The use of various geophysical methods to characterize the velocity profile of a deep soil site

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ABSTRACT: A site characterization study was conducted at a greenfield site in western Georgia in the southeast of the United States of America. The site islocated in the East Gulf Coastal Plain physiographic province approximately 20 miles south of the Fall Line, the contact between the sediments of the Coastal Plain physiographic province to the south and the bedrock of the Piedmont physiographic province to the north. Basement rock was determined to underlie the site at a depth of 1,665 feet. Part of site characterization was to develop a shear wave velocity (Vs) profile extending to hard rock (Vs > 9,200 feet/second). Various seismic methods, including Spectral-Analysis-of-Surface-Waves (SASW) testing, Microtremor Array Measurements (MAM), Multi-channel Analysis-of-Surface-Waves (MASW) testing and suspension P-S velocity logging were used to evaluate the shear wave velocity profile. The Vs profiles developed from these seismic methods show good agreement. The data sets illustrate the value of combining both active and passive seismic methods and how these combined methods can be used to robustly characterize the Vs of a deep soil site in the Coastal Plain.

Keywords: shear wave velocity; coastal plain; site characterization; dispersion curve, spectral analysis

1. Introduction

A geotechnical site characterization study was conducted at a greenfield site located in the southwest corner of Georgia, approximately 20 miles south of Columbus, Georgia in the United States of America as shown on Figure 1. The project area is located along the Chattahoochee River as shown on Figure 2. A steep bluff is located along the river's edge on the northwestern portion of the site, while a wide floodplain borders the western portion of the site. At the time of the study, the floodplain was in agricultural use. The area east of the floodplain is characterized with rugged forested uplands. Steep gullies with evidence of significant erosion are abundant throughout the uplands. At the time of the study, many of these erosional uplands were being logged for timber. A plateau area was located east of the eroded uplands. This area was in agricultural use and was the focus of the site characterization study.

Limited subsurface data were available for the site and no data were available below a depth of 600 feet. Based on geology references, bedrock was expected between depths of 1,500 to 2,000 feet. One of the objectives of the exploration program was to determine the depth to rock and establish the design shear wave velocity profile for the site. A program that incorporated both passive and active geophysical methods was developed to determine the shear wave velocity profile.

1.1. Regional and site geology

The project area is located in the East Gulf Coastal Plain physiographic province in the southeastern United States, as shown on Figure 1. Columbus, Georgia to the north is located on the Fall Line, the boundary between the East Gulf Coastal Plain to the south and the Piedmont physiographic province to the north. The geology of the East Gulf Coastal Plain is characterized by alternating layers of sands, silts, and clays overlying bedrock. These deposits thicken, and thus the depth to bedrock increases, with increasing distance from the Fall Line as shown on Figure 3. At the project site, baed on the projection of the Fall Line, crystalline bedrock (hard rock with a shear wave velocity > 9,200 feet/second [fps]) was estimated between 1,500 to 2,000 feet below ground surface (bgs).

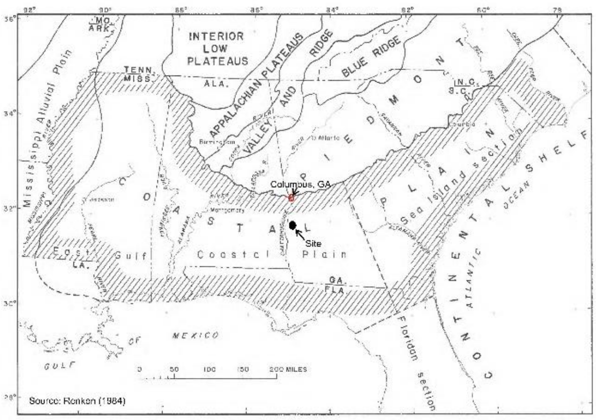

Figure 1. Site Location

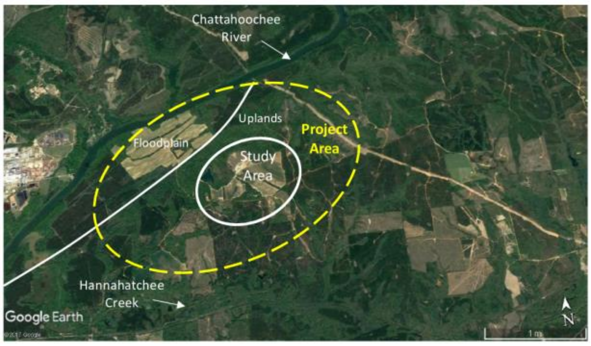

Figure 2. Study Area

A previous study in the area (Law, 1972), with a maximum exploration depth of 425 feet, encountered (from oldest [deep] to youngest [shallow]) the Eutaw, Blufftown, and Cusseta Sand formations. The Tuscaloosa formation, reported to underly the Eutaw formation, was not encountered.

