** 4"
DRILLING CONTRACTOR IPES
GROUND WATER LEVELS:
DRILLING METHOD 4" SSA
AT TIME OF DRILLING --- Not Encountered
LOGGED BY Grimm **CHECKED BY** Lidholm
AT END OF DRILLING --- Not Encountered
NOTES Borehole backfilled upon completion
0.25hrs AFTER DRILLING --- Not Encountered

DEPTH (ft)	MATERIAL DESCRIPTION	Elev.	SAMPLE TYPE NUMBER	RECOVERY LENGTH	BLOW COUNTS (N VALUE)	POCKET PEN. (tsf)	UNC. COMP. (tsf)	DRY UNIT WT. (pcf)	MOISTURE CONTENT (%)	ATTERBERG LIMITS: LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX
0.5	TOPSOIL (6-inches)	737.5										
3.0	UNDOCUMENTED FILL: Lean to fat clay, brown and light brown, trace sand and gravel, trace to with roots and root hairs, medium	735.0	ST 1	15		1500		100	23			
4.4	UNDOCUMENTED FILL: Sand, brown, trace to with roots and debris	733.6	ST 2A	16					17			
8.0	LEAN TO FAT CLAY: Brown and light brown, trace rust stains, trace sand and gravel, stiff to very stiff (possible glacial drift)	730.0	ST 2B	8		5000	2260	101	24			
13.0	LEAN TO FAT CLAY: Light brown and gray, with rust stains, trace to with sand and gravel, stiff to very stiff (glacial drift)	725.0	ST 3	17		6000	3930	104	23			
18.0	SHALEY LEAN CLAY: Light gray, trace brown, trace sand and gravel, very stiff to hard	720.0	ST 4	14		9000	6580	117	17	36	18	18
22.5	WEATHERED SHALE: Light gray, trace to with gravel, possible cobbles and boulders, hard	715.5	SPT 5	16	11-16-16 (32)	9000			12			
23.0	LIMESTONE: Hard	715.0										

Auger Refusal at 23.0 feet.
Bottom of borehole at 23.0 feet.

SAMPLE LENGTH REPORT (TSF) - LAT-LONG TEMPLATE.GDT - 3/8/19 12:42 - V:\==PROJECTS==\GEOT PROJECTS\2018\G18363.1 - CP190721 TPMC\SUPPORTING DOCUMENTS.1\G18363.1.GPJ

Figure 8: NextGen Borehole 15

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CROCKETT GEOTECHNICAL - TESTING LAB

BORING NUMBER B-16

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CLIENT University of Missouri - Campus Facilities
PROJECT NAME CP190721 TPMC
PROJECT NUMBER G18363.2
PROJECT LOCATION Columbia, Missouri
DATE STARTED 1/22/19 **COMPLETED** 1/22/19
GROUND ELEVATION 741 ft MSL **HOLE SIZE** 4"
DRILLING CONTRACTOR IPES
GROUND WATER LEVELS:
DRILLING METHOD 4" SSA
▽ **AT TIME OF DRILLING** 17.00 ft / Elev 724.00 ft
LOGGED BY Grimm **CHECKED BY** Lidholm
▼ **AT END OF DRILLING** 18.00 ft / Elev 723.00 ft
NOTES Borehole backfilled upon completion
▼ **0.25hrs AFTER DRILLING** 18.00 ft / Elev 723.00 ft

DEPTH (ft)	MATERIAL DESCRIPTION	Elev.	SAMPLE TYPE NUMBER	RECOVERY LENGTH	BLOW COUNTS (N VALUE)	POCKET PEN. (tsf)	UNC. COMP. (tsf)	DRY UNIT WT. (pcf)	MOISTURE CONTENT (%)	ATTERBERG LIMITS: LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX
0.5	ASPHALT (6-inches)	740.5										
1.5	BASE ROCK (12-inches)	739.5										
3.3	UNDOCUMENTED FILL: Lean to fat clay, gray and brown, trace rust stains, trace to with gravel, very stiff	737.8	SPT 1	15	4-3-6 (9)	7000			19			
	LEAN TO FAT CLAY: Gray, trace brown, trace rust stains, trace sand and gravel, stiff to very stiff (glacial drift)		ST 2	12		6000	7060	108	18			
9.4	--: with sand, occasional sandy zones, trace to with gravel	731.6	ST 3A	16		4500	2410	112	16			
	CLAYEY SAND: Gray and brown, trace gravel, hard (glacial drift)		ST 3B	8		9000			13			
12.0		729.0										
	SANDY LEAN TO FAT CLAY: Light brown and gray, trace rust stains, trace to with gravel, stiff (glacial drift)		ST 4	13		4000	2350	110	19			
	--: gravelly, very loose		SPT 5	12	4-1-1 (2)				22			
21.0		720.0										
	GRAVELLY WEATHERED SHALE: Light gray and light brown, occasional clayey zones, possible cobbles and boulders, hard, dense		SPT 6	14	11-25-34 (59)	9000			15			
	--: very dense		SPT 7	4	50/4"	9000			13			
32.5		708.5										
33.0	LIMESTONE: Hard	708.0										

Auger Refusal at 33.0 feet.
Bottom of borehole at 33.0 feet.

Figure 9: NextGen Borehole 16

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BORING NUMBER B-17
PAGE 1 OF 1

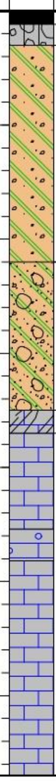
CLIENT University of Missouri - Campus Facilities
PROJECT NAME CP190721 TPMC
PROJECT NUMBER G18363.2
PROJECT LOCATION Columbia, Missouri
DATE STARTED 1/19/19 **COMPLETED** 1/19/19
GROUND ELEVATION 736 ft MSL **HOLE SIZE** 4"
DRILLING CONTRACTOR IPES
GROUND WATER LEVELS:
DRILLING METHOD 4" SSA
AT TIME OF DRILLING --- Not Encountered
LOGGED BY Grimm **CHECKED BY** Lidholm
AT END OF DRILLING --- Not Encountered
NOTES Borehole backfilled upon completion
AFTER DRILLING ---

DEPTH (ft)	MATERIAL DESCRIPTION	ELEV.	SAMPLE TYPE NUMBER	RECOVERY LENGTH	BLOW COUNTS (N VALUE)	POCKET PEN. (tsf)	UNC. COMP. (tsf)	DRY UNIT WT. (pcf)	MOISTURE CONTENT (%)	ATTERBERG LIMITS: LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX
0.5	TOPSOIL (6-inches)	735.5										
	LEAN TO FAT CLAY: Brown, trace rust stains, trace gravel, trace to with roots and root hairs, stiff to very stiff (possible undocumented fill)		SPT 1	13	2-3-4 (7)	4500			18			
5			SPT 2	12	4-4-5 (9)	2500			22			
8.0	LEAN TO FAT CLAY: Brown and gray, trace rust stains, trace to with sand, trace gravel, stiff (possible glacial drift)	728.0	SPT 3	18	4-4-4 (8)	3500			18			
11.5	GRAVELLY LEAN TO FAT CLAY: Brown, with rust stains, with sand, possible cobbles and boulders, dense (glacial drift)	724.5	SPT 4	16	12-14-17 (31)				17			
17.0	WEATHERED LIMESTONE: Light gray, severely weathered, hard	719.0										
18.5	LIMESTONE: Gray, fossiliferous, coarsely crystalline, occasional chert nodules, occasional stylolites throughout	717.5	SPT 5	1	50/1"				3			
20	--: shale seam from 21' to 21.1' RQD = 68% --: occasional chert nodules from 21.7' to 24' Unc. Comp. Strength = 781 tsf		RC 6	54.5								
24.5	--: shale seam from 24.5' to 25' RQD = 65%	711.5	RC 7	55								
30	--: shale seam from 30.5' to 30.7' Unc. Comp. Strength = 1065 tsf RQD = 80%		RC 8	60								
33.5		702.5										

Split Spoon Sampler Refusal at 18.6 feet.
Bottom of borehole at 33.5 feet.

SAMPLE LENGTH REPORT (TSF) - LAT-LONG TEMPLATE.GDT - 3/8/19 12:42 - V:\==PROJECTS==\GEOT PROJECTS\2018\G18363.1 - CP190721 TPMC\SUPPORTING DOCUMENTS.1\G18363.1.GPJ

Figure 10: NextGen Borehole 17



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BORING NUMBER B-18
PAGE 1 OF 1

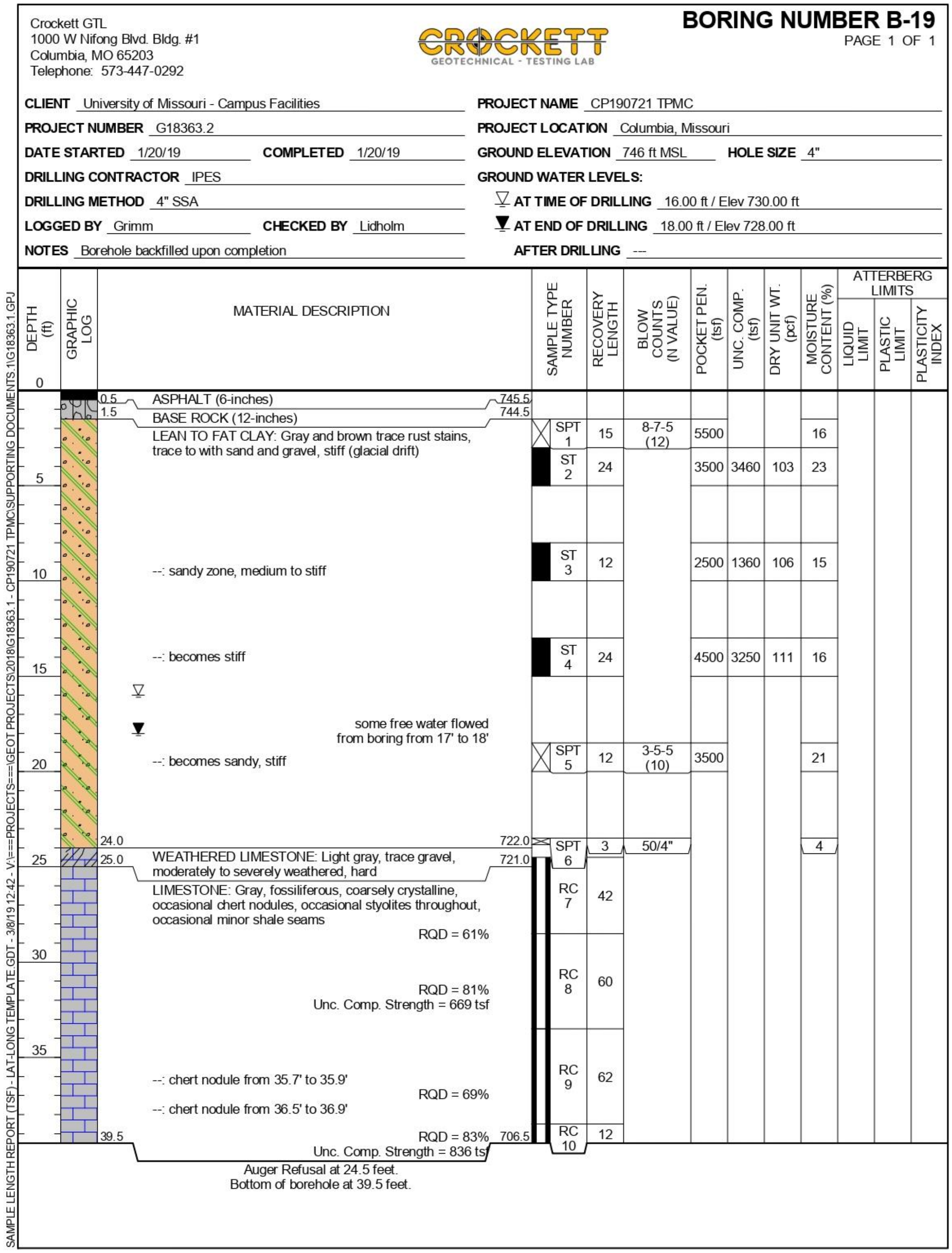
CLIENT University of Missouri - Campus Facilities
PROJECT NAME CP190721 TPMC
PROJECT NUMBER G18363.2
PROJECT LOCATION Columbia, Missouri
DATE STARTED 1/19/19 **COMPLETED** 1/19/19
GROUND ELEVATION 737 ft MSL **HOLE SIZE** 4"
DRILLING CONTRACTOR IPES
GROUND WATER LEVELS:
DRILLING METHOD 4" SSA
AT TIME OF DRILLING --- Not Encountered
LOGGED BY Grimm **CHECKED BY** Lidholm
AT END OF DRILLING --- Not Encountered
NOTES Borehole backfilled upon completion
AFTER DRILLING ---

DEPTH (ft)	MATERIAL DESCRIPTION	Elev.	SAMPLE TYPE NUMBER	RECOVERY LENGTH	BLOW COUNTS (N VALUE)	POCKET PEN. (tsf)	UNC. COMP. (tsf)	DRY UNIT WT. (pcf)	MOISTURE CONTENT (%)	LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX
0.6	ASPHALT (7-inches)	736.4										
1.5	Base Rock (11 inches)	735.5										
	LEAN TO FAT CLAY: Brown and gray, trace rust stains, trace to with sand, trace gravel, very stiff (glacial drift)		SPT 1	0	4-5-8 (13)							
			ST 2	15		5500	4790	105	21			
			ST 3	19		6500	4610	109	21			
11.0	CLAYEY GRAVEL: Light brown, possible cobbles and boulders, very stiff, very dense (glacial drift)	726.0										
			SPT 4	15	11-17-40 (57)	5500			11			
17.5	WEATHERED LIMESTONE: Light gray, trace gravel, severely weathered, hard	719.5										
18.5	LIMESTONE: Gray, fossiliferous, coarsely crystalline, occasional chert nodules, occasional stylolites throughout RQD = 51%	718.5	SPT 5	2	50/2"				5			
	--: occasional chert nodules from 22.7' to 24.1'		RC 6	53								
	Unc. Comp. Strength = 963 tsf RQD = 74%		RC 7	59								
	--: chert nodule from 27.9' to 30.3' RQD = 80% Unc. Comp. Strength = 1005 tsf		RC 8	60								
33.5	--: chert nodule from 32.7' to 33.2'	703.5										

Split Spoon Sampler Refusal at 18.7 feet.
Bottom of borehole at 33.5 feet.

SAMPLE LENGTH REPORT (TSF) - LAT-LONG TEMPLATE.GDT - 3/8/19 12:42 - V:\==PROJECTS==\GEOT PROJECTS\2018\G18363.1 - CP190721 TPMC\SUPPORTING DOCUMENTS.1\G18363.1.GPJ

Figure 11: NextGen Borehole 18



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CROCKETT GEOTECHNICAL - TESTING LAB

BORING NUMBER B-19
PAGE 1 OF 1

CLIENT University of Missouri - Campus Facilities
PROJECT NAME CP190721 TPMC
PROJECT NUMBER G18363.2
PROJECT LOCATION Columbia, Missouri
DATE STARTED 1/20/19 **COMPLETED** 1/20/19
GROUND ELEVATION 746 ft MSL **HOLE SIZE** 4"
DRILLING CONTRACTOR IPES
GROUND WATER LEVELS:
DRILLING METHOD 4" SSA
▽ **AT TIME OF DRILLING** 16.00 ft / Elev 730.00 ft
LOGGED BY Grimm **CHECKED BY** Lidholm
▼ **AT END OF DRILLING** 18.00 ft / Elev 728.00 ft
NOTES Borehole backfilled upon completion
AFTER DRILLING ---

DEPTH (ft)	MATERIAL DESCRIPTION	Elev.
0.5	ASPHALT (6-inches)	745.5
1.5	BASE ROCK (12-inches)	744.5
	LEAN TO FAT CLAY: Gray and brown trace rust stains, trace to with sand and gravel, stiff (glacial drift)	
	--: sandy zone, medium to stiff	
	--: becomes stiff	
	some free water flowed from boring from 17' to 18'	
	--: becomes sandy, stiff	
24.0		722.0
25.0	WEATHERED LIMESTONE: Light gray, trace gravel, moderately to severely weathered, hard	721.0
	LIMESTONE: Gray, fossiliferous, coarsely crystalline, occasional chert nodules, occasional stylolites throughout, occasional minor shale seams	
	RQD = 61%	
	RQD = 81% Unc. Comp. Strength = 669 tsf	
	--: chert nodule from 35.7' to 35.9'	
	RQD = 69%	
	--: chert nodule from 36.5' to 36.9'	
39.5	RQD = 83% Unc. Comp. Strength = 836 tsf	706.5
	Auger Refusal at 24.5 feet. Bottom of borehole at 39.5 feet.	

SAMPLE TYPE NUMBER	RECOVERY LENGTH	BLOW COUNTS (N VALUE)	POCKET PEN. (tsf)	UNC. COMP. (tsf)	DRY UNIT WT. (pcf)	MOISTURE CONTENT (%)	ATTERBERG LIMITS: LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX
SPT 1	15	8-7-5 (12)	5500			16			
ST 2	24		3500	3460	103	23			
ST 3	12		2500	1360	106	15			
ST 4	24		4500	3250	111	16			
SPT 5	12	3-5-5 (10)	3500			21			
SPT 6	3	50/4"				4			
RC 7	42								
RC 8	60								
RC 9	62								
RC 10	12								

SAMPLE LENGTH REPORT (TSF) - LAT-LONG TEMPLATE.GDT - 3/8/19 12:42 - V:\===PROJECTS===\GEOT PROJECTS\2018\G18363.1 - CP190721 TPMC\SUPPORTING DOCUMENTS.1\G18363.1.GPJ

Figure 12: NextGen Borehole 19

Crockett GTL
1000 W Nifong Blvd. Bldg. #1
Columbia, MO 65203
Telephone: 573-447-0292

CROCKETT
GEOTECHNICAL - TESTING LAB

BORING NUMBER B-21

PAGE 1 OF 2

CLIENT University of Missouri - Campus Facilities
PROJECT NAME CP190721 TPMC
PROJECT NUMBER G18363.2
PROJECT LOCATION Columbia, Missouri
DATE STARTED 1/28/19 **COMPLETED** 1/28/19
GROUND ELEVATION 742 ft MSL **HOLE SIZE** 4"
DRILLING CONTRACTOR IPES
GROUND WATER LEVELS:
DRILLING METHOD 4" SSA
AT TIME OF DRILLING --- Not Encountered
LOGGED BY Grimm **CHECKED BY** Lidholm
AT END OF DRILLING --- Not Encountered
NOTES Borehole backfilled upon completion
0.25hrs AFTER DRILLING --- Not Encountered

DEPTH (ft)	MATERIAL DESCRIPTION	Elevation (ft)
0.4	ASPHALT (5-inches)	741.6
1.0	BASE ROCK (7-inches)	741.0
7.0	UNCONTROLLED FILL: Gravelly lean to fat clay, trace rust stains, trace to with sand, stiff to very stiff	735.0
18.0	LEAN TO FAT CLAY: Gray and brown, trace rust stains, with sand to sandy, trace gravel, very stiff (glacial drift)	724.0
23.0	SHALEY LEAN TO FAT CLAY: Light gray, trace rust stains, trace sand, hard	719.0
29.0	CLAYEY SHALE: Light gray, trace light brown, hard	713.0
	WEATHERED SHALE: Gray, trace sand, moderately to severely weathered, hard	

SAMPLE TYPE NUMBER	RECOVERY LENGTH	BLOW COUNTS (N VALUE)	POCKET PEN. (tsf)	UNC. COMP. (tsf)	DRY UNIT WT. (pcf)	MOISTURE CONTENT (%)	ATTERBERG LIMITS: LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX
SPT 1	10	2-6-7 (13)	3000			12			
SPT 2	10	5-5-3 (8)	5000			9			
SPT 3	21	2-3-5 (8)	4500			24			
SPT 4	15	2-3-4 (7)	5000			16			
SPT 5	11	6-8-11 (19)	9000			17			
SPT 6	19	12-12-14 (26)	9000			14			
SPT 7	12	27-50/4"	9000			13			
SPT 8	6	50/3"	9000			6			
SPT 9	14	50/5"	9000			9			
SPT 10	9	50/5"	9000			10			

SAMPLE LENGTH REPORT (TSF) - LAT-LONG TEMPLATE.GDT - 3/8/19 12:43 - V:\===PROJECTS===\GEOT PROJECTS\2018\G18363.1 - CP190721 TPMC\SUPPORTING DOCUMENTS.1\G18363.1.GPJ

(Continued Next Page)

Figure 13: NextGen Borehole 21

Crockett GTL
1000 W Nifong Blvd. Bldg. #1
Columbia, MO 65203
Telephone: 573-447-0292

CROCKETT
GEOTECHNICAL - TESTING LAB

BORING NUMBER B-21
PAGE 2 OF 2

CLIENT University of Missouri - Campus Facilities
PROJECT NAME CP190721 TPMC
PROJECT NUMBER G18363.2
PROJECT LOCATION Columbia, Missouri

DEPTH (ft)	GRAPHIC LOG	MATERIAL DESCRIPTION		SAMPLE TYPE NUMBER	RECOVERY LENGTH	BLOW COUNTS (N VALUE)	POCKET PEN. (tsf)	UNC. COMP. (tsf)	DRY UNIT WT. (pcf)	MOISTURE CONTENT (%)	ATTERBERG LIMITS: LIQUID LIMIT	ATTERBERG LIMITS: PLASTIC LIMIT	ATTERBERG LIMITS: PLASTICITY INDEX
45		WEATHERED SHALE: Gray, trace sand, moderately to severely weathered, hard *(continued)*											
50		--: trace coal		SPT 11	11	50/3"	9000			11			
52.0			690.0										
52.5		LIMESTONE: Hard	689.5	SPT 12	19	50/1"				10			

Auger Refusal at 52.5 feet.
Split Spoon Sampler Refusal at 52.6 feet.
Bottom of borehole at 52.6 feet.

SAMPLE LENGTH REPORT (TSF) - LAT-LONG TEMPLATE.GDT - 3/8/19 12:43 - V:\==PROJECTS==\GEOT PROJECTS\2018\G18363.1 - CP190721 TPMC\SUPPORTING DOCUMENTS.1\G18363.1.GPJ

Figure 14: NextGen Borehole 21 (Continue)

Crockett GTL
1000 W Nifong Blvd. Bldg. #1
Columbia, MO 65203
Telephone: 573-447-0292

CROCKETT
GEOTECHNICAL - TESTING LAB

BORING NUMBER B-22

CLIENT University of Missouri - Campus Facilities
PROJECT NAME CP190721 TPMC
PROJECT NUMBER G18363.2
PROJECT LOCATION Columbia, Missouri
DATE STARTED 1/28/19 **COMPLETED** 1/28/19
GROUND ELEVATION 745 ft MSL **HOLE SIZE** 4"
DRILLING CONTRACTOR IPES
GROUND WATER LEVELS:
DRILLING METHOD 4" SSA
AT TIME OF DRILLING --- Not Encountered
LOGGED BY Grimm **CHECKED BY** Lidholm
AT END OF DRILLING --- Not Encountered
NOTES Borehole backfilled upon completion
0.25hrs AFTER DRILLING --- Not Encountered

DEPTH (ft)	MATERIAL DESCRIPTION	Elev.	SAMPLE TYPE NUMBER	RECOVERY LENGTH	BLOW COUNTS (N VALUE)	POCKET PEN. (tsf)	UNC. COMP. (tsf)	DRY UNIT WT. (pcf)	MOISTURE CONTENT (%)	ATTERBERG LIMITS: LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX
0.5	ASPHALT (6-inches)	744.5										
1.0	BASE ROCK (6-inches)	744.0										
	UNCONTROLLED FILL: Sandy lean to fat clay, brown, trace rust stains, trace gravel, loose		SPT 1	4	3-3-5 (8)				22			
	--: gravelly		SPT 2	4	4-4-4 (8)				18			
7.0	LEAN TO FAT CLAY: Gray and brown, trace rust stains, with sand to sandy, trace gravel, very stiff (glacial drift)	738.0										
8.5	CLAYEY SAND: Light brown, medium dense (glacial drift)	736.5	SPT 3	19	6-6-6 (12)	5000			10			
13.5	LEAN TO FAT CLAY: Light brown, trace gray, trace rust stains, trace to with sand and gravel, very stiff (glacial drift)	731.5										
18.5		726.5										
18.8	LIMESTONE: Hard	726.2	SPT 4	2	50/1"	6500			15			

Split Spoon Refusal at 18.6 feet.
Auger Refusal at 18.8 feet.
Bottom of borehole at 18.8 feet.

Figure 15: NextGen Borehole 22

APPENDIX A-9

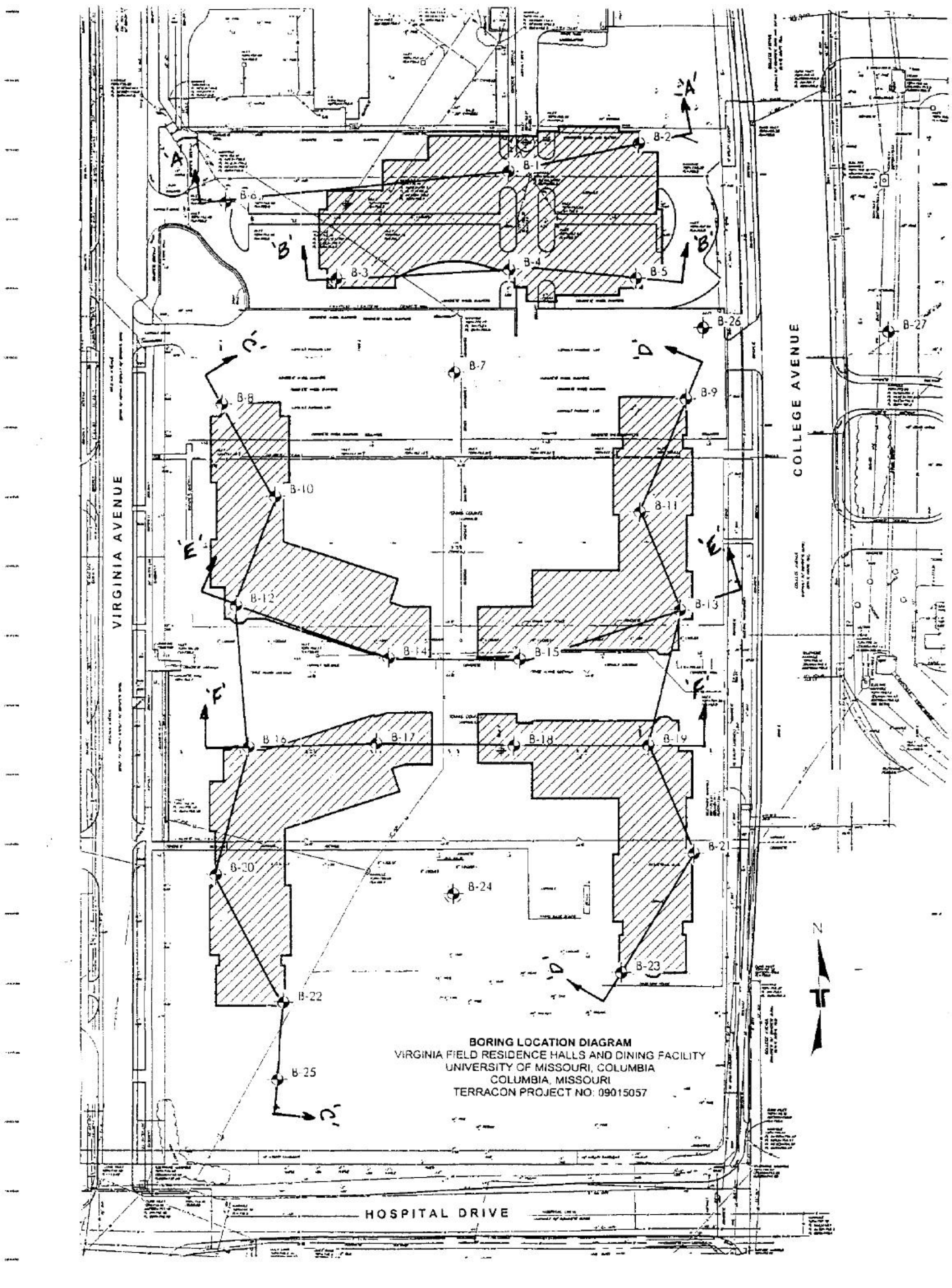

Figure 1: Virginia Ave. Housing and Dining Complex boring plan (Aerial View), prepared by Terracon

LOG OF BORING NO. B-3

CLIENT: UNIVERSITY OF MISSOURI - COLUMBIA	ARCHITECT / ENGINEER
SITE: COLUMBIA, MISSOURI	PROJECT: VIRGINIA FIELD HOUSING AND DINING

DESCRIPTION (Approx. Surface Elev.: 766 ft)	DEPTH, ft.	USCS SYMBOL	SAMPLES: NUMBER	TYPE	RECOVERY, in.	SPT - N BLOWS / ft.	TESTS: WATER CONTENT, %	DRY UNIT WT pcf	UNCONFINED STRENGTH, psf	ATTERBERG LIMITS (LL, PL, PI)
0.6 7" ASPHALT 765.5				HSA						
1.3 8" CRUSHED LIMESTONE GRAVEL 764.5										
FILL, lean to fat clay, trace sand, gravel and brick fragments, dark olive gray, brown and tan, very stiff		CL CH	1	ST	16		22.0	105	6000*	
		CL	2	ST	16		22.0	104	5000*	42, 18, 24
5.5 760.5	5	CL	3	ST	23		20.0	108	3700	
LEAN CLAY, trace sand and gravel, with sand and silt lenses, yellowish brown mottled gray, jointed, stiff to very stiff				HSA						
		CL	4	ST	14		17.0	112	4560	
(Glacial Drift)	10			HSA						
12 754										
SILTY SAND, fine to coarse, trace clay, yellowish brown, very dense		SM	5	SS	16	63	15.0			
	15			HSA						
17 749										
LEAN CLAY, trace sand and gravel, with sand and silt lenses, yellowish brown mottled gray, jointed, very stiff		CL	6	SS	18	28	21.0		7000*	
(Glacial Drift)	20			HSA						
--: grading hard		CL	7	SS	18	31	16.0		+9000*	
	25			HSA						
▼		CL	8	SS	18	42	18.0		+9000*	
	30			HSA						
--: grading yellowish brown to dark gray		CL	9	SS	18	38	18.0		+9000*	
	35									

Continued Next Page

The stratification lines represent the approximate boundary lines between soil and rock types: in-situ, the transition may be gradual.

*Calibrated Hand Penetrometer

WATER LEVEL OBSERVATIONS, ft			
WL	▽ NONE	WD ▼ 29	AB
WL	▼	▼	
WL			

Terracon

BORING STARTED			8-7-01
BORING COMPLETED			8-7-01
RIG	MOBILE B-47	FOREMAN	CRB
APPROVED	WAB	JOB #	09015057

BOREHOLE 09015057.GPJ TERRACON.GDT 10/9/01

Figure 2: Virginia Ave. Housing and Dining Complex Borehole 3

LOG OF BORING NO. B-3

Page 2 of 2

CLIENT	ARCHITECT / ENGINEER
UNIVERSITY OF MISSOURI - COLUMBIA	
SITE	PROJECT
COLUMBIA, MISSOURI	VIRGINIA FIELD HOUSING AND DINING

GRAPHIC LOG	DESCRIPTION		DEPTH, ft.	USCS SYMBOL	SAMPLES: NUMBER	SAMPLES: TYPE	SAMPLES: RECOVERY, in.	SAMPLES: SPT - N BLOWS / ft.	TESTS: WATER CONTENT, %	TESTS: DRY UNIT WT pcf	TESTS: UNCONFINED STRENGTH, psf	TESTS: ATTERBERG LIMITS (LL, PL, PI)
	LEAN CLAY, trace sand and gravel, dark gray, hard					HSA						
39	--: gravelly	727			10	SS	18	183	8.0		+9000*	
	SHALE, weathered, gray		40			HSA						
42.2		724			11	SS	6	50/1"	10.0		+9000*	

AUGER REFUSAL AT 42.2 FT.

BOTTOM OF BORING

** Rock classification estimated from disturbed samples. Core samples and petrographic analysis may reveal other rock types

The stratification lines represent the approximate boundary lines between soil and rock types: in-situ, the transition may be gradual.

*Calibrated Hand Penetrometer

WATER LEVEL OBSERVATIONS, ft				Terracon	BORING STARTED		8-7-01
WL	NONE	WD	29 AB		BORING COMPLETED		8-7-01
WL					RIG MOBILE B-47	FOREMAN	CRB
WL					APPROVED WAB	JOB #	09015057

BOREHOLE 09015057.GPJ TERRACON.GDT 10/9/01

Figure 3: Virginia Ave. Housing and Dining Complex Borehole 3 Continue

LOG OF BORING NO. B-5

CLIENT	ARCHITECT / ENGINEER
UNIVERSITY OF MISSOURI - COLUMBIA	
SITE	**PROJECT**
COLUMBIA, MISSOURI	VIRGINIA FIELD HOUSING AND DINING

DESCRIPTION (Approx. Surface Elev.: 769 ft)		DEPTH, ft.	USCS SYMBOL	SAMPLES: NUMBER	TYPE	RECOVERY, in.	SPT - N BLOWS / ft.	TESTS: WATER CONTENT, %	DRY UNIT WT pcf	UNCONFINED STRENGTH, psf	ATTERBERG LIMITS (LL, PL, PI)
0.6 7" ASPHALT	768.5				HSA						
1.3 9" CRUSHED LIMESTONE GRAVEL	767.5										
FILL, lean clay, trace gravel, olive gray and dark gray mottled brown, very stiff			CL	1	ST	12		19.0	107	5510	
			CL	2	ST	11		14.0	113	8000*	
5	764	5									
LEAN TO FAT CLAY, trace sand and gravel, yellowish brown mottled gray, stiff			CL CH	3	ST	17		23.0	103	2920	
7.5	761.5				HSA						
LEAN CLAY, trace sand and gravel, with sand and silt lenses, yellowish brown mottled gray, very stiff			CL	4	ST	19		18.0	115	7000*	
(Glacial Drift)		10			HSA						
--: grading hard			CL	5	ST	23		17.0	116	+9000*	
		15			HSA						
			CL	6	SS	17	24	18.0		9000*	
		20			HSA						
--: with silt lenses			CL	7	SS	18	15	21.0		8000*	
		25			HSA						
			CL	8	SS	18	25	21.0		+9000*	
		30			HSA						
			CL	9	SS	18	50	16.0		+9000*	
		35									

Continued Next Page

The stratification lines represent the approximate boundary lines between soil and rock types: in-situ, the transition may be gradual.

*Calibrated Hand Penetrometer

WATER LEVEL OBSERVATIONS, ft				BORING STARTED		8-6-01
WL	▽ 43 WD	▼ 33	AB	BORING COMPLETED		8-6-01
WL	▼ 22,0.5HR AB	▽		RIG MOBILE B-47	FOREMAN	CRB
WL				APPROVED WAB	JOB #	09015057

Terracon

BOREHOLE 09015057.GPJ TERRACON.GDT 10/9/01

Figure 4: Virginia Ave. Housing and Dining Complex Borehole 5

LOG OF BORING NO. B-5

Page 2 of 2

CLIENT	ARCHITECT / ENGINEER
UNIVERSITY OF MISSOURI - COLUMBIA	
SITE	PROJECT
COLUMBIA, MISSOURI	VIRGINIA FIELD HOUSING AND DINING

GRAPHIC LOG	DESCRIPTION	DEPTH, ft.	USCS SYMBOL	SAMPLES: NUMBER	TYPE	RECOVERY, in.	SPT - N BLOWS / ft.	TESTS: WATER CONTENT, %	DRY UNIT WT pcf	UNCONFINED STRENGTH, psf	ATTERBERG LIMITS (LL, PL, PI)
	LEAN CLAY, yellowish brown, hard				HSA						
37	732										
	CLAYEY SAND, trace gravel, yellowish brown, extremely dense		SC	10	SS	12	89/6"	15.0			
		40			HSA						
42	727										
	LEAN CLAY, trace sand and gravel, yellowish brown mottled gray, hard										
43.7	725.5										
44.2	**SHALE, weathered, light gray 725			11	SS	15	100/4"	13.0		+9000*	

AUGER REFUSAL AT 44.2 FT.

BOTTOM OF BORING

** Rock classification estimated from disturbed samples. Core samples and petrographic analysis may reveal other rock types

The stratification lines represent the approximate boundary lines between soil and rock types: in-situ, the transition may be gradual.

*Calibrated Hand Penetrometer

WATER LEVEL OBSERVATIONS, ft			
WL	43	WD 33	AB
WL	22.0.5HR	AB	
WL			

Terracon

BORING STARTED	8-6-01
BORING COMPLETED	8-6-01
RIG MOBILE B-47	FOREMAN CRB
APPROVED WAB	JOB # 09015057

BOREHOLE 09015057.GPJ TERRACON.GDT 10/9/01

Figure 5: Virginia Ave. Housing and Dining Complex Borehole 5 (Continue)

LOG OF BORING NO. B-6

CLIENT UNIVERSITY OF MISSOURI - COLUMBIA	ARCHITECT / ENGINEER
SITE COLUMBIA, MISSOURI	PROJECT VIRGINIA FIELD HOUSING AND DINING

Approx. Surface Elev.: 763 ft

GRAPHIC LOG (Depth, ft)	DESCRIPTION	Elev.
0.7	8" ASPHALT	762.5
1.3	8" CRUSHED LIMESTONE GRAVEL	761.5
3	LEAN CLAY, trace sand, gray mottled brown, stiff	760
5	SILT, with fine sand, light brown, very stiff	758
7.5	LEAN CLAY, trace sand, light yellowish brown, stiff	755.5
27	LEAN CLAY, trace sand and gravel, with sand lenses, gray mottled reddish brown, very stiff (Glacial Drift) --: with silt lenses, yellowish brown and gray, stiff --: grading very stiff -: with sand lenses	736
32	SILTY SAND, medium to coarse, with gravel, light yellowish brown, extremely dense	731
	LEAN CLAY, trace sand and gravel, dark gray, hard	

USCS SYMBOL	SAMPLES: NUMBER	TYPE	RECOVERY, in.	SPT - N BLOWS / ft.	TESTS: WATER CONTENT, %	DRY UNIT WT pcf	UNCONFINED STRENGTH, psf	ATTERBERG LIMITS (LL, PL, PI)
		HSA						
CL	1	ST	19		25.0	101	3790	
ML	2	ST	22		15.0	112	5000*	
CL	3	ST	24		16.0	115	3000*	
		HSA						
CL	4	ST	20		15.0	114	6500*	
		HSA						
CL	5	ST	22		21.0	105	3000*	
		HSA						
CL	6	SS	14	20	18.0		5000*	
		HSA						
CL	7	SS	12	15	20.0		8000*	
		HSA						
SM	8	SS	18	106	21.0			
		HSA						
CL	9	SS	18	30	19.0		9000*	

Continued Next Page

The stratification lines represent the approximate boundary lines between soil and rock types: in-situ, the transition may be gradual.

*Calibrated Hand Penetrometer

WATER LEVEL OBSERVATIONS, ft				
WL	28.5	WD	21	AB
WL				
WL				

Terracon

BORING STARTED	8-6-01		
BORING COMPLETED	8-6-01		
RIG	MOBILE B-47	FOREMAN	CRB
APPROVED	WAB	JOB #	09015057

BOREHOLE 09015057.GPJ TERRACON.GDT 10/9/01

Figure 6: Virginia Ave. Housing and Dining Complex Borehole 6

LOG OF BORING NO. B-6

Page 2 of 2

CLIENT	ARCHITECT / ENGINEER
UNIVERSITY OF MISSOURI - COLUMBIA	
SITE	PROJECT
COLUMBIA, MISSOURI	VIRGINIA FIELD HOUSING AND DINING

GRAPHIC LOG	DESCRIPTION		DEPTH, ft.	USCS SYMBOL	SAMPLES: NUMBER	SAMPLES: TYPE	SAMPLES: RECOVERY, in.	SAMPLES: SPT - N BLOWS / ft.	TESTS: WATER CONTENT, %	TESTS: DRY UNIT WT pcf	TESTS: UNCONFINED STRENGTH, psf	TESTS: ATTERBERG LIMITS (LL, PL, PI)
	LEAN CLAY, trace sand and gravel, dark gray, hard					HSA						
38.5	(Glacial Drift)	724.5										
38.6	**LIMESTONE, weathered, dark gray	724.5			10	SS	1	50/1"				

AUGER REFUSAL AT 38.6 FT.

BOTTOM OF BORING

** Rock classification estimated from disturbed samples. Core samples and petrographic analysis may reveal other rock types

The stratification lines represent the approximate boundary lines between soil and rock types: in-situ, the transition may be gradual.

*Calibrated Hand Penetrometer

WATER LEVEL OBSERVATIONS, ft			BORING STARTED	8-6-01
WL	28.5 WD	21 AB	BORING COMPLETED	8-6-01
WL			RIG MOBILE B-47	FOREMAN CRB
WL			APPROVED WAB	JOB # 09015057

Terracon

BOREHOLE 09015057 GPJ TERRACON GDT 10/9/01

Figure 7: Virginia Ave. Housing and Dining Complex Borehole 6 (Continue)