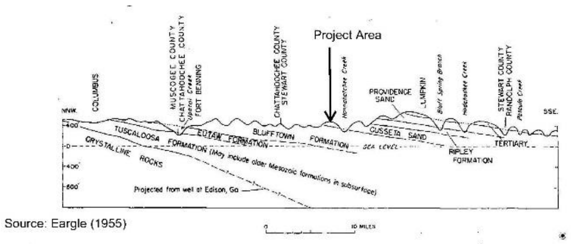

Figure 3. East Gulf Coastal Plain Profile

Subsequent exploration programs, with maximum depths of 600 feet, were conducted during which the upper portions of the Eutaw formation were again encountered. Shear wave velocity (Vs) measurements were acquired to depths of 600 feet. These data are discussed in later sections of this paper.

2. Site characterization

A recent (2016) subsurface exploration was conducted to further characterize the geologic, geotechnical and seismological site conditions. Field and laboratory test programs were conducted. The field test program included soil borings, cone penetration testing, test pits, and downhole and surface geophysics, as summarized in the following paragraphs. Most explorations were located on the plateau area, previously described; although some borings and test pits were taken in the floodplain area to evaluate borrow sources.

The following paraphaphs desicribe the various componenets of the exploration program. Various passive and active methods were used to collect and evaluate shear wave velocity data

2.1. Soil borings

Soil borings were advanced using mud rotary wash-drilling methods (ASTM D5783). Drilling was done with AWJ, BWJ, and NWJ rods and side discharge roller cone bits or wing bits. Standard penetration tests (SPT) (ASTM D1586) were conducted. Drilling fluid additives, such as powdered bentonite clay, were used to provide borehole stability. Generally, soil boring depths ranged from 30 to 600 feet. One boring, which included rock coring, extended to a depth of 1,871 feet. A total of 168 borings, 34,055 linear feet of drilling, were conducted with 136 borings taken in the plateau area and 32 borings taken in the floodplain. Offset borings were drilled to obtain intact samples and conduct downhole geophysics. SPT sampling was conducted in borings to a depth of approximately 200 feet. Soil coring was conducted at depths below 200 feet.

SPTs were performed using 2-inch split-barrel samplers. Eight drilling rigs, each equipped with automatic trip hammers, were used to collect SPT samples. Hammer weights and drop heights were verified to be in conformance with ASTM D1586. Hammer energy measurements were performed on each of the automatic hammers in accordance with ASTM D4633 to determine the energy transfer ratio (ETR), the ratio of the measured transferred energy to the theoretical potential energy for SPT sampling (i.e. 140 lb hammer falling 30 inches, or 350 ft-lbs). Measurements showed average overall ETR values for the eight drill rig hammers ranged between 88.1% and 94.4%. SPT sampling was performed on an approximate 2.5-foot interval to a depth of about 15 feet, on a 5-foot interval from about 15 feet to 100 feet, and on a 10-foot interval from about 100 feet to 200 feet.

Rotary soil coring was conducted below a depth of about 200 feet. At six borings soil coring was conducted at shallower depths. Coring was conducted in accordance with ASTM D2113 using a triple-tube split inner barrel wireline core system with an H-size core barrel. A double-tube coring system was used for soil coring in the deep boring. Individual soil core runs were limited to a maximum length of 5 feet. Recovered soil core samples were visually logged, photographed, wrapped in plastic, and stored. Selected samples were removed for testing..

2.2. Rock coring

Bedrock rock was encountered in the deep boring at a depth of 1,665 feet and drilled to a depth of 1,871 feet. Rock coring was performed in accordance with ASTM D2113 using a triple-tube split inner barrel wireline core system with an H-size core barrel. Recovered rock cores were visually logged, photographed, and stored. Selected core samples were removed for testing.

2.3. Test pits

Test pits, excavated at thirteen locations using a track-mounted excavator, were taken to evaluate potential borrow sources. Four of these tests pits were in the floodplain. Test pits were logged as the excavation proceeded. Materials exhibiting differing characteristics were segregated into stockpiles on the ground surface. Generally, the excavation was terminated when the maximum extent of the excavator was reached or the sidewalls became unstable, primarily due to groundwater inflow. Photographs were taken of the excavation and segregated materials. Bulk samples, for laboratory testing, were taken of representative materials.

2.4. Cone penetration testing

Seismic piezocone (SCPTu) soundings were conducted at ten locations shown on Figure 4. Soundings, conducted in accordance with ASTM D5778, were pushed to refusal, with a maximum depth of 112 feet. At two locations, where refusal was encountered, the hard layer was drilled through and the sounding was continued. In each sounding, cone tip resistance, sleeve friction and penetration pore water pressure were recorded at 5-centimeter intervals. Seismic velocity measurements were taken in the soundings at intervals of about 3.3 feet (1 meter). Pore pressure dissipation tests were conducted in selected more pervious zones.

2.5. Downhole geophysics

A suite of downhole geophysical test methods was conducted by GEOVision Geophysical Services of Corona, California in seven boreholes, at locations shown on Figure 4. Methods included natural gamma, dual induction, three-arm caliper, spontaneous potential, acoustic televiewer, and P-S velocity logging. Offset boreholes were used in an effort to reduce the degradation of the borehole sidewalls in the primary boring after repeated tripping in and out to recover SPT and soil core samples. Boring locations for downhole geophysical testing were located in the plateau area and were selected to provide aerial coverage of proposed development. Natural gamma, dual induction, and spontaneous potential logs were used in part to identify unit contacts, in particular the contact between the Blufftown and Eutaw formations. Caliper logs were used to determine the diameter and profile of the borehole walls. Acoustic televiewer logs were used to characterize cemented zones encountered in the Blufftown formation as well as to determine the verticality of the boreholes.

P-S suspension logging was conducted by in seven boreholes for this study. The P-S logging system directly determines the average compression and shear wave velocities of a segment of the soil/rock column surrounding the boring by measuring the elapsed time between arrivals of a wave propagating upward through the soil/rock column. Measurements of compression (P) and shear (S) wave velocity were recorded at 0.5 meter (1.64-foot) intervals.

Figure 4. P-S Velocity Logging Boreholes and SCPTu Soundings

2.6. Surface geophysics

Both active and passive surface geophysical methods were used to collect Vs data. The active methods consisted of the spectral analysis of surface waves (SASW) method and the multichannel analysis of surface waves (MASW) method. The passive method consisted of the two-dimensional (2D) microtremor array measurements (MAM) method. The locations of these arrays are shown on Figure 5.

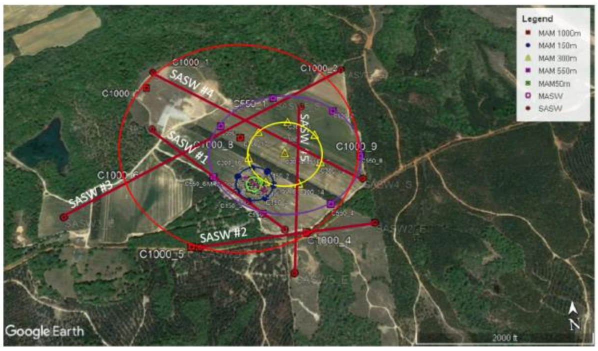

Figure 5. Surface Geophysical Array Locations

2.7. Spectral-analysis-of-surface waves

SASW testing was conducted by the University of Texas-Austin (UTA) Geotechnical Engineering Center (GEC) under the direction of Dr. Kenneth Stokoe, II. The program consisted of SASW testing along five linear areas. The application and theory behind SASW testing and evaluation are not discussed herein but can be found in Stokoe et al., (1994), Joh (1996), Stokoe et al., (2005) and Lin et al., (2008).

The five SASW arrays, of varying distances, were laid out across the site depending on access and surface obstructions. The basic configuration of the source and receivers used in field testing at each array location is illustrated in Figure 6. Generally, three receivers were used with the sledge hammer source and four receivers were used with vibroseis (aka Liquidator, Figure 9) source. This arrangement enabled two or four sets of SASW test results to be obtained at the same time, thereby cutting testing time significantly as compared to using only two receivers. The middle receiver (denoted Receiver #2 in both the 3-receiver and 4-receiver arrays) was always located at the center line of the test array. When different spacings were used and/or reverse directions were tested, only Receivers #1, #3, and #4 and the source were moved. For the shorter spacings, usually source-to-receiver spacings of 25 feet or less, tests were performed in both the forward and reverse directions using the sledge hammer for an impact source. For the larger spacings, usually source-to-receiver spacings of 25 feet and greater, testing was generally performed only in the forward direction using the large vibroseis source.