APPENDIX B

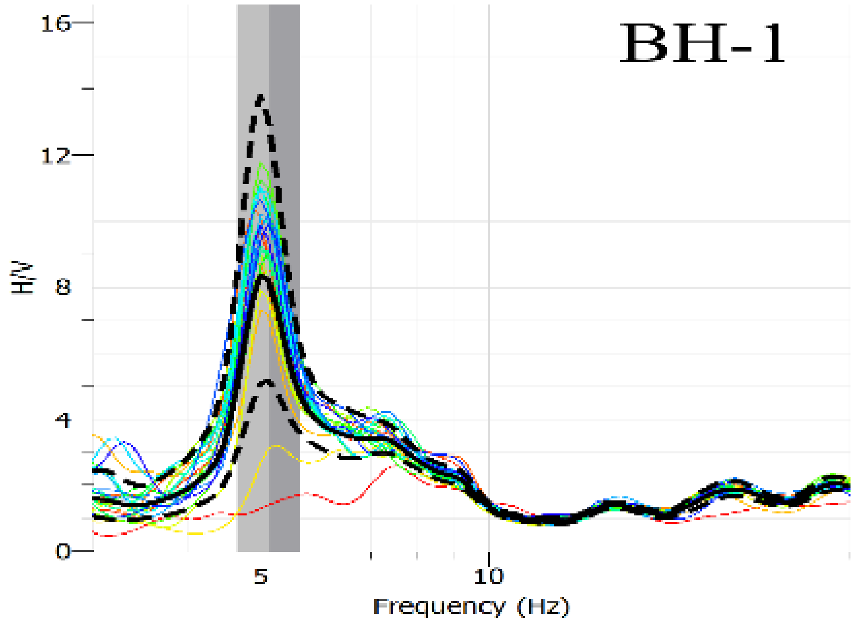

Figure 1: HVSR plots from Ellis Library borehole 1

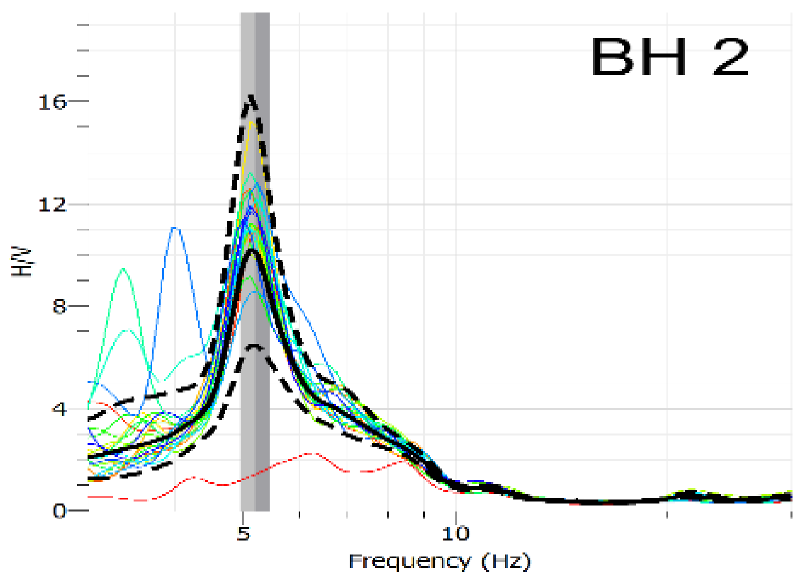

Figure 2: HVSR plots from Ellis Library borehole 2

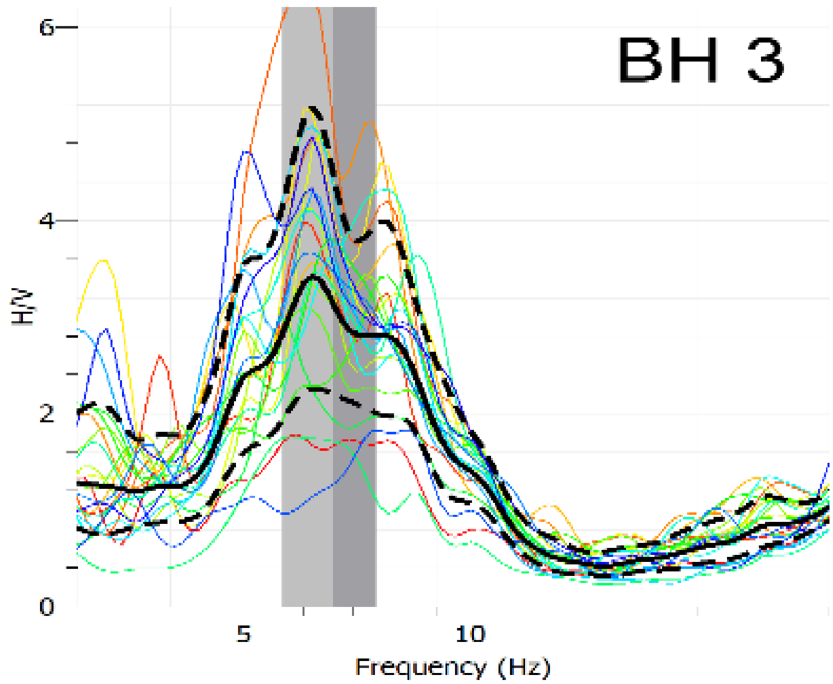

Figure 3: HVSR plots from Ellis Library borehole 3

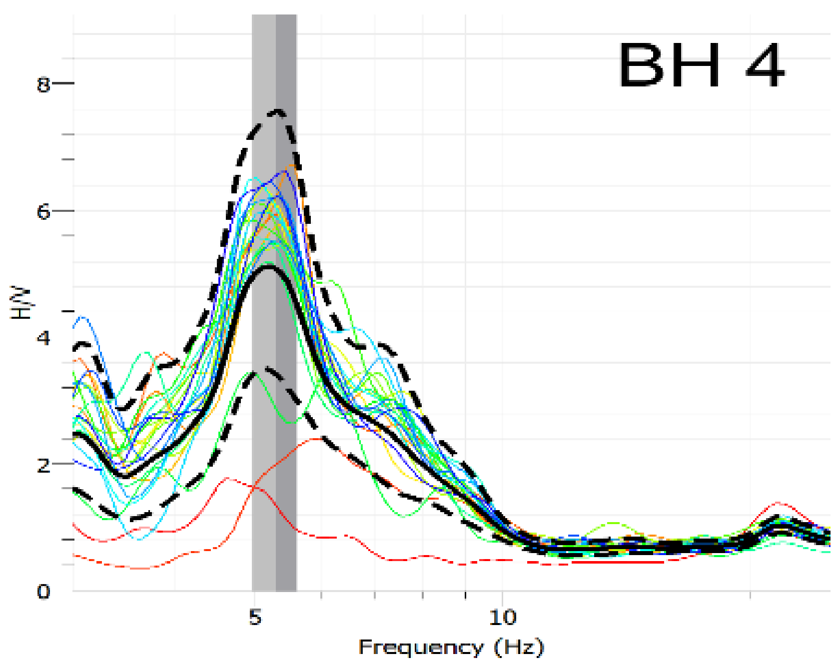

Figure 4: HVSR plots from Ellis Library borehole 4

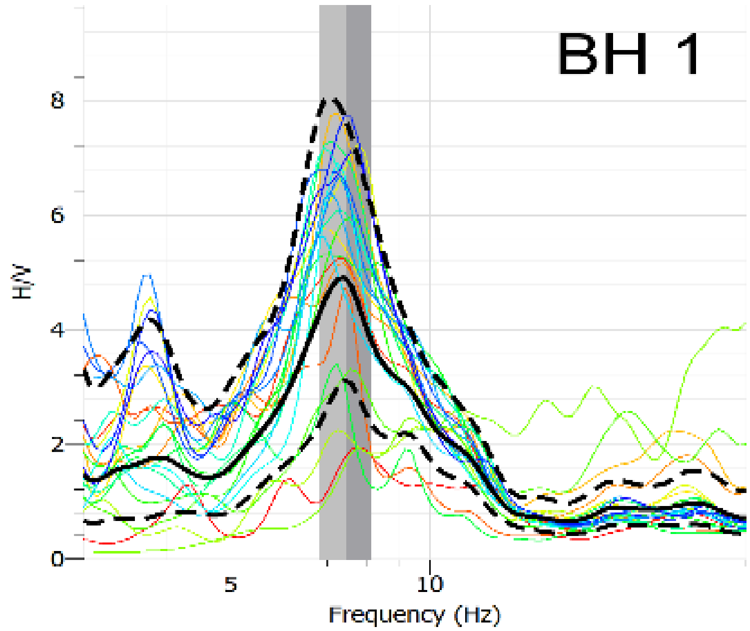

Figure 5: HVSR plots from Gateway Residence Hall borehole 1

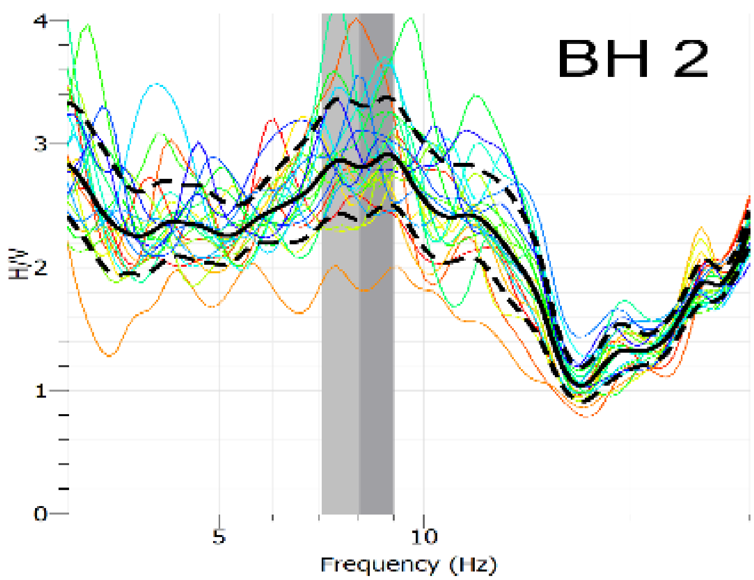

Figure 6: HVSR plots from Gateway Residence Hall borehole 2

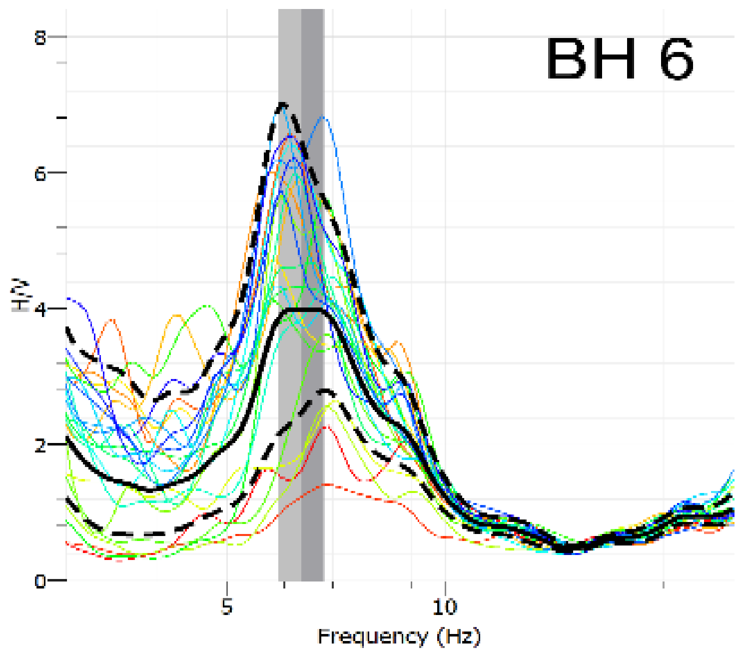

Figure 7: HVSR plots from Gateway Residence Hall borehole 6

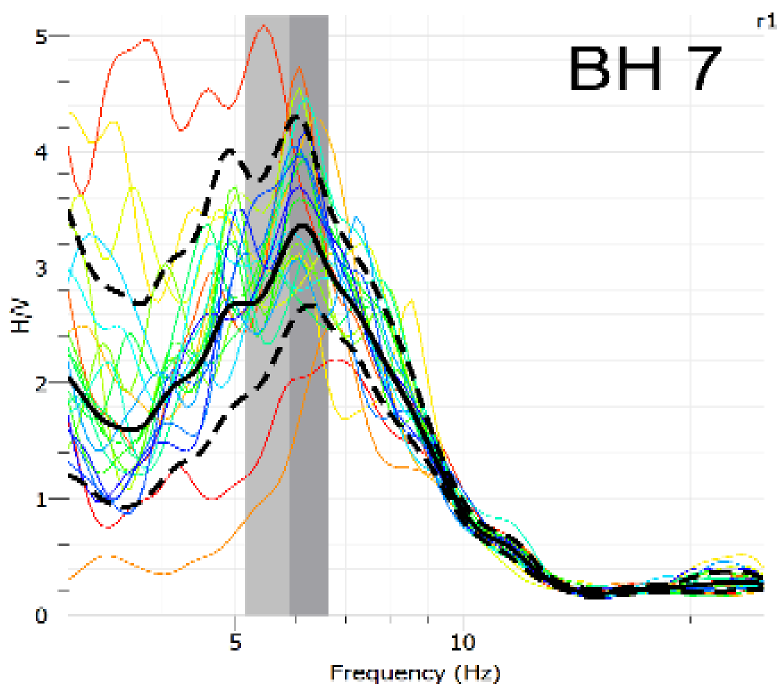

Figure 8: HVSR plots from Gateway Residence Hall borehole 7

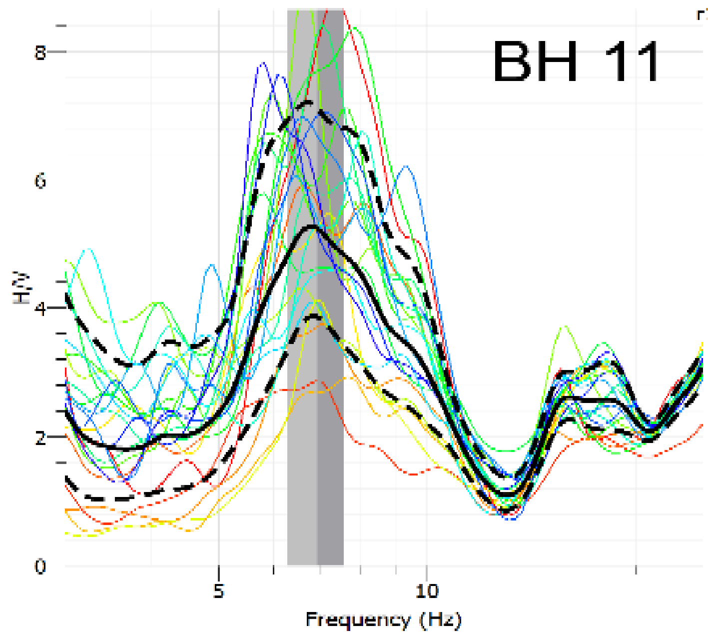

Figure 9: HVSR plots from Gateway Residence Hall borehole 11

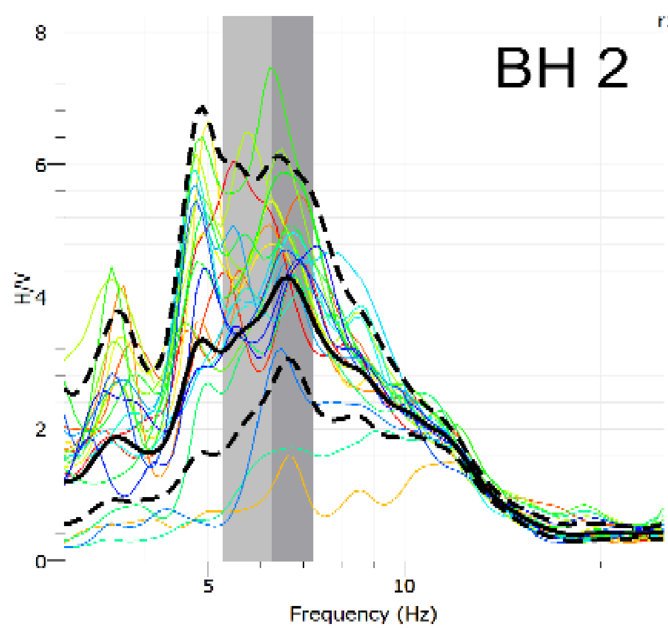

Figure 10: HVSR plots from Journalism Building borehole 2

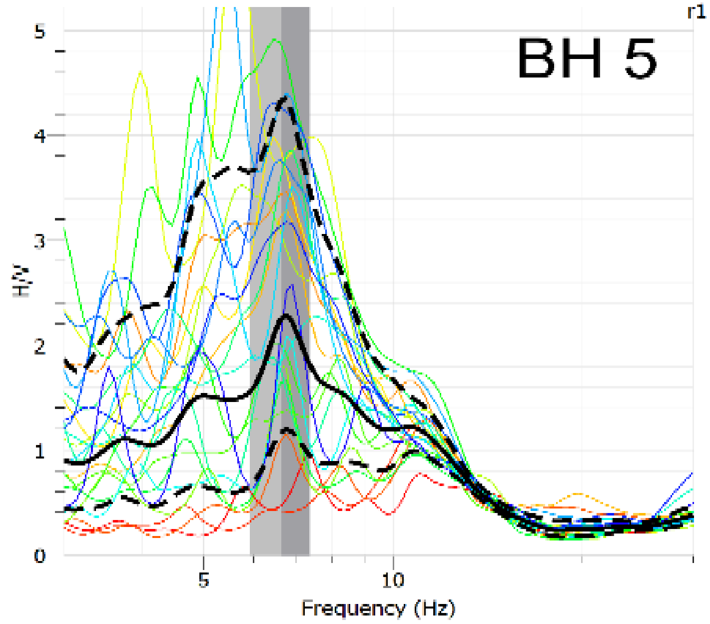

Figure 11: HVSR plots from Journalism Building borehole 5

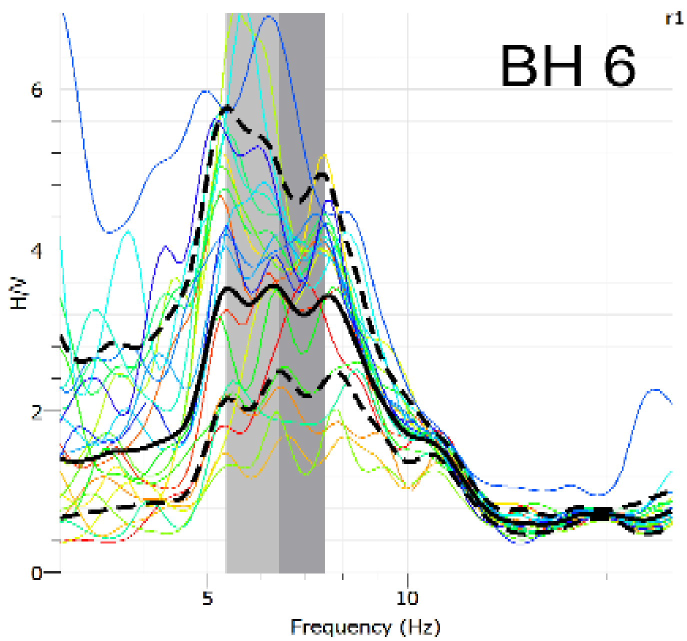

Figure 12: HVSR plots from Journalism Building borehole 6

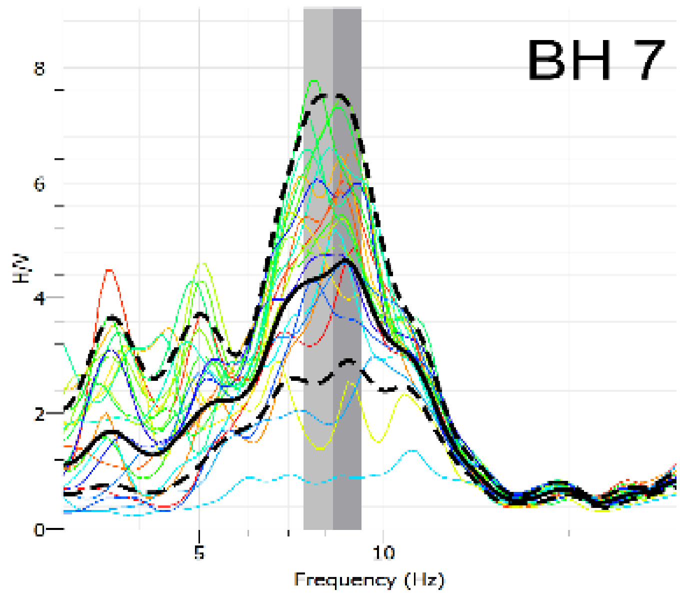

Figure 13: HVSR plots from Journalism Building borehole 7

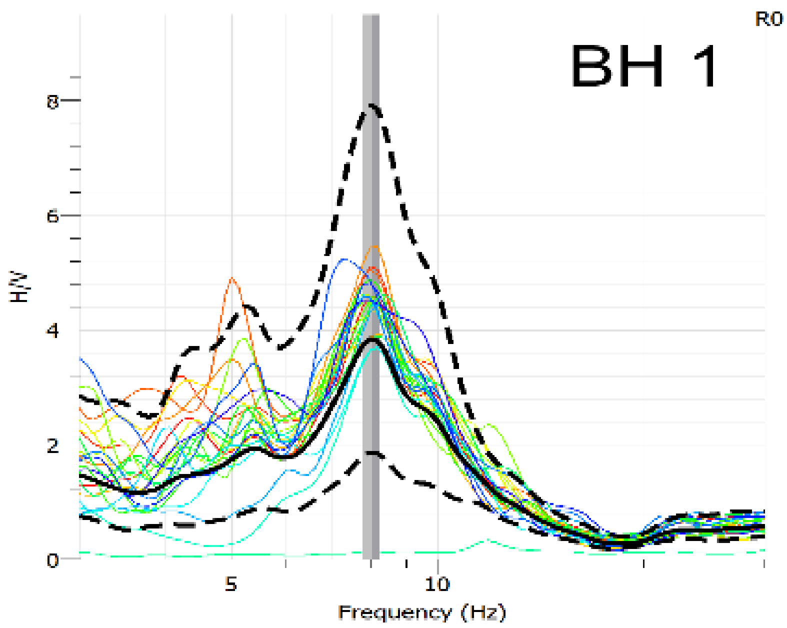

Figure 14: HVSR plots from Lee's Hall borehole 1

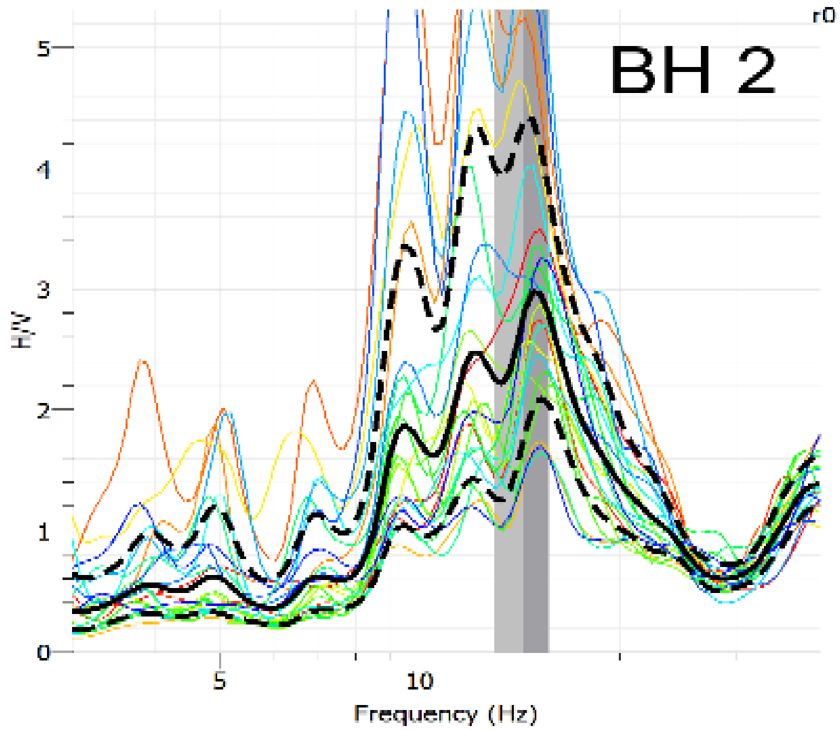

Figure 15: HVSR plots from Lee's Hall borehole 2

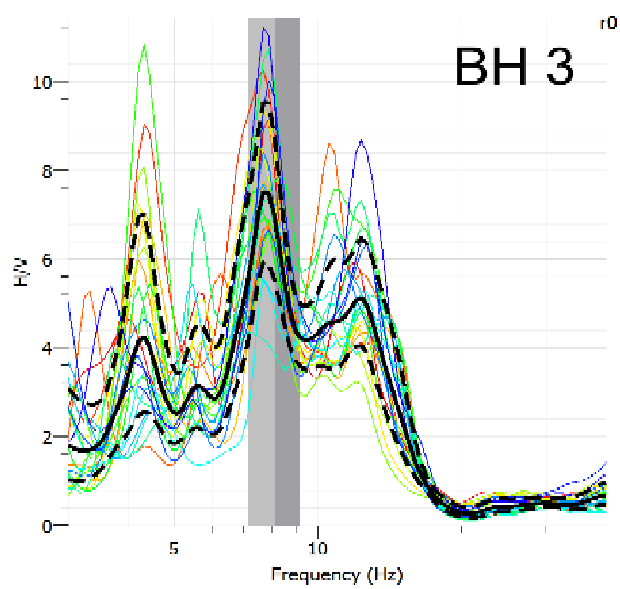

Figure 16: HVSR plots from Lee's Hall borehole 3

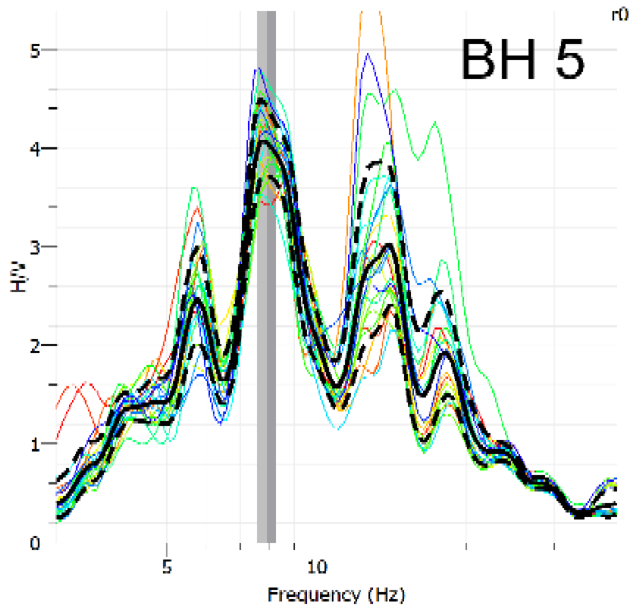

Figure 17: HVSR plots from Lee's Hall borehole 5

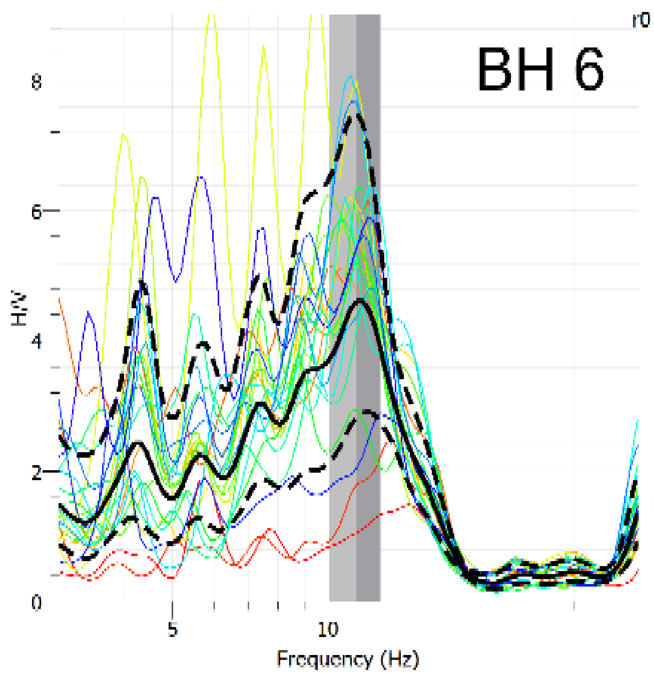

Figure 18: HVSR plots from Lee's Hall borehole 6

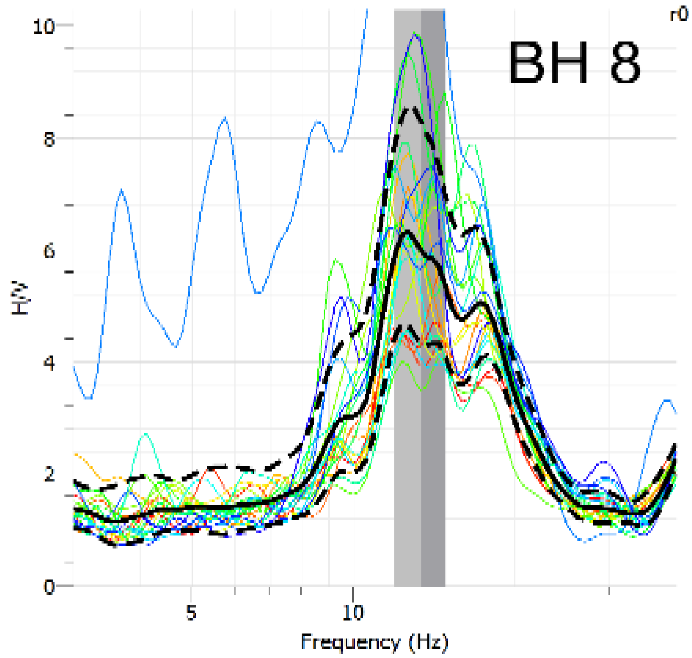

Figure 19: HVSR plots from Lee's Hall borehole 8

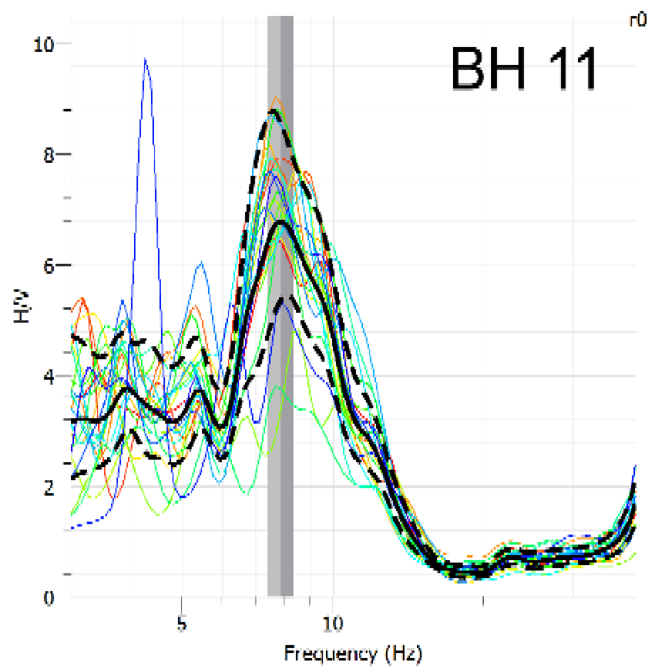

Figure 20: HVSR plots from Lee's Hall borehole 11

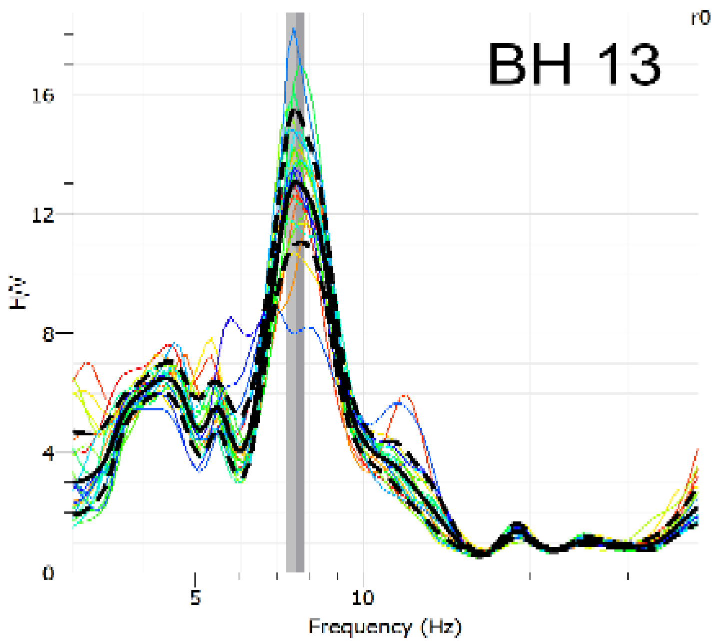

Figure 21: HVSR plots from Lee's Hall borehole 13

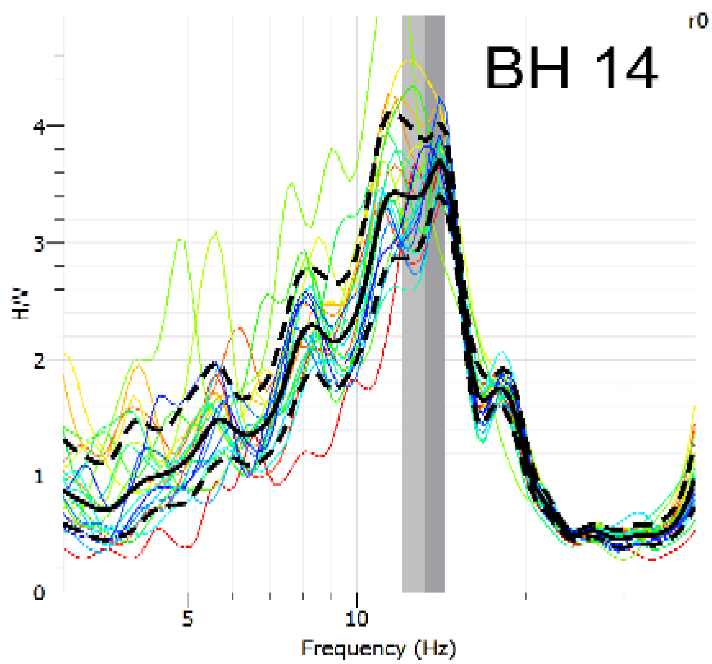

Figure 22: HVSR plots from Lee's Hall borehole 14

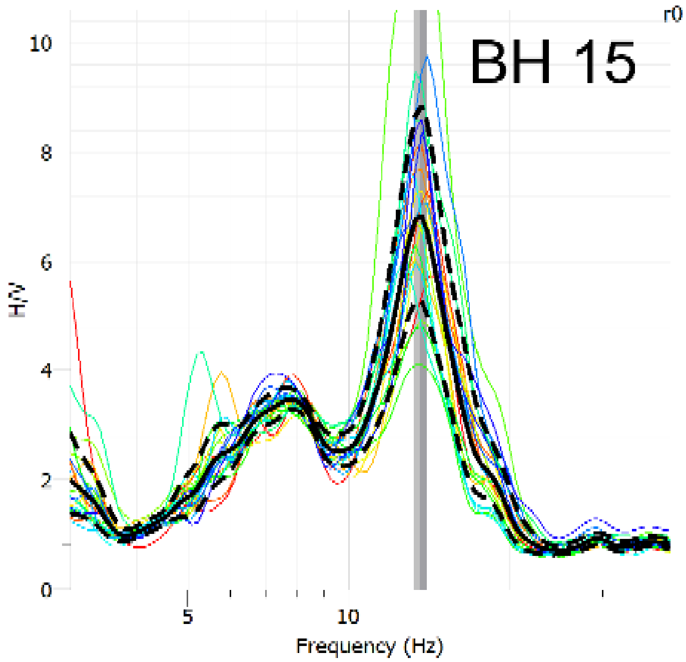

Figure 23: HVSR plots from Lee's Hall borehole 15

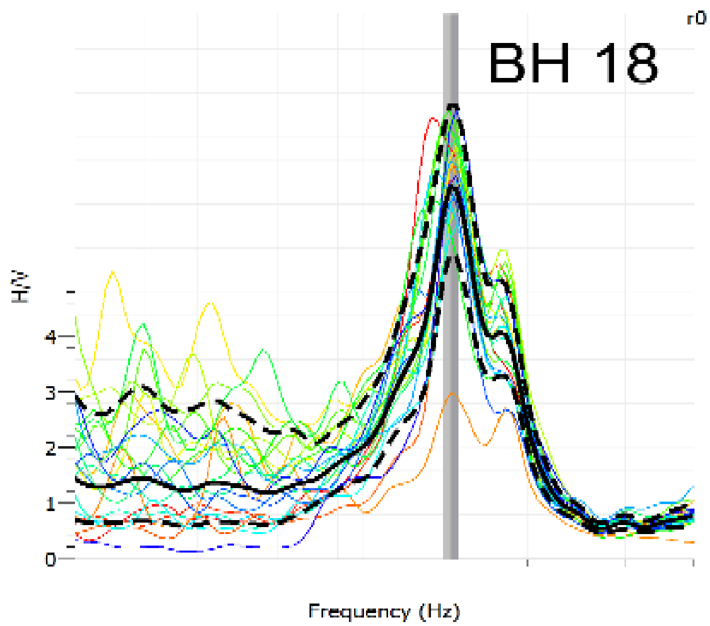

Figure 24: HVSR plots from Lee's Hall borehole 18

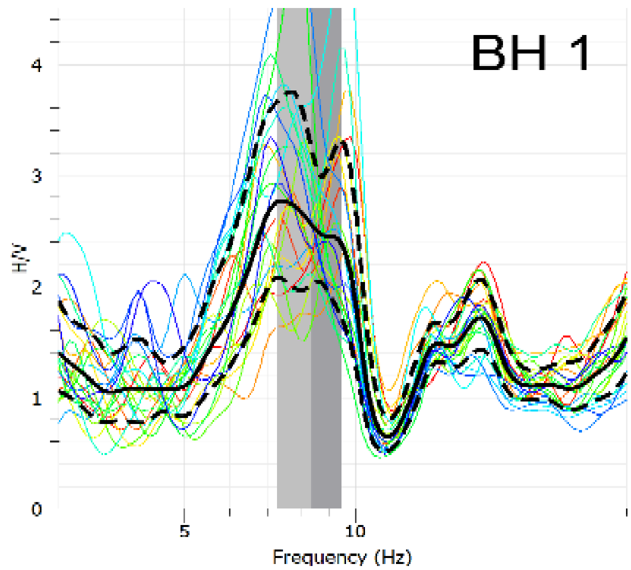

Figure 25: HVSR plots from MUHC borehole 1

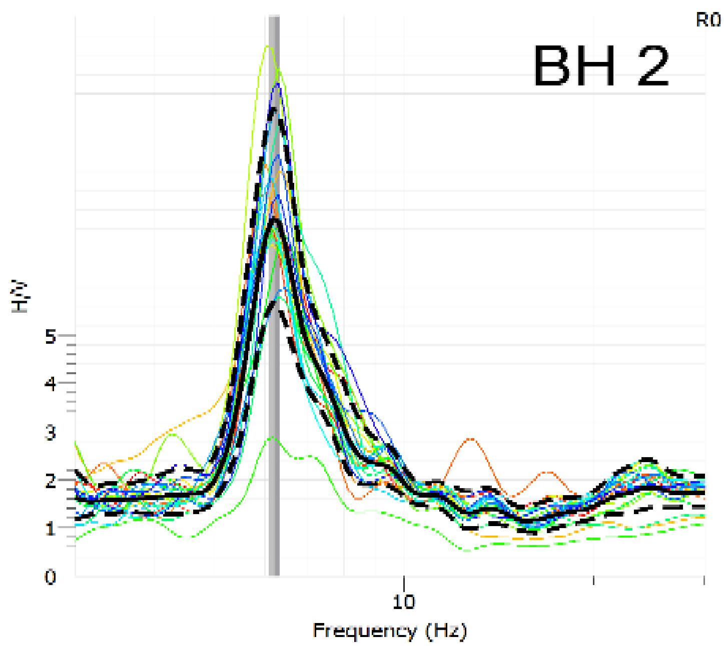

Figure 26: HVSR plots from MUHC borehole 2

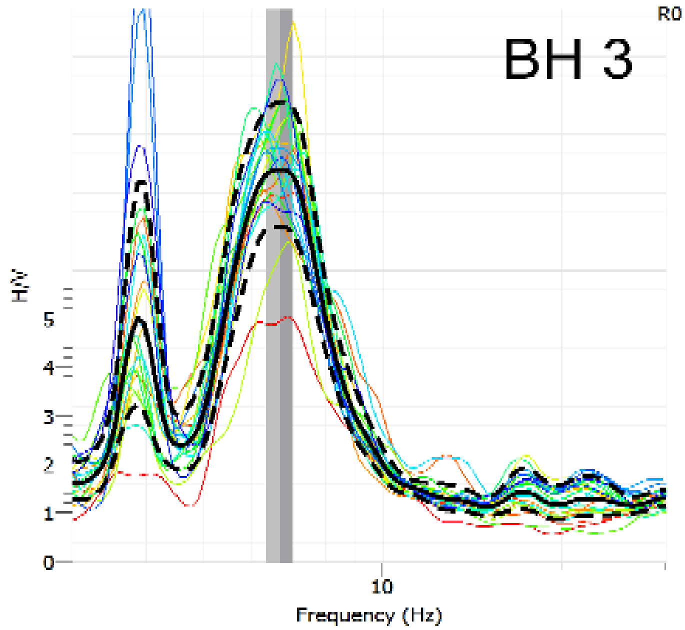

Figure 27: HVSR plots from MUHC borehole 3

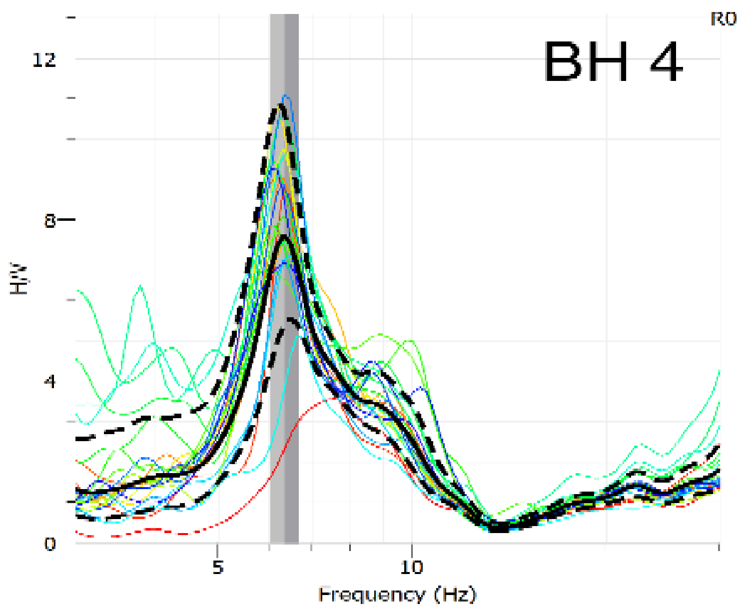

Figure 28: HVSR plots from MUHC borehole 4

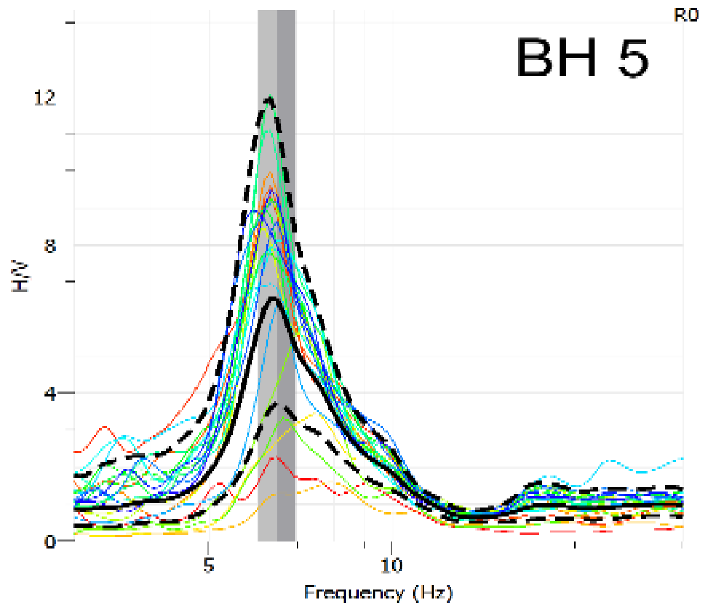

Figure 29: HVSR plots from MUHC borehole 5

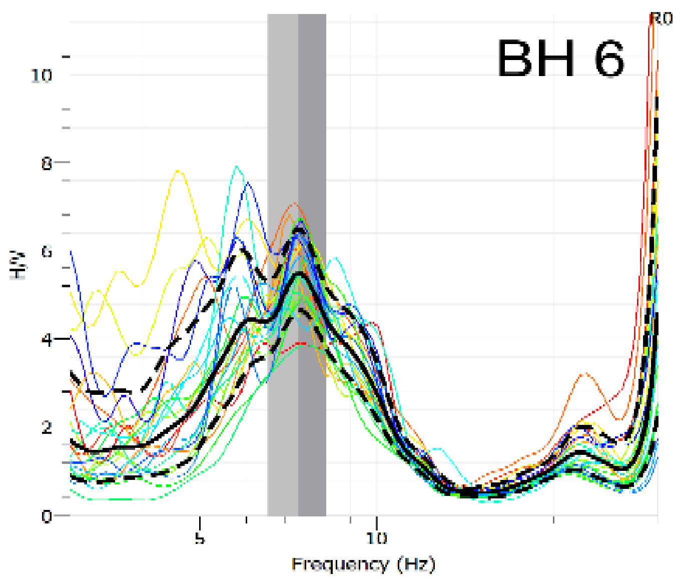

Figure 30: HVSR plots from MUHC borehole 6

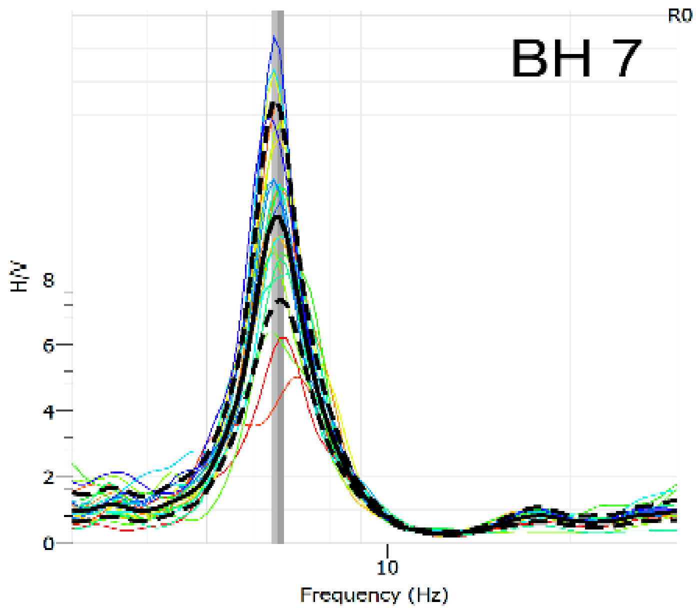

Figure 31: HVSR plots from MUHC borehole 7

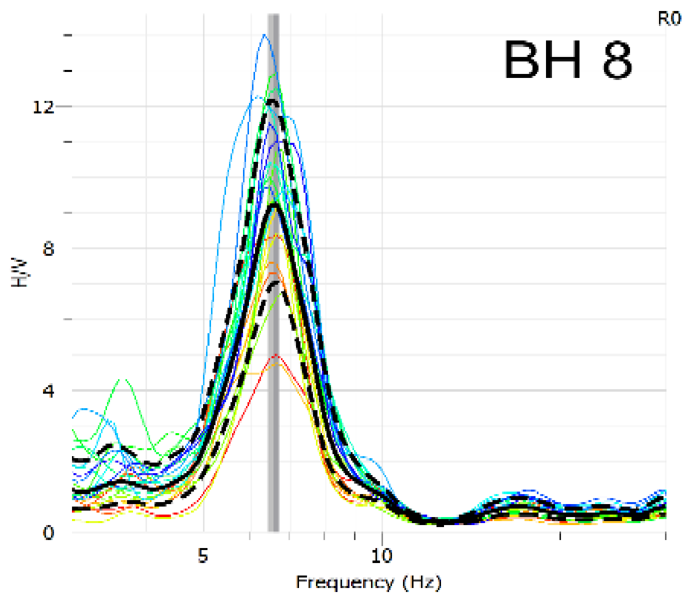

Figure 32: HVSR plots from MUHC borehole 8

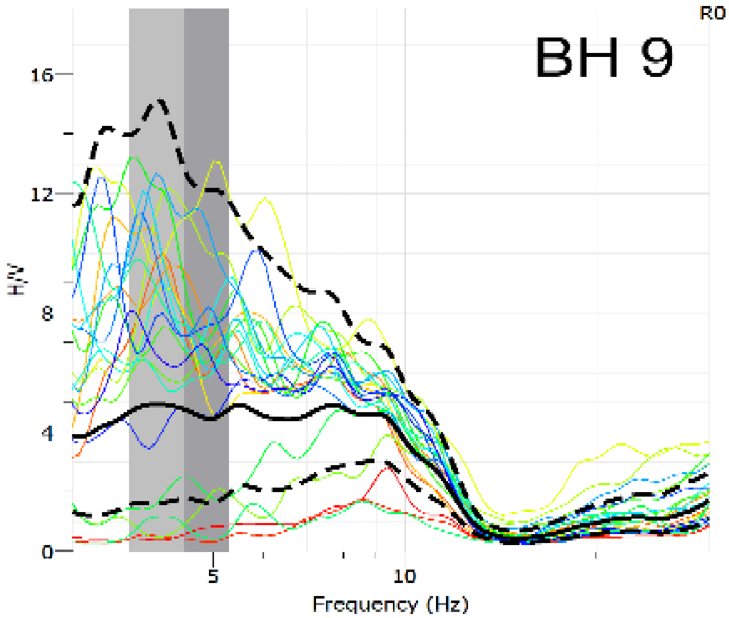

Figure 33: HVSR plots from MUHC borehole 9

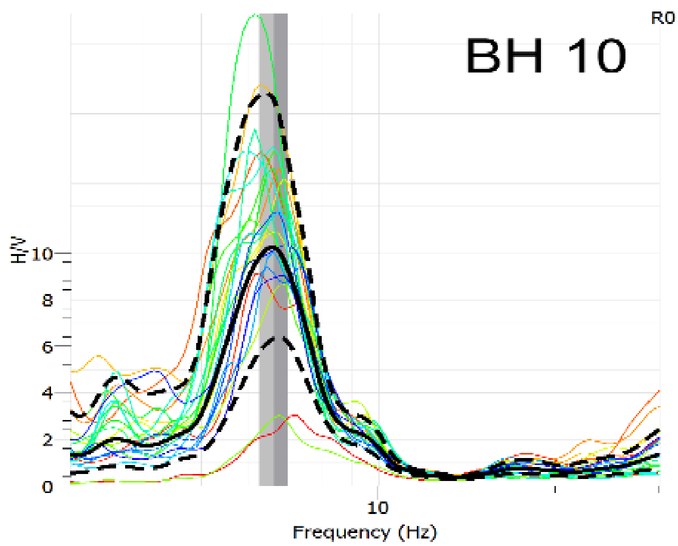

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Figure 34: HVSR plots from MUHC borehole 10

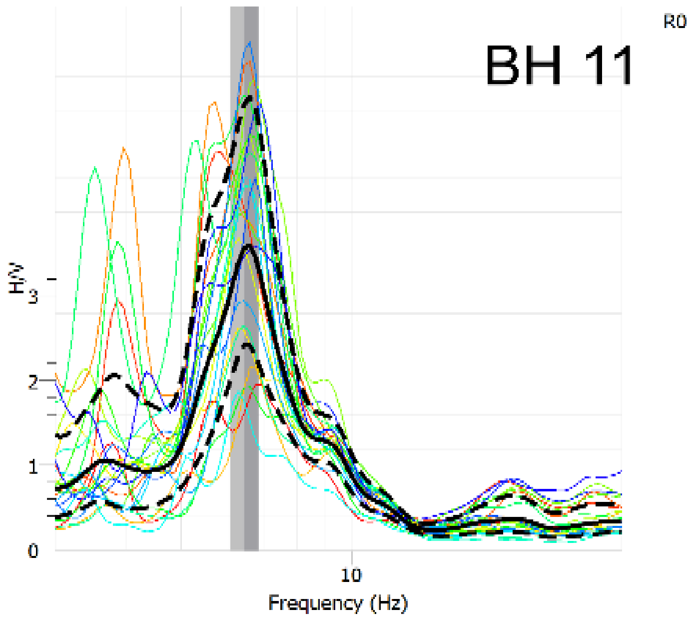

Figure 35: HVSR plots from MUHC borehole 11

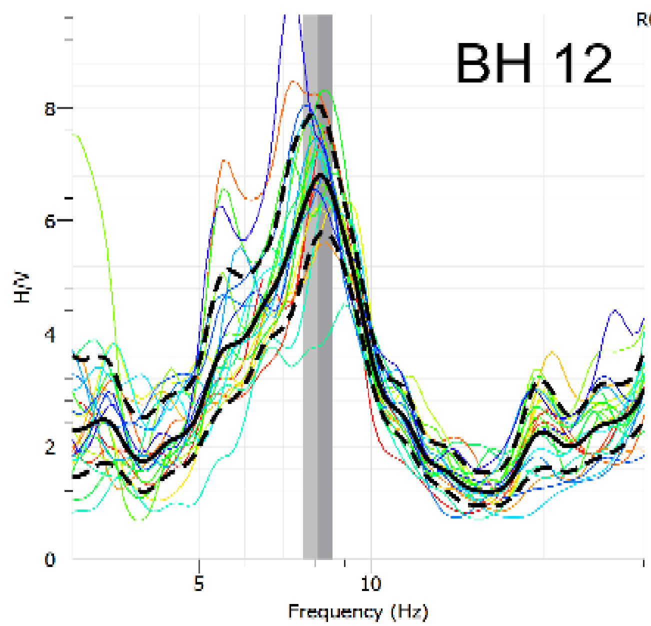

Figure 36: HVSR plots from MUHC borehole 12

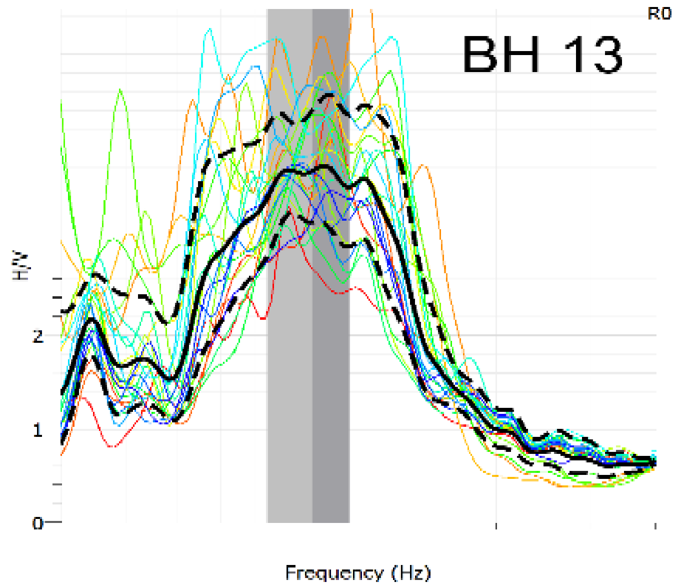

Figure 37: HVSR plots from MUHC borehole 13

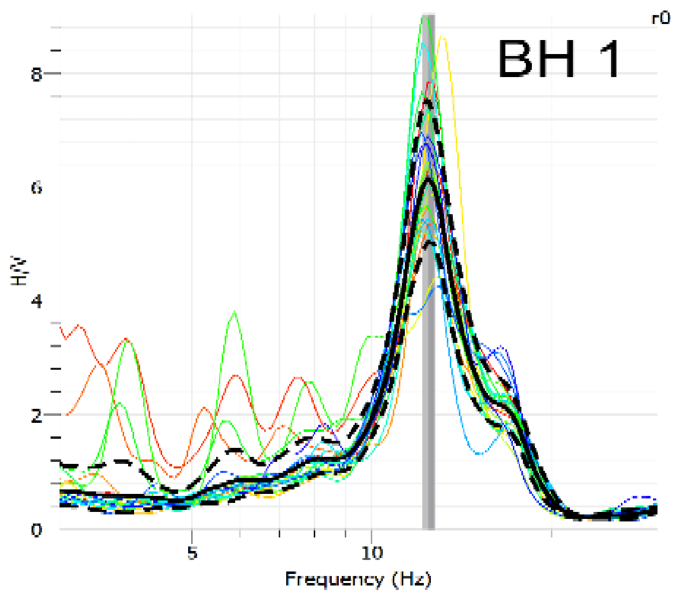

Figure 38: HVSR plots from SHSMO borehole 1

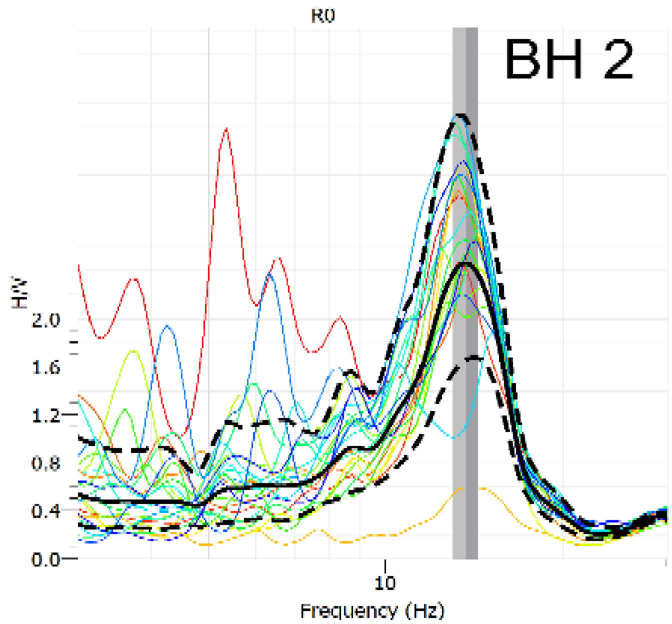

Figure 39: HVSR plots from SHSMO borehole 2

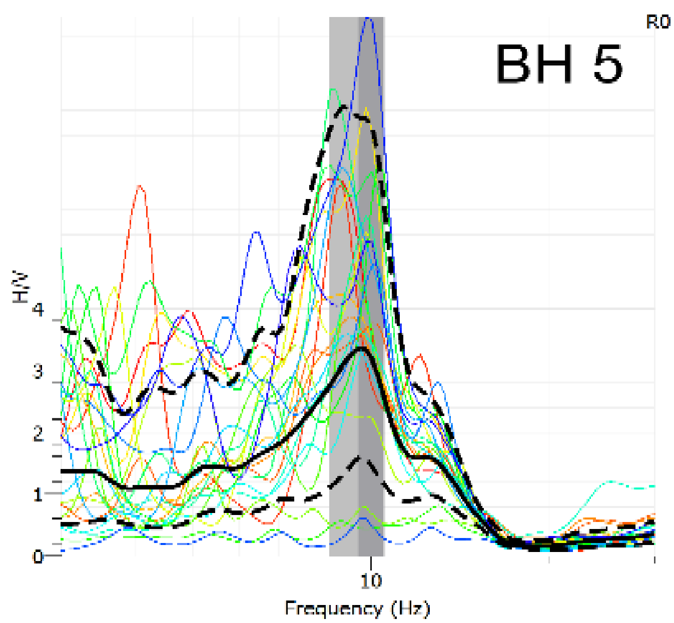

Figure 40: HVSR plots from SHSMO borehole 5

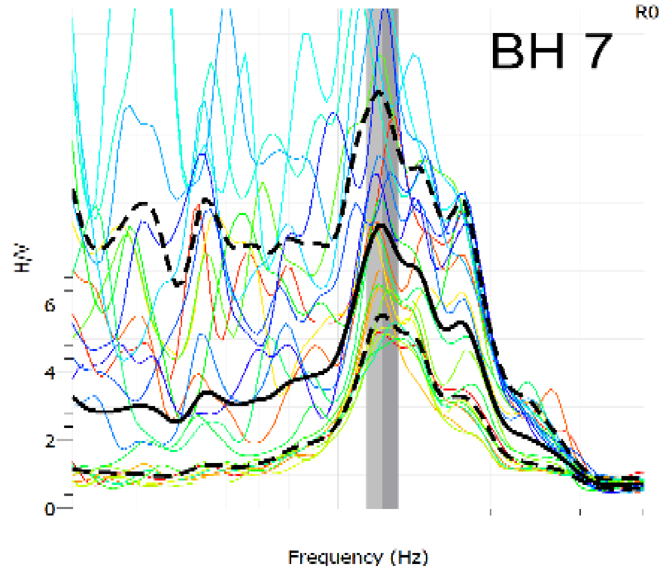

Figure 41: HVSR plots from SHSMO borehole 7

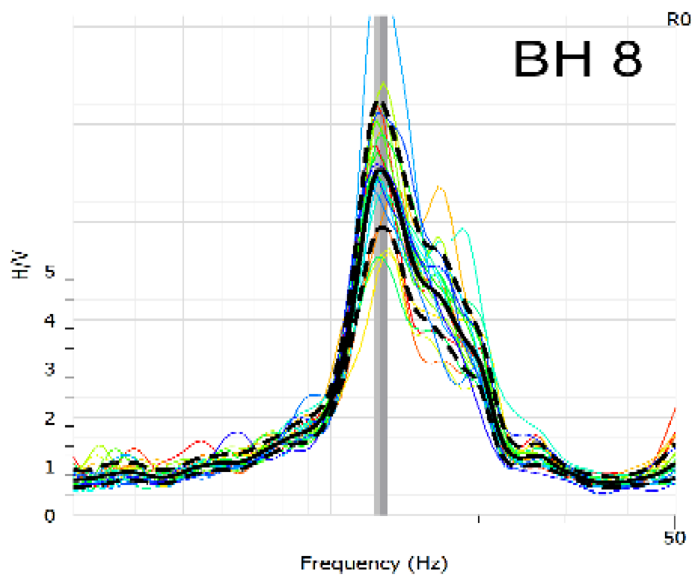

Figure 42: HVSR plots from SHSMO borehole 8

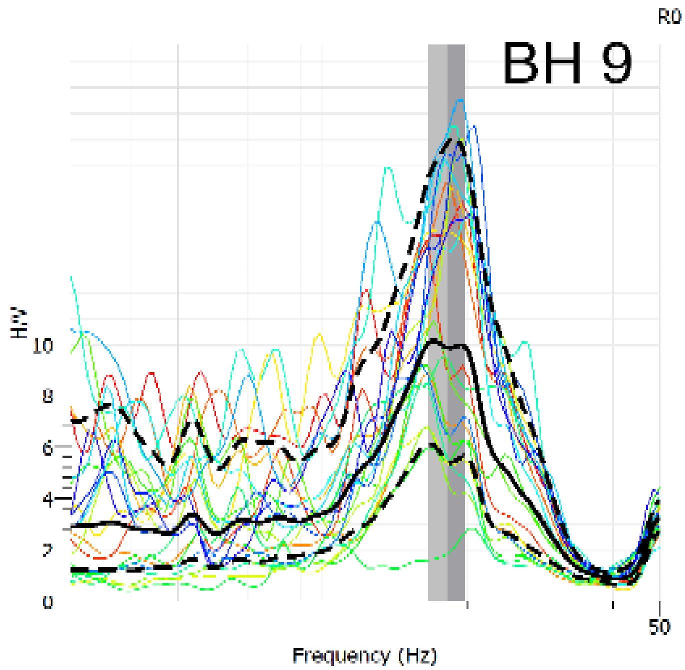

Figure 43: HVSR plots from SHSMO borehole 9

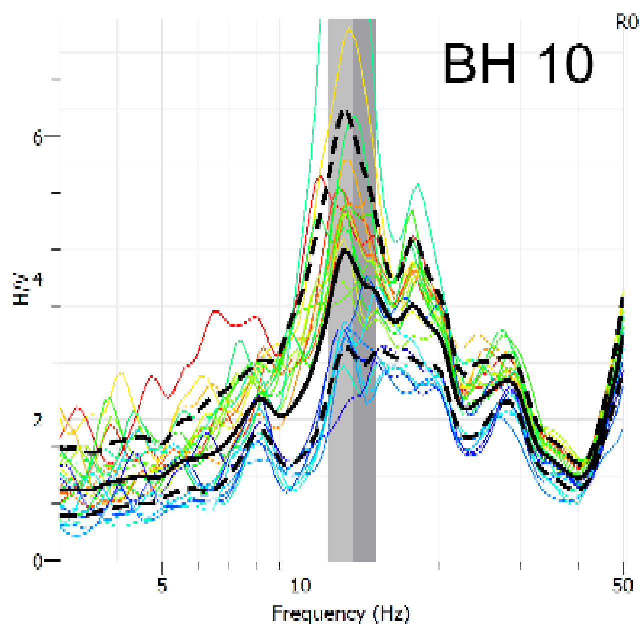

Figure 44: HVSR plots from SHSMO borehole 10

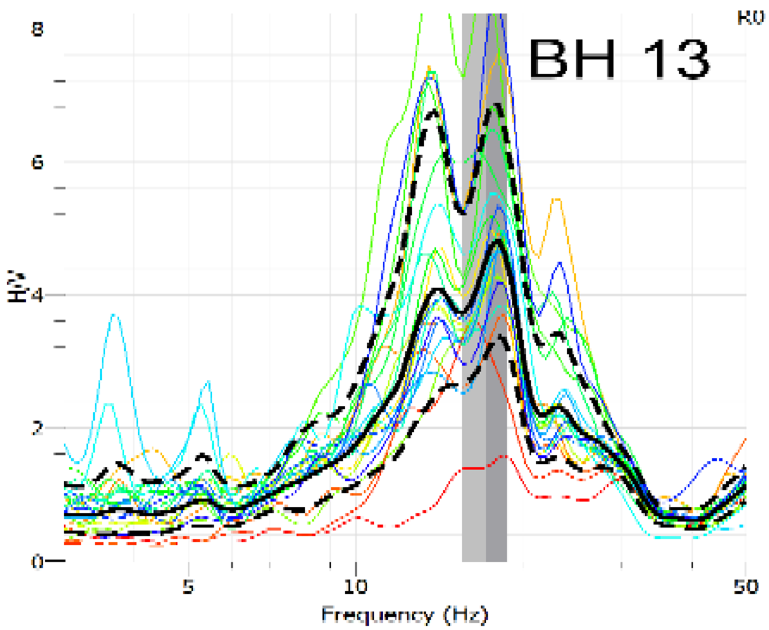

Figure 45: HVSR plots from SHSMO borehole 13

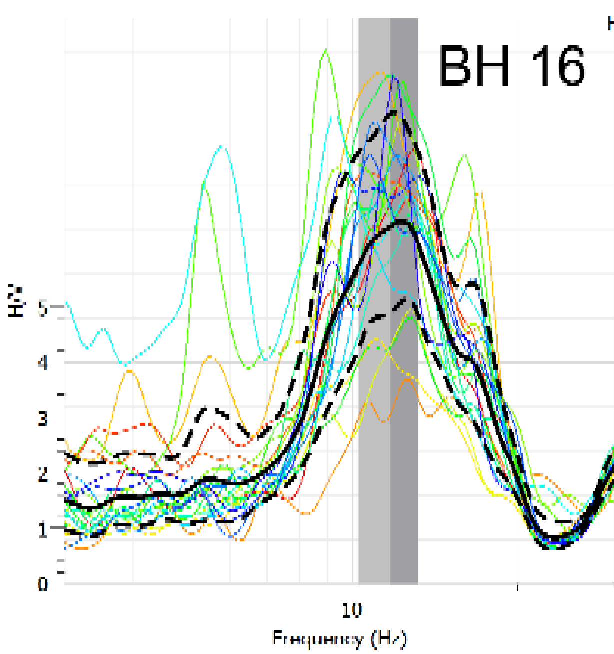

Figure 46: HVSR plots from SHSMO borehole 16

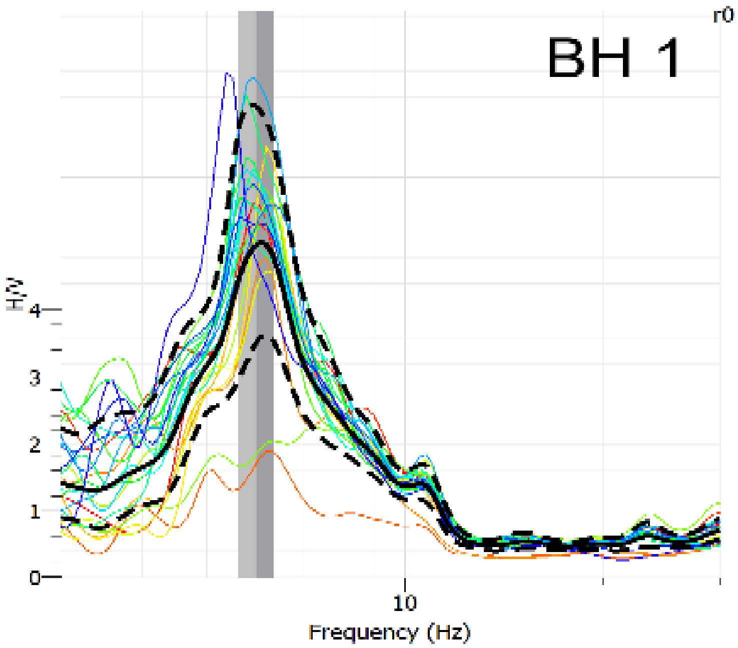

Figure 47: HVSR plots from Stewart Hall borehole 1

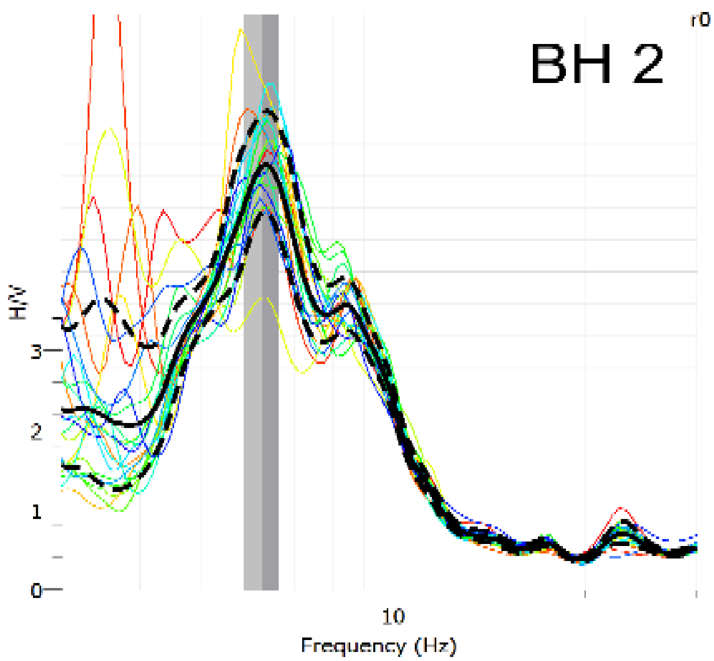

Figure 48: HVSR plots from Stewart Hall borehole 2

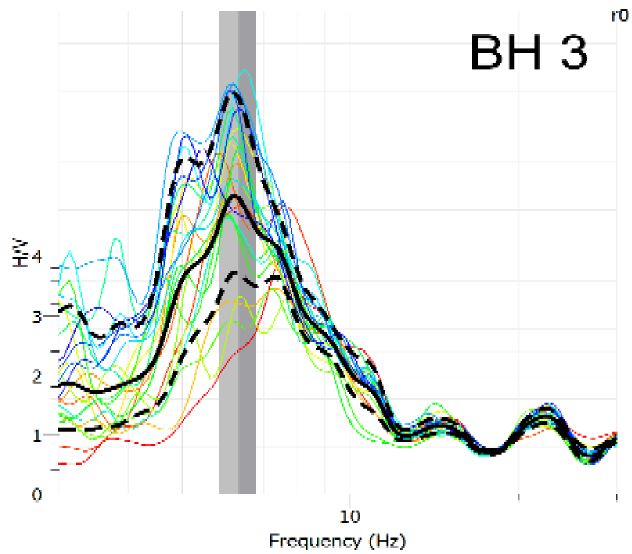

Figure 49: HVSR plots from Stewart Hall borehole 2'

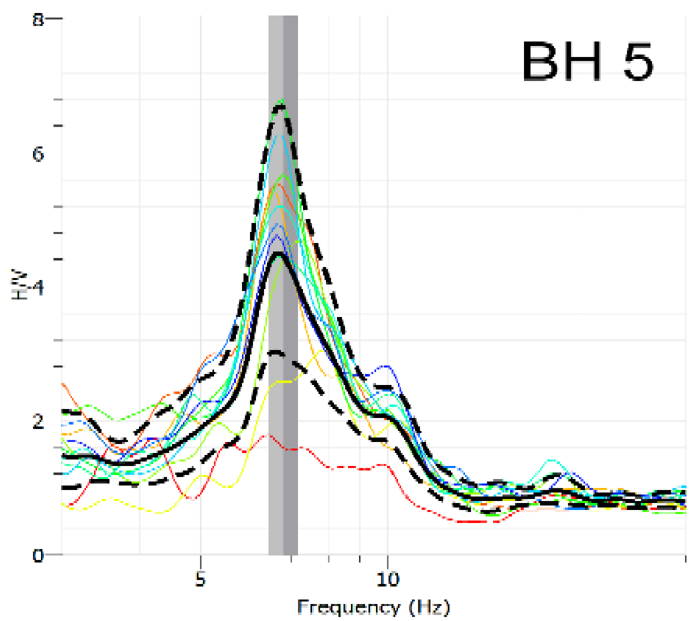

Figure 50: HVSR plots from NextGen borehole 5

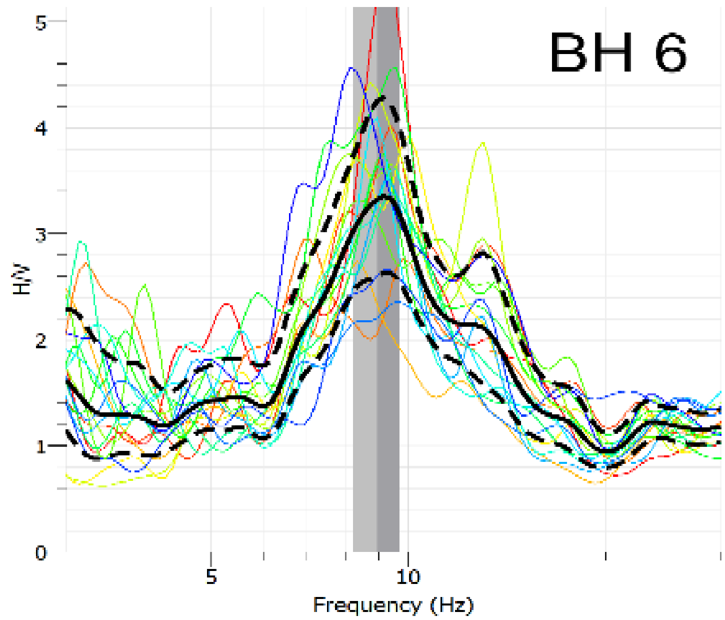

Figure 51: HVSR plots from NextGen borehole 6

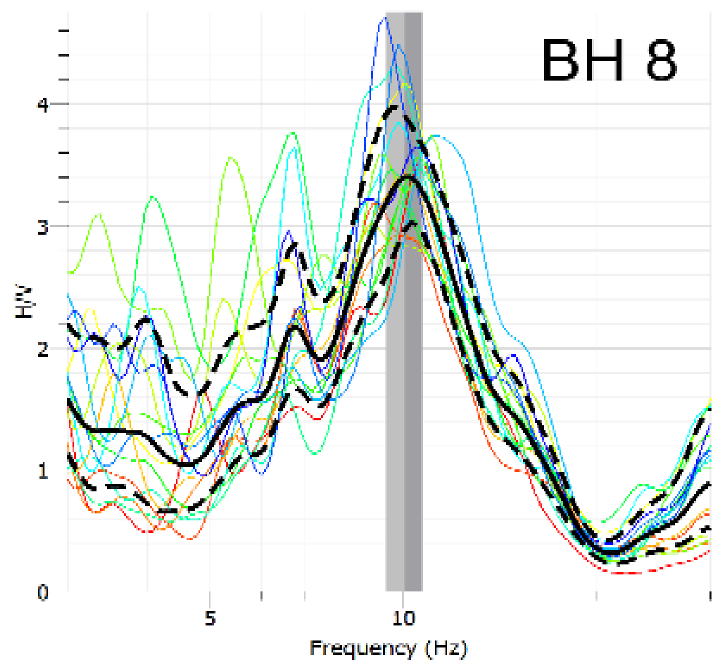

Figure 52: HVSR plots from NextGen borehole 8

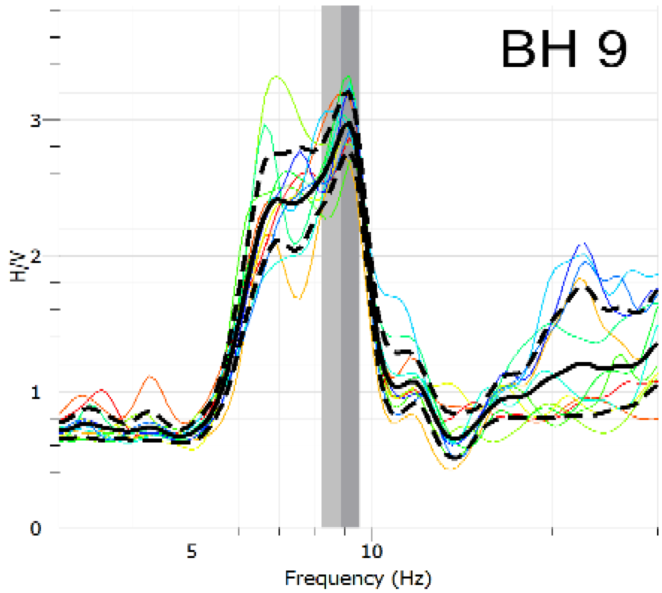

Figure 53: HVSR plots from NextGen borehole 9

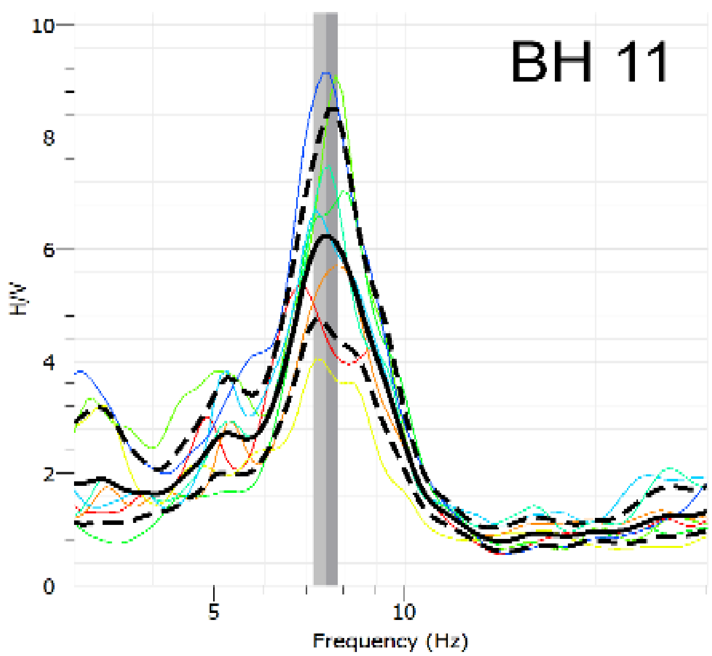

Figure 54: HVSR plots from NextGen borehole 11

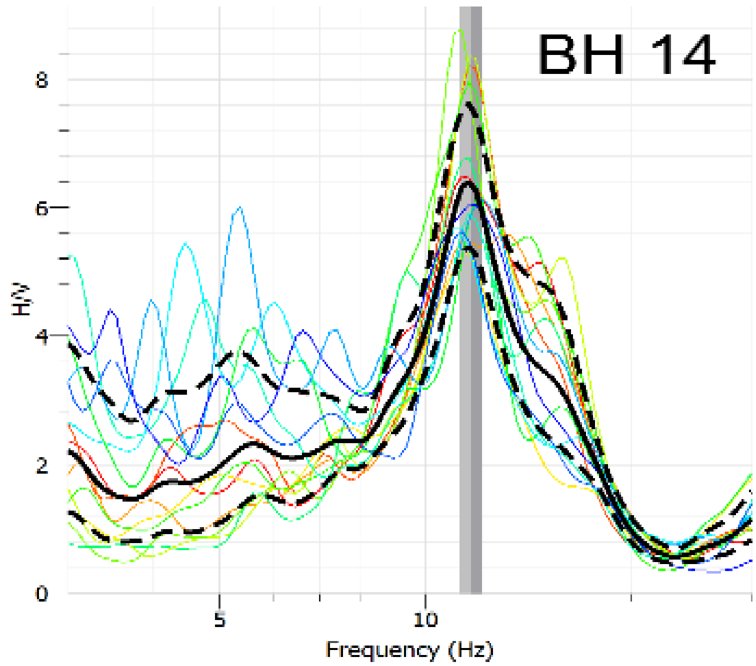

Figure 55: HVSR plots from NextGen borehole 14

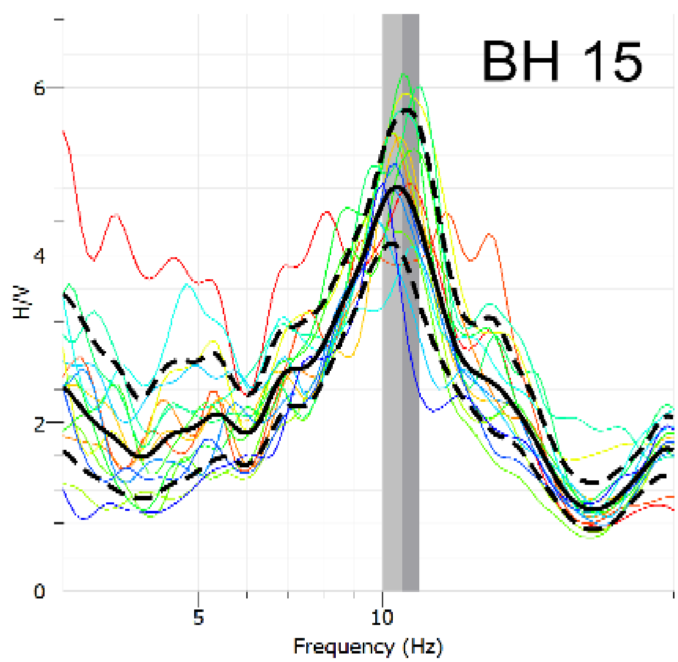

Figure 56: HVSR plots from NextGen borehole 15

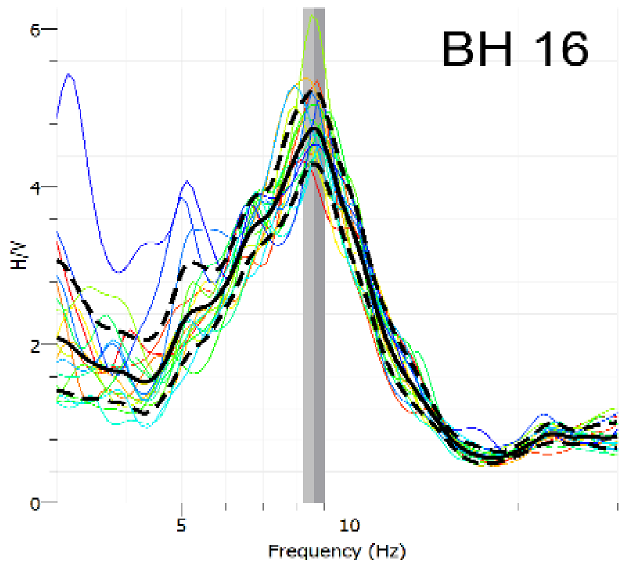

Figure 57: HVSR plots from NextGen borehole 16

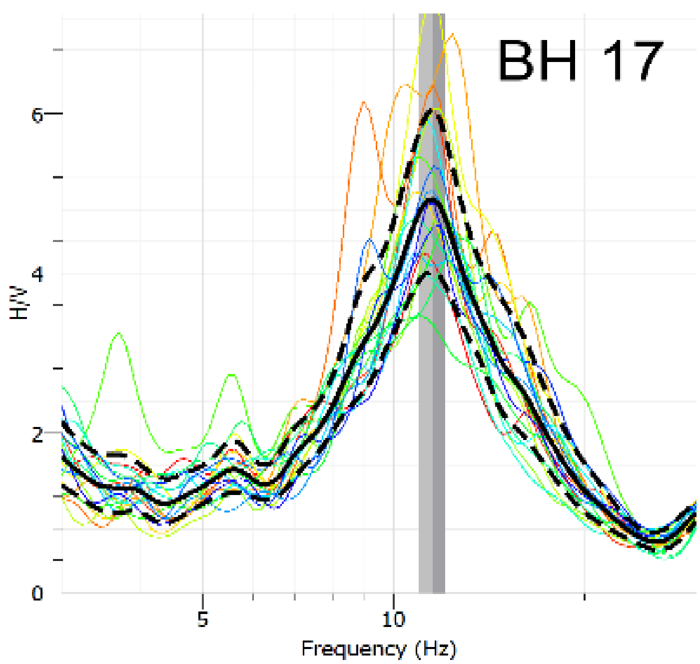

Figure 58: HVSR plots from NextGen borehole 17

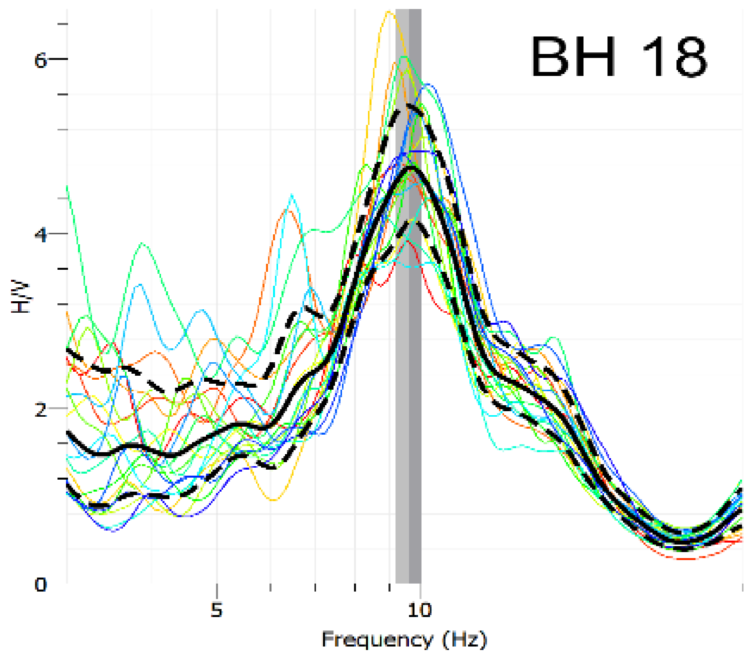

Figure 59: HVSR plots from NextGen borehole 18

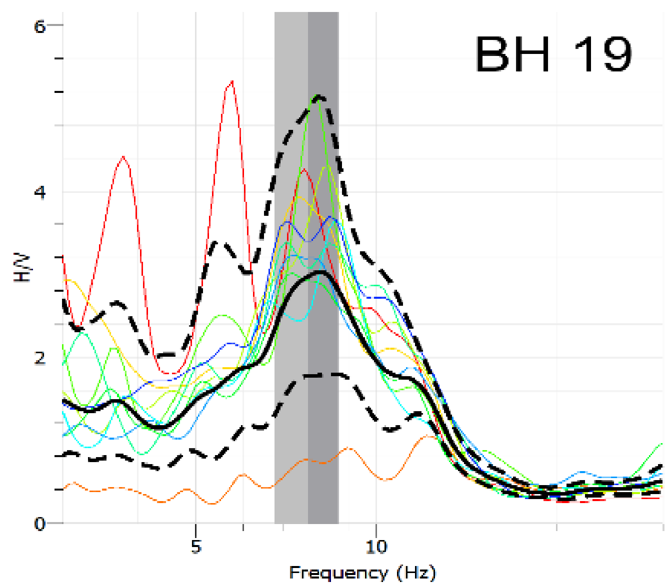

Figure 60: HVSR plots from NextGen borehole 19

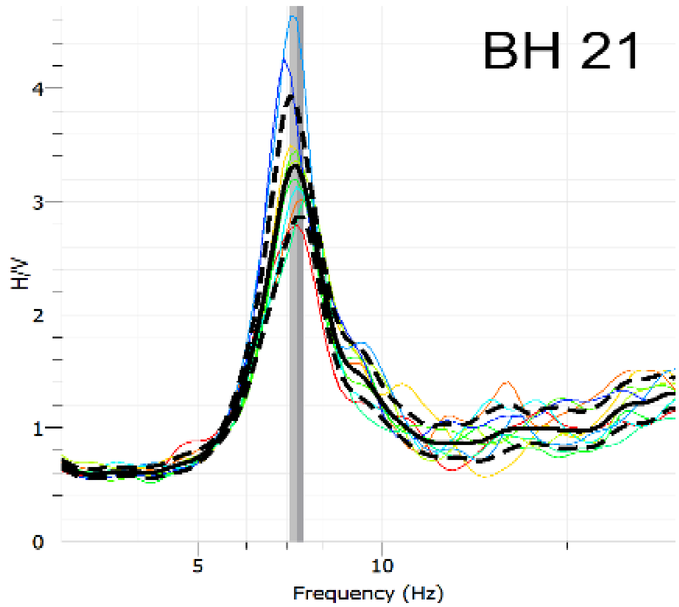

Figure 61: HVSR plots from NextGen borehole 21

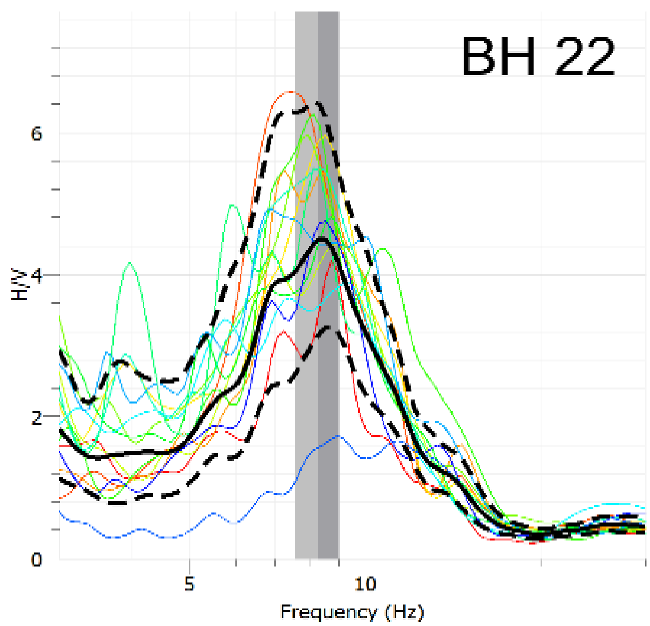

Figure 62: HVSR plots from NextGen borehole 22

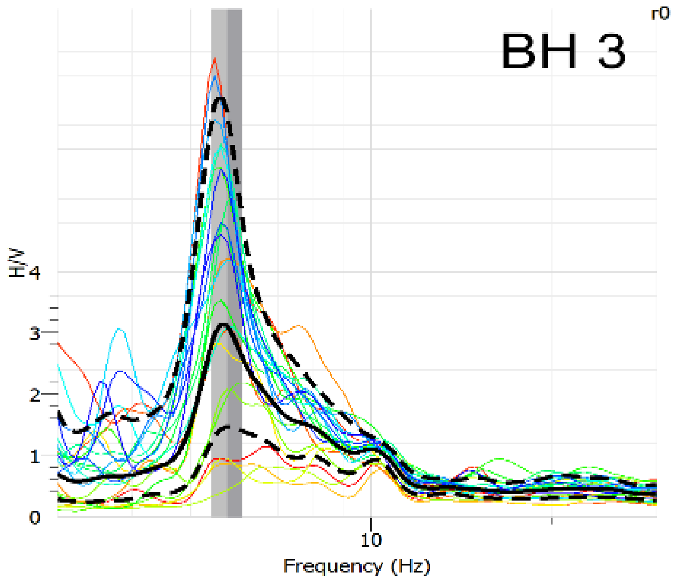

Figure 63: HVSR plots from Virginia Ave Dining borehole 3

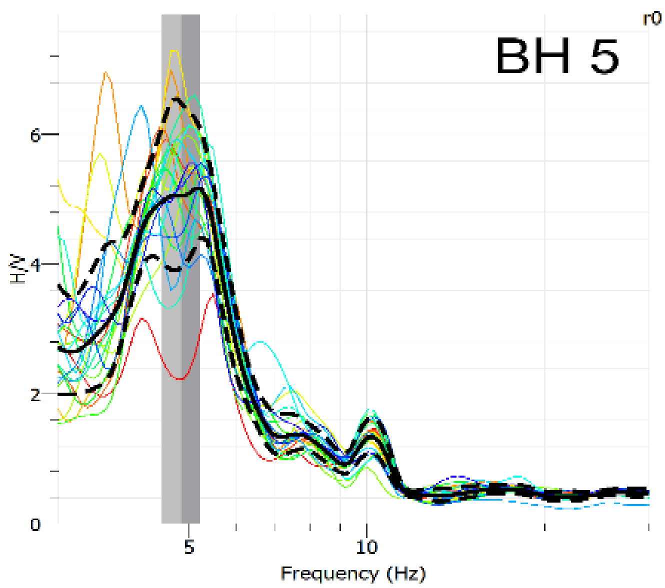

Figure 64: HVSR plots from Virginia Ave Dining borehole 5

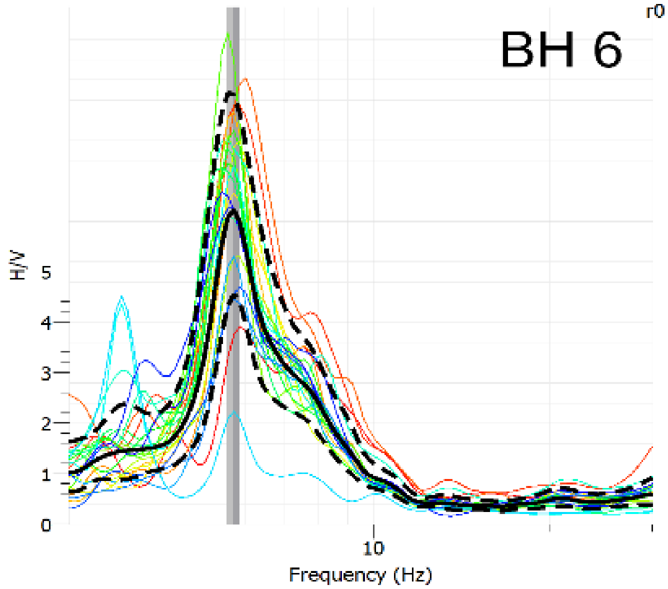

Figure 65: HVSR plots from Virginia Ave Dining borehole 6

APPENDIX C

The V_s profile for soil can also be modeled with a power function relationship that depends on the soil structure and composition (A) and effective stress (σ'_v):

$$V_s = A(\sigma'_v)^m \quad \text{(Eq. 2.1)}$$

The exponent, m, can often be assumed to be about 0.25

If we assumed no water table, the unit weight of soil is ~ 120 pcf and the pressure is 2000 psf, the Eq. 2.1 can be expressed as:

$$V_s = A(120z/2000)^{0.25} \quad \text{(Eq. App. C-1)}$$

$$V_s = A(0.5)z^{0.25} \quad \text{(Eq. App. C-2)}$$

Where z is the depth and V_s is shear wave velocity.

Average the V_s through the slowness average equation, as presented below:

$$V_{s,AVG} = \frac{H}{\sum \frac{Z_i}{V_i}} \quad \text{(Eq. 2.5)}$$

where $V_{s,AVG}$ = average shear velocity; H = total sediment thickness; V_i = shear velocity at depth z; and Z_i= sediment thickness.

If we used both Eq. App. C-1 and Eq. 2.5, we obtained the following:

$$V_{s,AVG} = \frac{H}{\sum \frac{Z_i}{0.5 \, Az^{0.25}}}$$

$$V_{s,AVG} = \frac{H}{\frac{1}{0.5A} \int z^{0.25} dz}$$

$$V_{s,AVG} = \frac{0.5H*A}{\int_0^H z^{0.75}}$$

$$V_{s,AVG} = \frac{0.5H*A}{H^{0.75}}$$

$$V_{s,AVG,slowness} = 0.5(A)H^{0.25} \qquad \text{(Eq. App. C-3)}$$

Where H is the depth and V_s is shear wave velocity.

Average the V_s through the simple weighted average, as presented below:

$$V_{s,AVG} = \frac{\sum V_i Z_i}{H} \qquad \text{(Eq. 2.4)}$$

where $V_{s,AVG}$ is the average V_s ; H is the total sediment thickness; V_i is the V_S at depth z; and Z_i is the sediment thickness of individual layers.

If we used both Eq. App. C-1 and Eq. 2.4, we obtained the following:

$$V_{s,AVG} = \frac{\int A(0.5)z^{0.25}dz}{H}$$

$$V_{s,AVG} = \frac{A(0.5)\int z^{.025}dz}{H}$$

$$V_{s,AVG} = \frac{A(0.5)\int_0^H \frac{z^{1.25}}{1.25}}{H}$$

$$V_{s,AVG} = \frac{A(0.5)H^{1.25}}{1.25H}$$

$$V_{s,AVG} = \frac{A(0.5)H^{0.25}}{1.25} \qquad \text{(Eq. App. C-4)}$$

The simple relationship, as expressed to be:

$$f_r = V_{s,AVG}/4H \qquad \text{(Eq. 2.3)}$$

where f_r is the resonant frequency, $V_{s,AVG}$ is the average shear wave velocity of the layers and the H is sediment thickness.