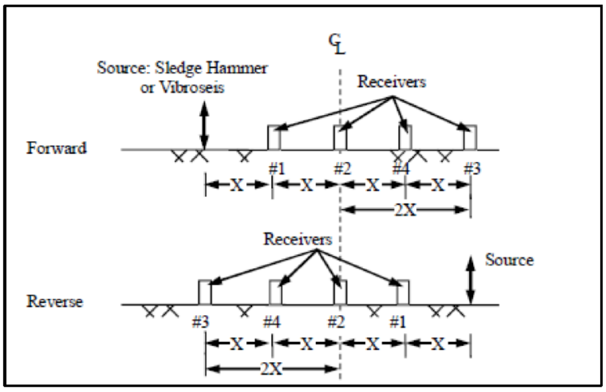

Figure 6. General SASW Array Layout

2.8. Multichannel analysis of surface waves and microtremor array measurements

The active MASW method was used to develop the the near surface Vs structure while the passive MAM method was used to enhance the deeper Vs structure. Testing was conducted by UTA-GEC under the direction of Dr. Brady Cox. MAM was conducted using circular arrays of 50, 150, 300, 550, and 1000 m as shown on Figure 5. One MASW array, located through the center of the 50m MAM array as shown on Figure 5, was conducted. The application and theory behind MASW and MAM testing and evaluation are not discussed herein but can be found in Foti et al., (2014), Garofalo et al., (2016), Griffiths et al., (2016) and Cox and Teague (2016).

MASW testing was performed using 4.5-Hz vertical geophones (Geospace Technologies GS-11D) coupled to the ground surface with a 7.6-cm spike. A total of 48 vertical geophones were placed in a linear array with a spacing of 2 m between successive geophones, resulting in an array length of 94 m. Two 24-channel portable seismographs (Geometrics Geode) were used to record the MASW field data. Wavefields with strong Rayleigh wave content were generated by striking a square aluminum strike-plate with a 7.3 kg (16 lb) sledgehammer. Wavefields were generated at four distinct “shot” locations (i.e. 5, 10, 20, and 30 m) off both ends of the array, with the shot location defined by the absolute distance from the first geophone in the array. Five distinct blows were recorded per shot location. Waveforms generated by the shots were recorded for 4.0 seconds with a 1.0 second pre-trigger delay using a sampling rate (Δt) of 250 ms.

The circular MAM arrays were configured with eight broadband seismometers (seven along the circumference and one in the center). MAM stations recorded ambient vibrations for periods of 3 to 21 hours, with longer recording times corresponding to the larger arrays. It should be noted that the recording times for many MAM arrays were well in excess of what has been commonly used. However, larger arrays (i.e., 300, 550, and 1000 m) were allowed to record overnight in order to provide redundancy in the data. Data were recorded with a sampling frequency of 100 Hz (i.e., Δt = 10 ms).

Three-component broadband seismometers with a flat frequency response between either 120 seconds and 100 Hz (Nanometrics Inc. Trillium Compact 120s) or 20 seconds and 100 Hz (Nanometrics Inc. Trillium Compact 20s) were used to record ambient vibrations for MAM testing. Seismometers were buried to provide adequate coupling with the ground surface and to mitigate the effects of wind vibrations.

Note that additional single-station noise measurements were obtained to compute horizontal-to-vertical (H/V) spectral ratios in areas outside of the circular MAM arrays (not discussed herein, but will be the subject of a future paper).

3. Site stratigraphy

Previous site exploration studies were limited to depths of about 600 feet with minimal penetration into the Eutaw formation. These studied did not reach to the depths of the underlying Tuscaloosa formation or bedrock. Knowledge of the underlying stratigraphy, including the crystalline bedrock, was obtained from geologic references.

The current study (2016) drilled and sampled through the Eutaw and Tuscaloosa formations, encountered crystalline bedrock at a depth of 1665 feet, and cored the bedrock. The study confirmed the previous general site stratigraphy in the power block area. The site is underlain by coastal plain sediments, generally consisting of sands, silty sands, clayey sands, and clays. The geologic units encountered in borings at the site included (descending order) Alluvium, Cusseta Sand, Blufftown Formation, Eutaw Formation, Tuscaloosa Formation, and bedrock.

Alluvium was identified in only a few exploration boreholes, less than 10 feet in depth. The is described as well-graded granular material with few fines and cobbles and varying amounts of gravel and sand.