Use the Eq. 2.3 and Eq. App. C-3, the slowness average can be expressed as:

$$f_r = \frac{0.5(A)H^{0.25}}{4H}$$

$$f_r = \frac{0.5(A)H^{-0.75}}{4}$$

$$f_r = 0.125AH^{-0.75}$$

$$H^{-0.75} = \frac{f_r}{0.125(A)}$$

$$H = \frac{f_r^{\ -4/3}}{0.125^{-4/3}(A^{-4/3})}$$

$$H = A^{\frac{4}{3}}(0.125^{4/3})\ f_r^{\ -4/3} \qquad \text{(Eq. App. C-5)}$$

$$H = A^{*}f_r^{\ -1.333} \qquad \text{(Eq. App. C-5)}$$

Assuming A is ~700 ft/s based on Stokoe et al. (2014), the Eq. App. C-5 can be expressed as:

$$H = 388\ f_r^{\ -1.333} \qquad \text{(Eq. App. C-6)}$$

Use the Eq. 2.3 and Eq. App. C-4, the weighted average can be expressed as:

$$f_r = \frac{0.5(A)H^{0.25}}{1.25 * 4H}$$

$$f_r = \frac{0.5(A)H^{0.25}}{6H}$$

$$f_r = \frac{0.5(A)H^{-0.75}}{6}$$

$$H^{-0.75} = \frac{f_r}{0.083(A)}$$

$$H = \frac{{f_r}^{-4/3}}{0.083^{-4/3}(A^{-4/3})}$$

$$H = A^{\frac{4}{3}}(0.083^{4/3})\ {f_r}^{-4/3} \qquad \text{(Eq. App. C-7)}$$

$$H = A^{*}{f_r}^{-1.333} \qquad \text{(Eq. App. C-7)}$$

Assuming A is ~700 ft/s based on Stokoe et al. (2014), the Eq. App. C-5 can be expressed as:

$$H = 288\ {f_r}^{-1.333} \qquad \text{(Eq. App. C-8)}$$

APPENDIX D

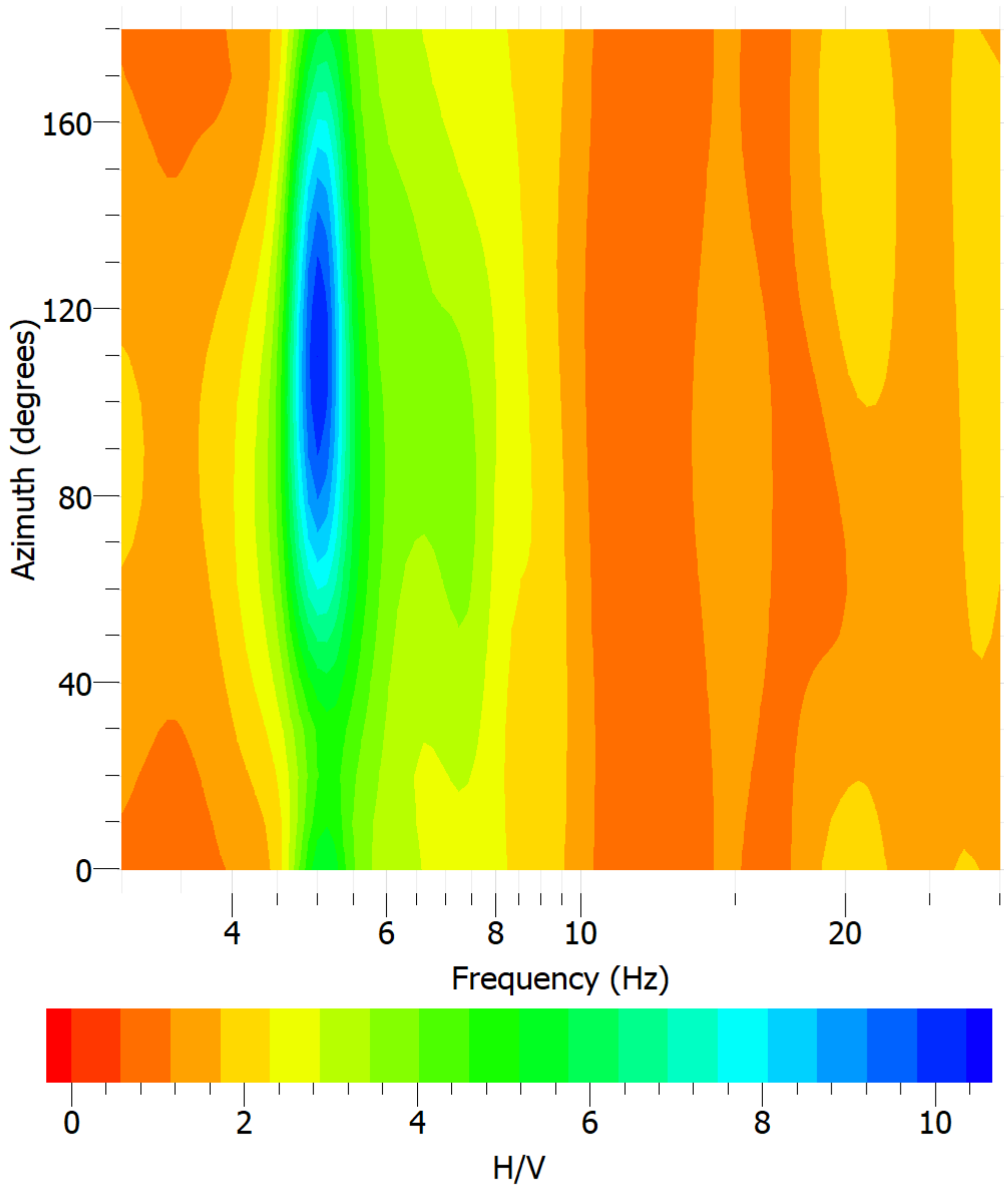

Figure 1: Ellis Library Borehole 1

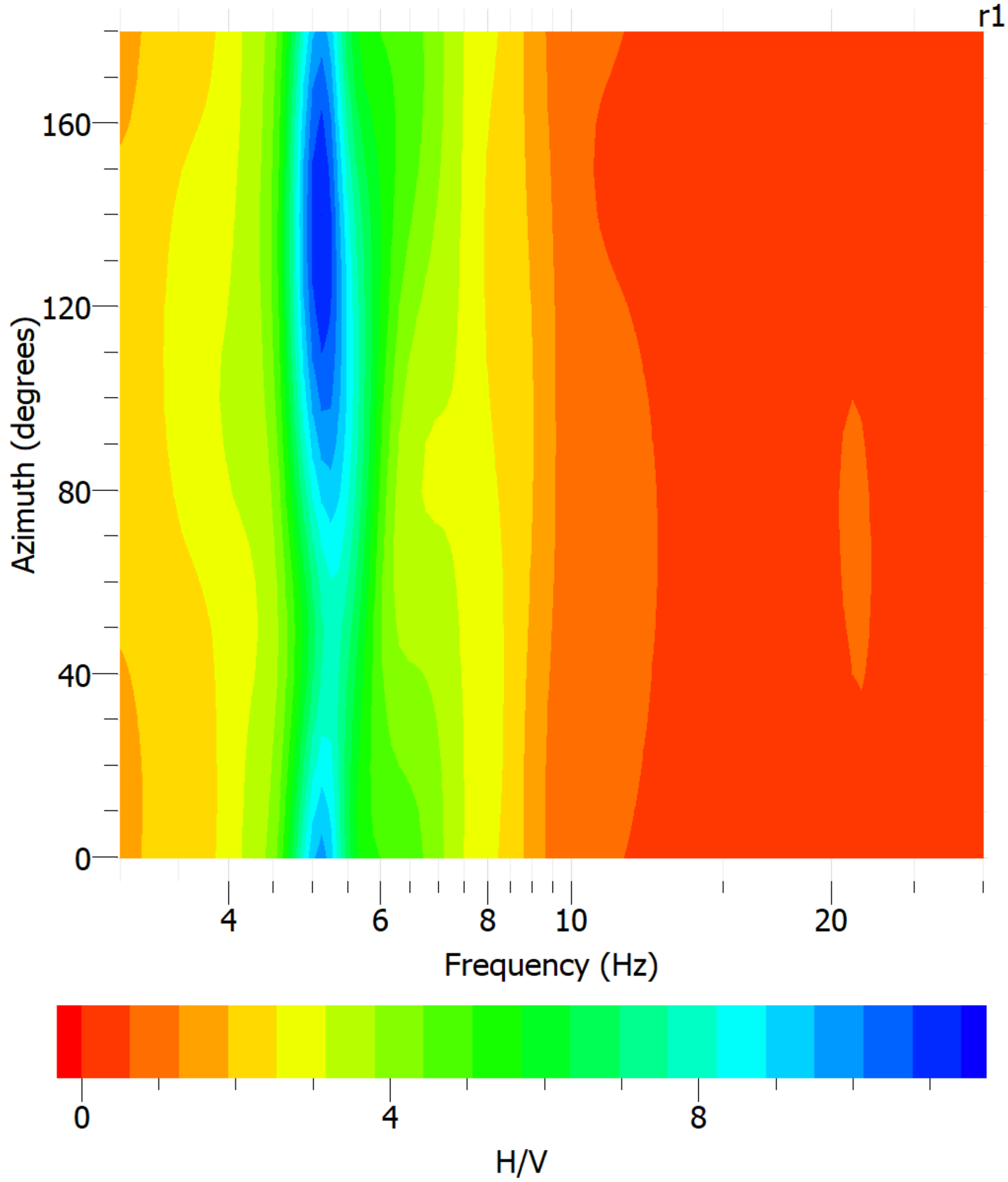

Figure 2: Ellis Library Borehole 2

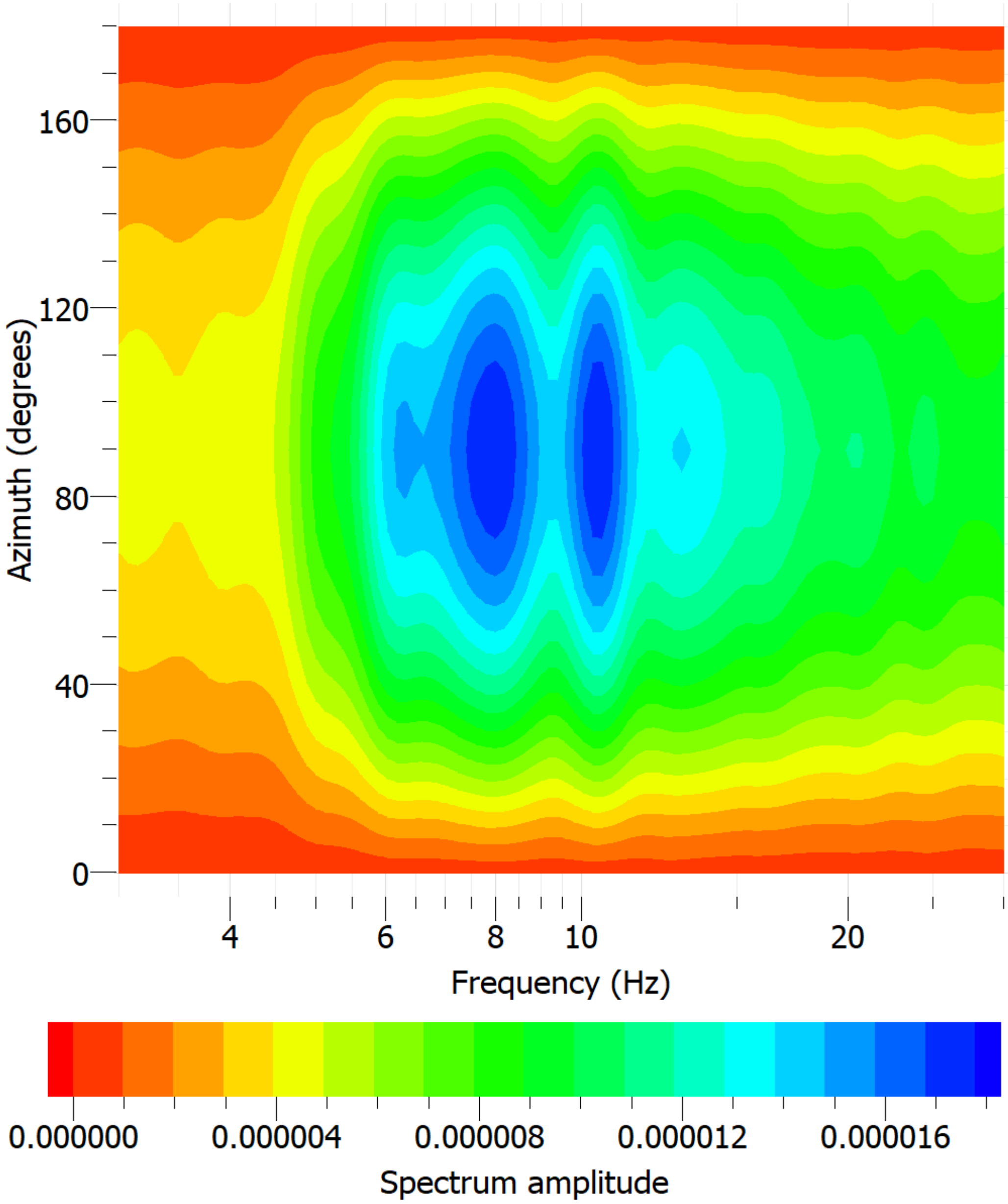

Figure 3: Ellis Library Borehole 3

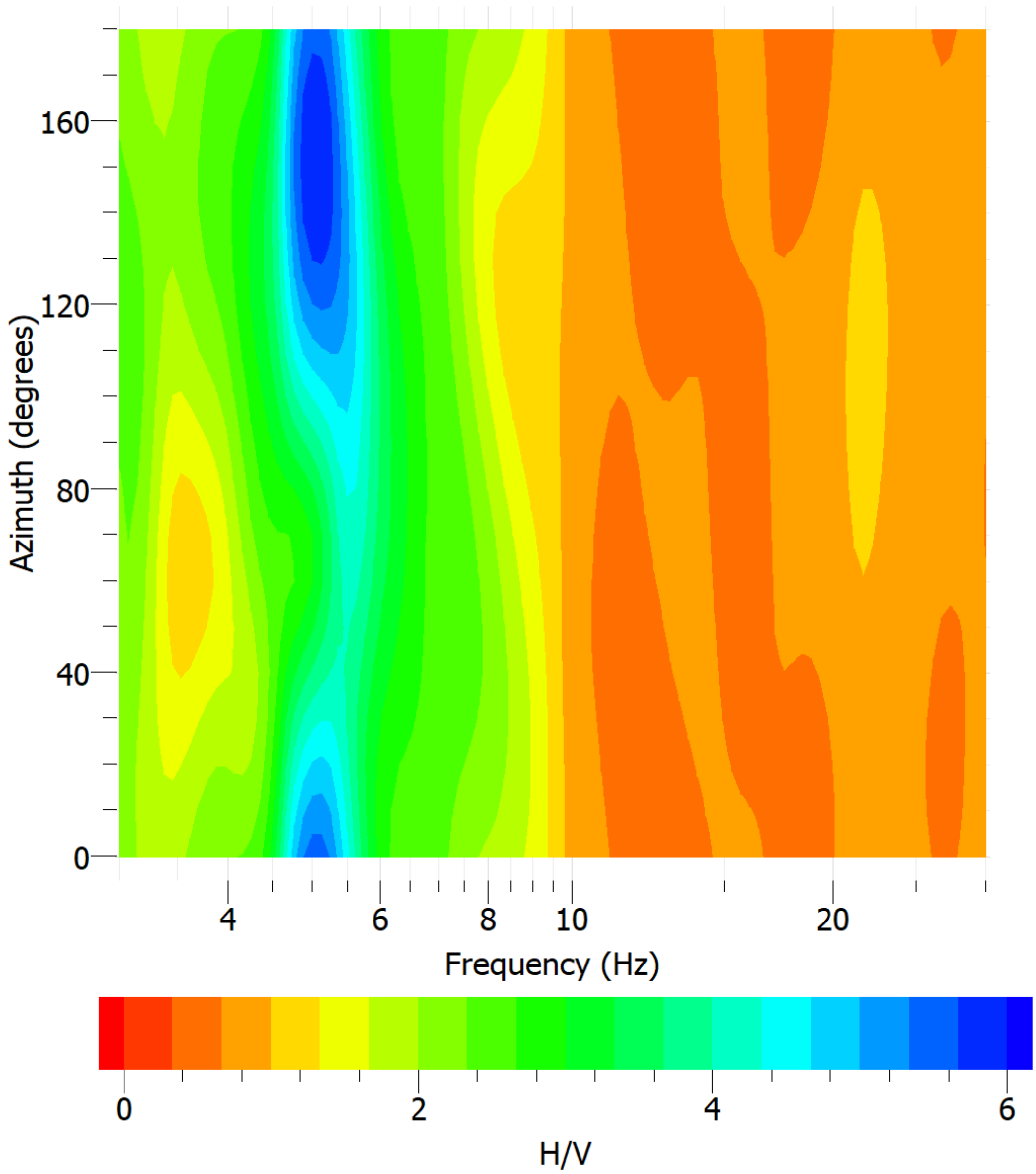

Figure 4: Ellis Library Borehole 4

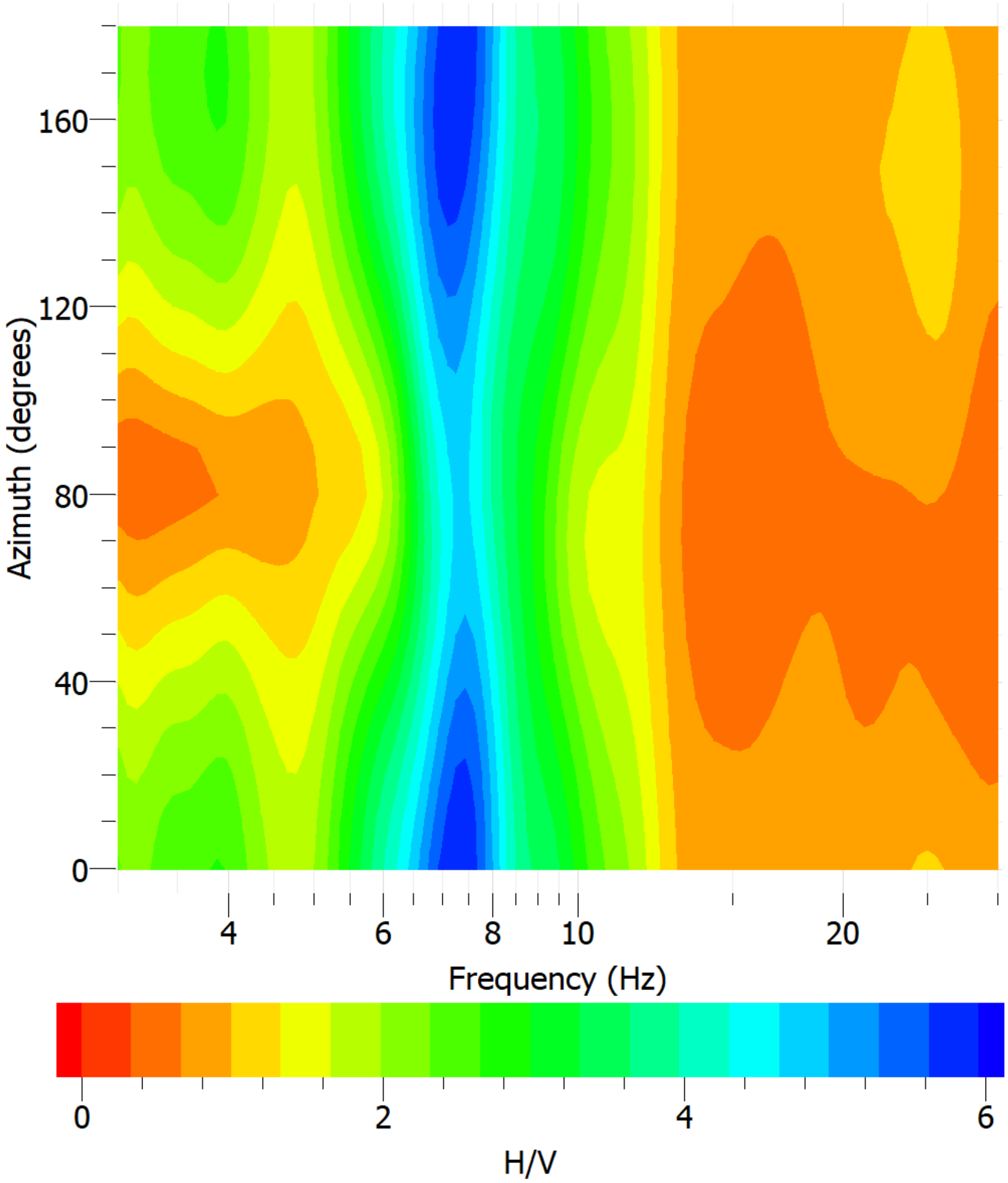

Figure 5: Gateway Borehole 1

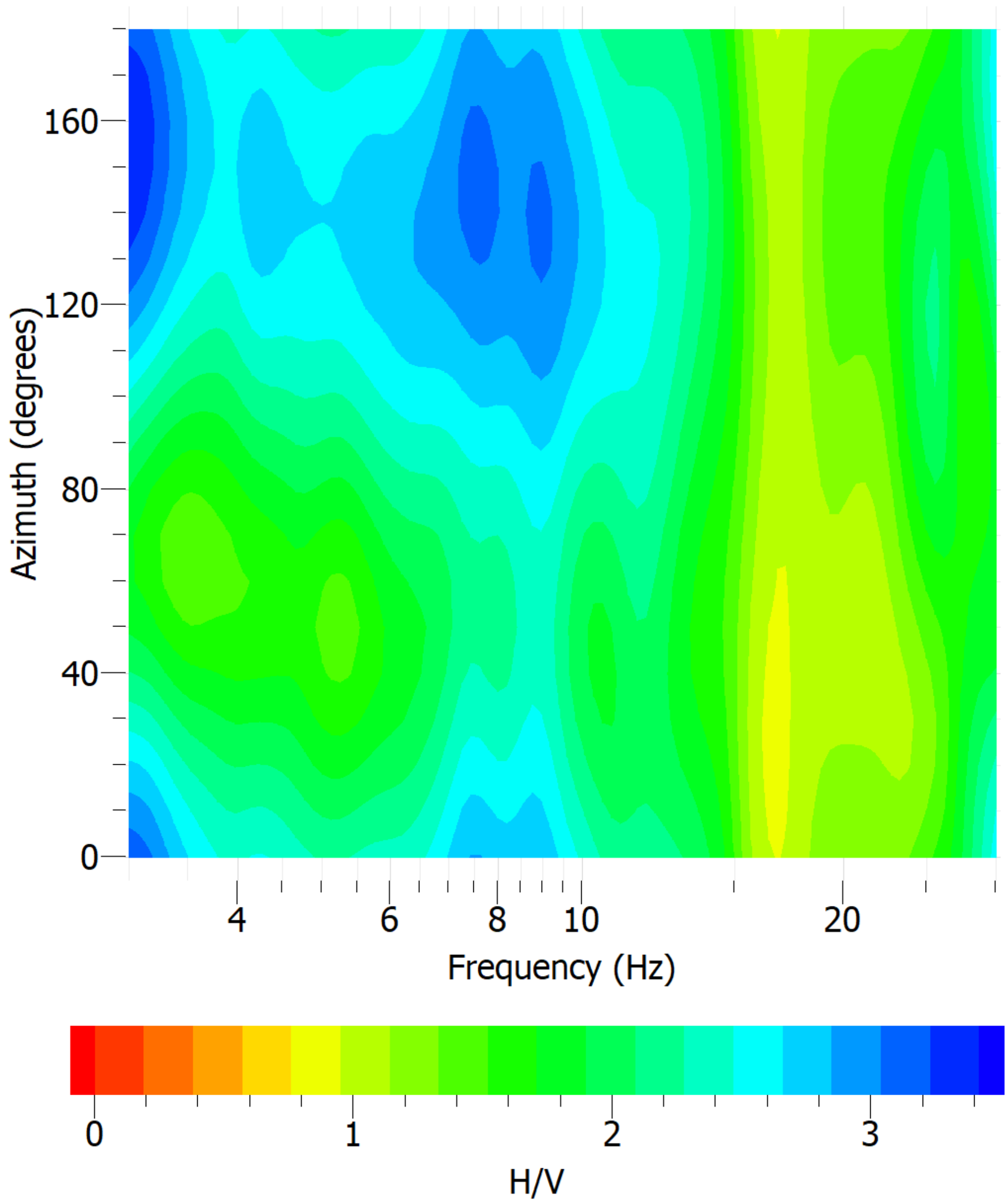

Figure 6: Gateway Borehole 2

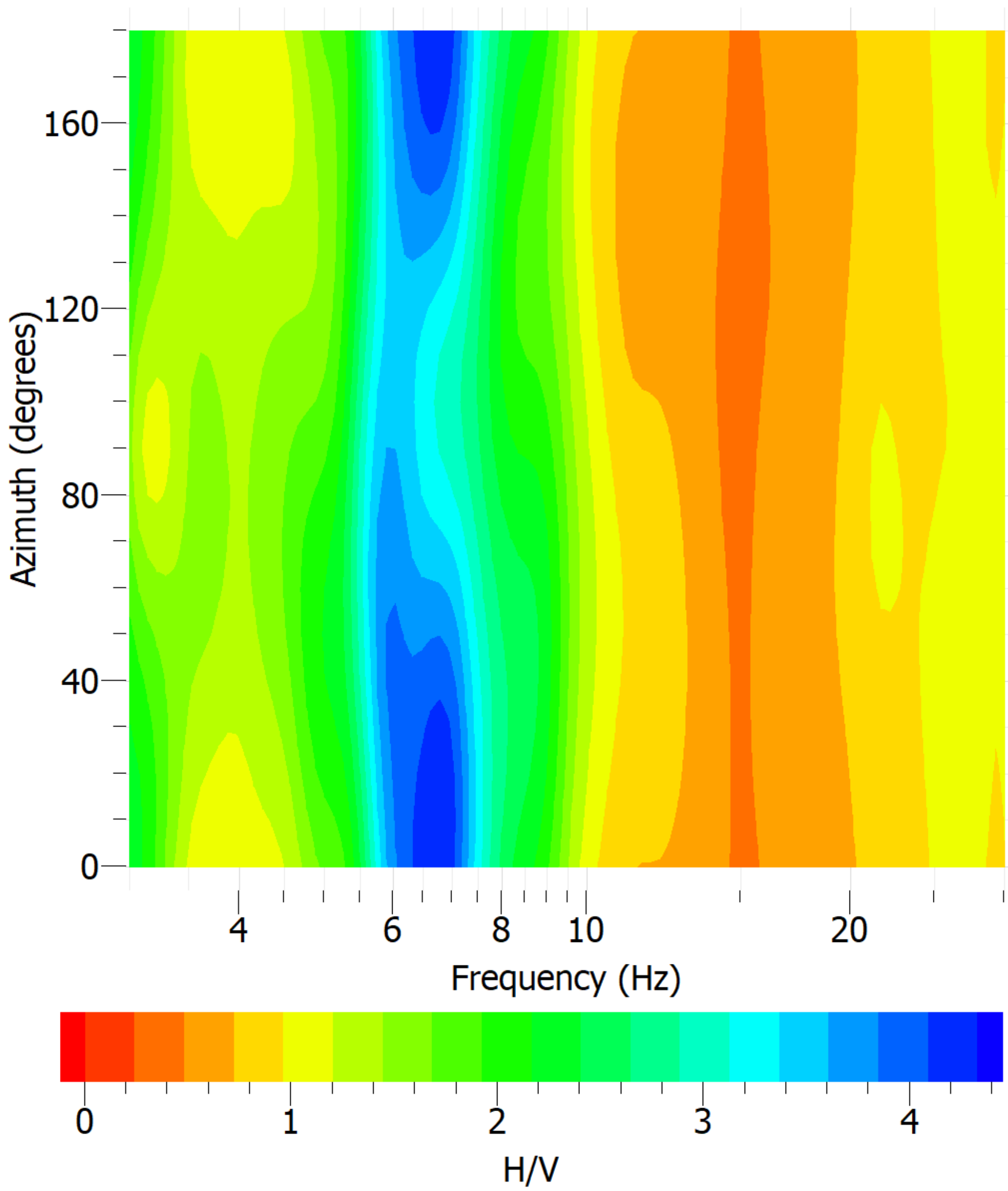

Figure 7: Gateway Borehole 6

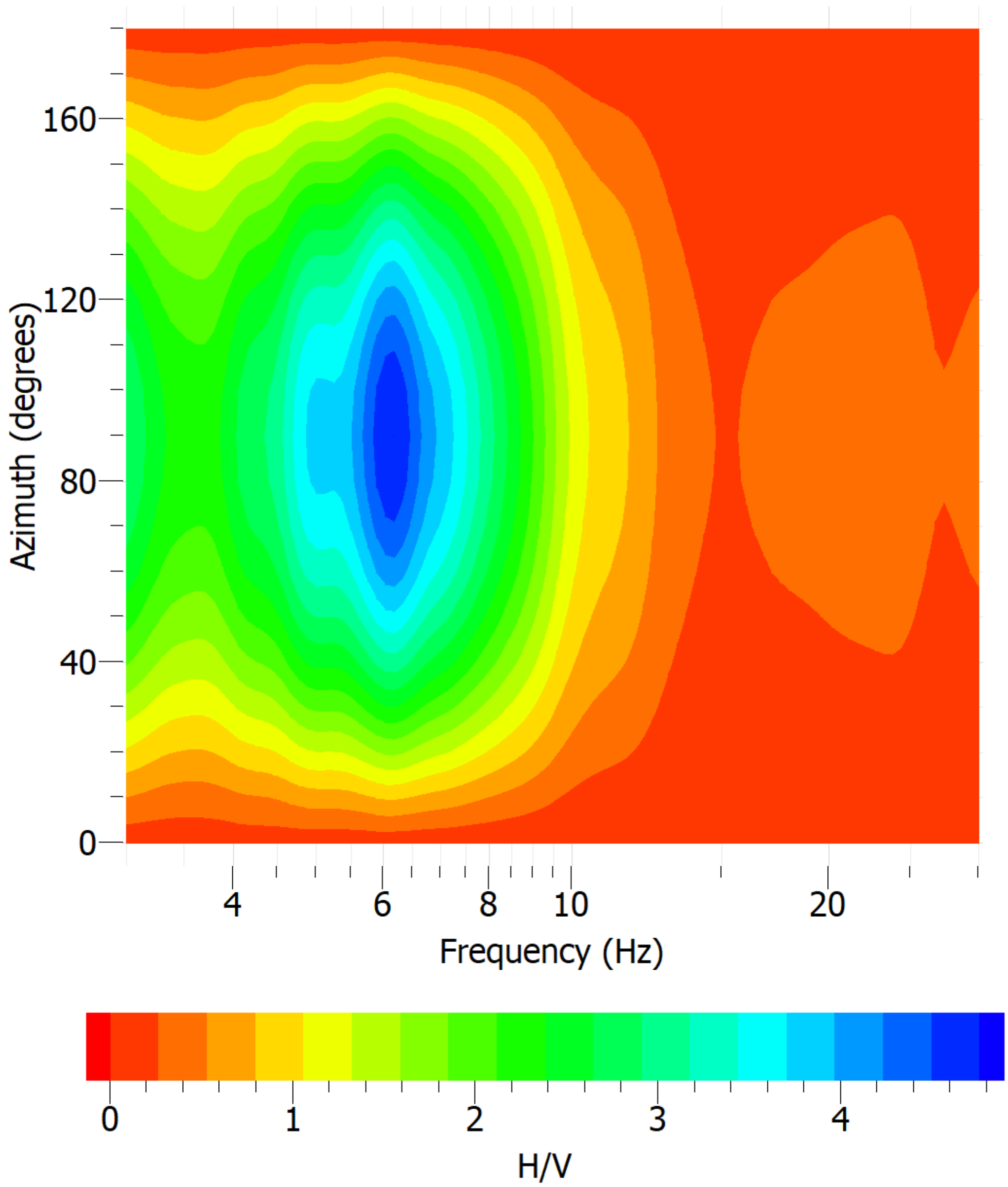

Figure 8: Gateway Borehole 7

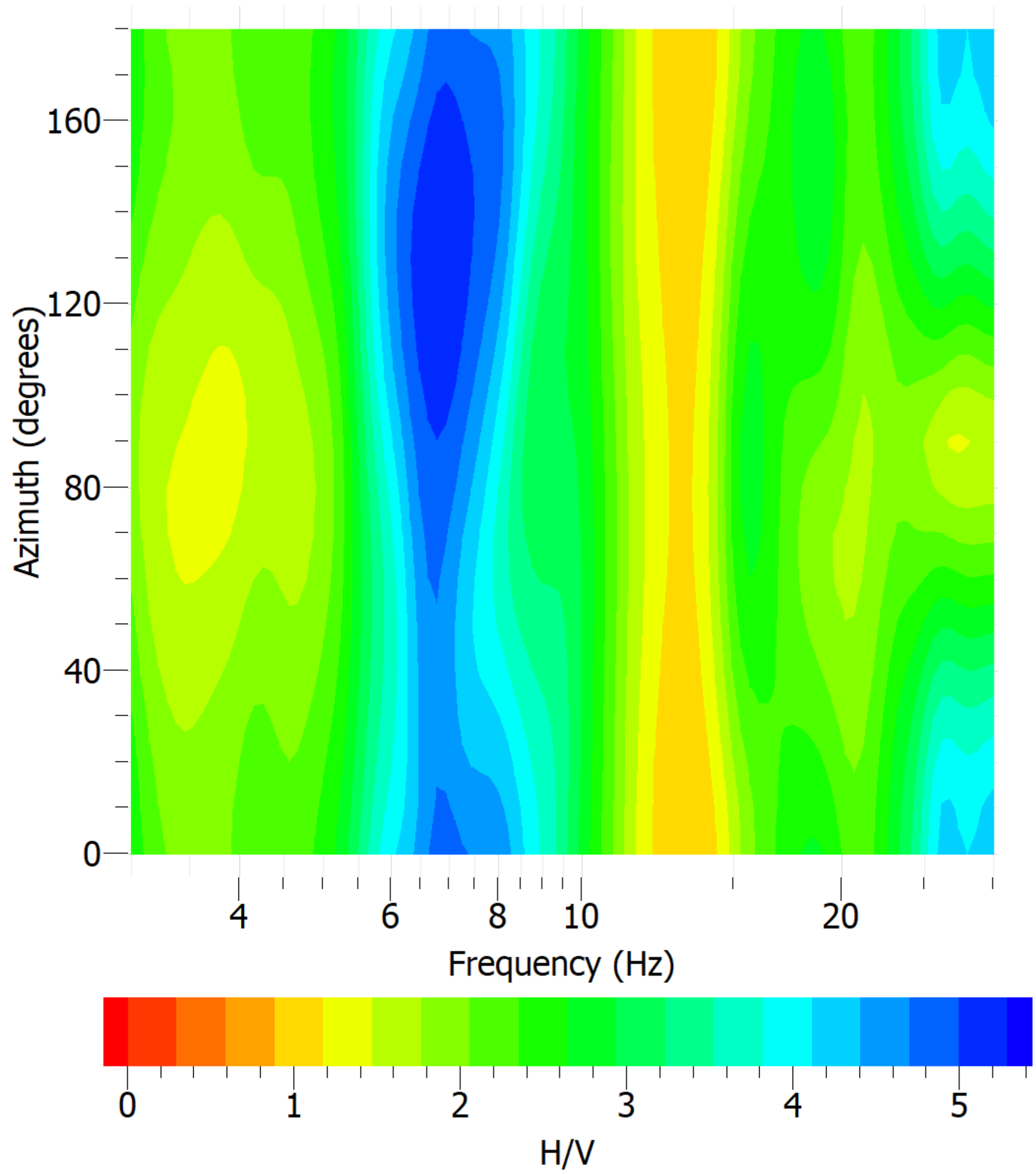

Figure 9: Gateway Borehole 11

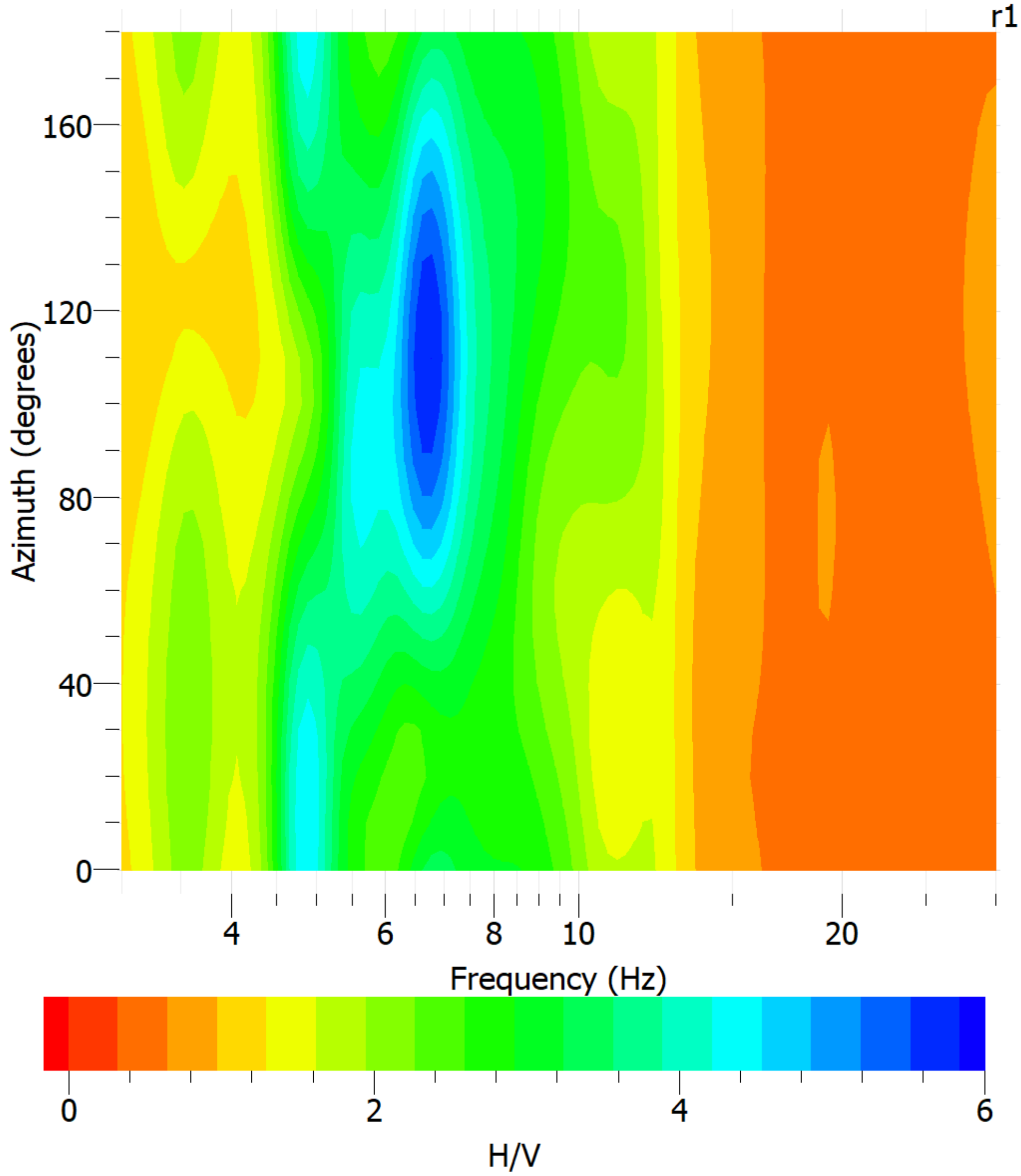

Figure 10: Journalism Borehole 2

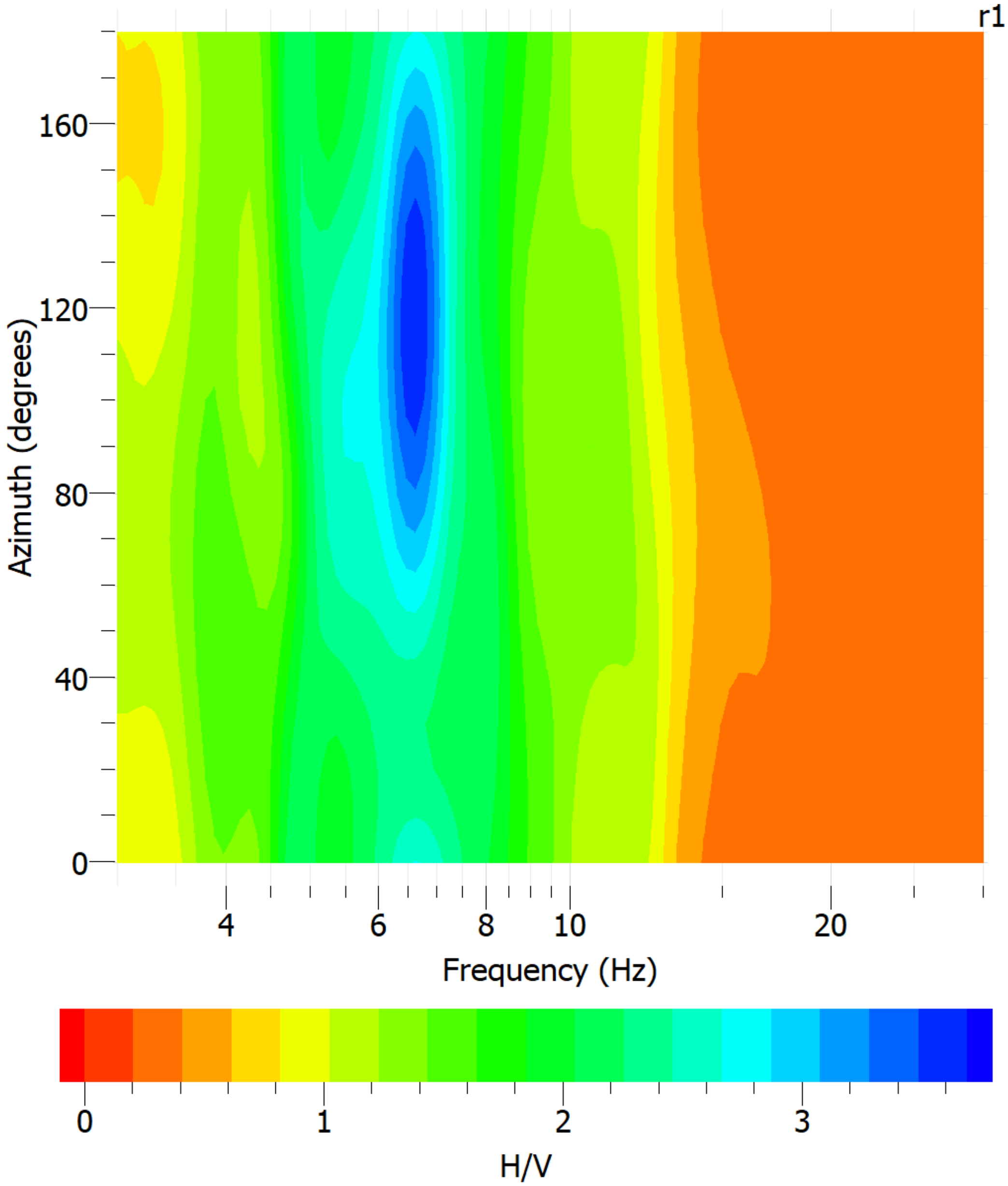

Figure 11: Journalism Borehole 5

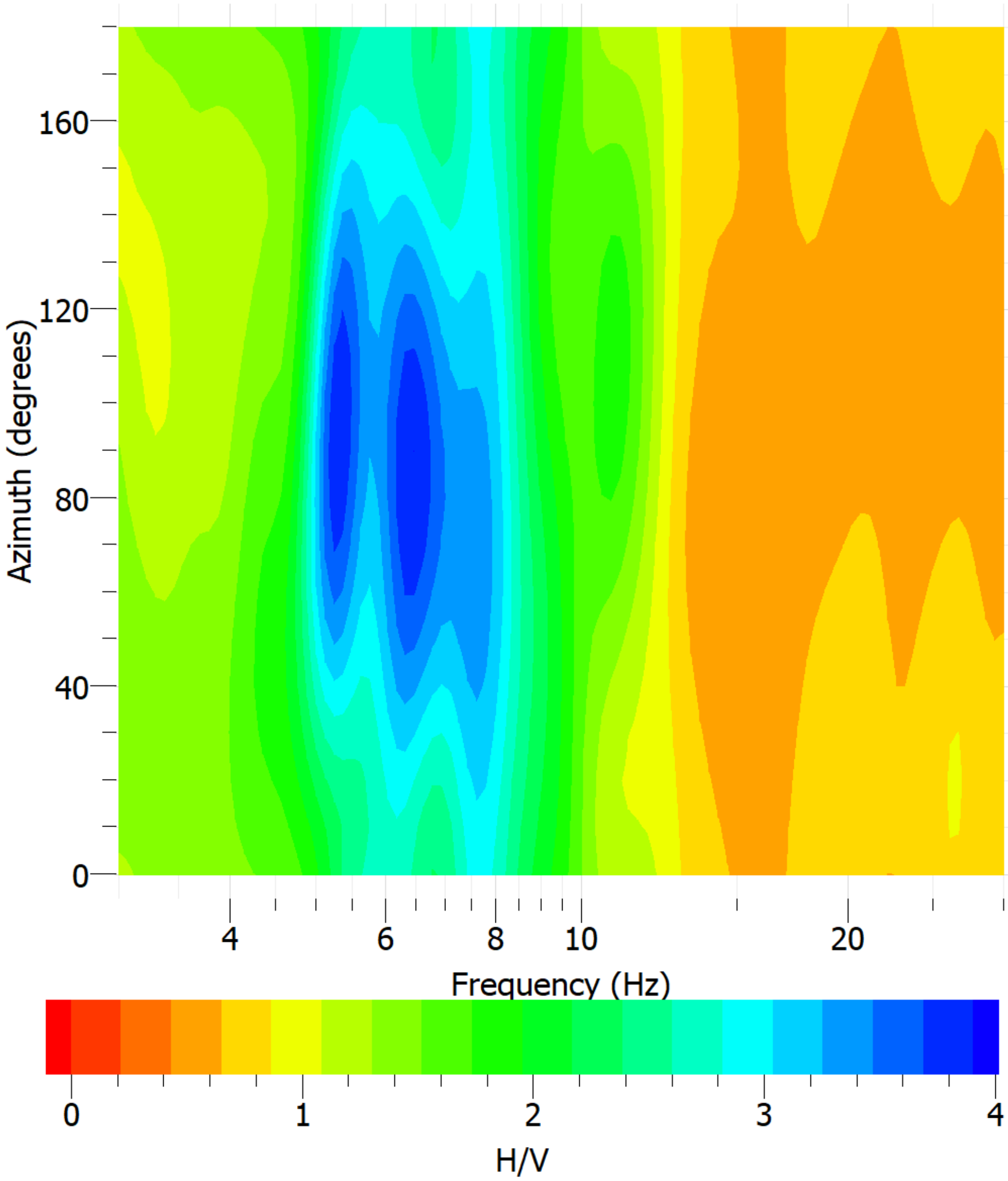

Figure 12: Journalism Borehole 6

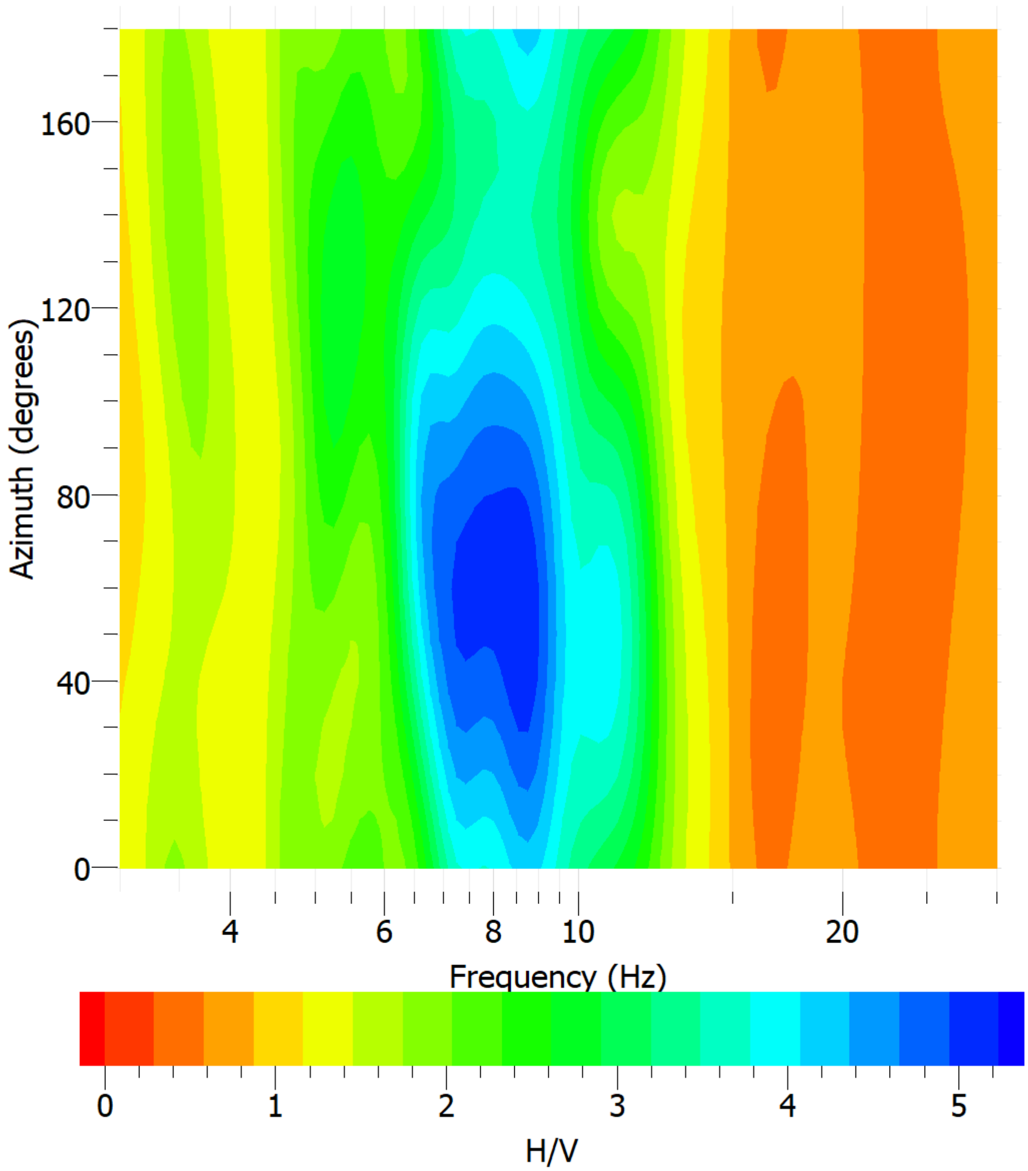

Figure 13: Journalism Borehole 7

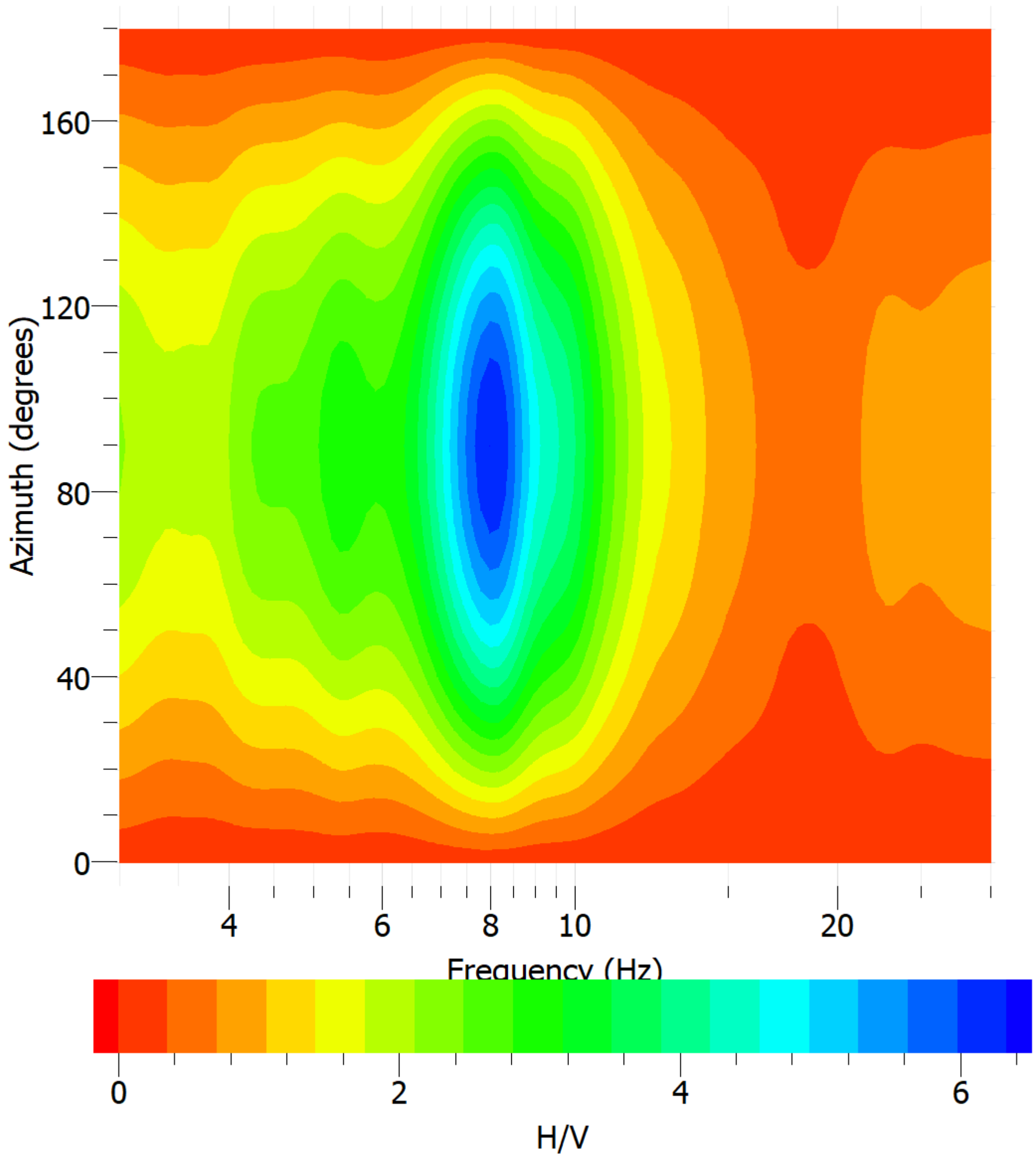

Figure 14: Lee’s Hall borehole 1

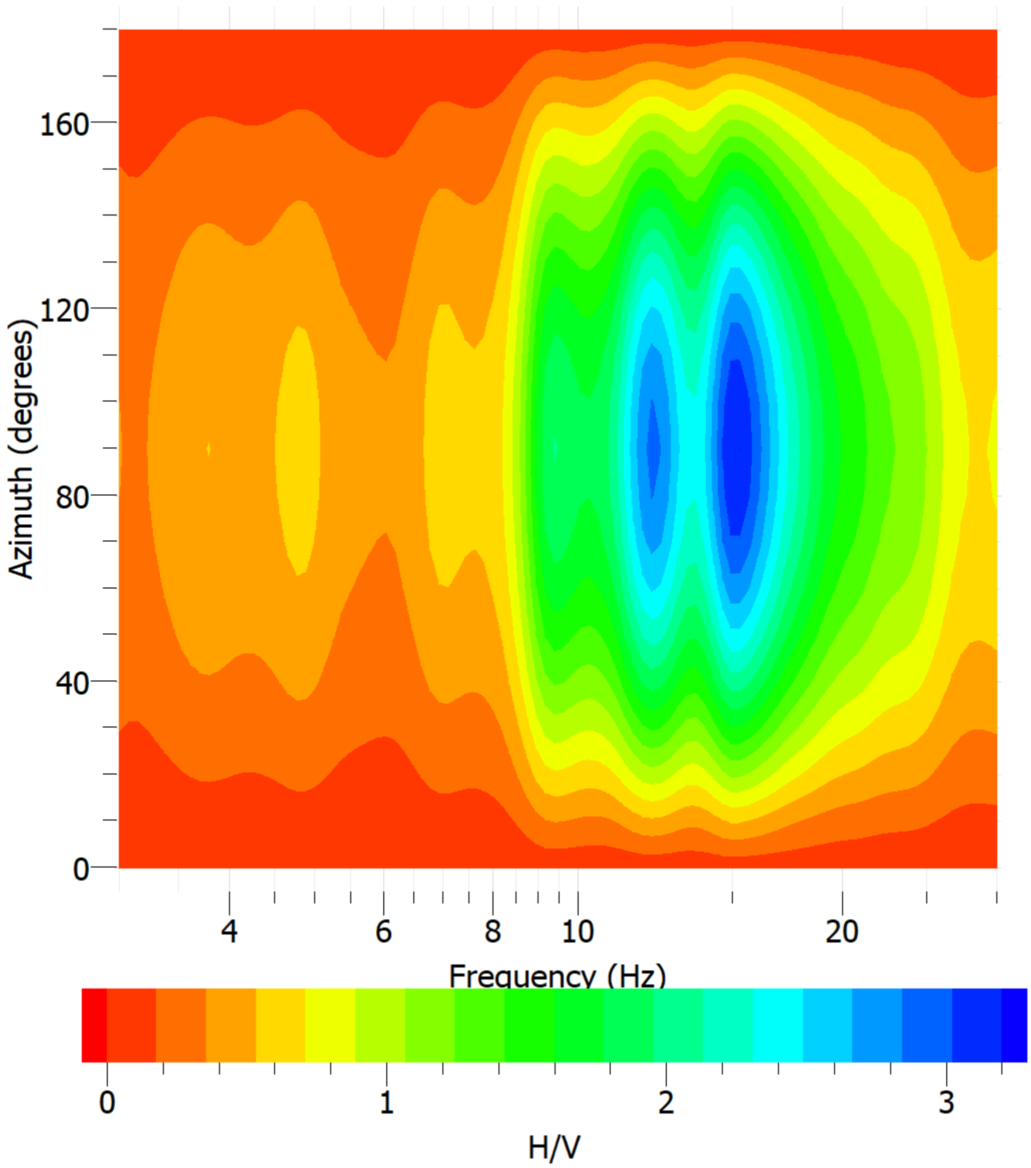

Figure 15: Lee's Hall borehole 2

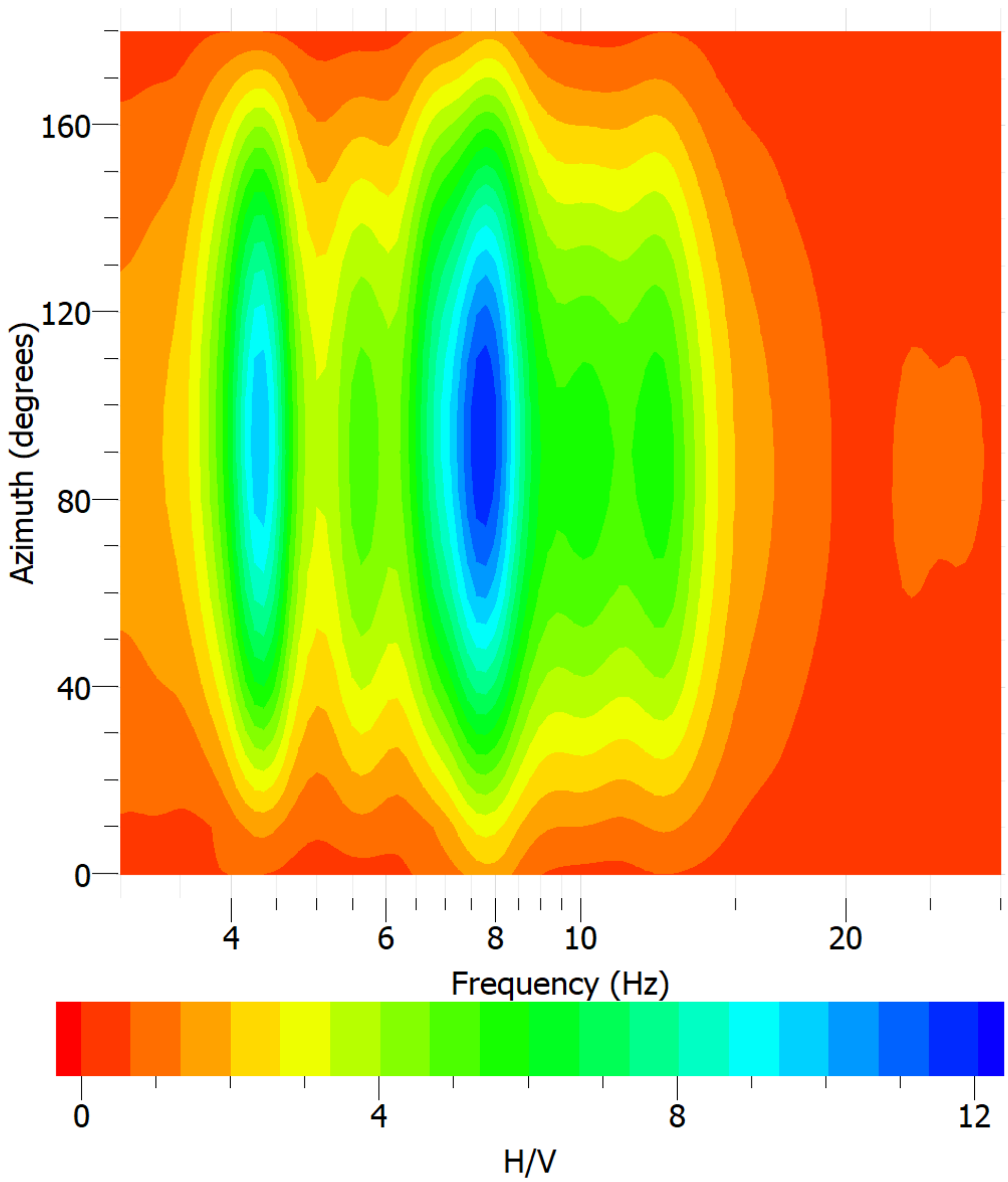