The Cusseta Sand was encountered from the ground surface to depths of about 30 feet bgs. In general, this formation consisted primarily of clayey sands and sandy clays, grading to more silty sand with depth.

The Blufftown formation extended from the base of the Cusseta Sand to a depth of about 550 to 575 feet bgs. The upper portions of the formation (20 to 30 feet thick) at the interface with the overlying Cusseta Sand formation is somewhat softened, previously described as “weathered”, with lower SPT N-values. Below this level the formation becomes denser. In general, the Blufftown formation consists of interbedded clays and sands of varying denseness and hardness. The upper 200 to 300 feet is primarily hard calcareous sandy, silty clay. The lower 100 feet is primarily dense, fine to coarse sand and clayey sand.

The Eutaw formation was only encountered in the deeper boreholes. The formation lies beneath the Blufftown (550 to 575 feet bgs) and extends to a depth of about 820 to 840 feet bgs. The Eutaw is similar to the Blufftown. Most samples collected from the Eutaw Formation are cohesive, although some granular samples were also recovered. Generally the Eutaw is characterized with hard locally calcareous clay with thin sandstone interbeds.

The Tuscaloosa formation was encountered in the one deep borehole that was drilled to bedrock. The formation lies beneath the Eutaw at a depth of about 825 feet bgs, and extends to the top of crystalline bedrock, at a depth of about 1,665 feet bgs. It consists of dense sands and gravels with interbedded clays and sandstones. At the base of the Tuscaloosa formation a dense sand, gravel, and cobble layer was identified that has been described as a Conglomerate. This layer overlies crystalline rock, at a depth of 1,665 feet. .

Basement crystalline bedrock was encountered in the single deep borehole at a depth of 1,665 feet. The upper portion of this material is weathered as indicated by the dashed line on Figure 8. The cored basement rock was identifed as metamorphic rock composed of amphibolite. Coring within the rock was carried out to a depth of 1,871 feet bgs (206 feet into crystalline rock). Individual core runs were limited to a maximum length of 5 feet. Core recoveries were typically near 100 percent. Rock quality designation (RQD) values of the core runs ranged from 28 to 81 percent in the weathered zone from depths of 1,667 to 1,691. RQD values below 1,691 feet ranged from 76 to 100 percent, but were typically 90 percent or greater. Figure 7 shows the rock coring results (RQD and recovery) versus depth for the deep borehole Downhole geophyscial measurements were taken in this borehole. Groundwater during drilling was measured at a depth of 30 feet in the deep borehole.

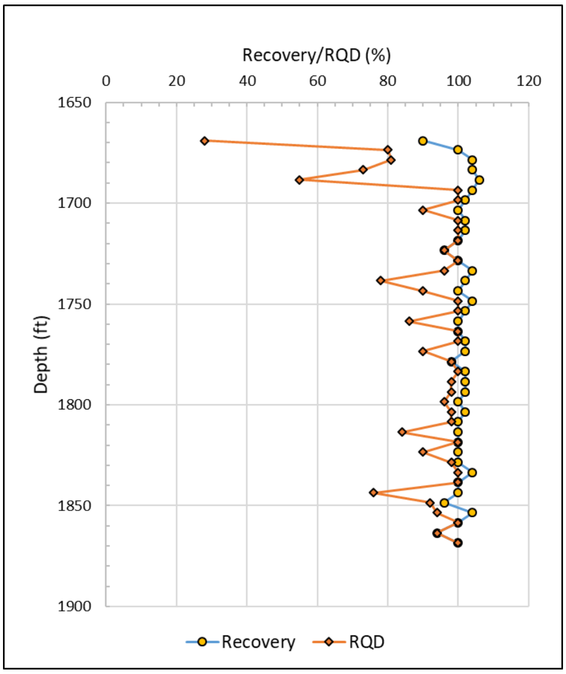

Figure 7. RQD and Recovery for Rock Core Results

4. Conclusions

Shear wave velocity measurements, as previously mentioned, were collected using several methods; 1) P-S suspension logging, 2) five linear SASW arrays, 3) 1 linear MASW array, 4) 5 circular MAM arrays, and 5) ten shallow SCPTu soundings. The results of each of these methods are presented below.