Figure 16: Lee's Hall borehole 3

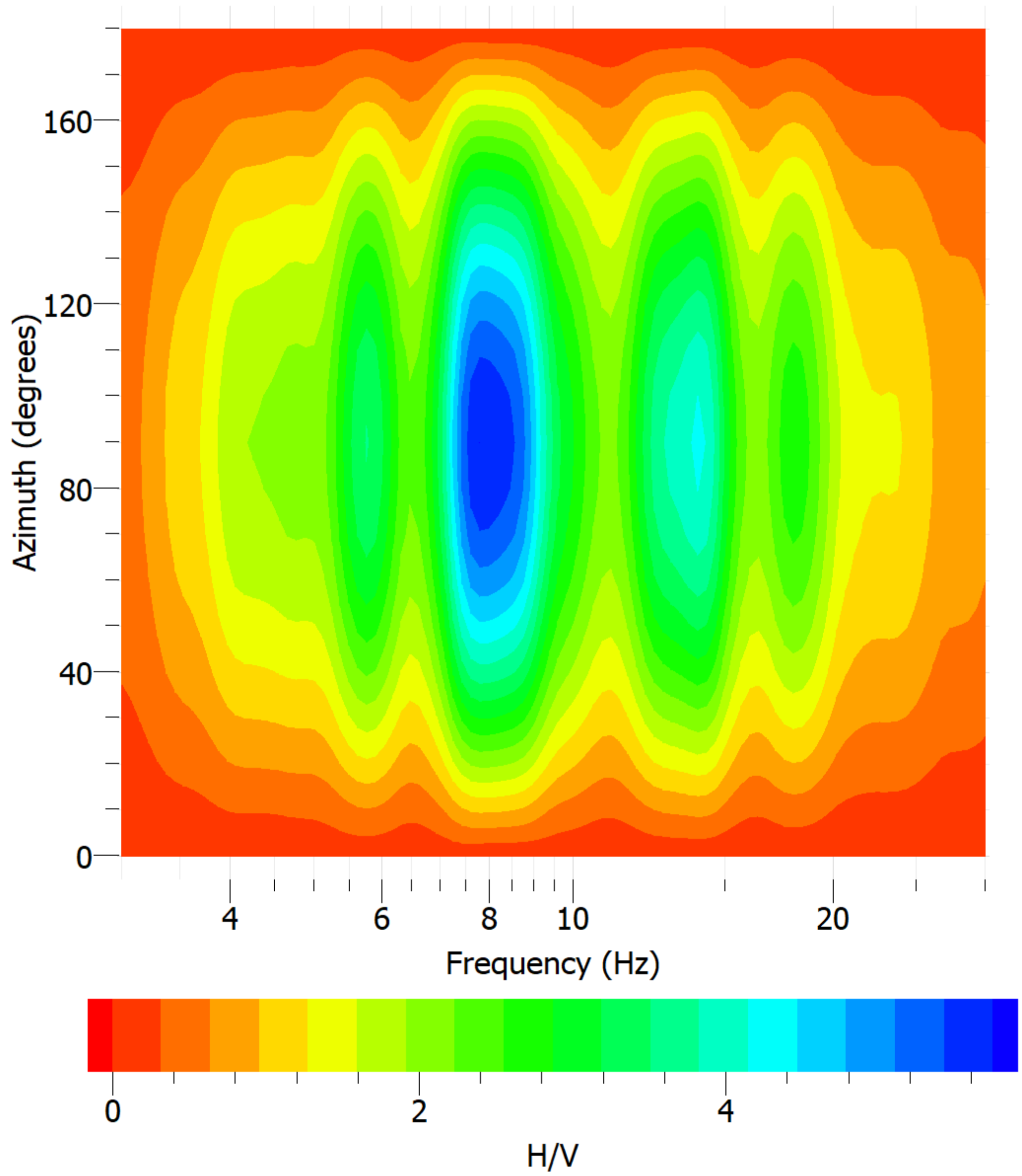

Figure 17: Lee's Hall borehole 5

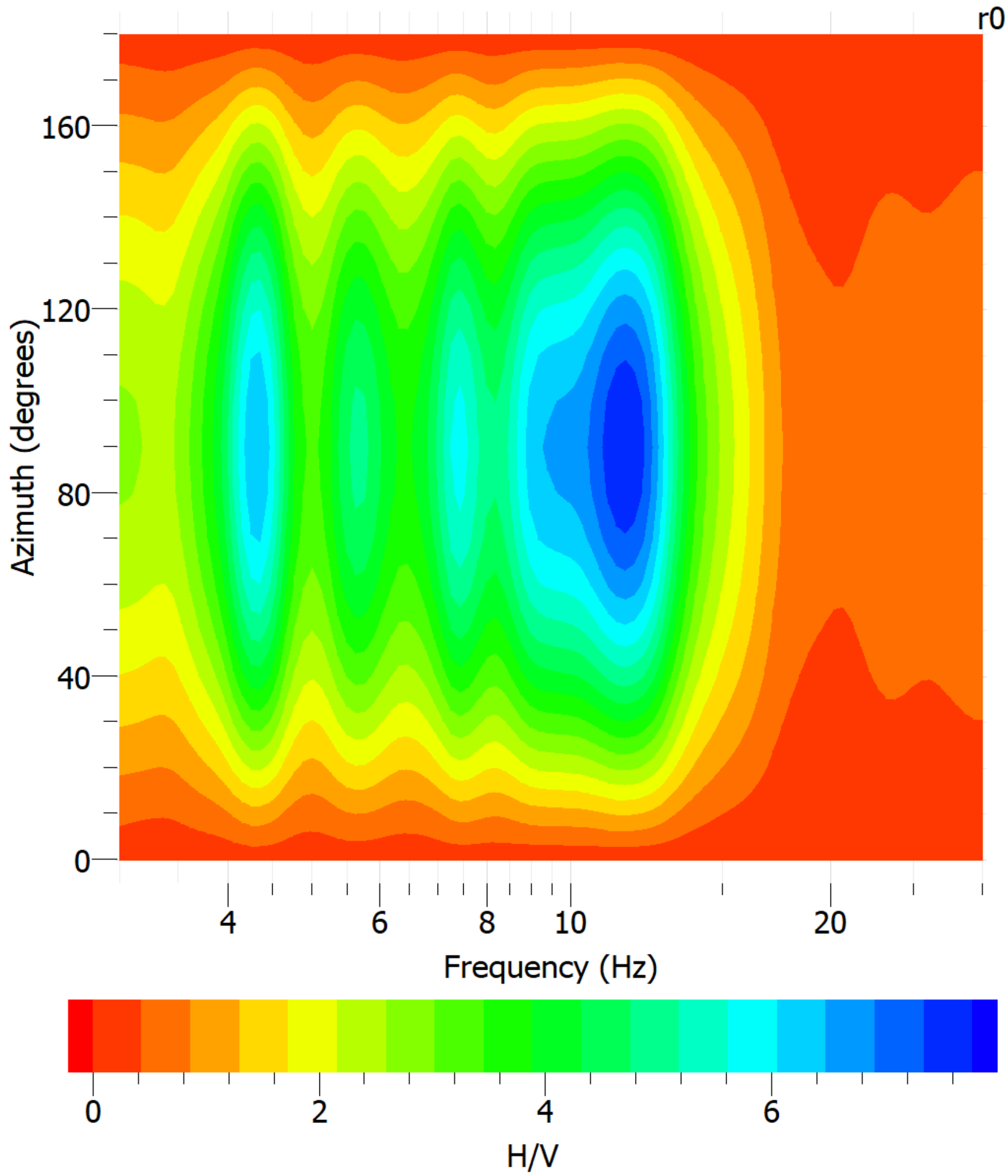

Figure 18: Lee's Hall borehole 6

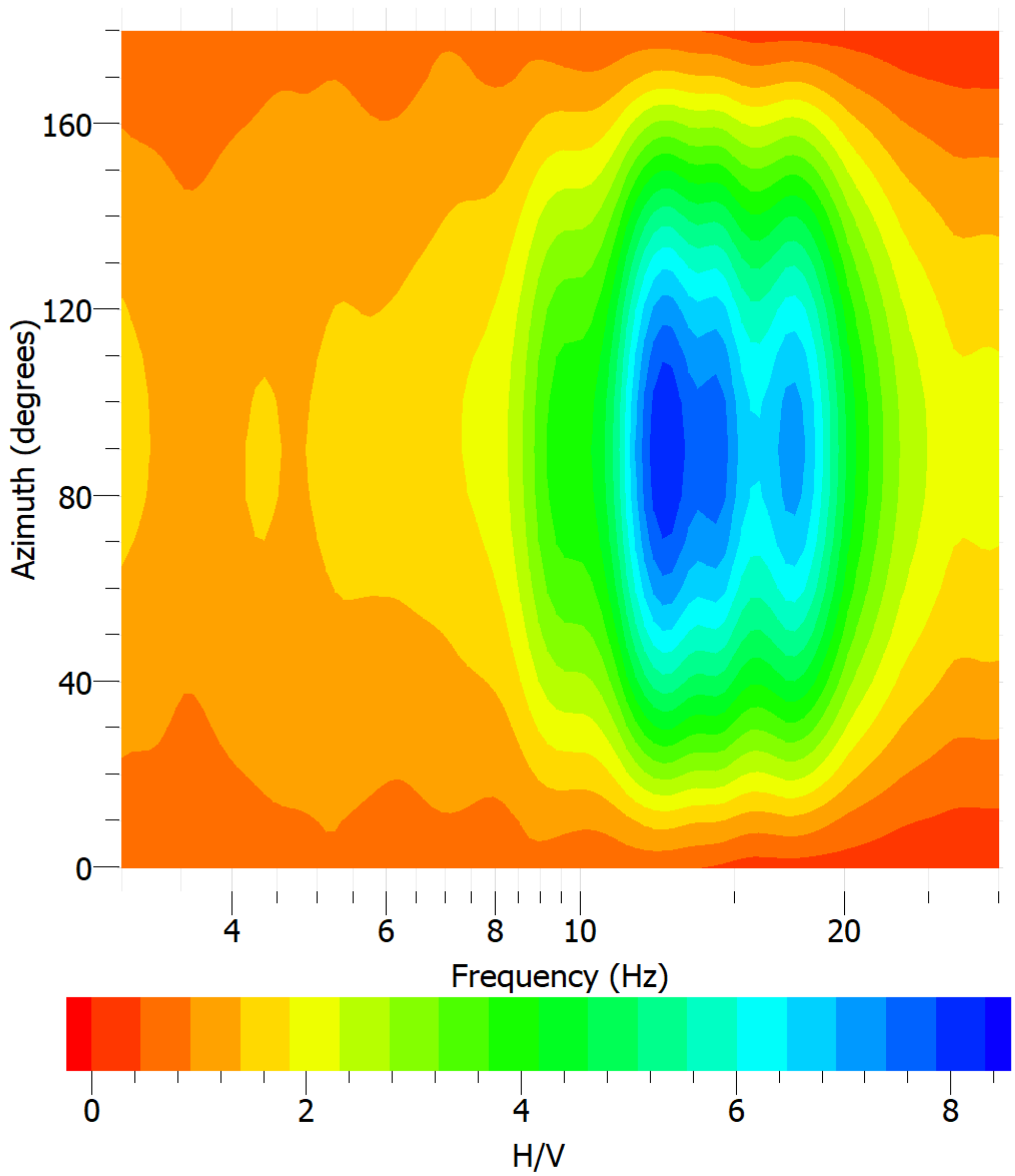

Figure 19: Lee's Hall borehole 8

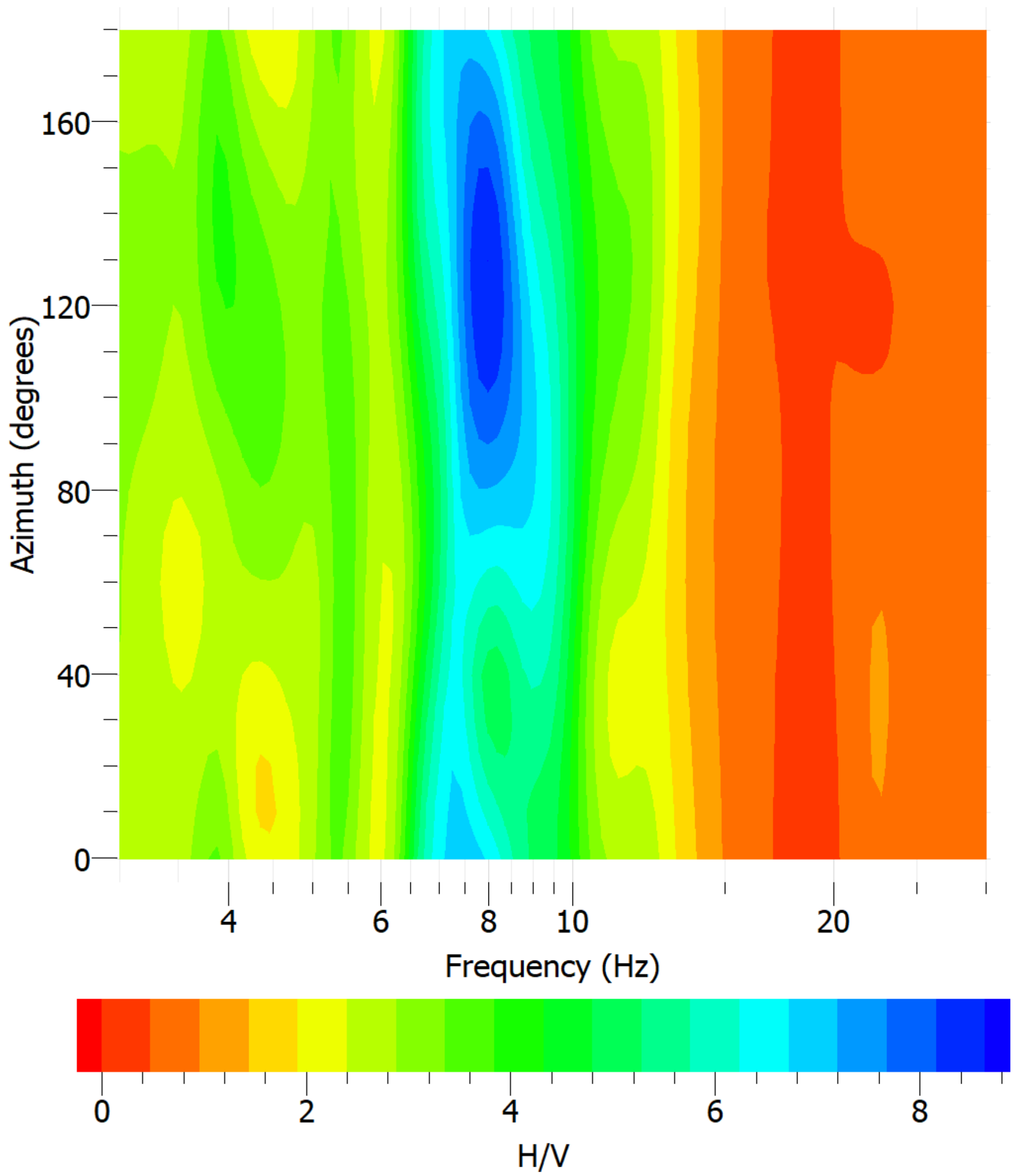

Figure 20: Lee's Hall borehole 11

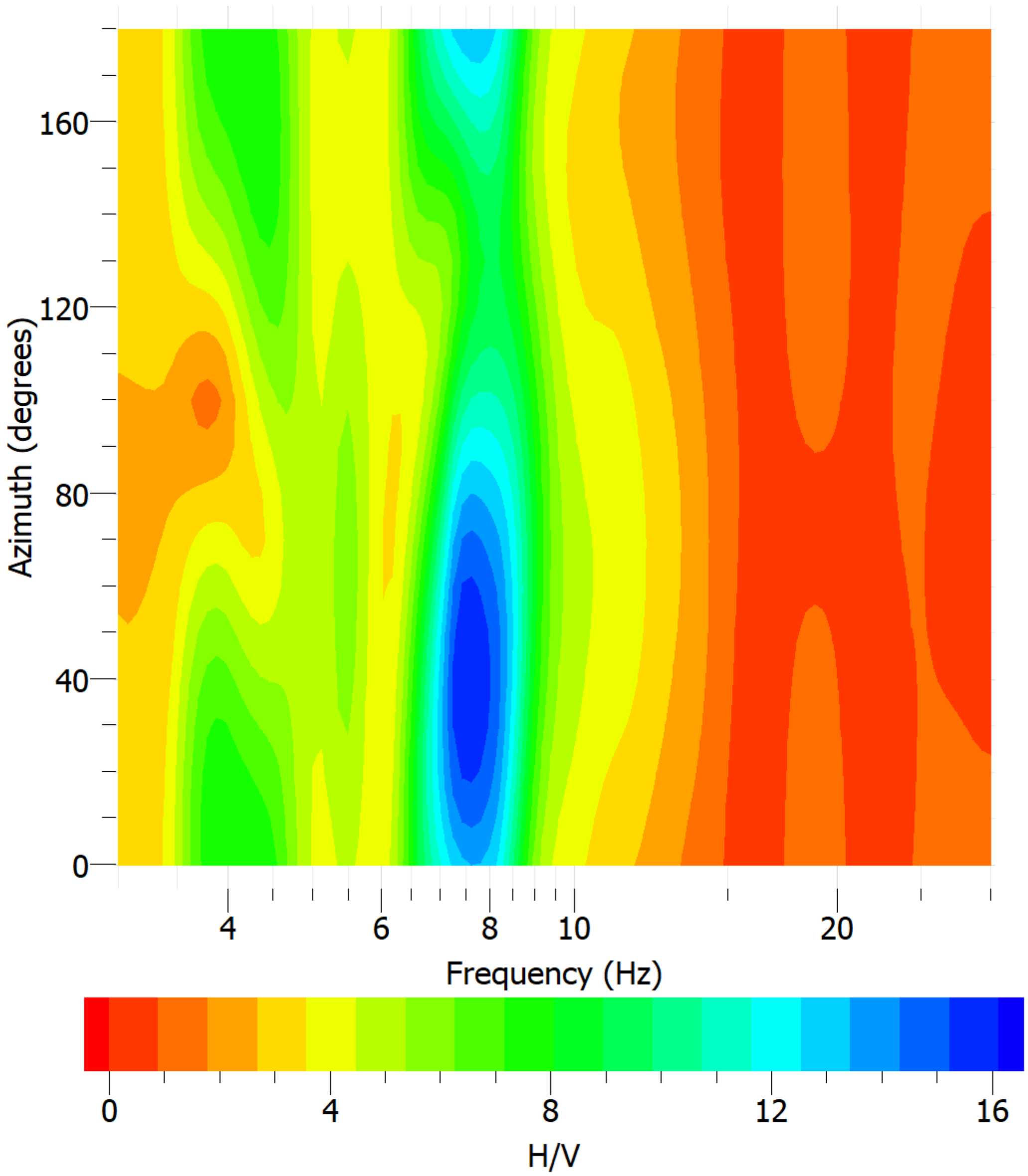

Figure 21: Lee's Hall borehole 13

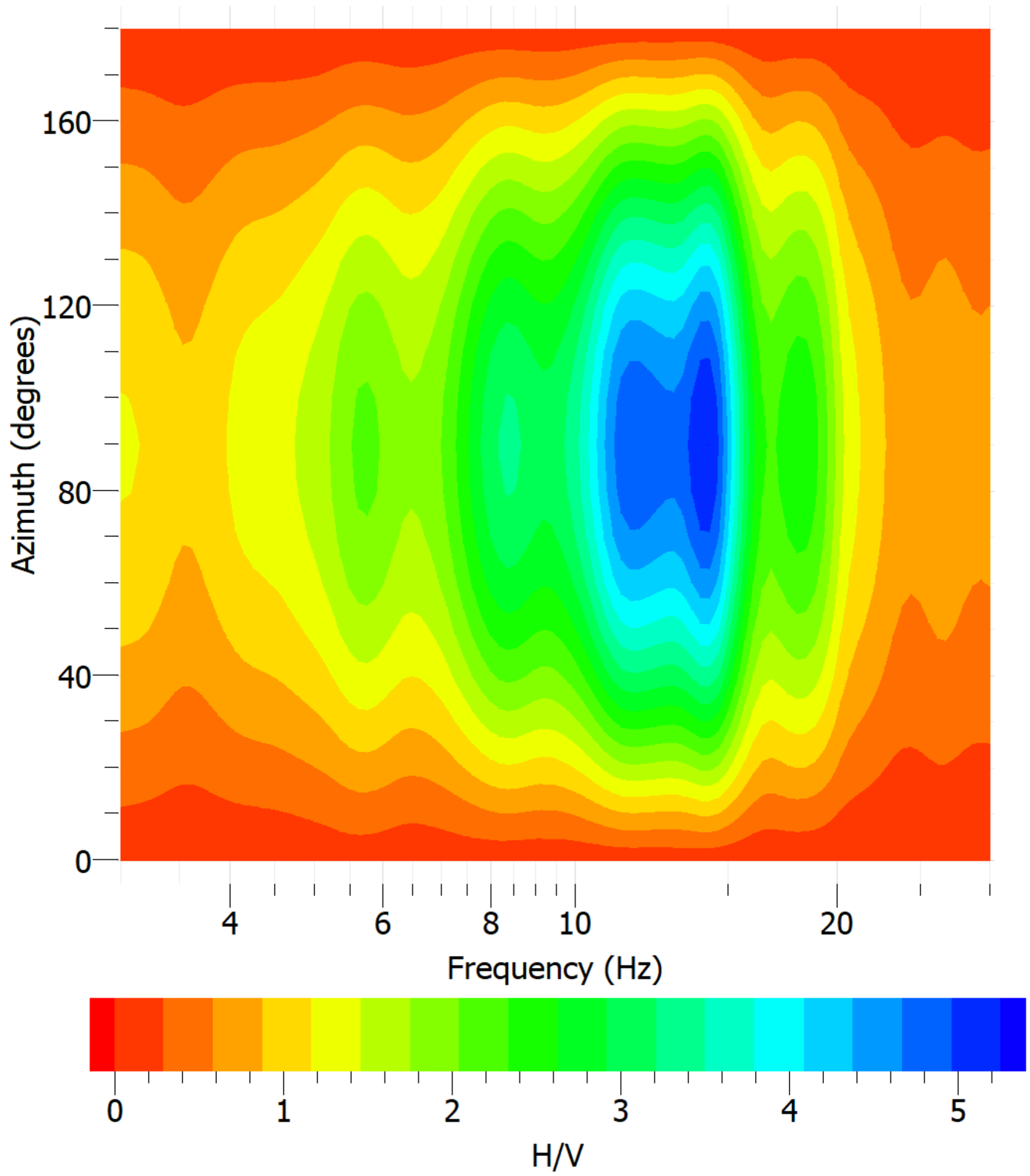

Figure 22: Lee's Hall borehole 14

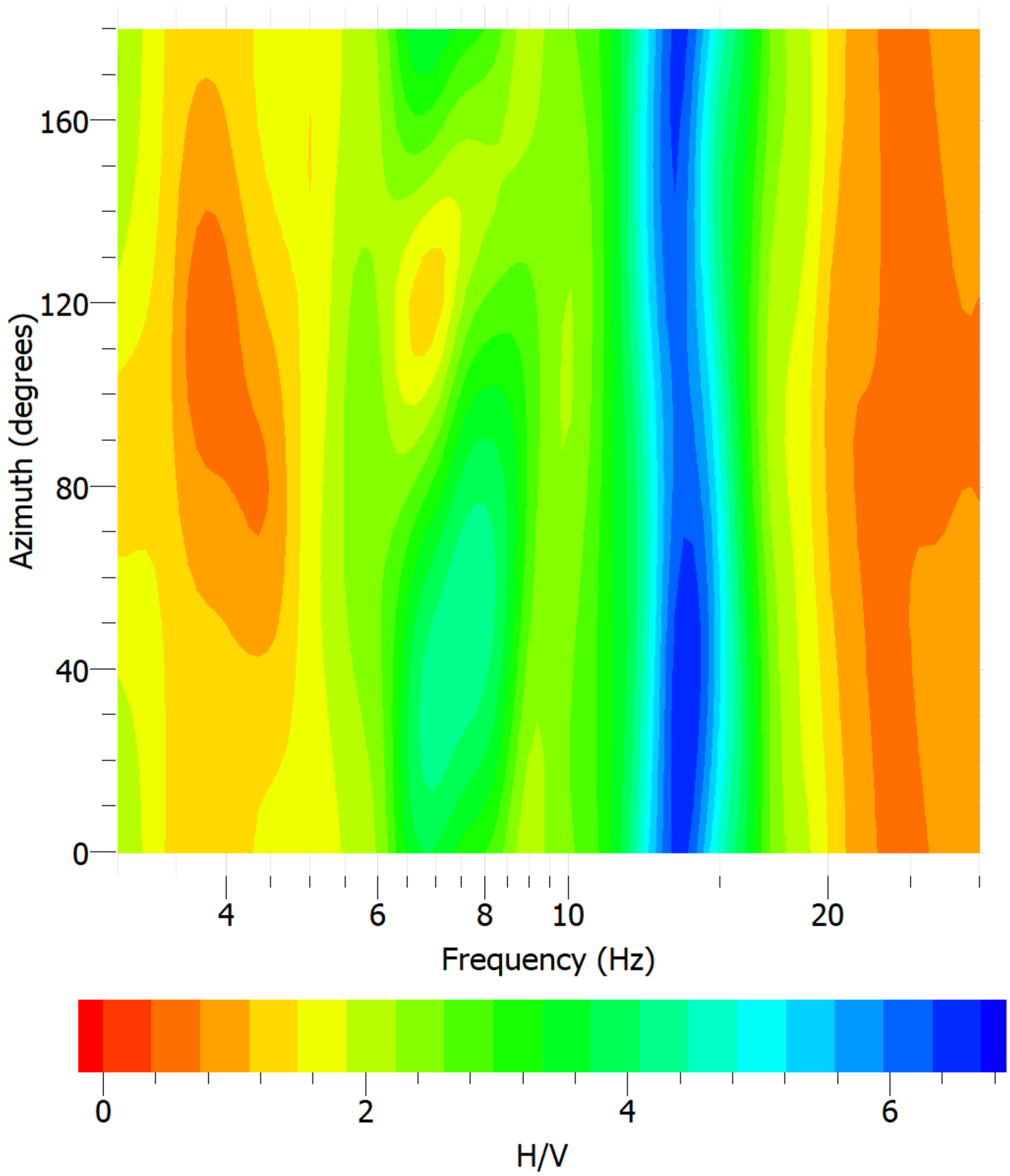

Figure 23: Lee's Hall borehole 15

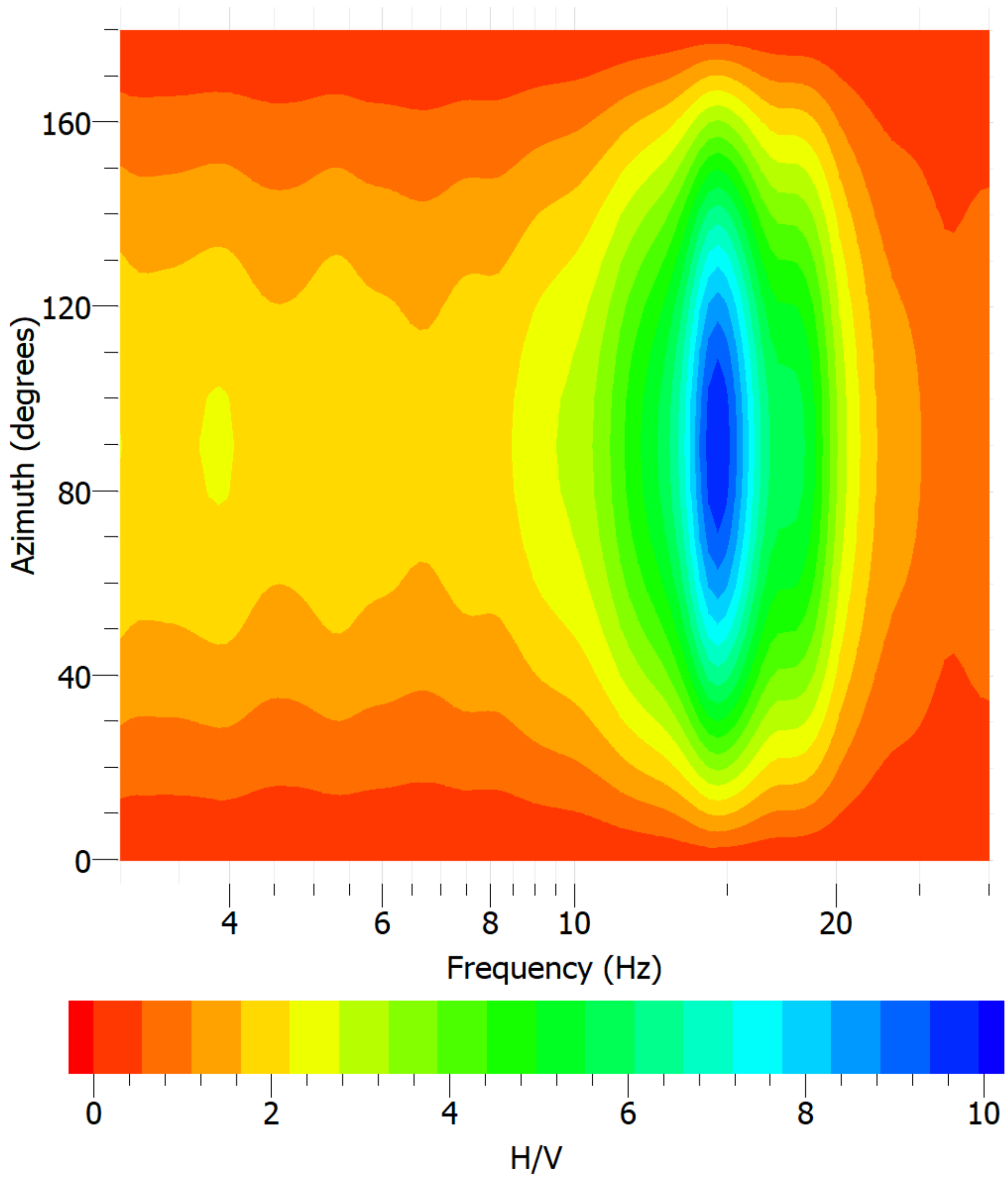

Figure 24: Lee’s Hall borehole 18

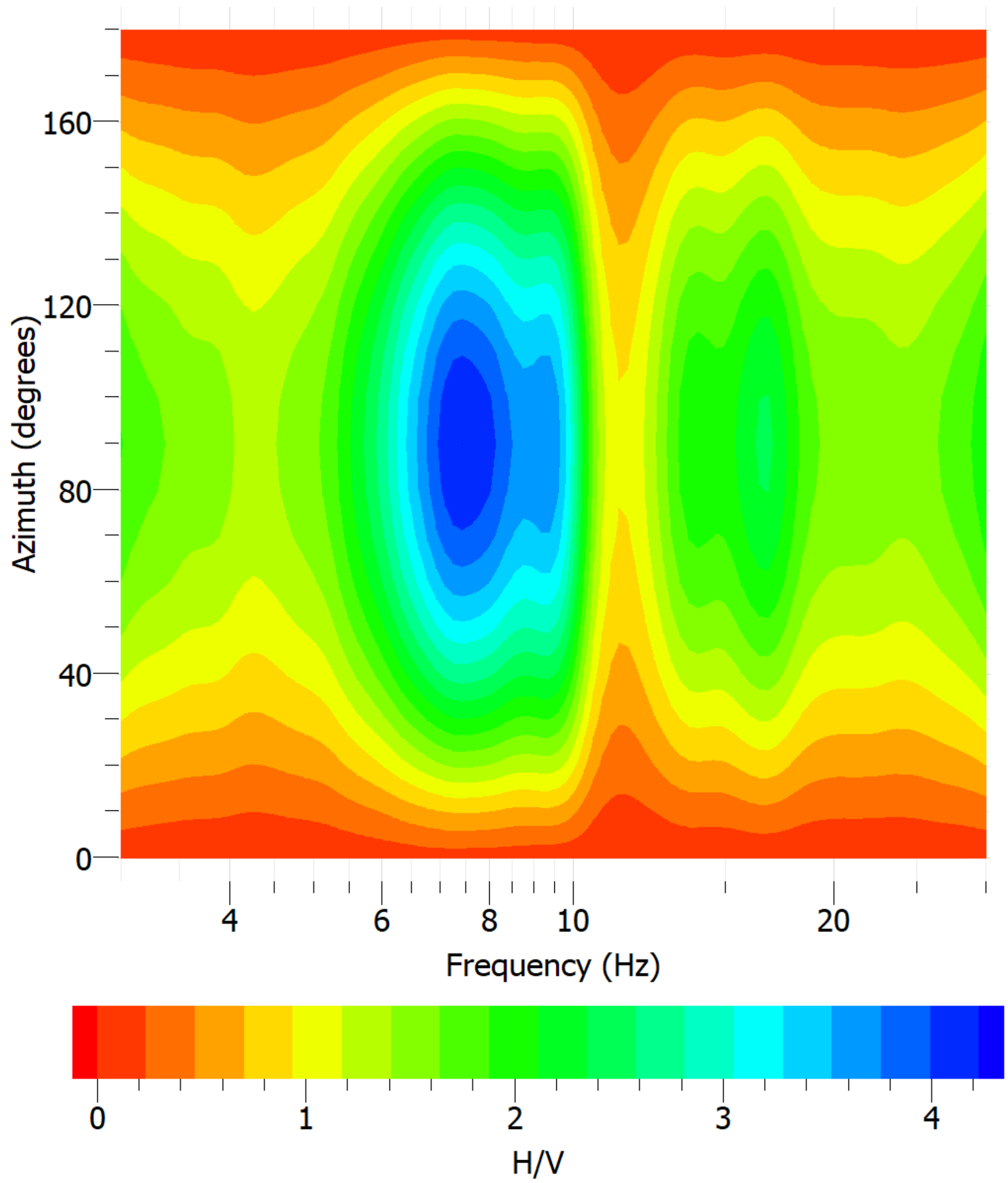

Figure 25: MUHC borehole 1

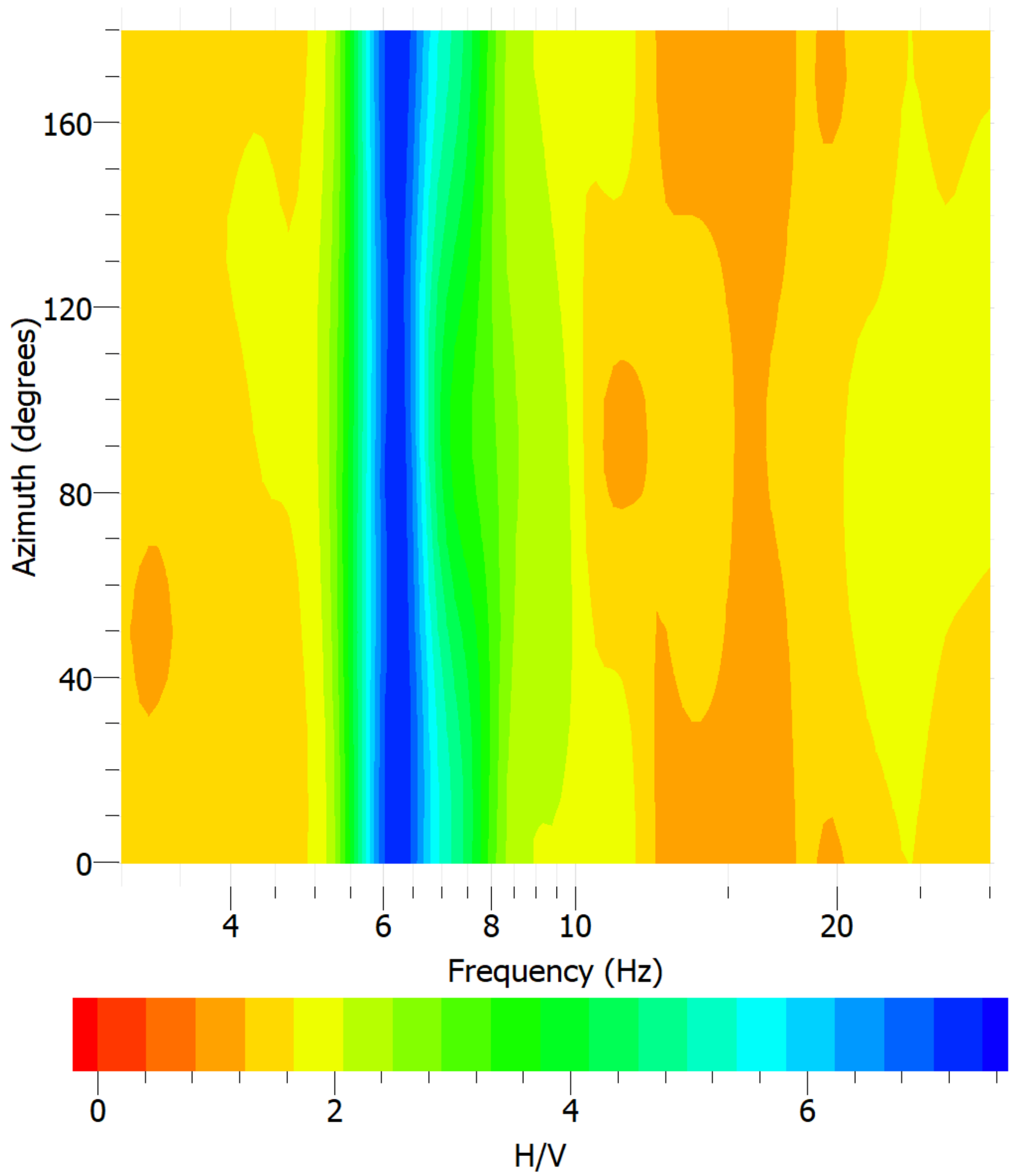

Figure 26: MUHC borehole 2

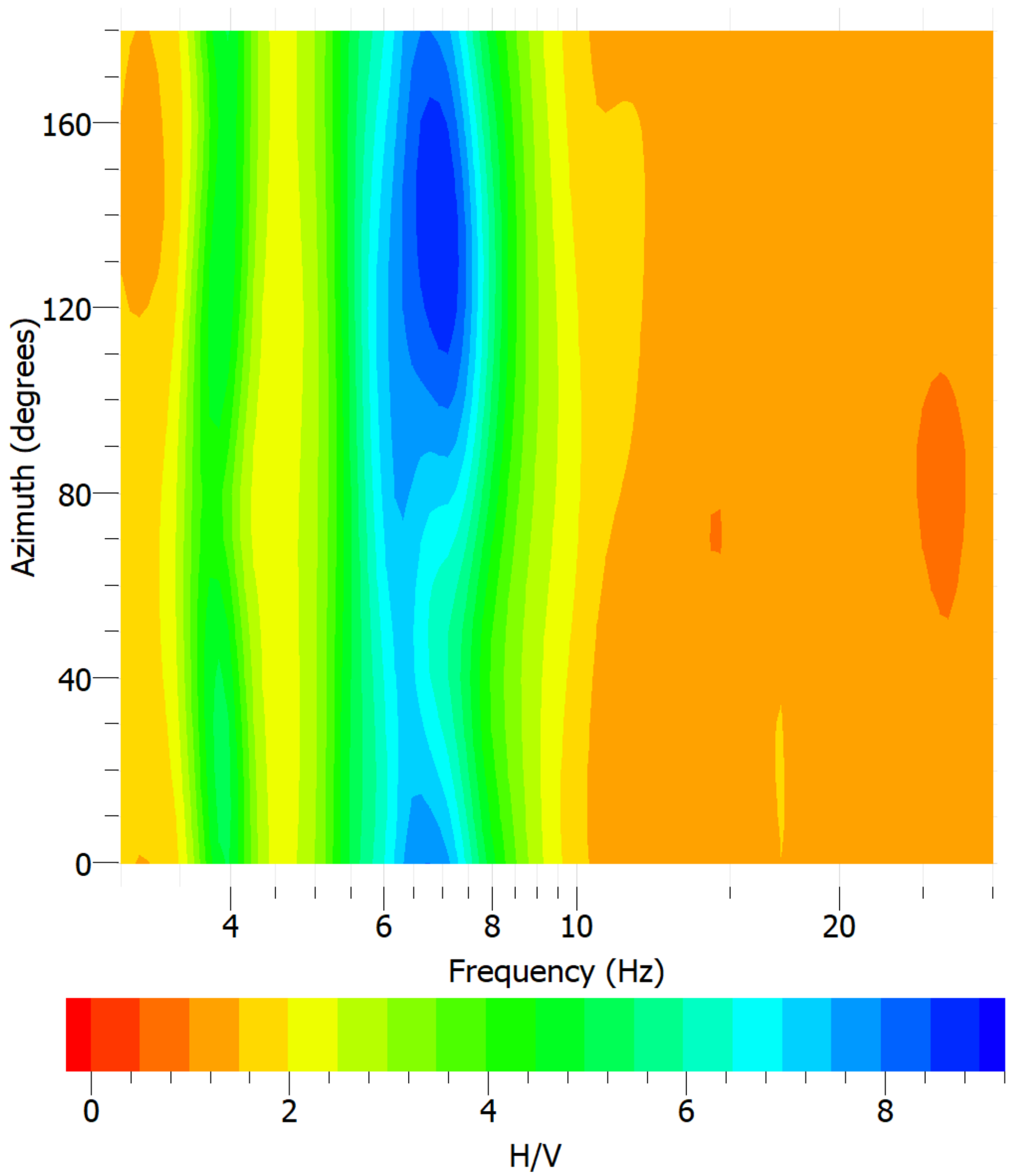

Figure 27: MUHC borehole 3

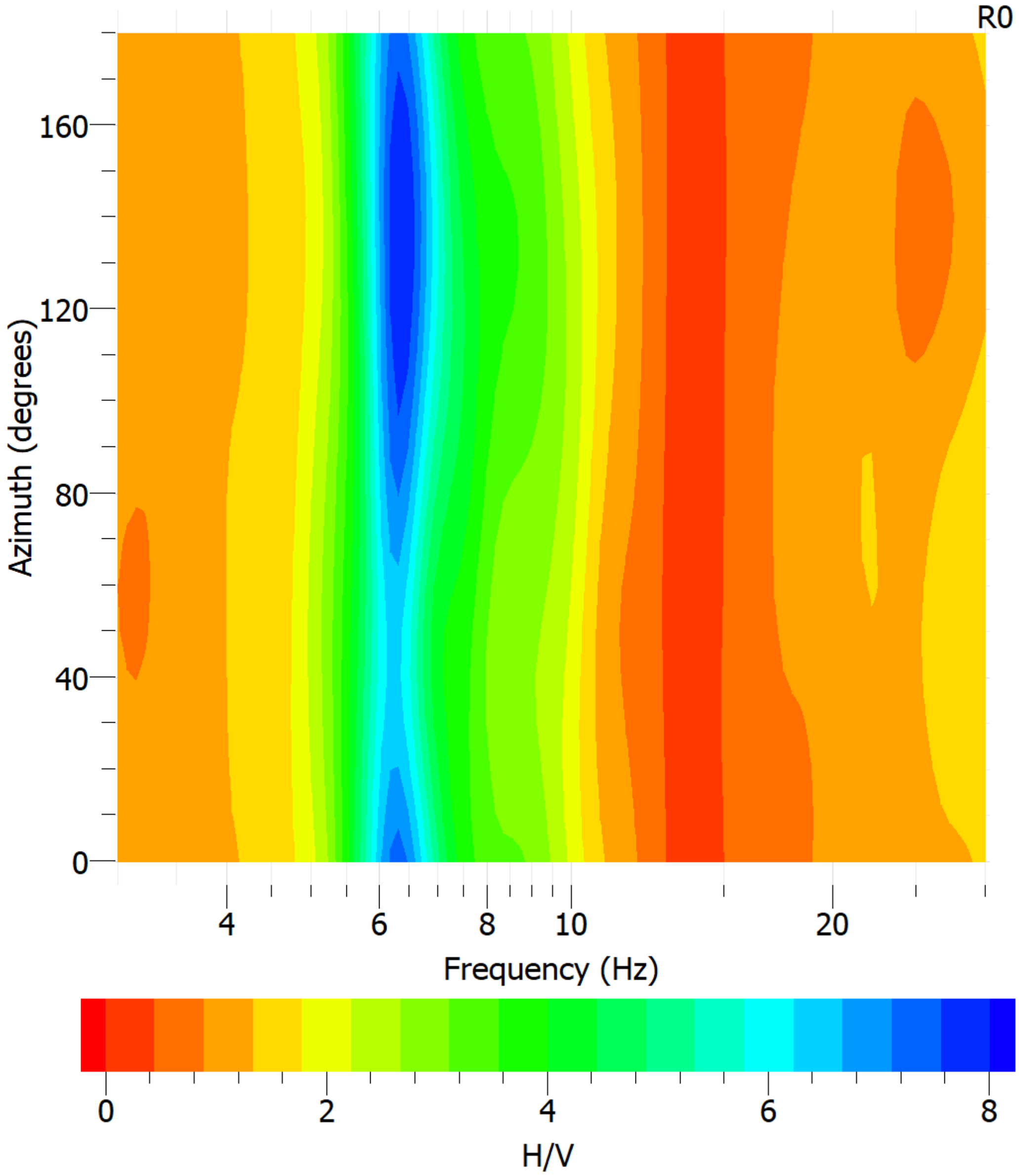

Figure 28: MUHC borehole 4

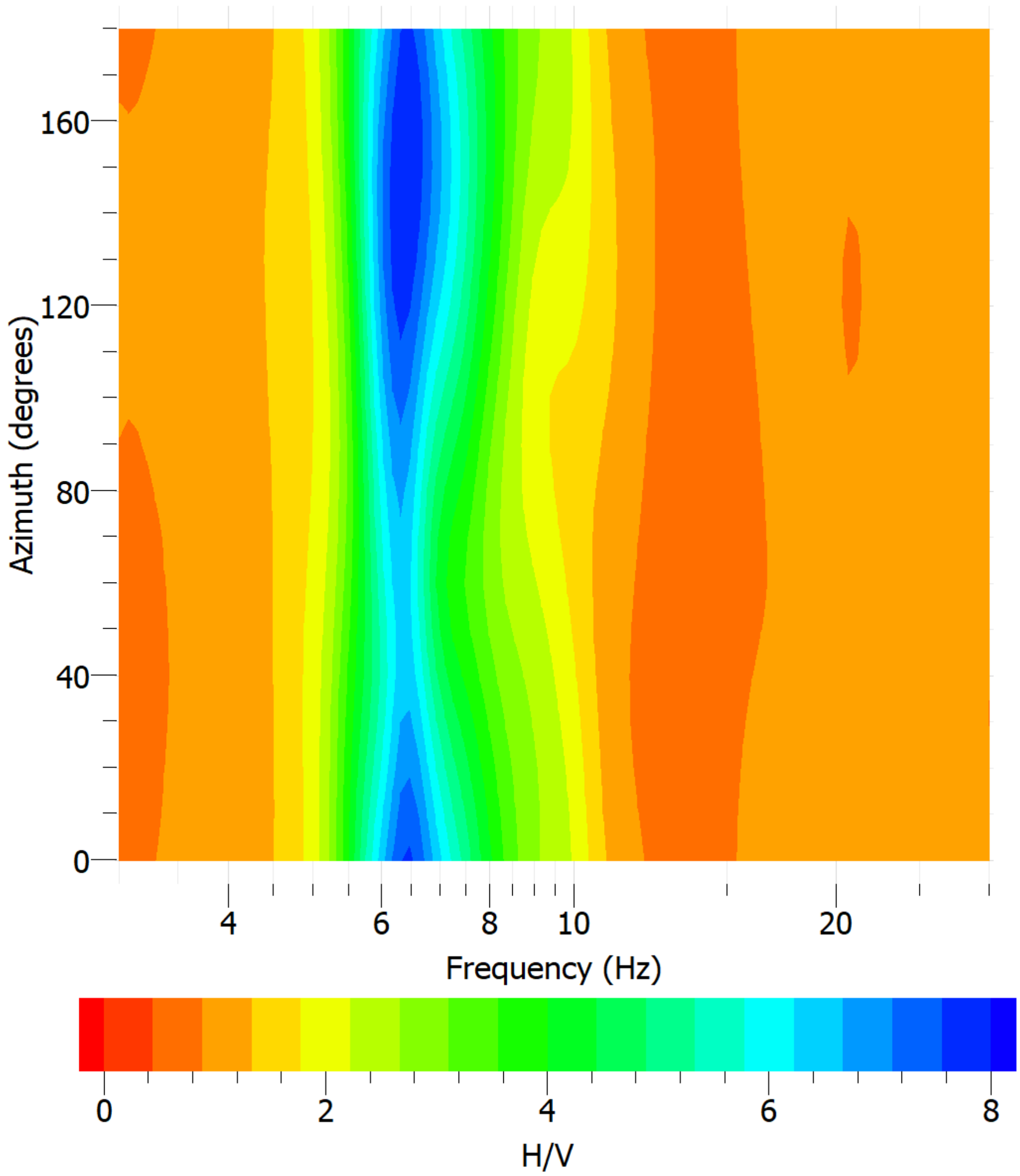

Figure 29: MUHC borehole 5

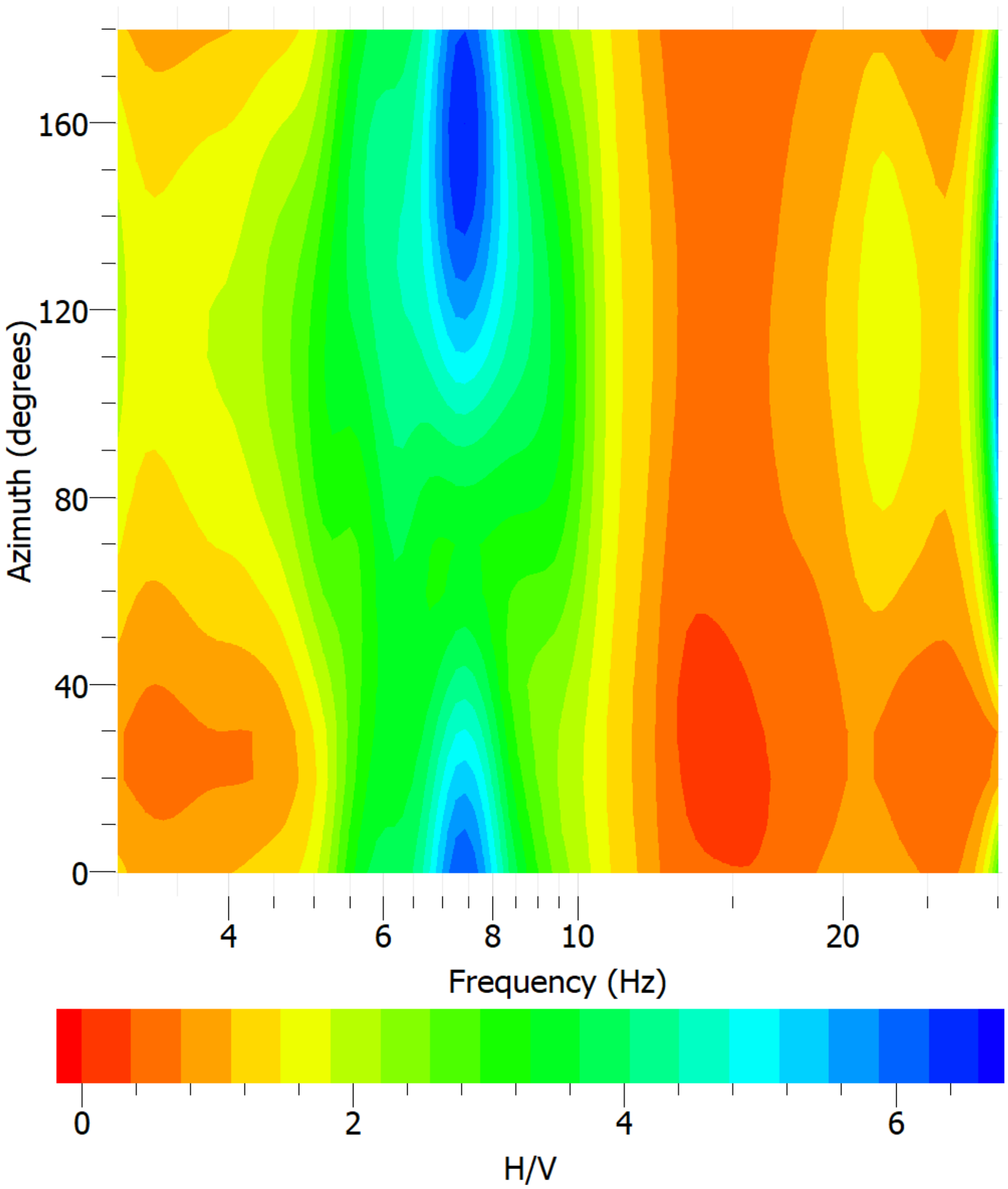

Figure 30: MUHC borehole 6

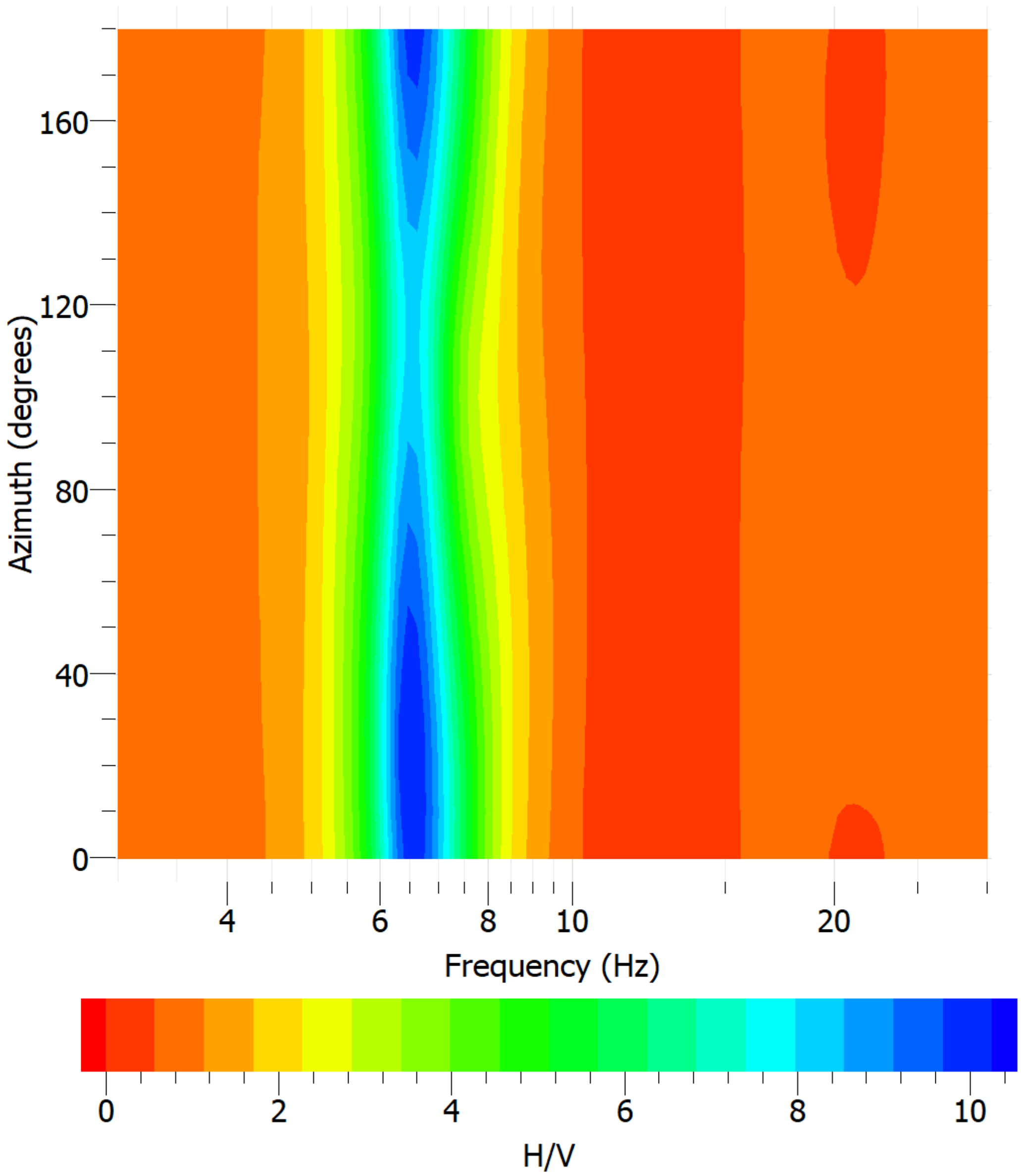

Figure 31: MUHC borehole 7

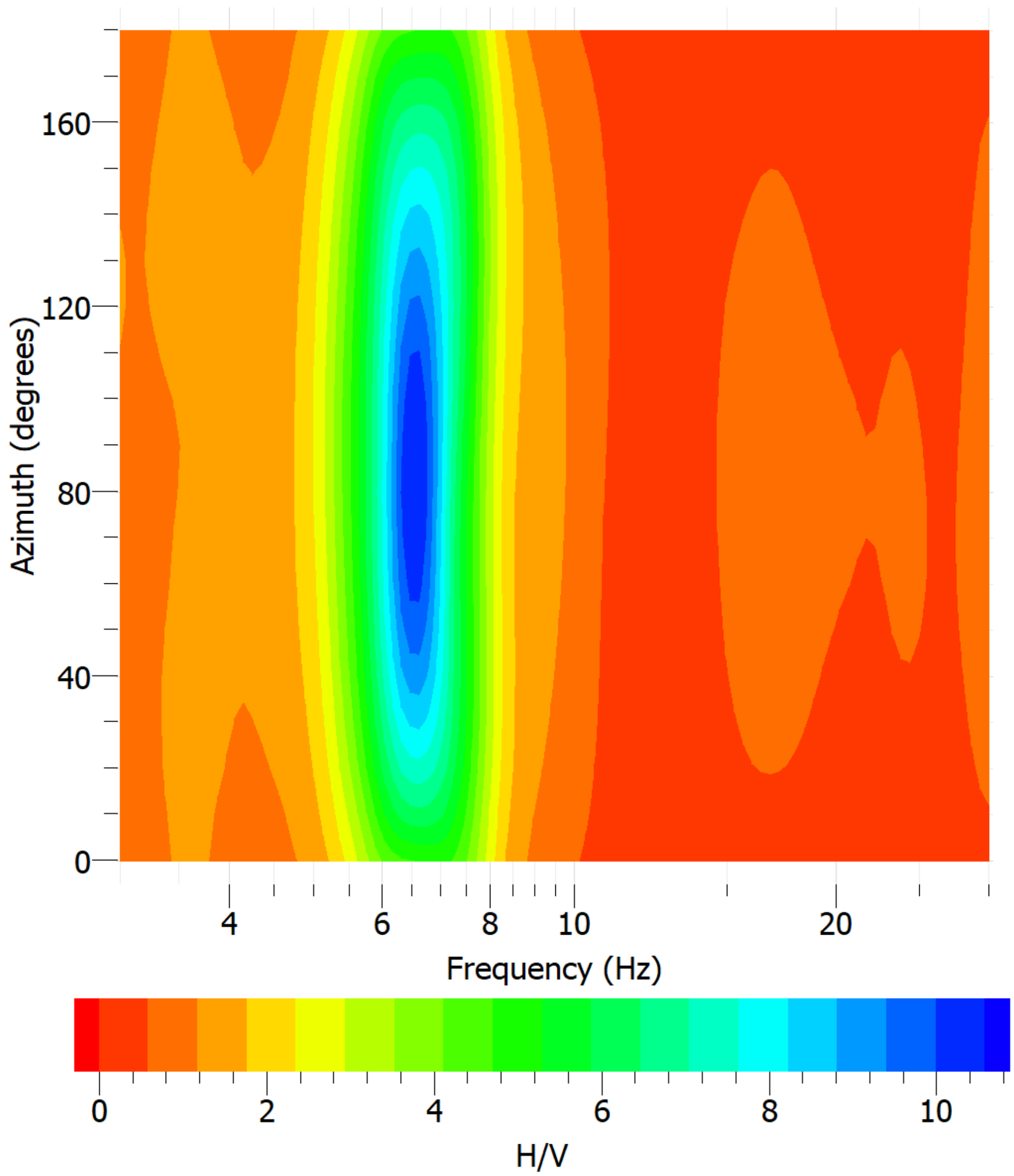

Figure 32: MUHC borehole 8