4.1. P-S suspension logging

P-S suspension logging was conducted in seven boreholes for this study. P-S logging, by the same contractor, was previously conducted in two borehole (B-501 and B-502) during a previous subsurface exploration. The locations of these boreholes are shown on Figure 4. Figure 8 provides a plot of these combined data. The stratigraphy illustrated on Figure 8 was developed from the deep borehole data. Vs data from the deep borehole (B-1023) is shown as a red trace and extends for the full depth of the soil/rock column. Vs data from the remaining eight boreholes ranges from between 300 and 600 feet bgs. Above 600 ft bgs, where multiple data sets are plotted, the data is very consistent and the Vs generally ranges between 2,000 to 3,00 fps. Some narrow bands of high velocity (4,000 fps) materials are noted in the Blufftown formation. These narrow, high velocity bands are also observed in the underlying Eutaw and Tuscaloosa formations. A higher velocity layer is noted at the base of the Tuscaloosa formation. This material was identied as layered cemented gravels and cemented sands and provides a Vs transition to bedrock. The underlying crystalline bedrock exhibits a Vs on the order of 12,500 fps.

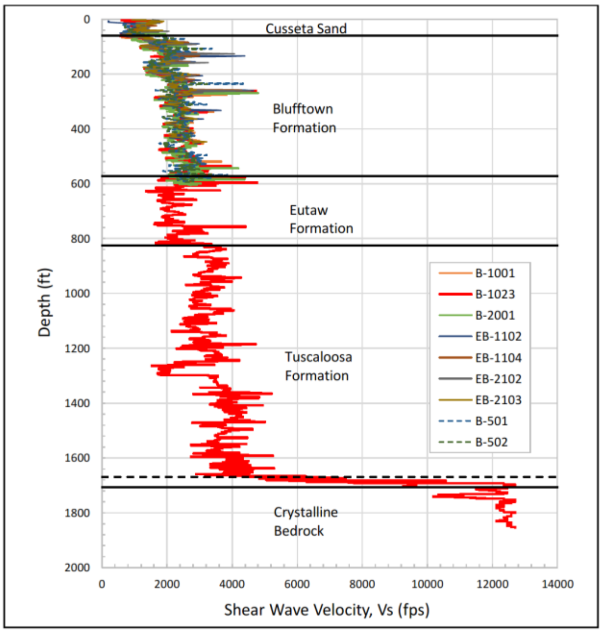

Figure 8. Measured Shear Wave Velocity, Borehole P-S Logging

4.2. Spectral analysis of surface waves (SASW)

The locations of the 5 linear SASW arrays are shown on Figure 5. These arrays varied in length from about 2200 feet (SASW#2) to about 4300 feet (SASW#3). Receivers were spaced along the arrays at distances of 5, 10, 12.5, 25, 50, 75, 150, 225, 450, 550 or 600, 900, 1000, 1100 or 1200, 1800, and 2000 feet. The maximum spacing was generally based on space considerations or the maximum energy of the source. The progression of receiver spacings resulted in extensive overlapping of the individual dispersion curves used to develop a composite field curve at each site, thereby enhancing the test reliability and indicating the degree of lateral variability over the test array. At SASW#3, for the longest receiver spacing of 2000 feet, Liquidator (vibroseis source) was operated in a first-ever, special high energy mode.

Liquidator was position atop a specialty build concrete bad to serve as a reaction platform as the whole body of the mobile shaker was lifted up and down, Figure 9. The resulting SASW Vs estimates are shown in Figure 10.

Due to the spacial limitations, only the longest array, SASW#3, provided dispersion curves to the depths of the bedrock. The averaged dispersion curves for each of the arrays within the Blufftown, Eutaw and upper poritons of the Tuscaloosa formations provided consistent results and nearly identical to the measured P-S logging Vs data.

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Figure 9. Liquidator as energy source for longer SASW lines (Stokoe et al., 2019)

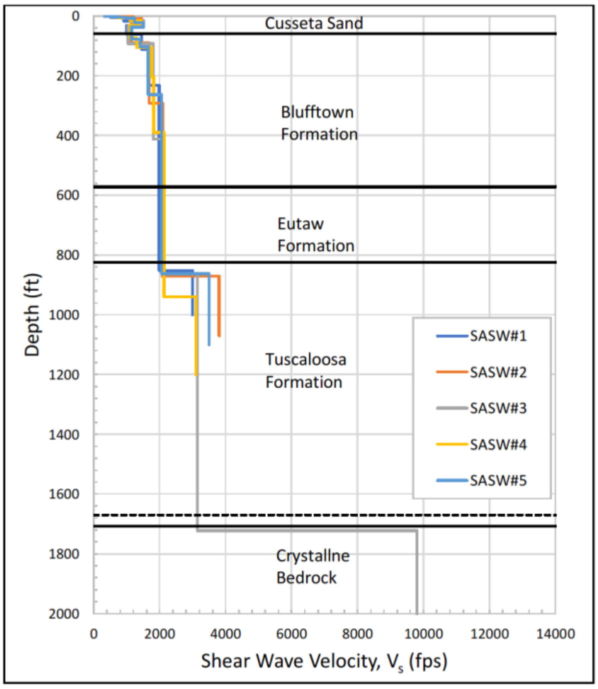

Figure 10. SASW Measured Shear Wave Velocity (Stokoe et al., 2019)

4.3. Multichannel analysis of surface waves (MASW) and microtremor array measurements (MAM)

The location of the MASW array (located at the center of the 50 m MAM array) and the locations of five circular MAM arrays, with diameters ranging from 50 m to 1000 m, are shown on Figure 5. The MASW and MAM dispersion data were combined/averaged to create a single, composite experimental dispersion curve with frequency-dependent uncertainty. This composite dispersion curve was inverted jointly with H/V data using the open-source software Geopsy. Inversions were performed using the "layering ratio" approach (Cox and Teague , 2016), which was used to systematically explore multiple layered earth model parameterizations. For each parameterization, approximately 1 million models were explored. For each trial model, a dispersion misfit value between the experimental dispersion data and the theoretical dispersion curve was computed. The best 100 Vs profiles from each parameterization were retained to quantify Vs uncertainty. Shear wave velocity profiles. Four distinct inversion parameterizations yielded suites of Vs profiles with low dispersion misfit values. The median Vs profiles from each acceptable parameterization are shown on Figure 11 with MAM#1, MAM#2, MAM#3, and MAM#4 corresponding to layering ratios/misfit values of 1.5/0.72, 2.0/0.47, 2.5/0.54, and 3.5/0.55, respectively

4.4. Seismic Piezocone Penetration Test Soundings (SCPTu)

Ten seismic piezocone test (SCPTu) soundings were advanced to depth across the site to obtain data in the near surface soils. The SCPTu testing was carried out by ConeTec Inc. The soundings were extended to depths ranging from about 81 to 112 feet where refusal was encountered. The soundings were performed using a Type 2 piezocone and a 25-ton CPT truck rig. Seismic velocity measurements were taken in the soundings at intervals of about 3.3 feet (1 m). The resulting SCPTu measured Vs data are shown in Figure 12.