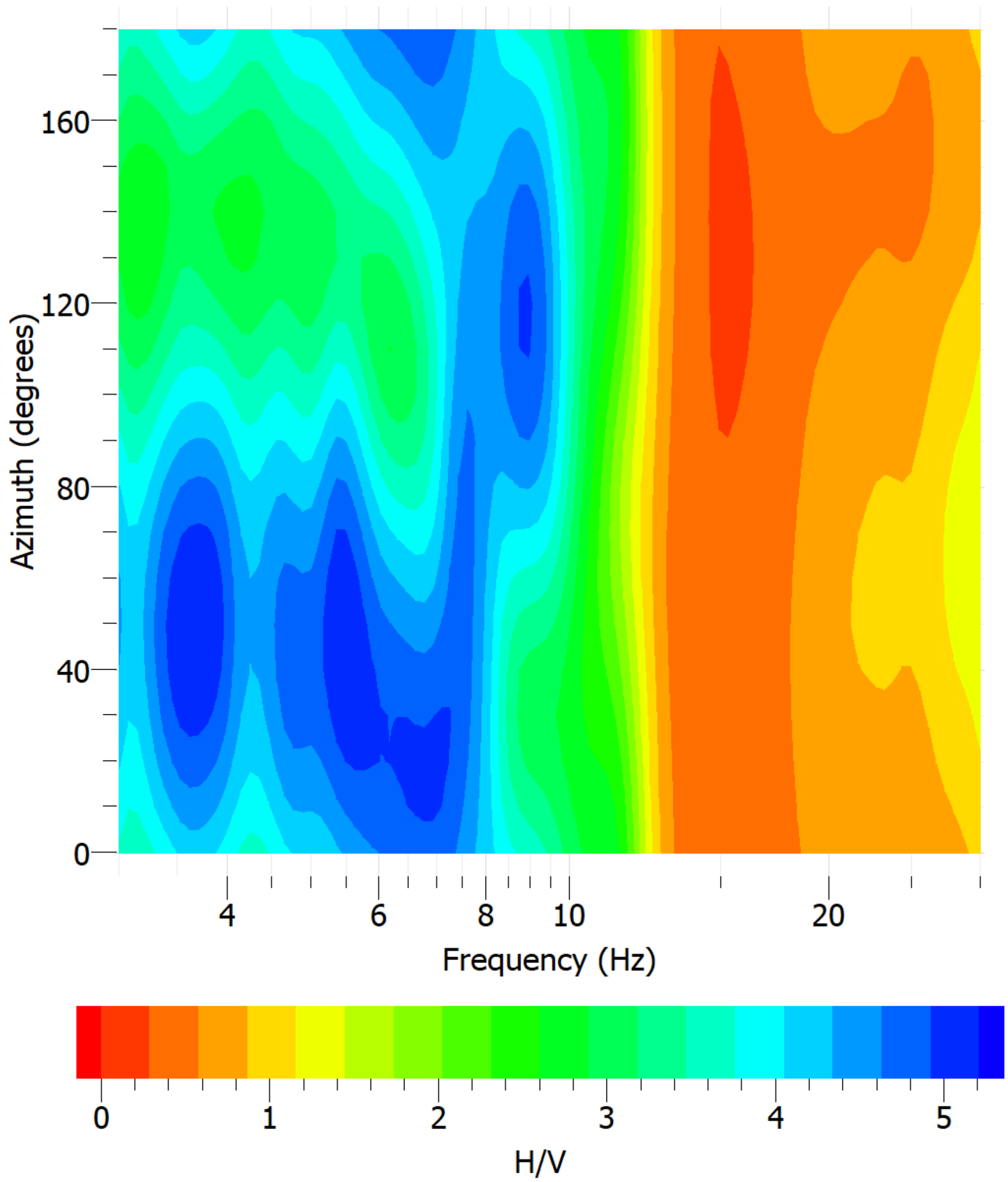

Figure 33: MUHC borehole 9

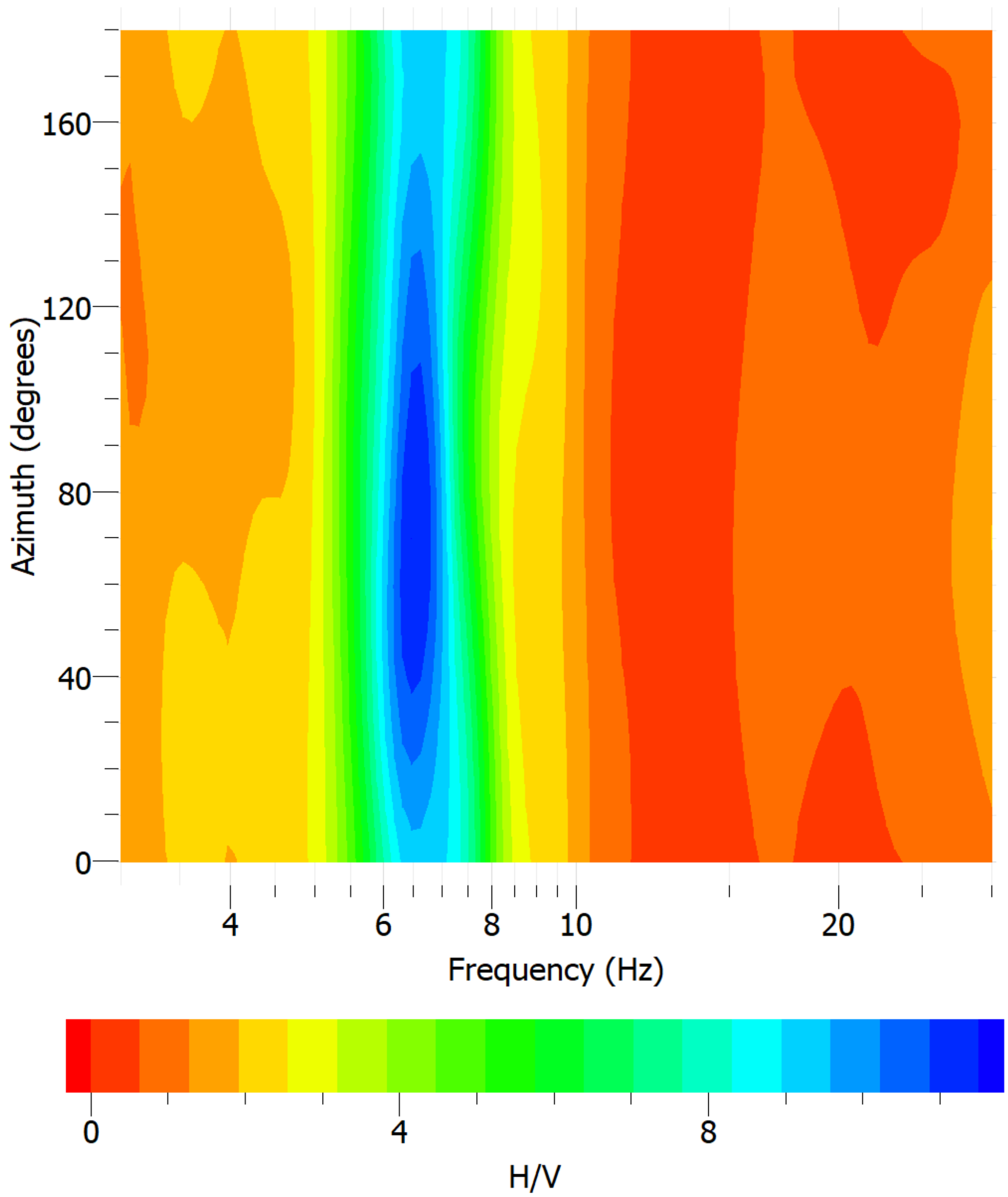

Figure 34: MUHC borehole 10

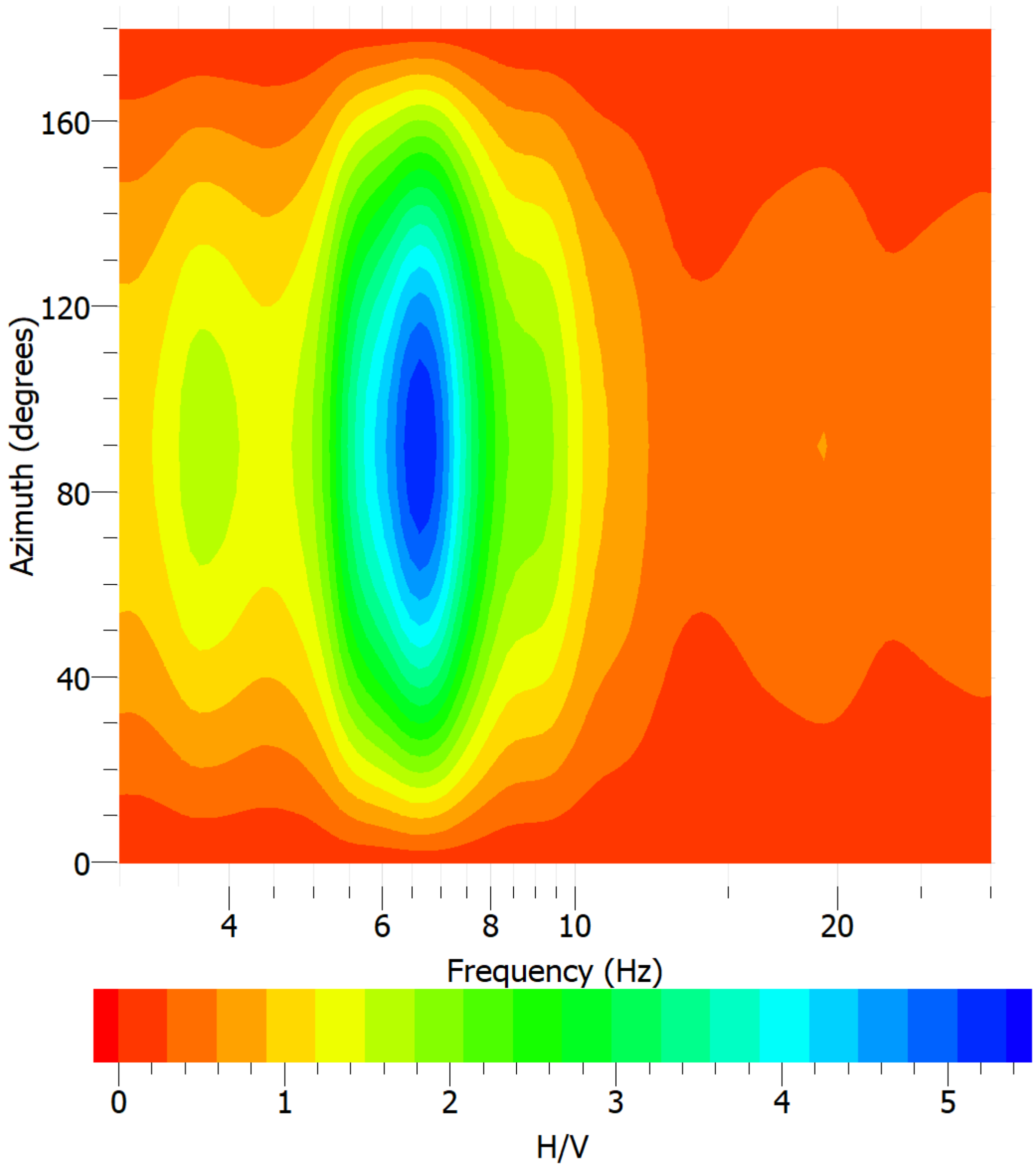

Figure 35: MUHC borehole 11

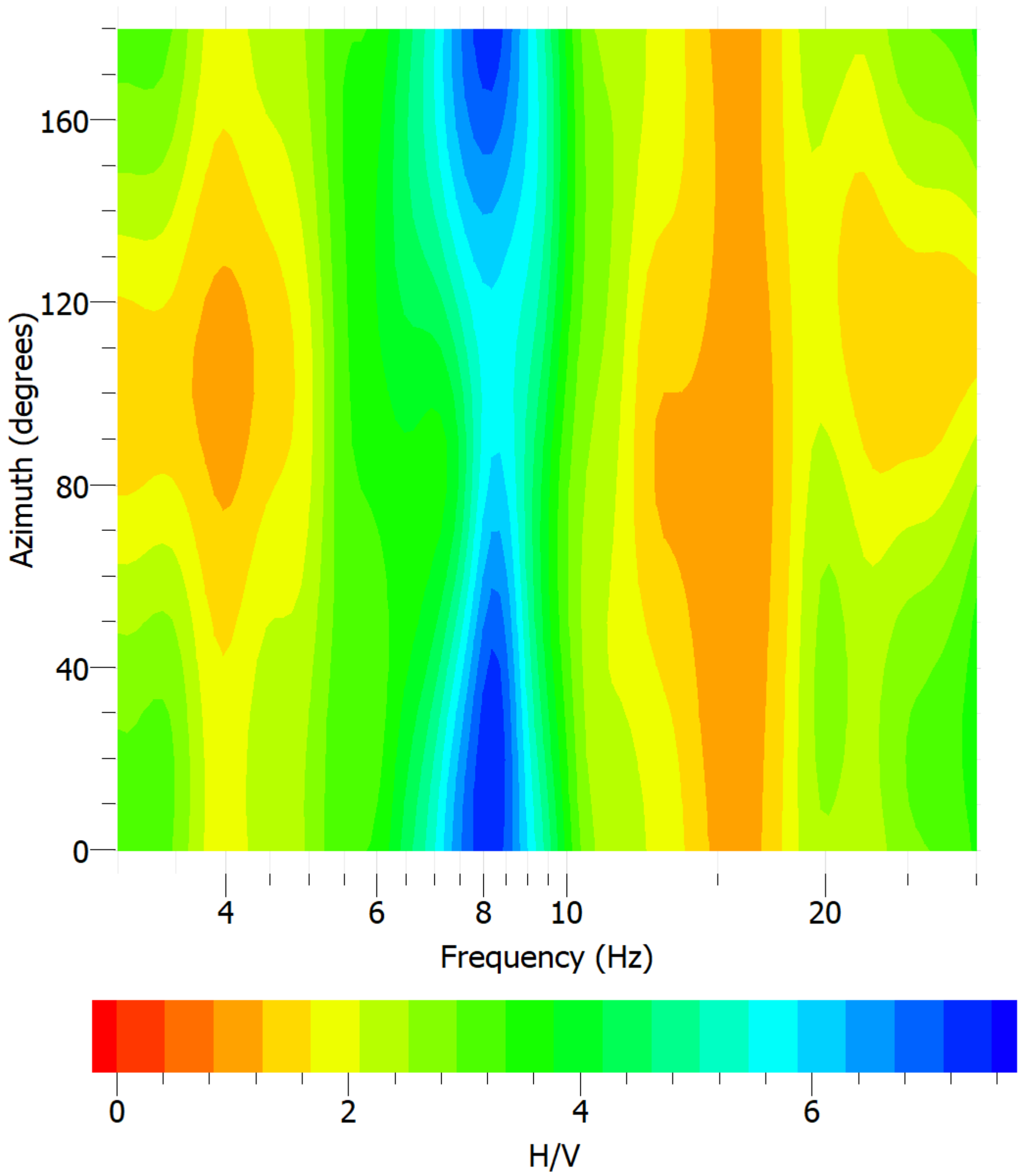

Figure 36: MUHC borehole 12

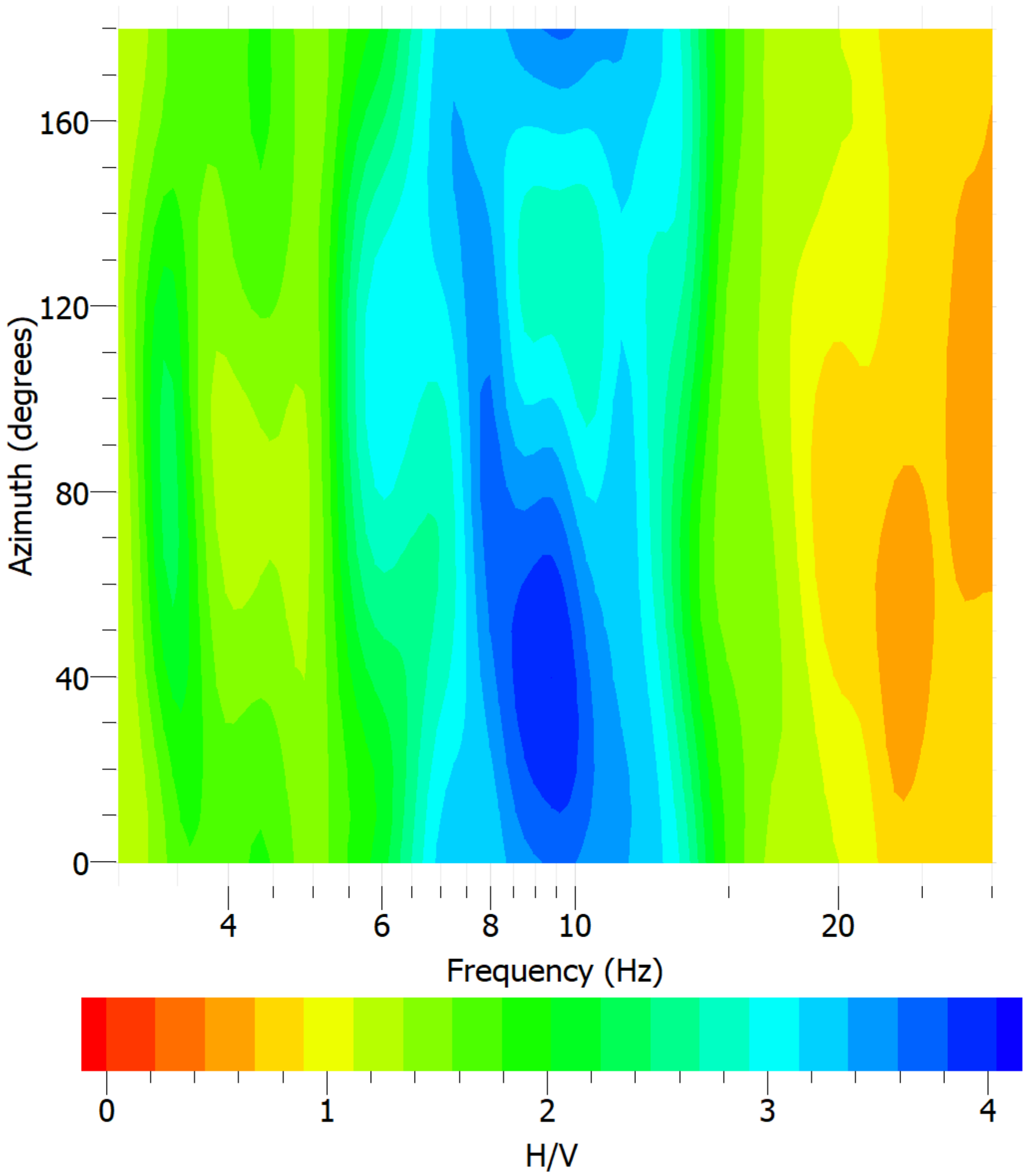

Figure 37: MUHC borehole 13

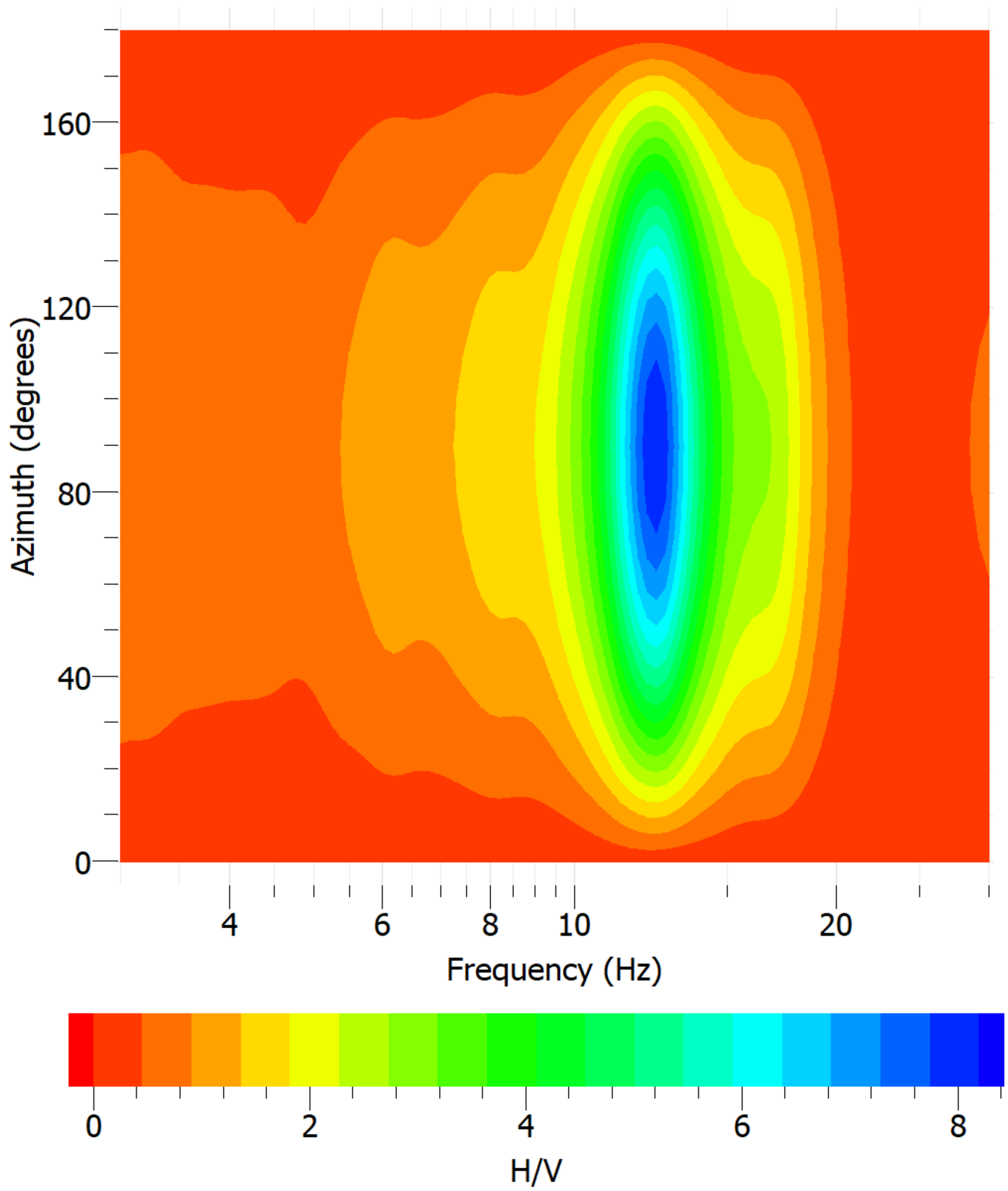

Figure 38: SHSMO borehole 1

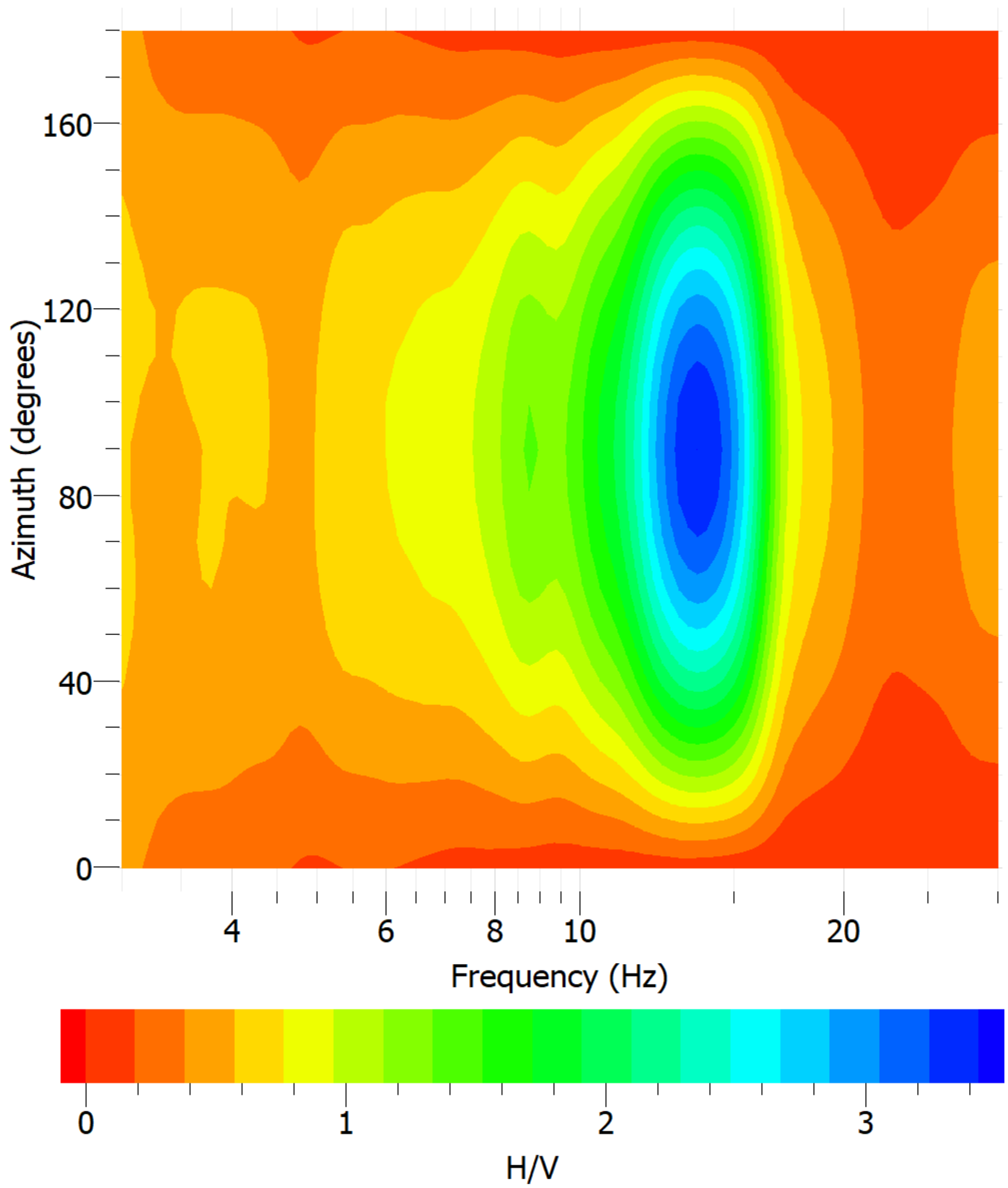

Figure 39: SHSMO borehole 2

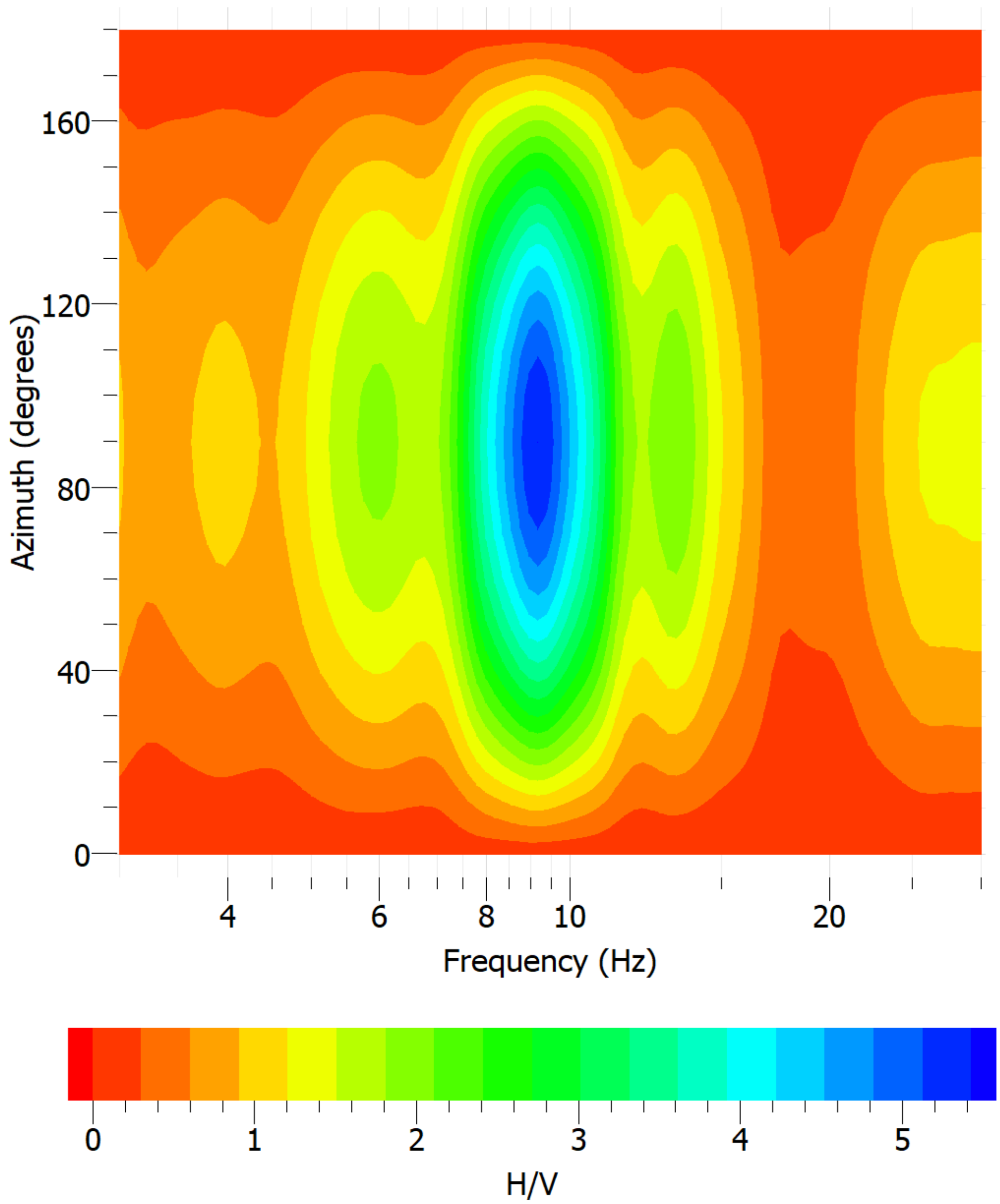

Figure 40: SHSMO borehole 5

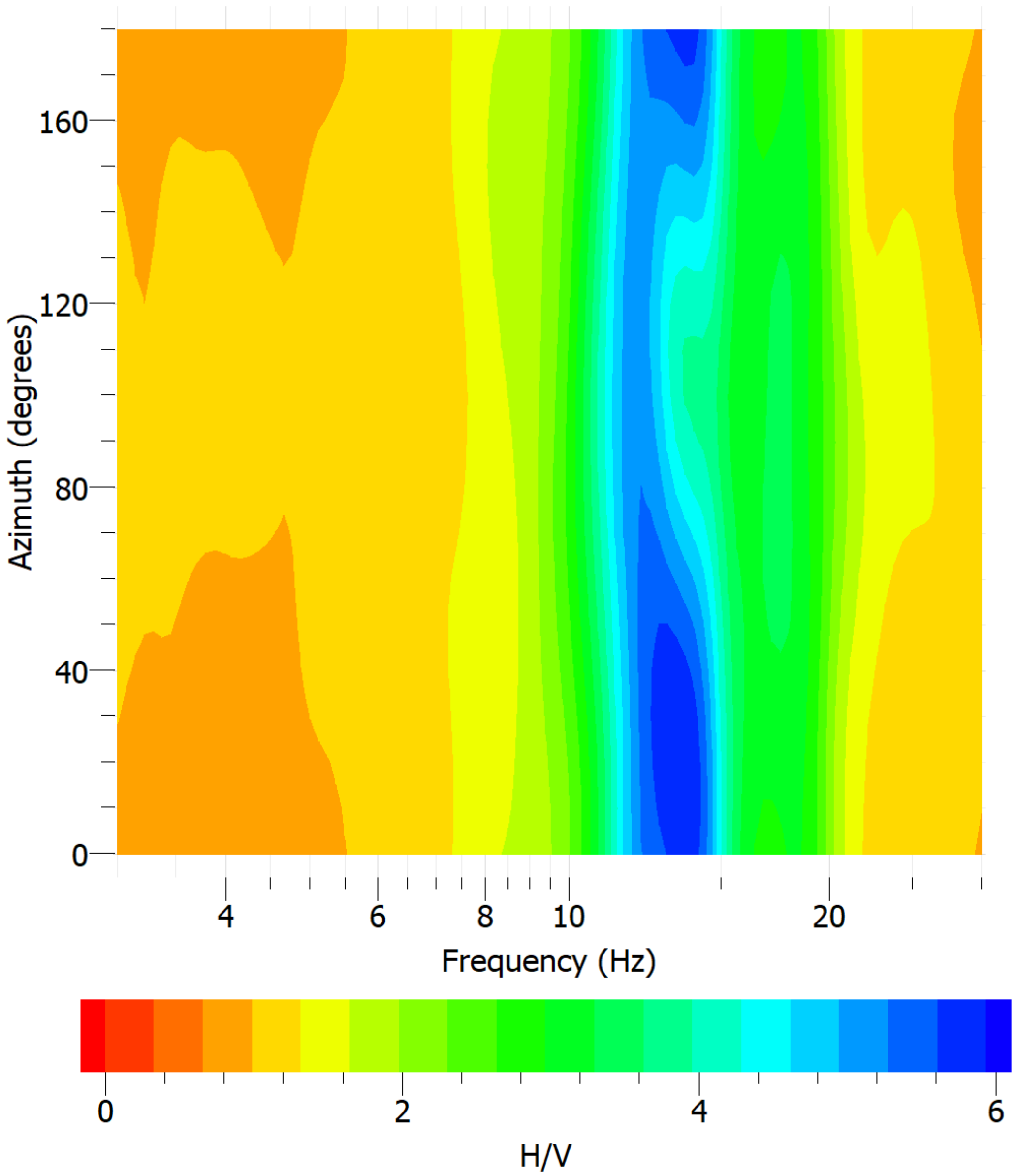

Figure 41: SHSMO borehole 7

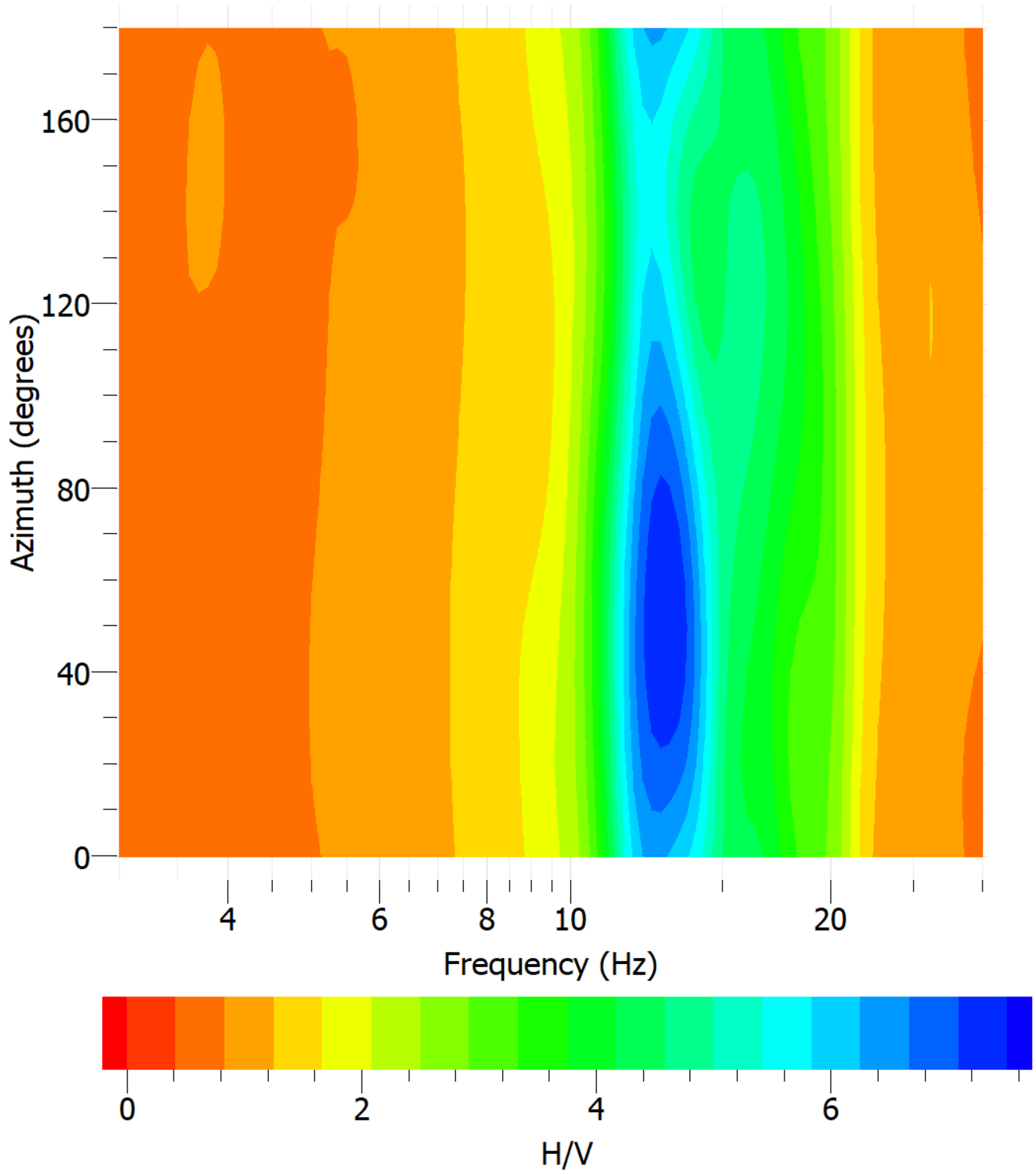

Figure 42: SHSMO borehole 8

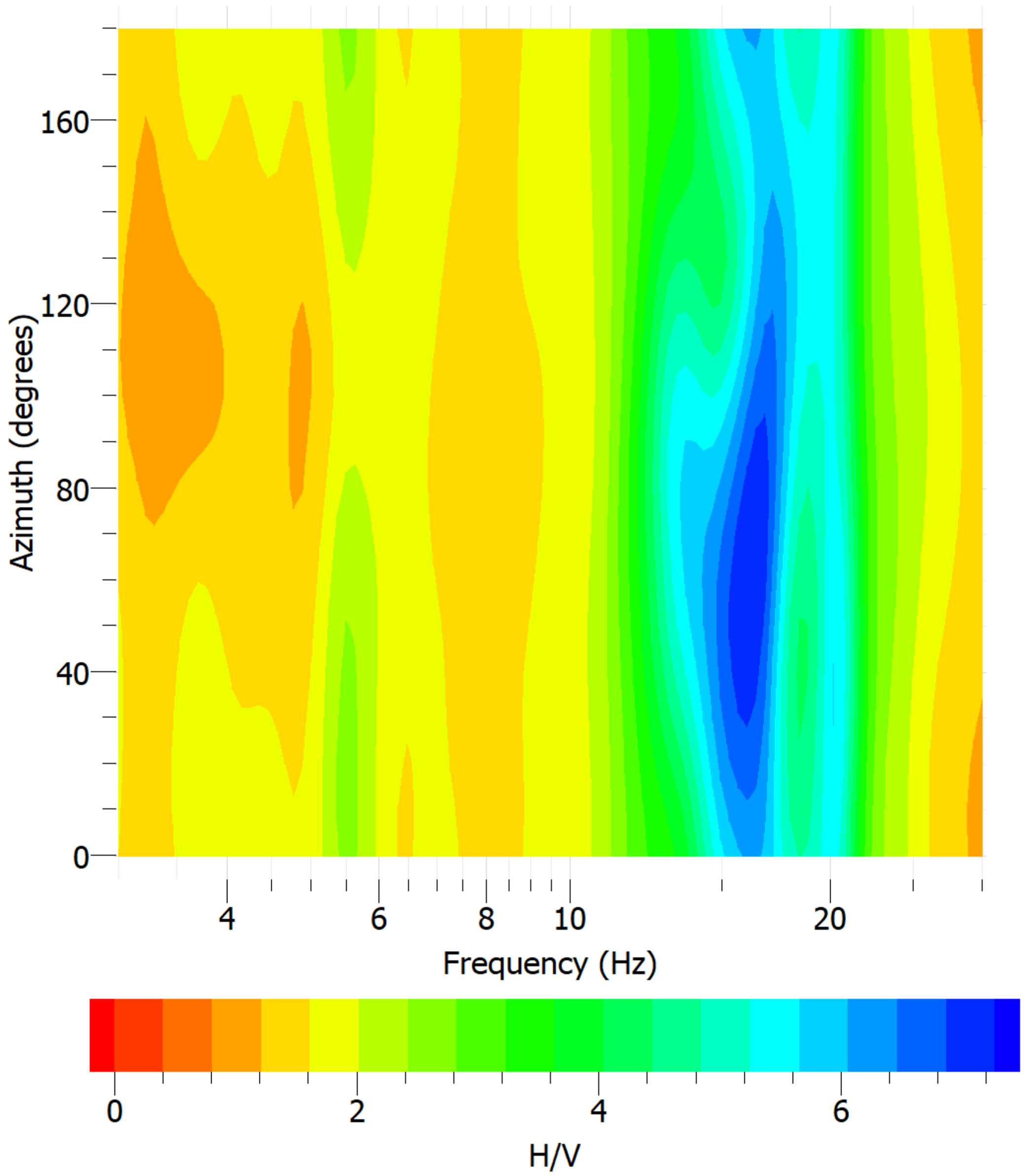

Figure 43: SHSMO borehole 9

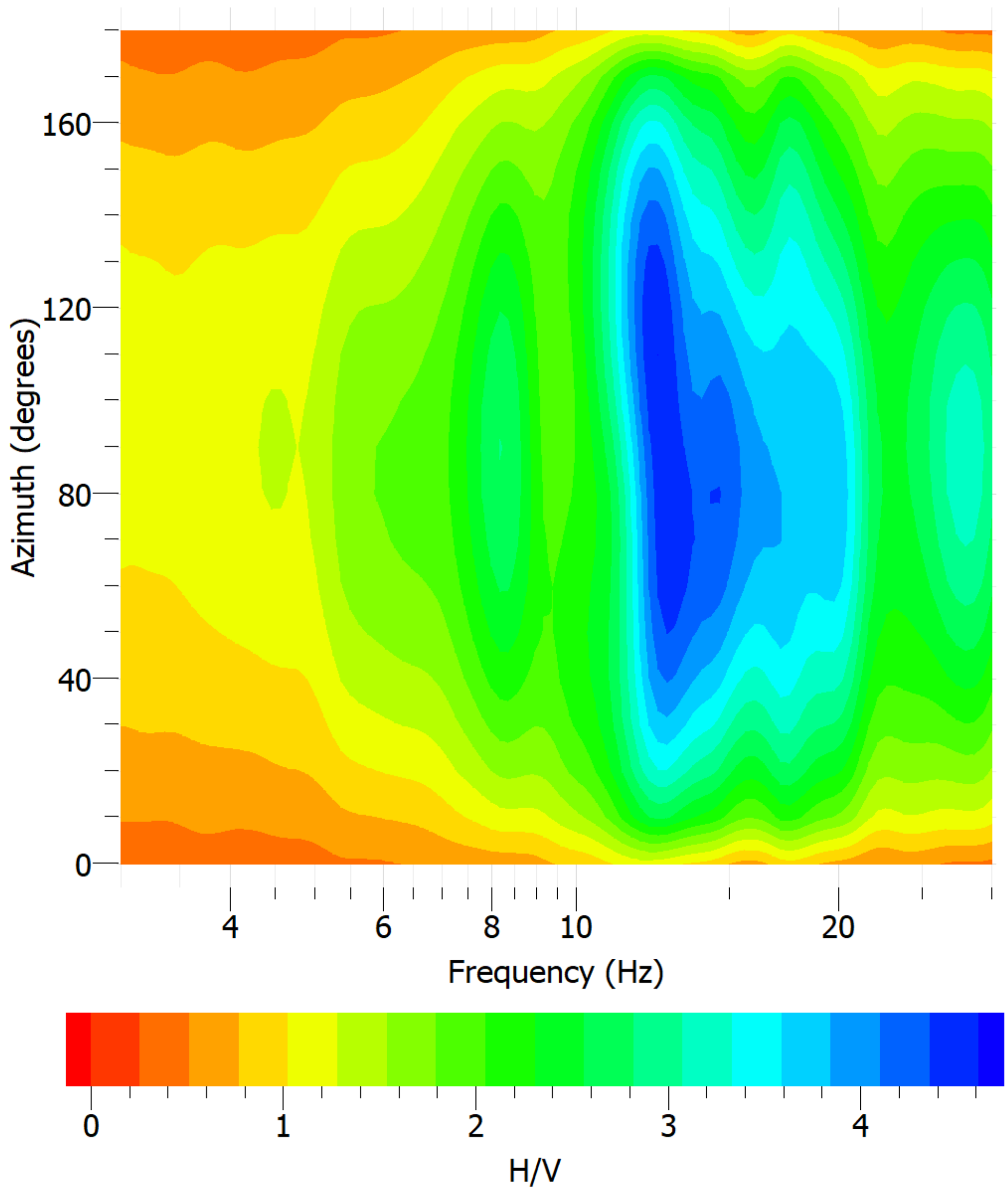

Figure 44: SHSMO borehole 10

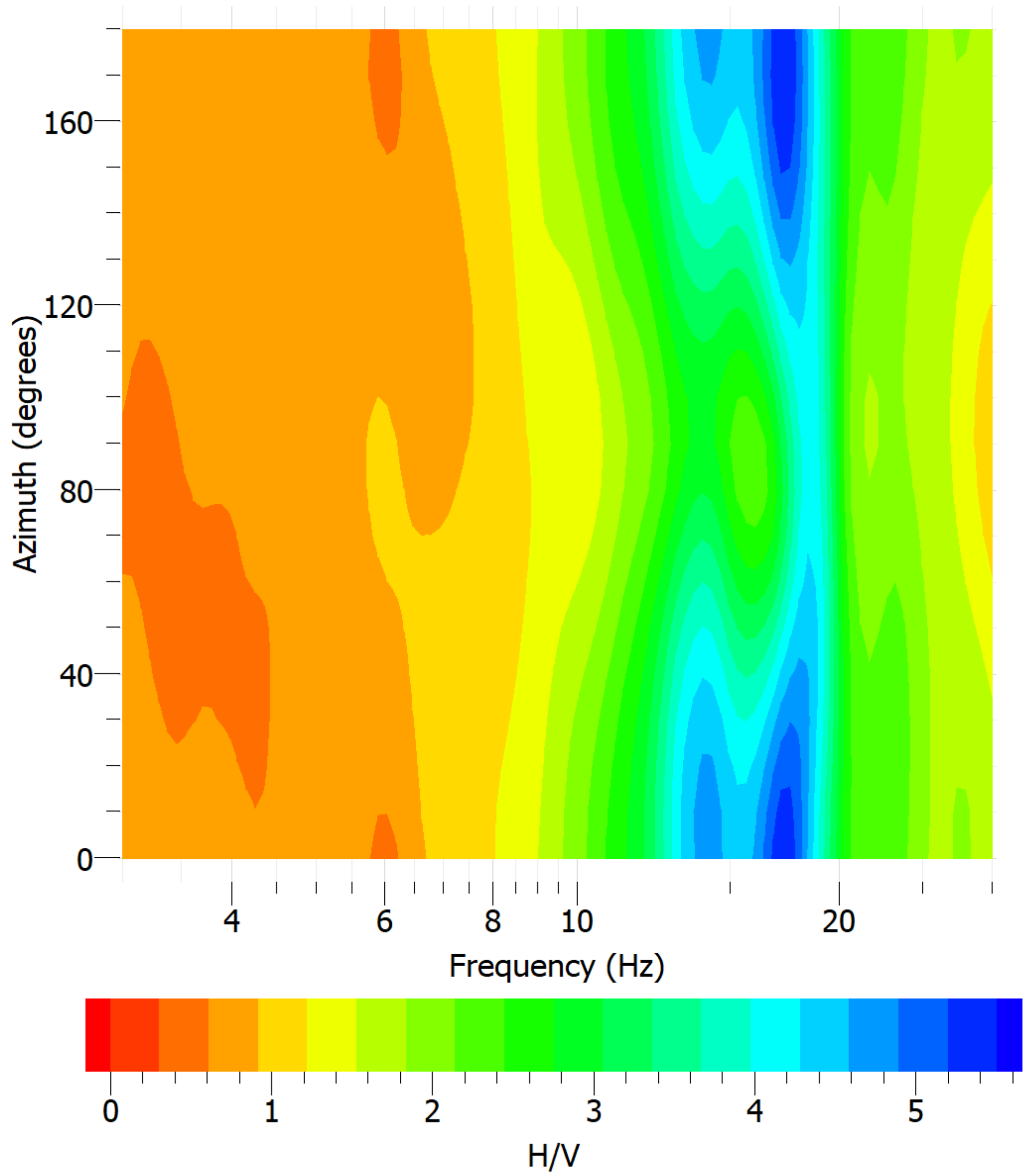

Figure 45: SHSMO borehole 13

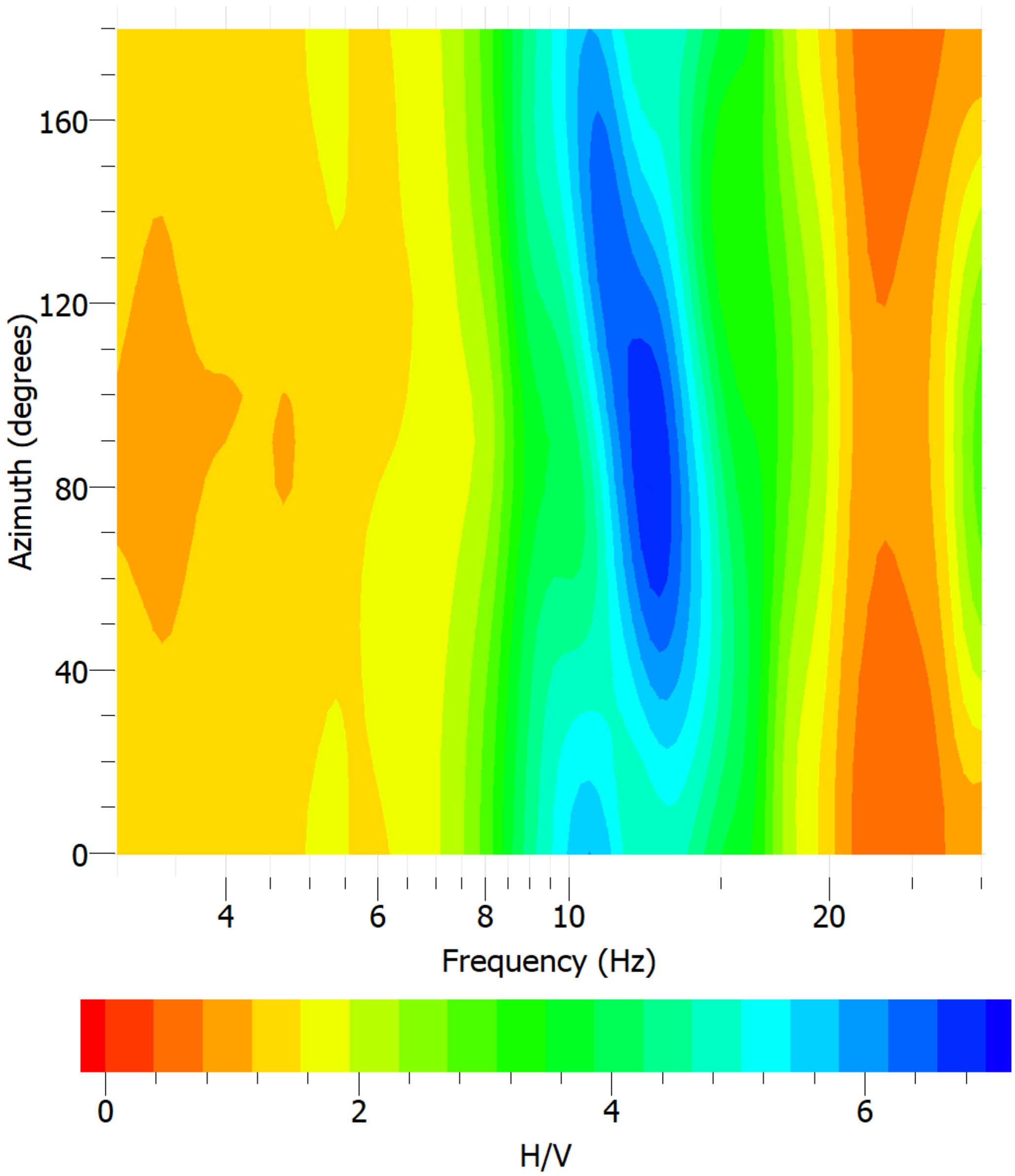

Figure 46: SHSMO borehole 16

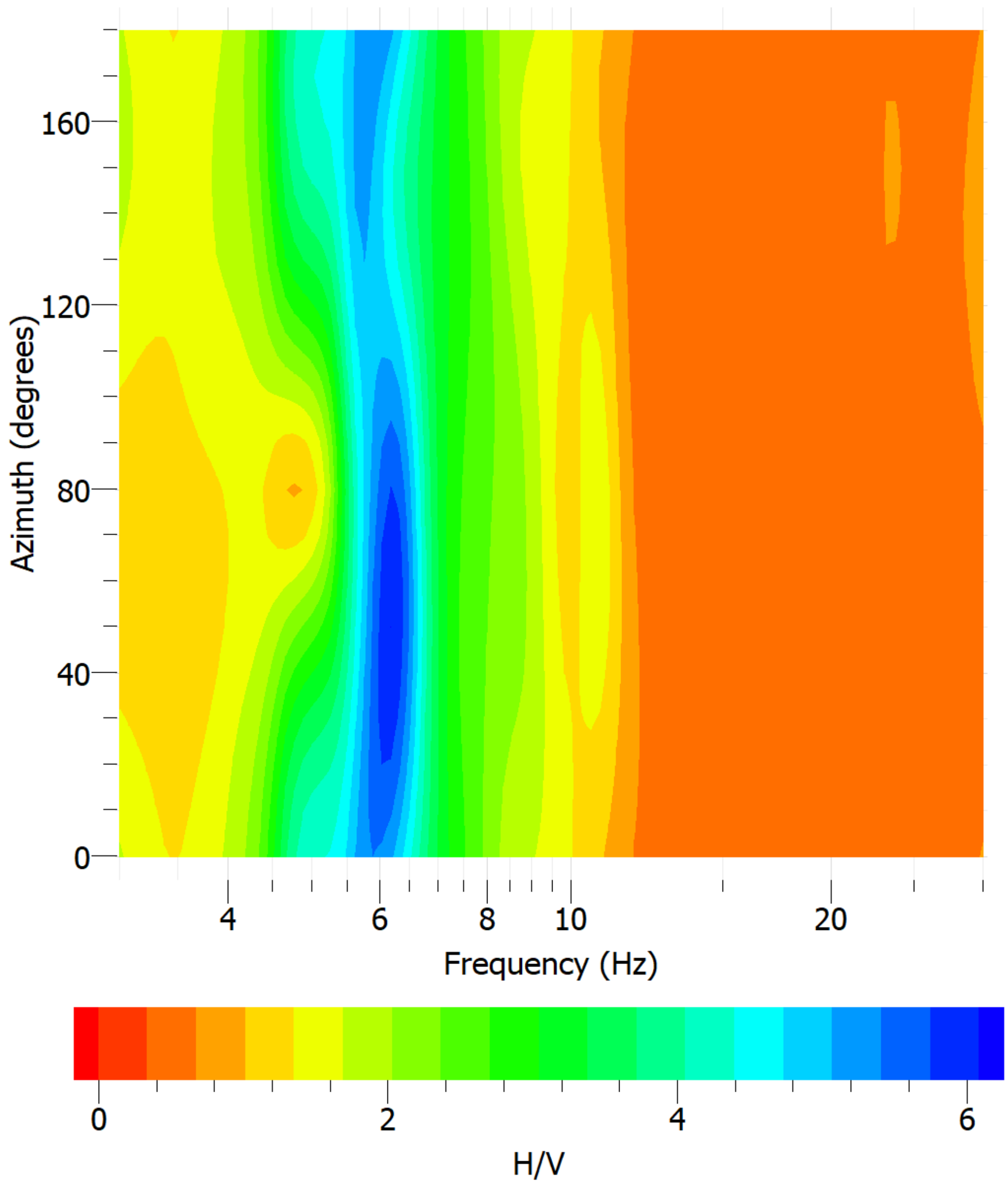

Figure 47: Stewart Hall borehole 1

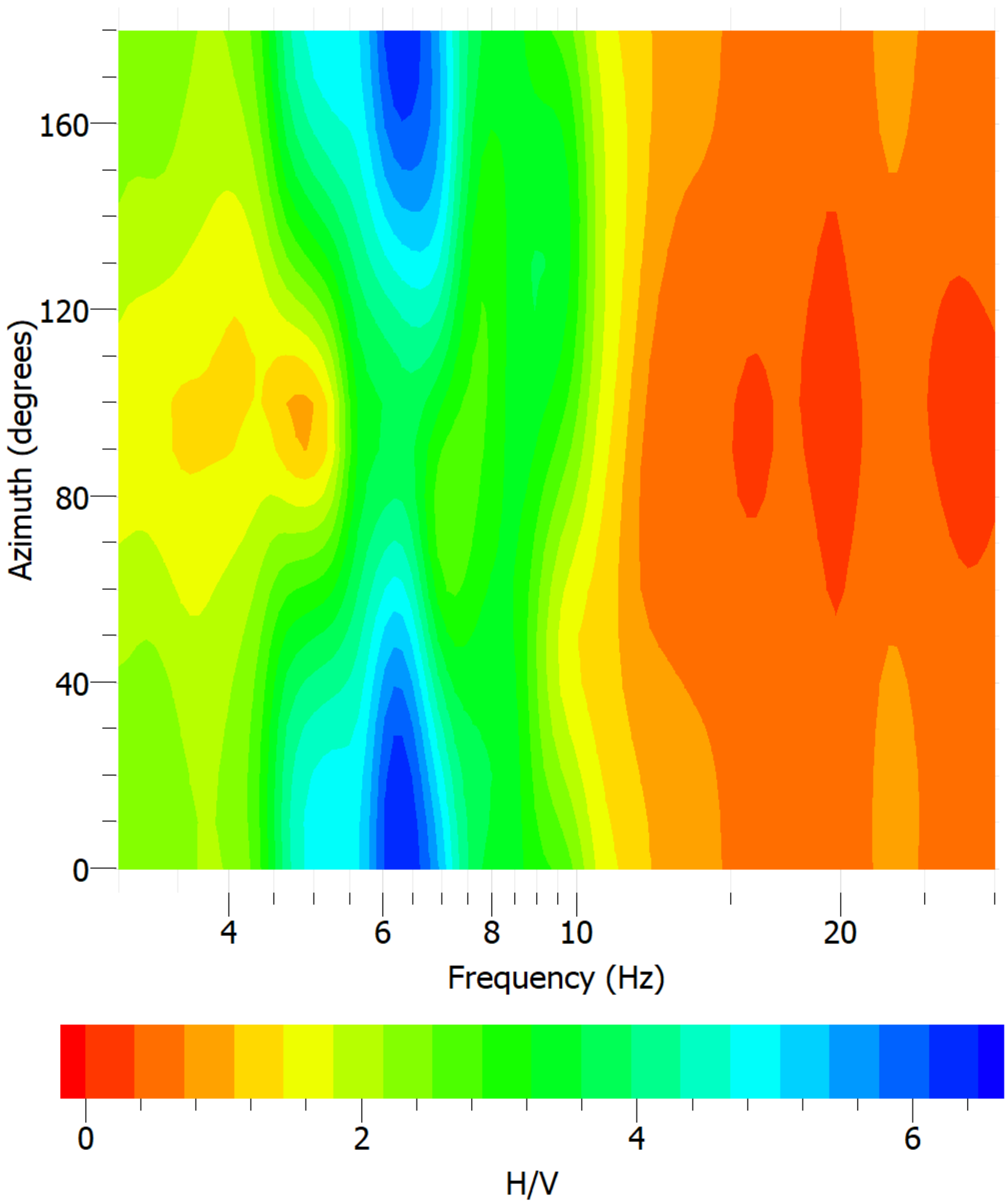

Figure 48: Stewart Hall borehole 2

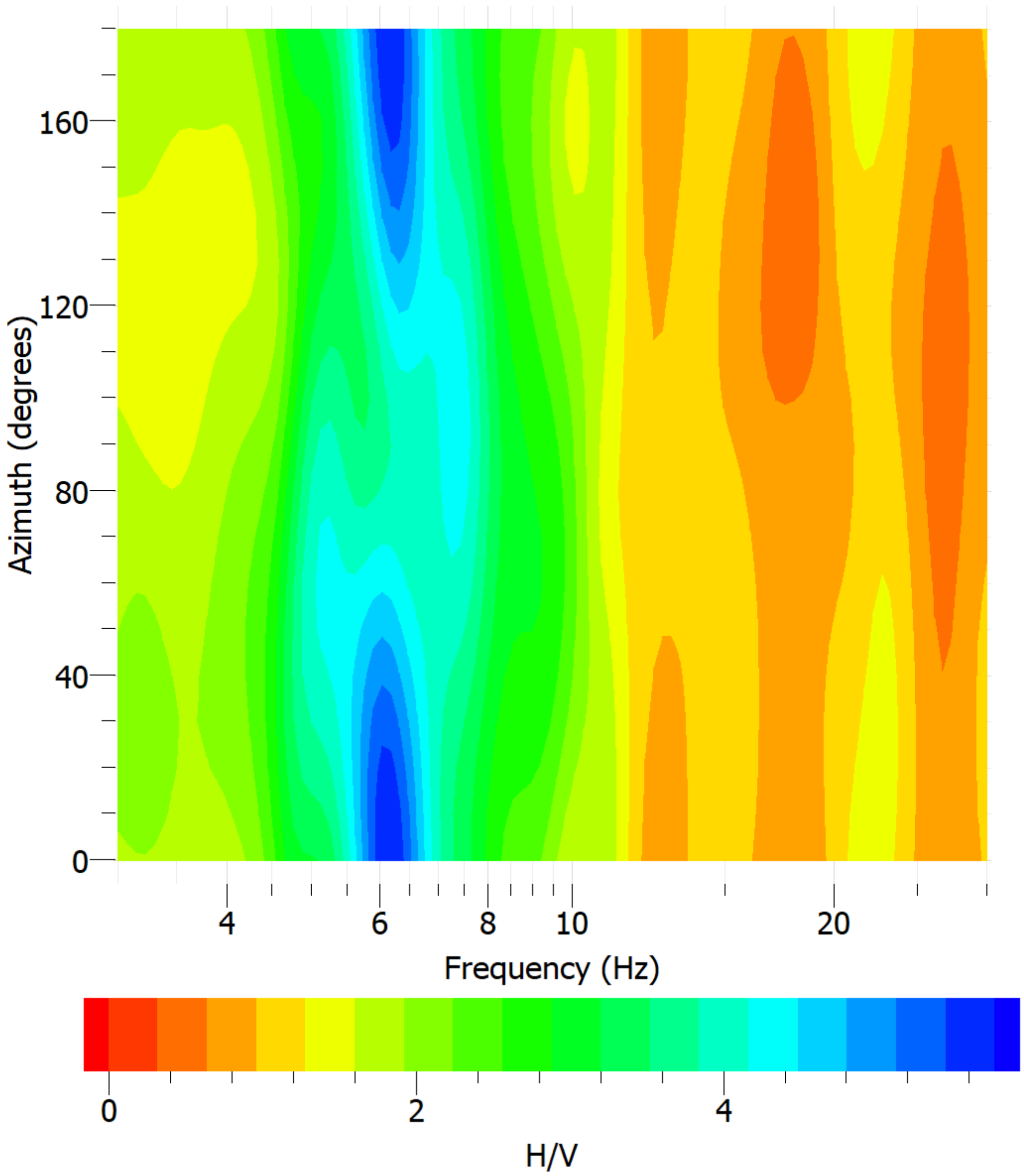

Figure 49: Stewart Hall borehole 2'

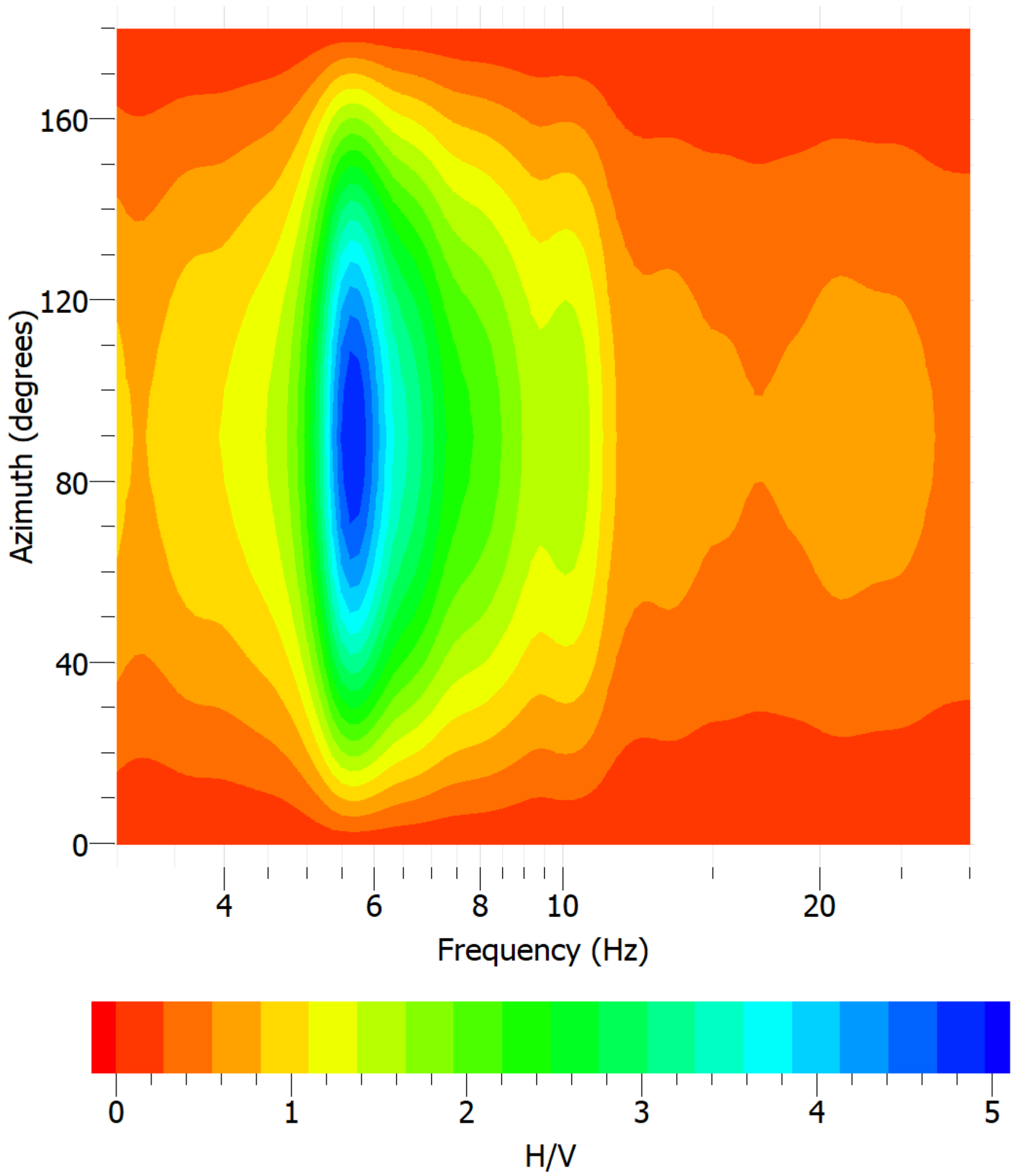

Figure 50: Virginia Ave Dining borehole 3

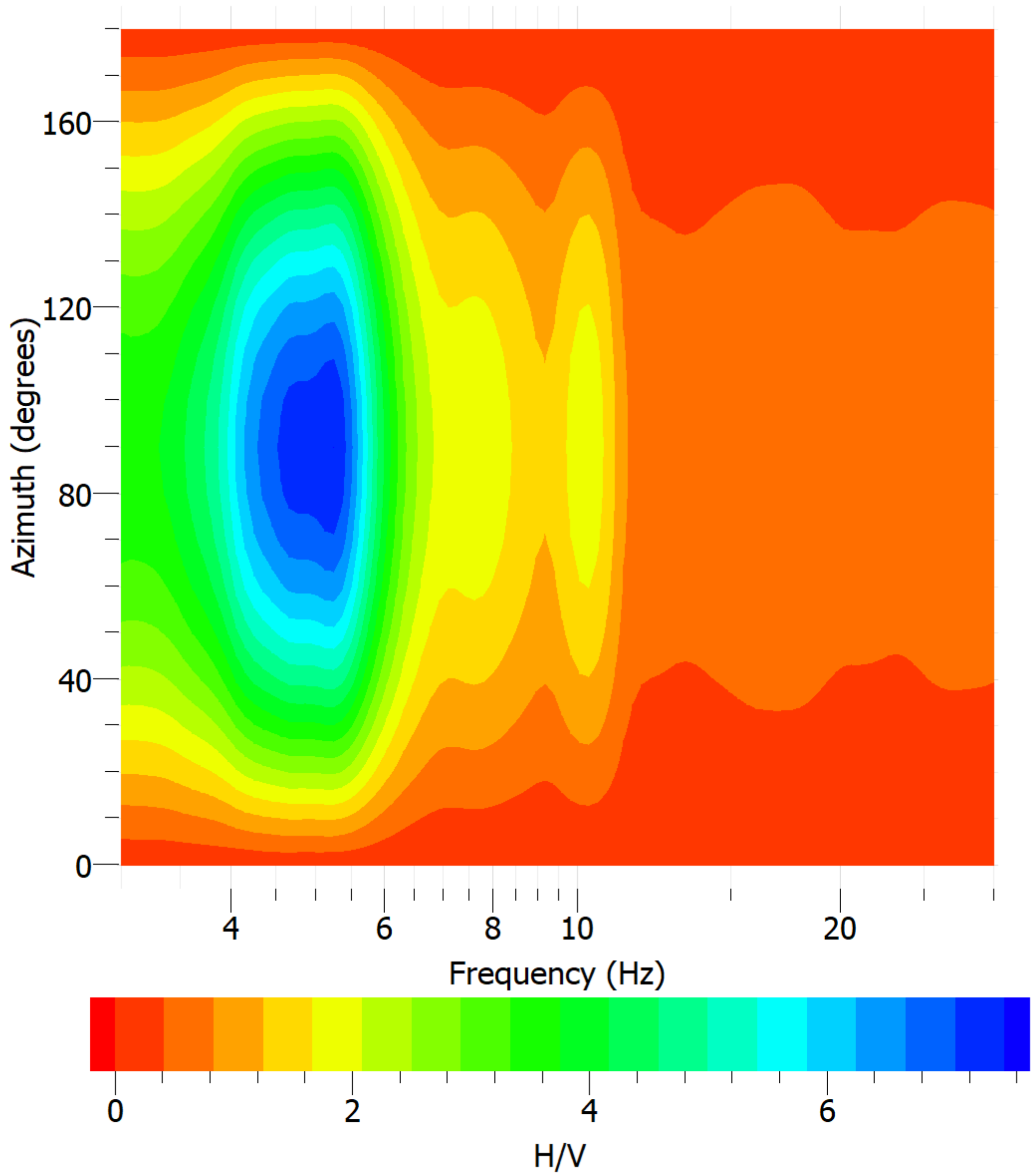

Figure 51: Virginia Ave Dining borehole 5

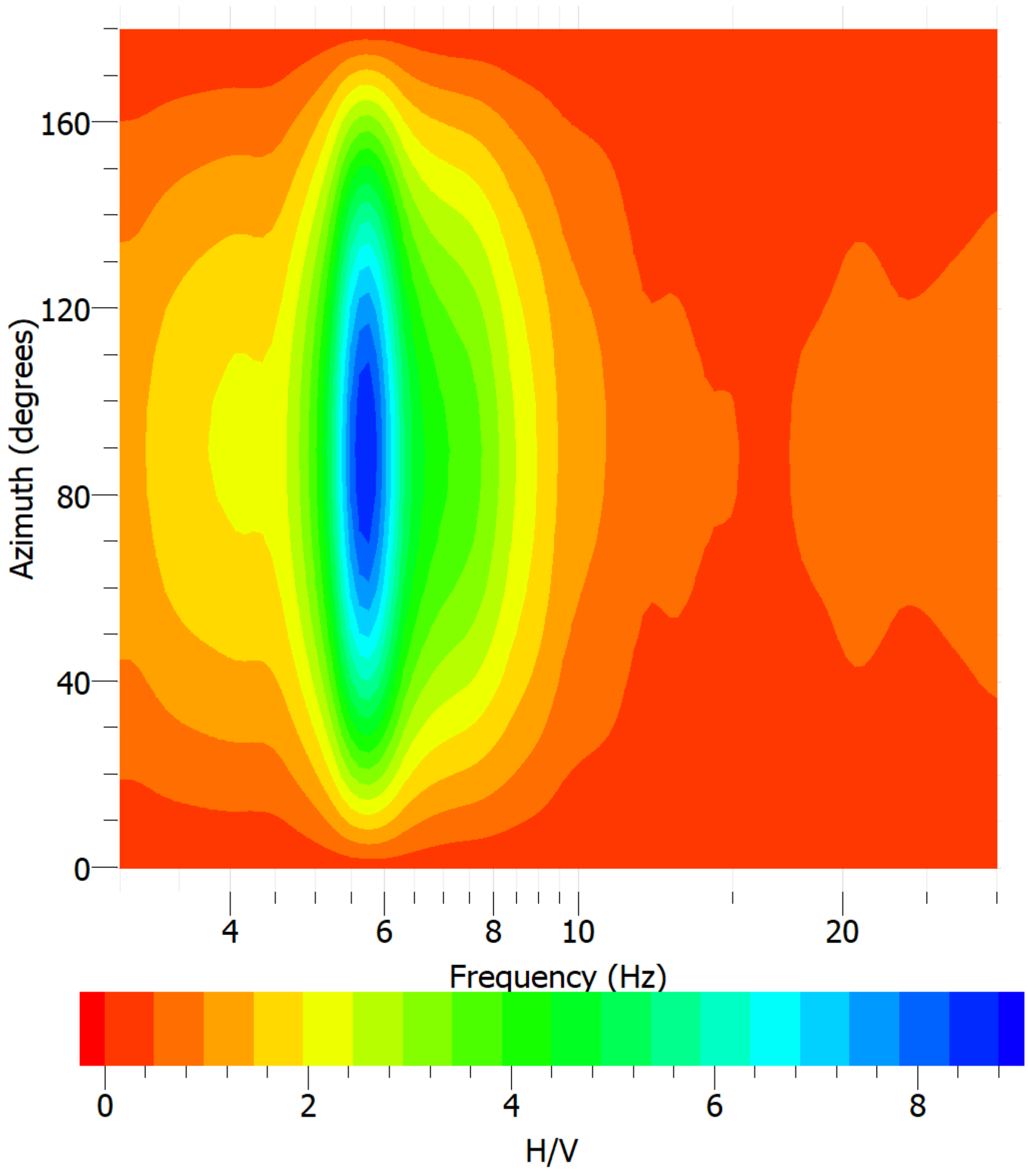

Figure 52: Virginia Ave Dining borehole 6

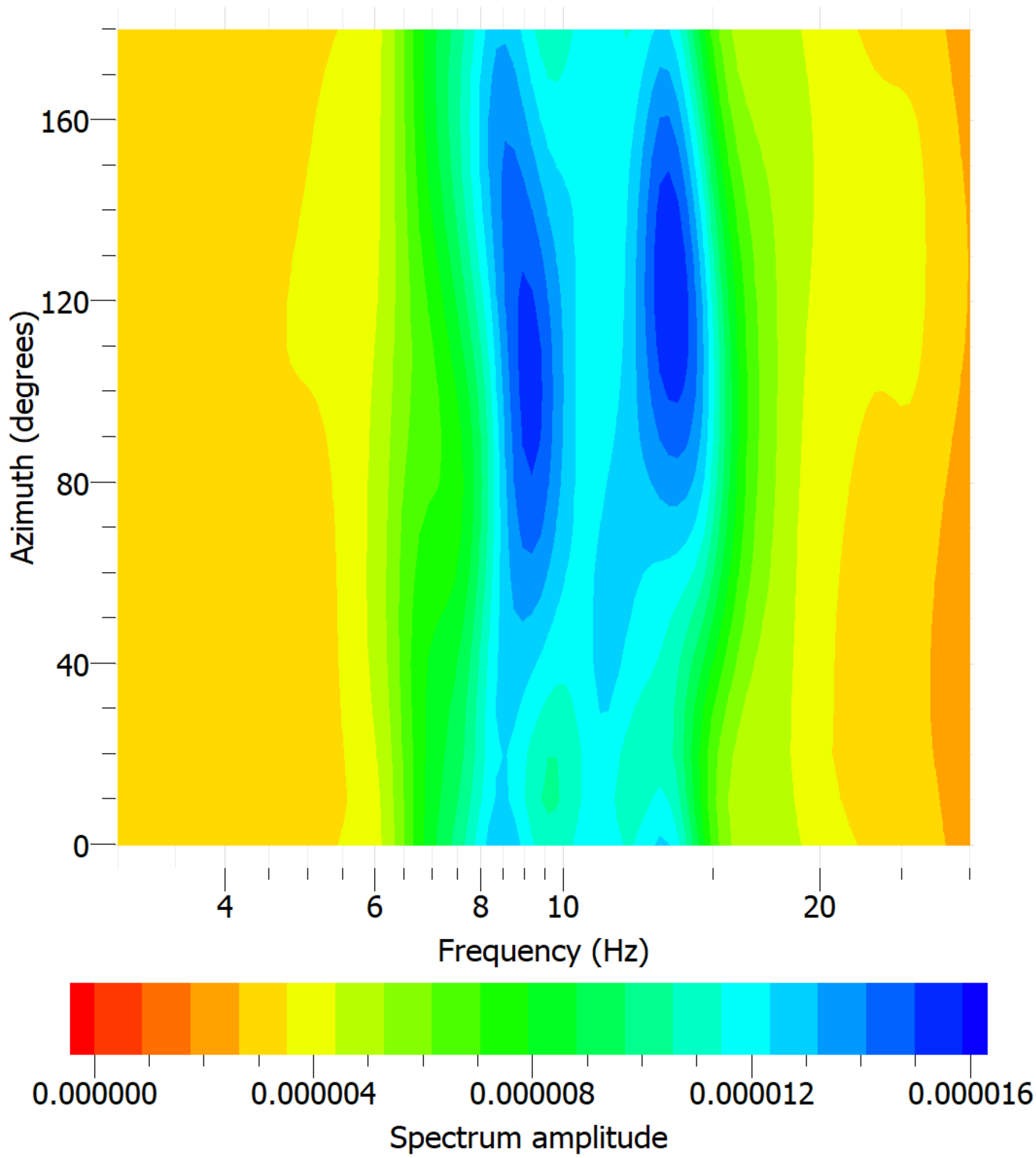

Figure 53: NextGen borehole 5

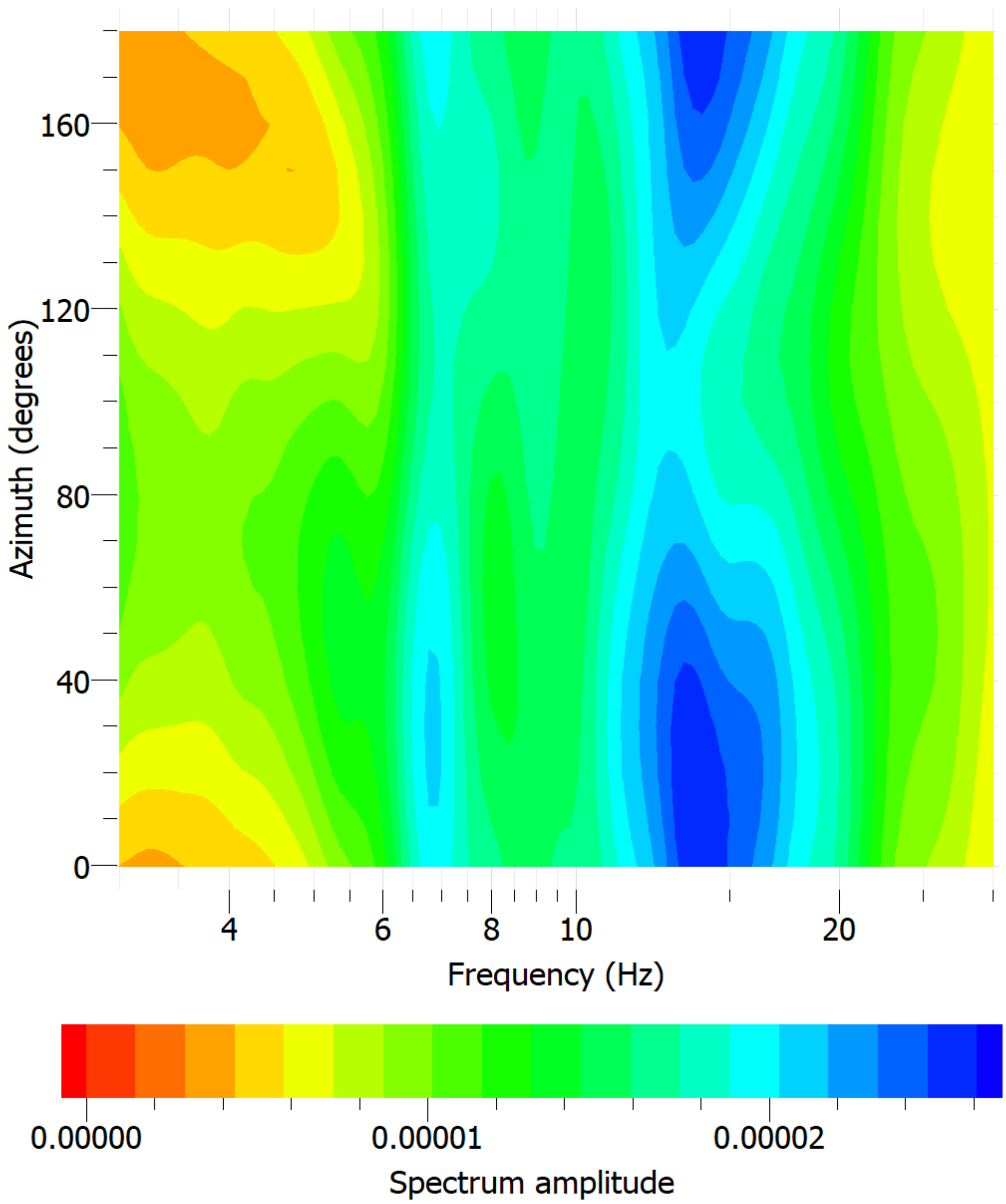

Figure 54: NextGen borehole 6 **Figure 53:** NextGen borehole 5

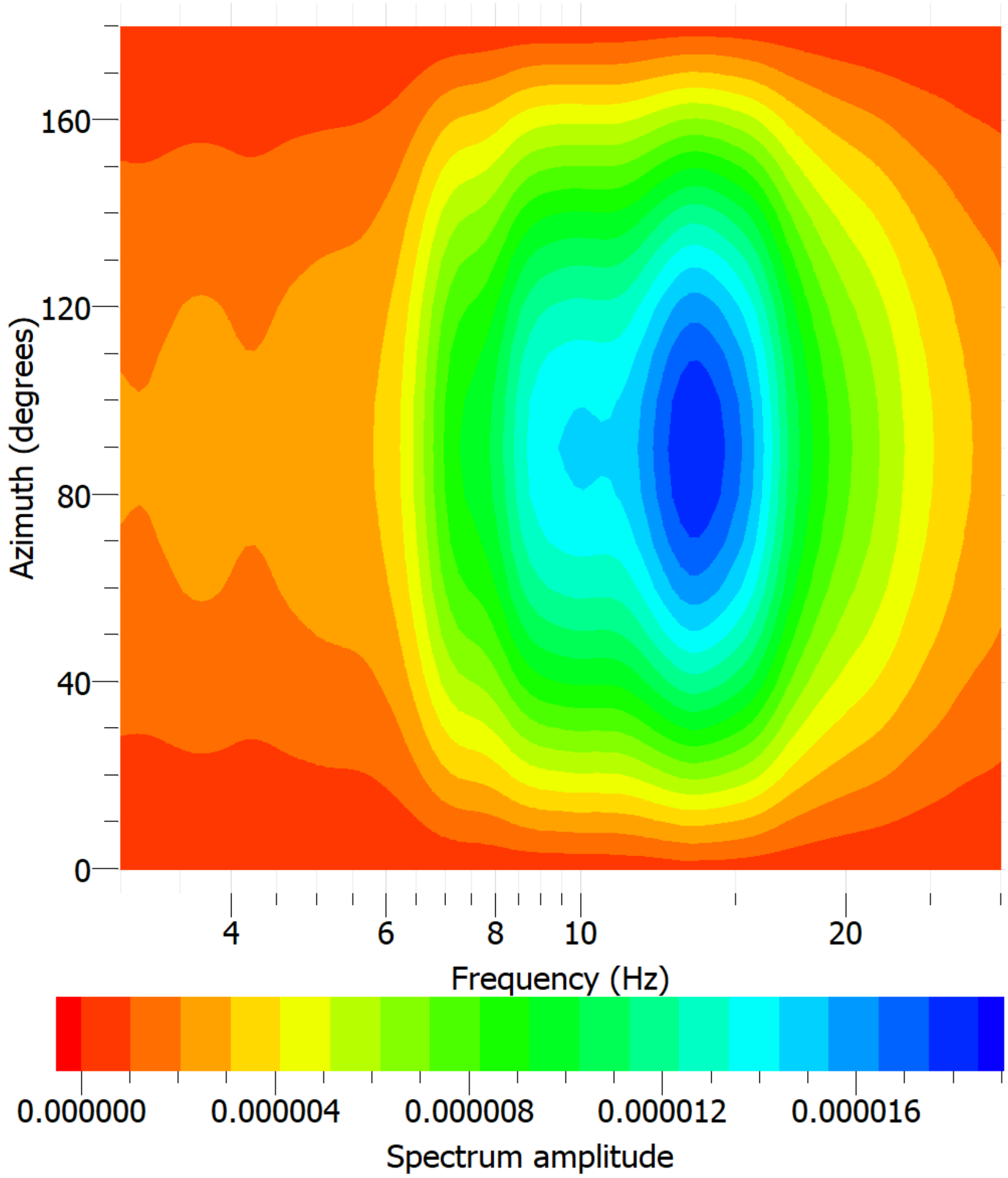

Figure 55: NextGen borehole 8

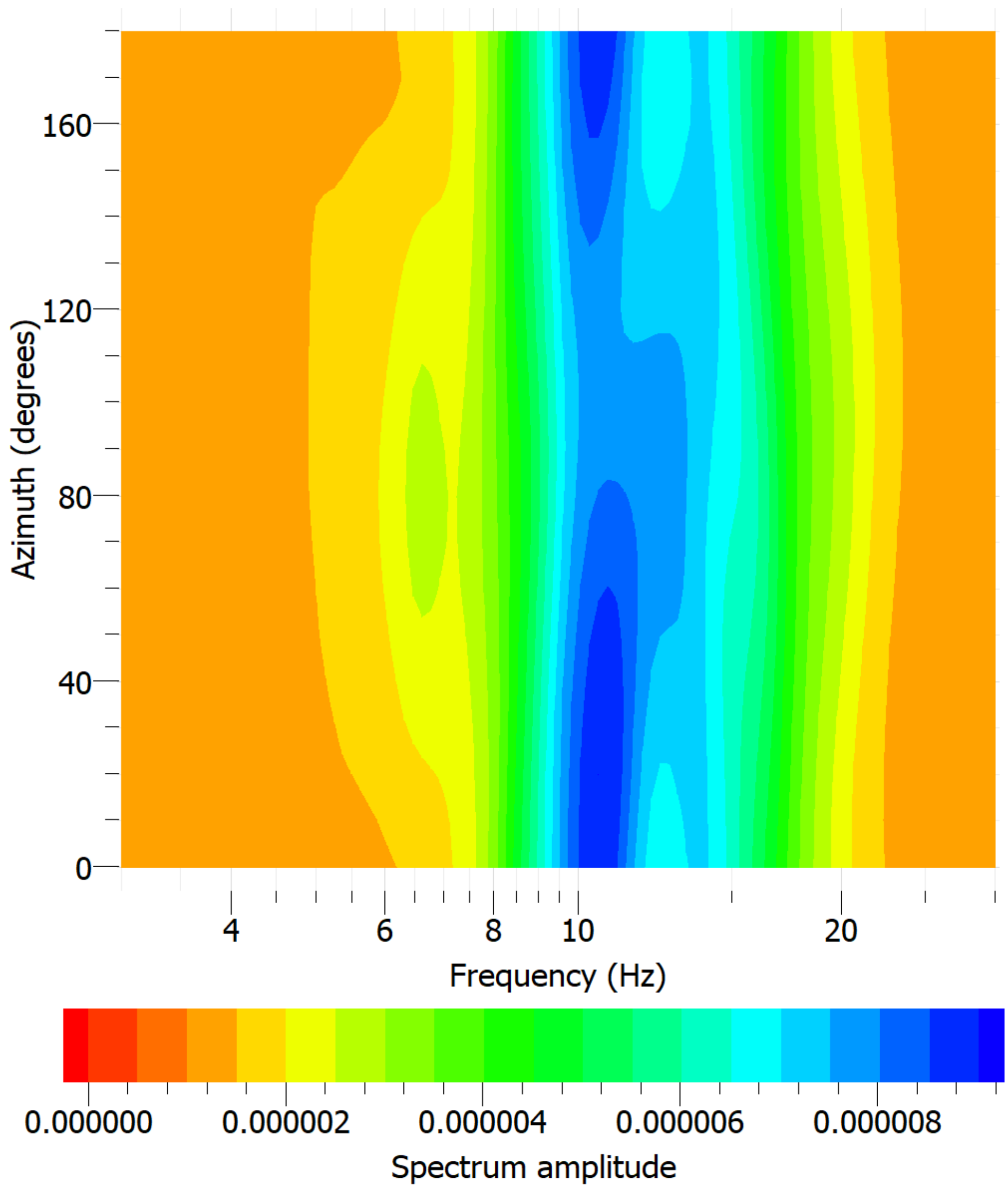

Figure 56: NextGen borehole 9

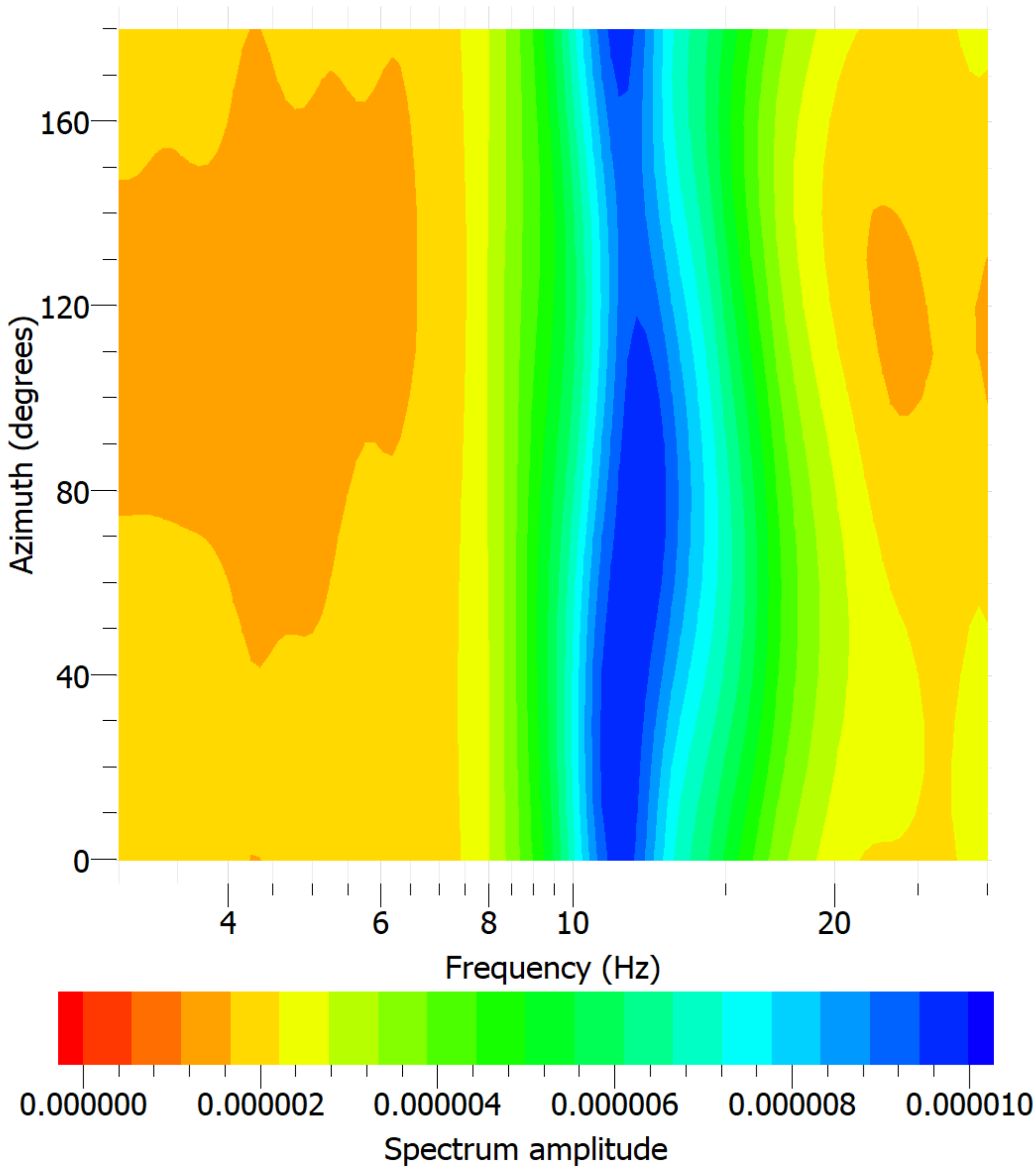

Figure 57: NextGen borehole 11

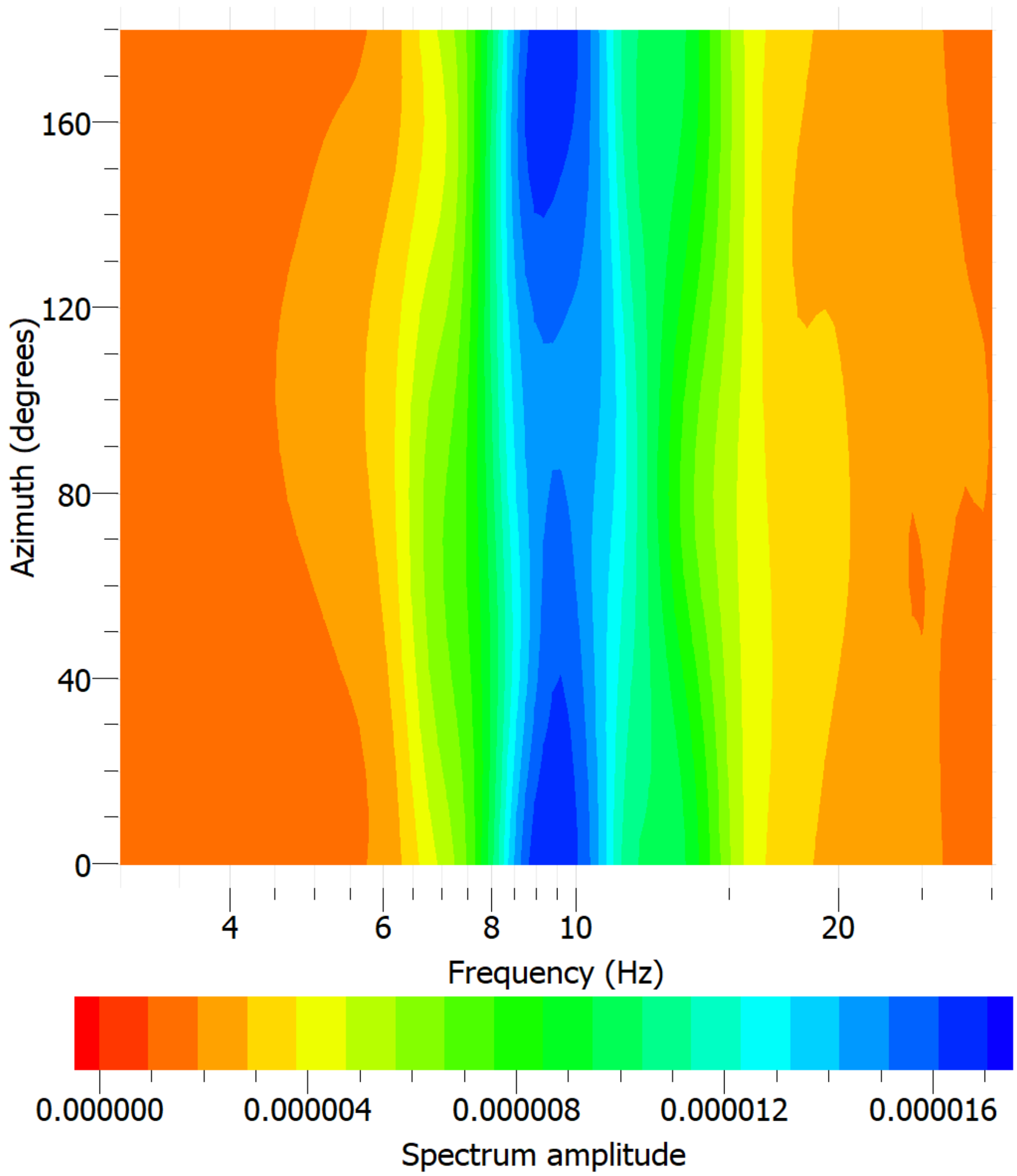

Figure 58: NextGen borehole 14

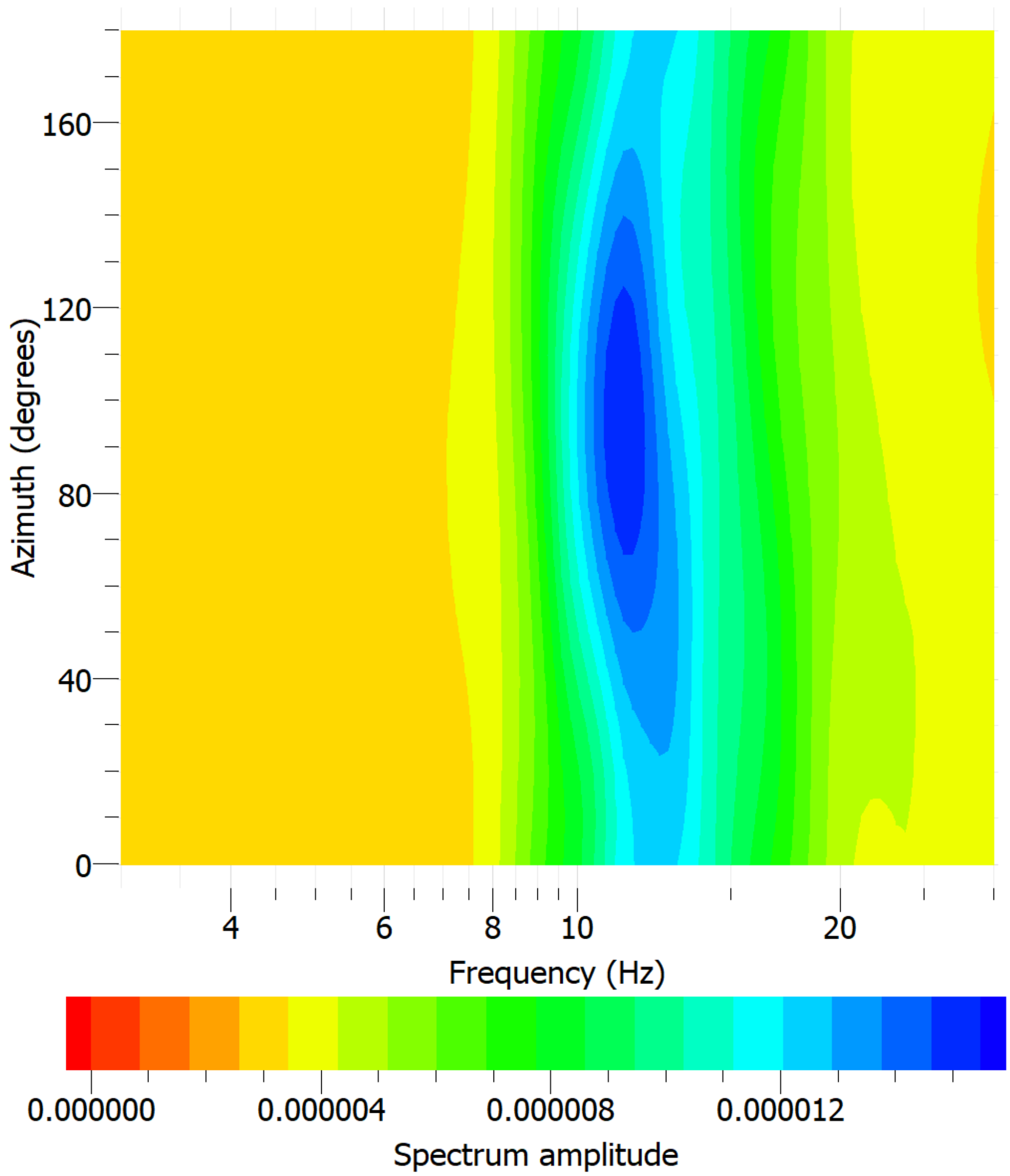

Figure 59: NextGen borehole 15

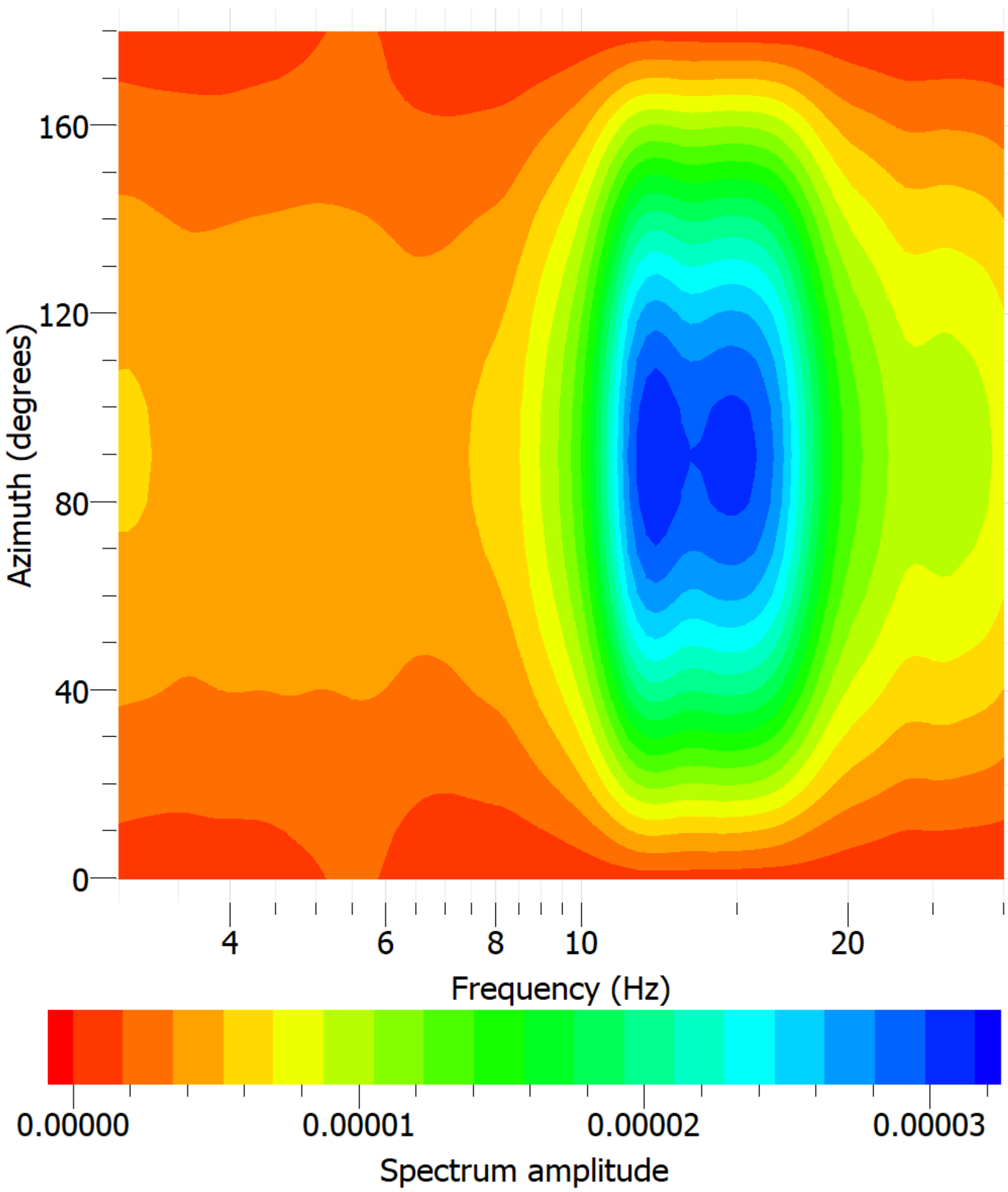

Figure 60: NextGen borehole 16

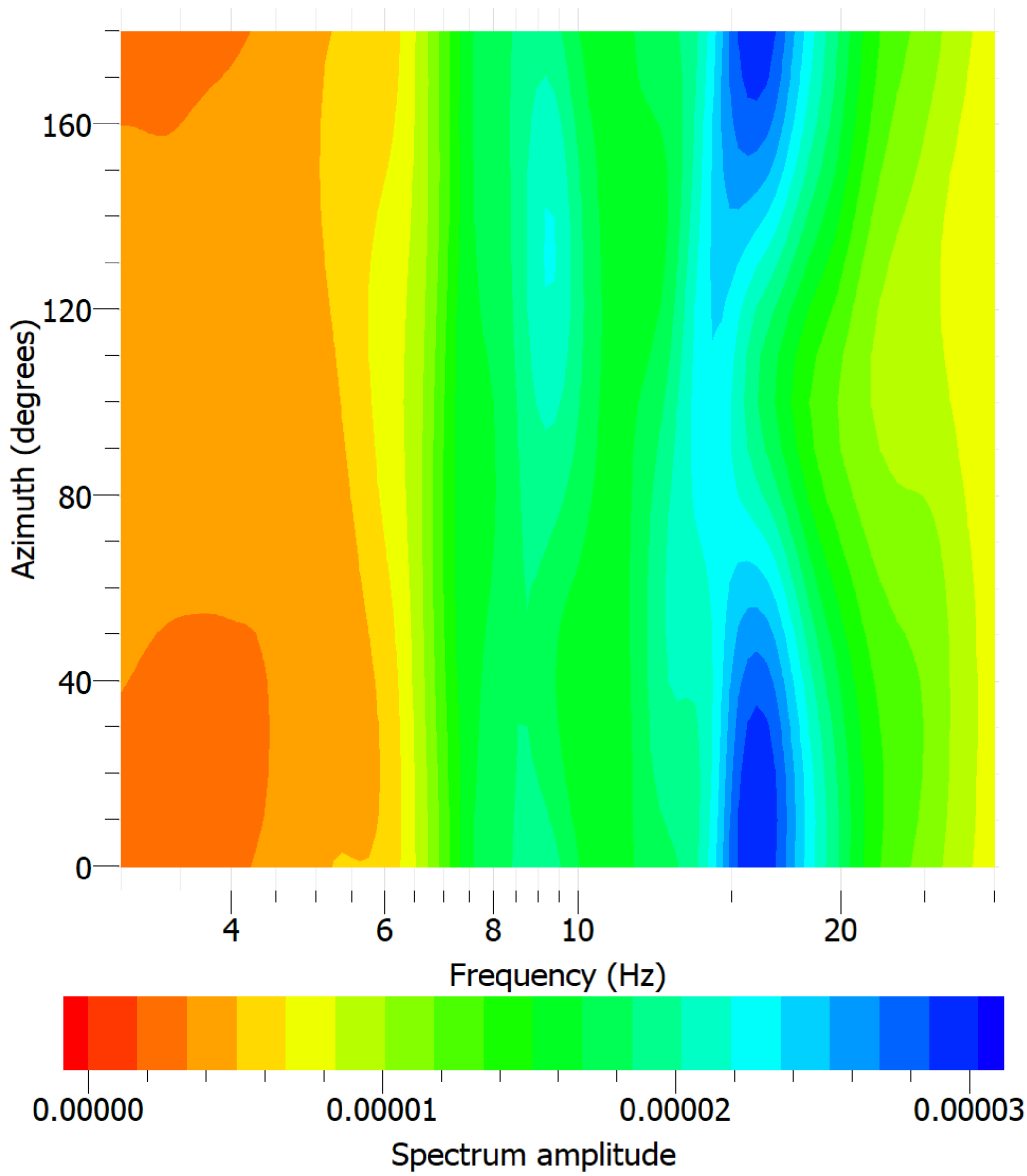

Figure 61: NextGen borehole 17

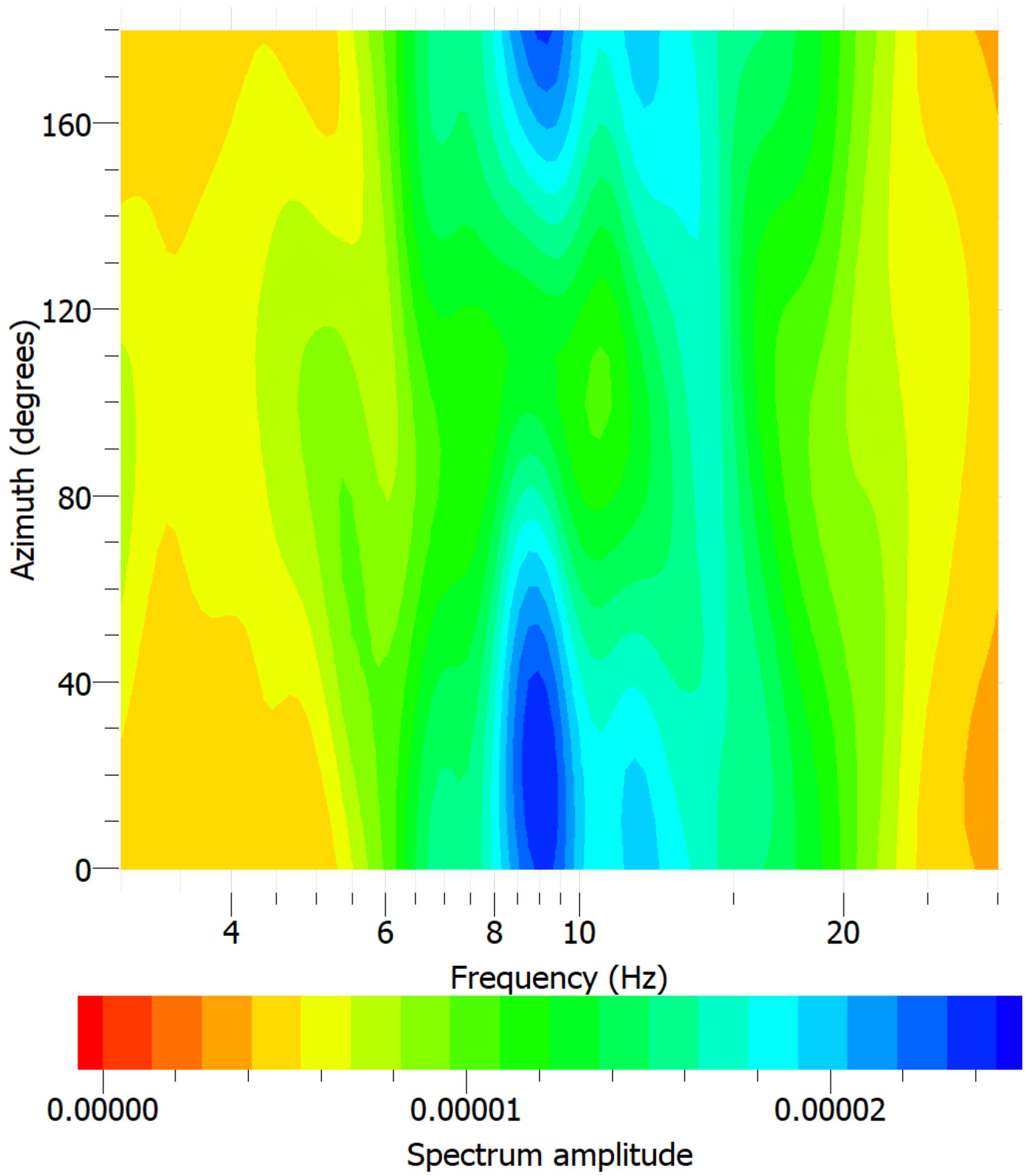

Figure 62: NextGen borehole 18

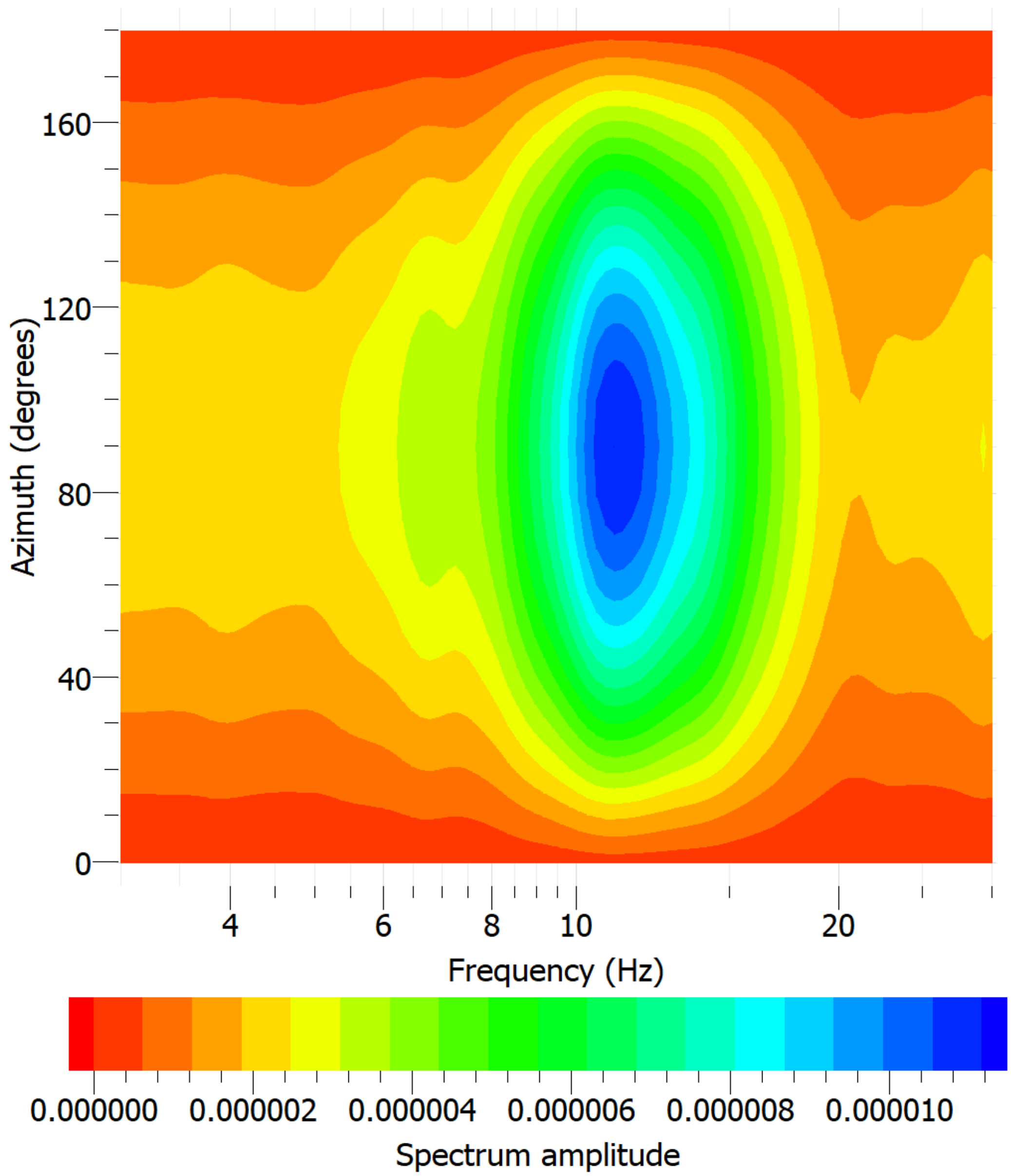

Figure 63: NextGen borehole 19

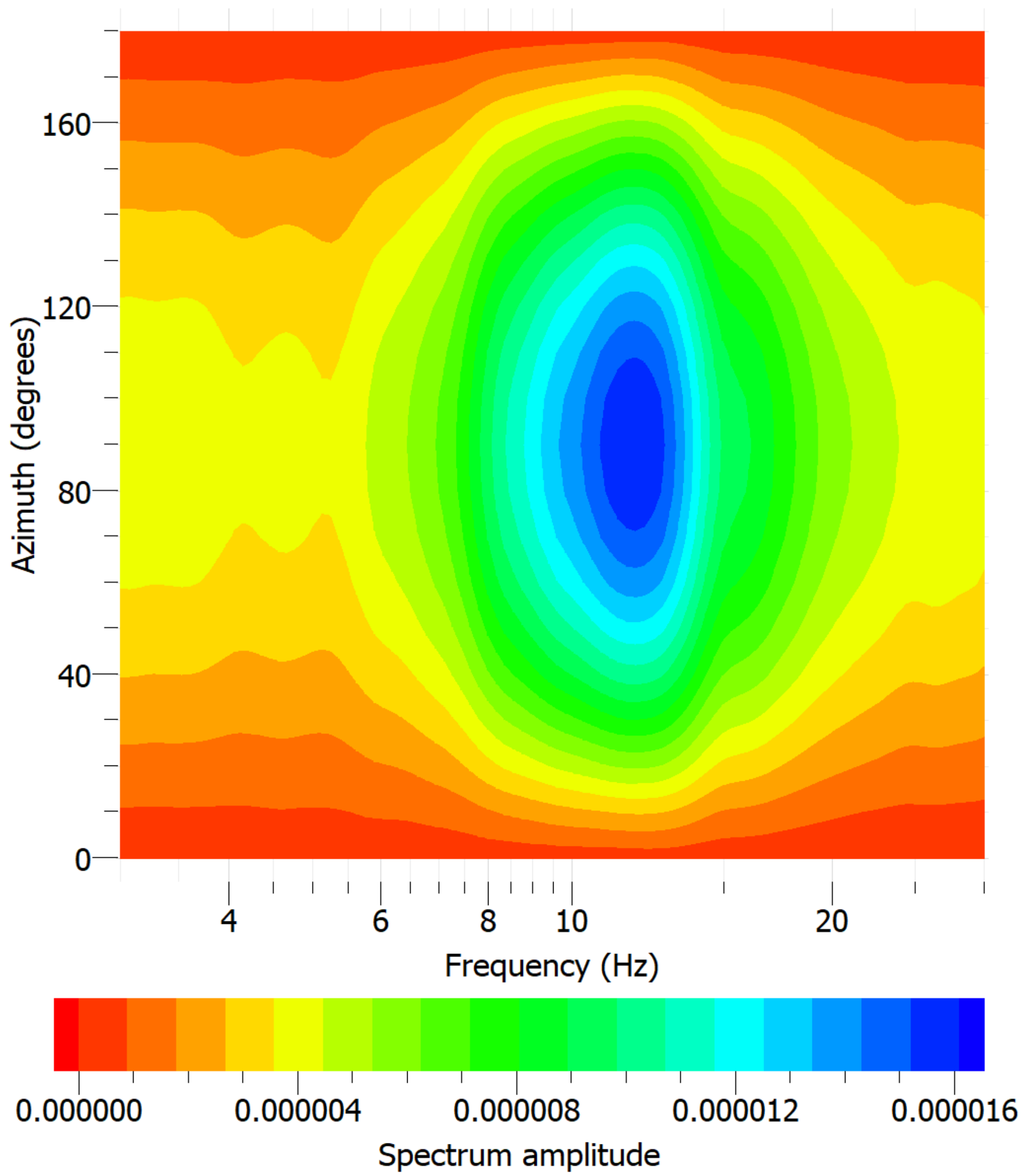

Figure 64: NextGen borehole 21

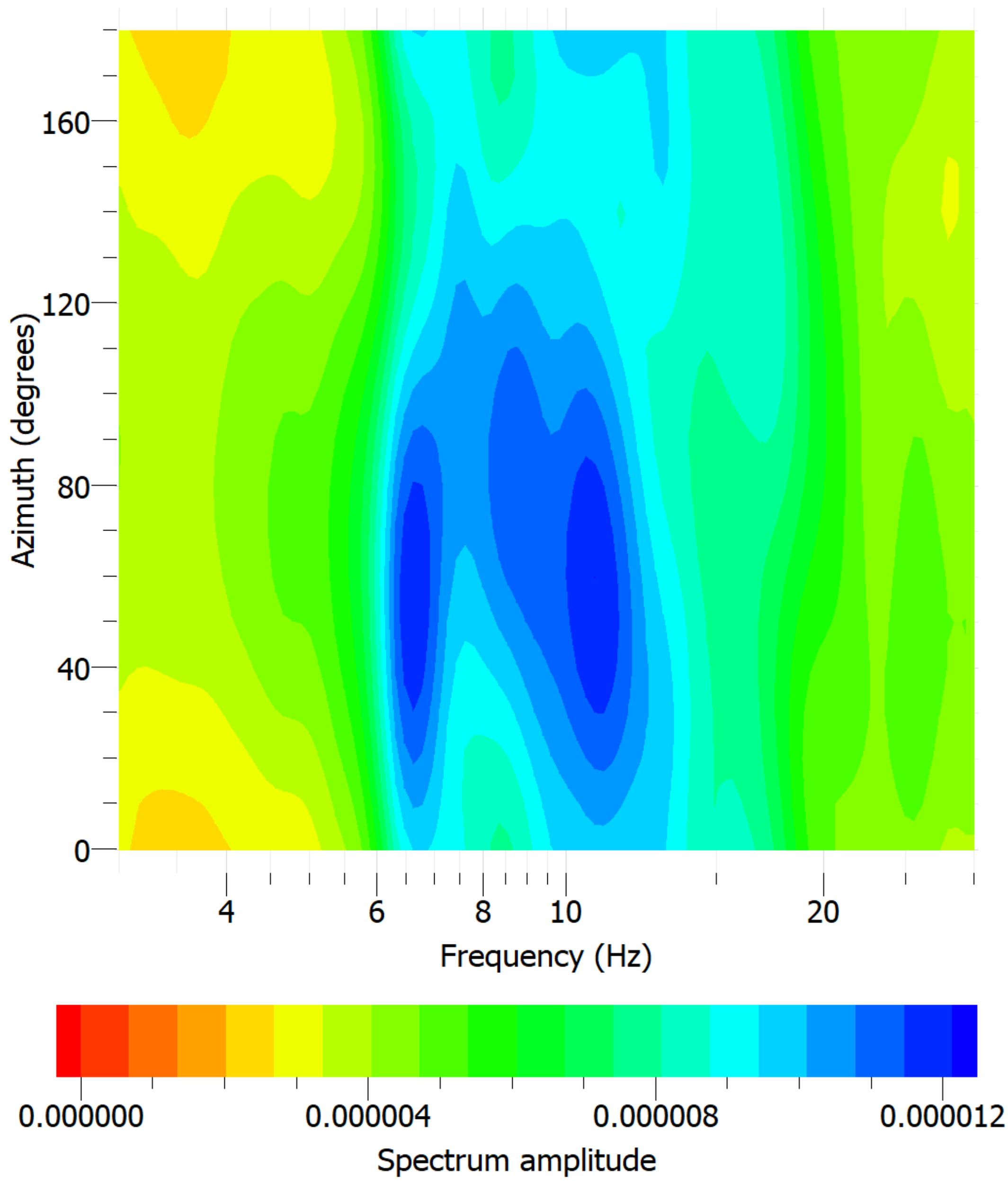

Figure 65: NextGen borehole 22