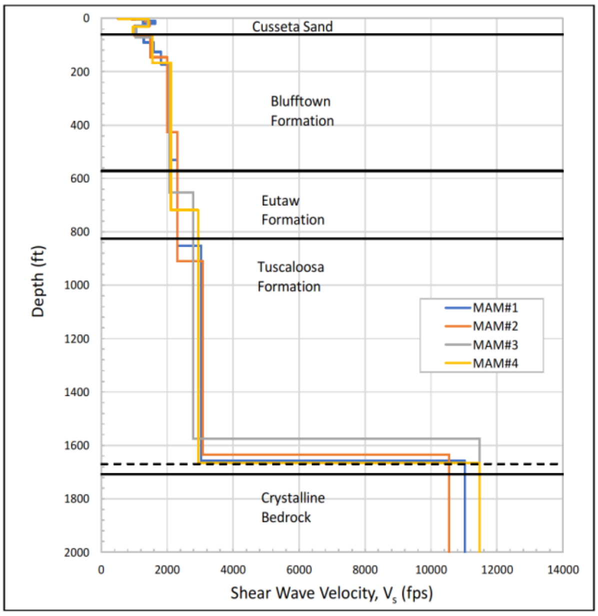

Figure 11. MASW-MAM Shear Wave Velocity Profile Models, Median Values

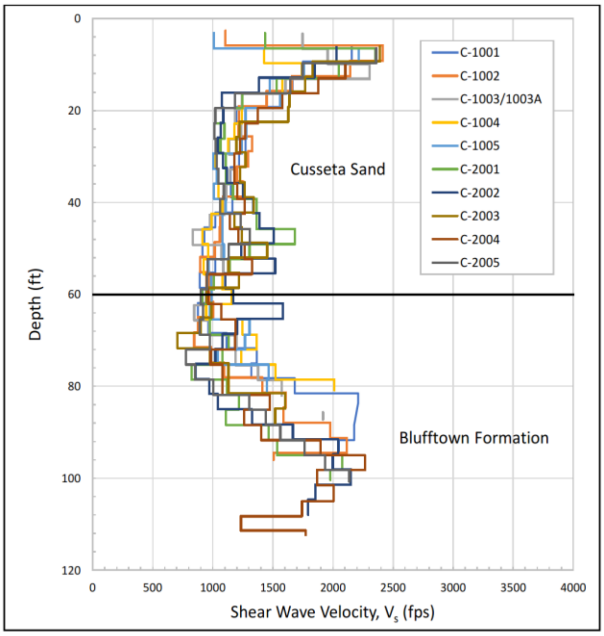

Figure 12. SCPTu Measured Shear Wave Velocity

4.5. Observations from shear wave measurements

The Vs data collected using five different methods are plotted on Figures 13 and 14. Figure 13 combines the shallow (≤ 200 feet deep) data while Figure 14 combines the data deeper than 200 feet.

Figure 13 shows that overall the data appear consistent except for shallow depths (< 10 feet) and between a depth of about 110 to 160 feet. In these two depth ranges, the SASW and MASW-MAM show lower velocities, which are more realistic near the ground surface.

Figure 14 shows that the deep (> 200 feet) velocity measurements appear to be relatively consistent except for the depth range 1300 to 1600 feet, where the P-S logging shows higher velocities, and variations around the major strata breaks. Note that the strata breaks shown on the figures (8, 10, 11, 12, 13, 14, and 15) are the same and are developed from the deep borehole (B-1023).

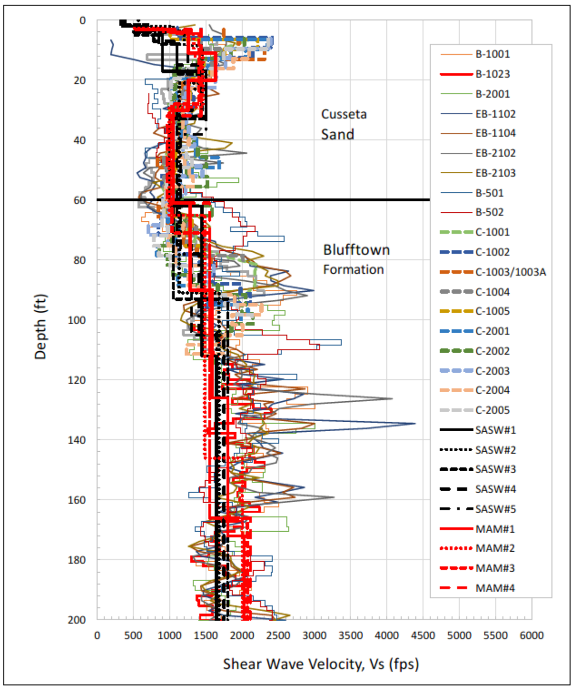

Figure 13. Shallow Shear Wave Velocities
(≤ 200 feet deep)

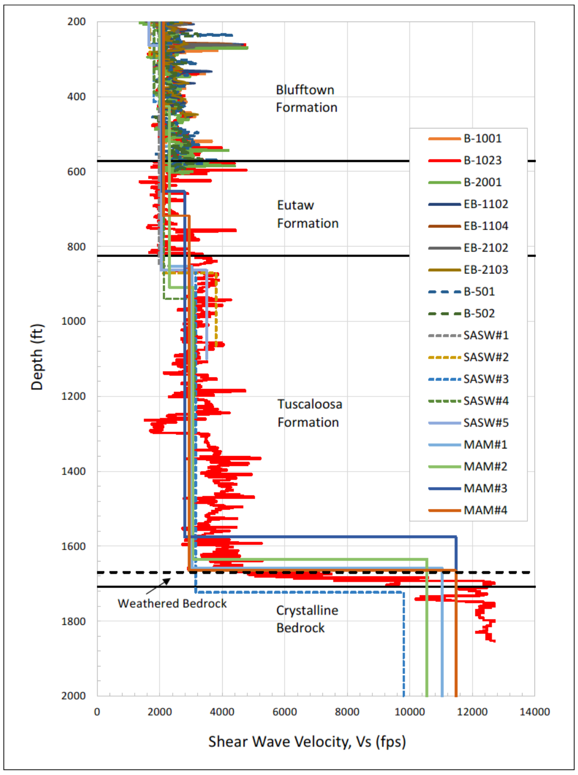

Figure 14. Deep Shear Wave Velocities
(> 200 feet deep)

Figure 15 presents the compiled Vs data on one plot with the various methods color coded. Note that SCPTu data is not shown given that it would not be discernable at the scale presented.

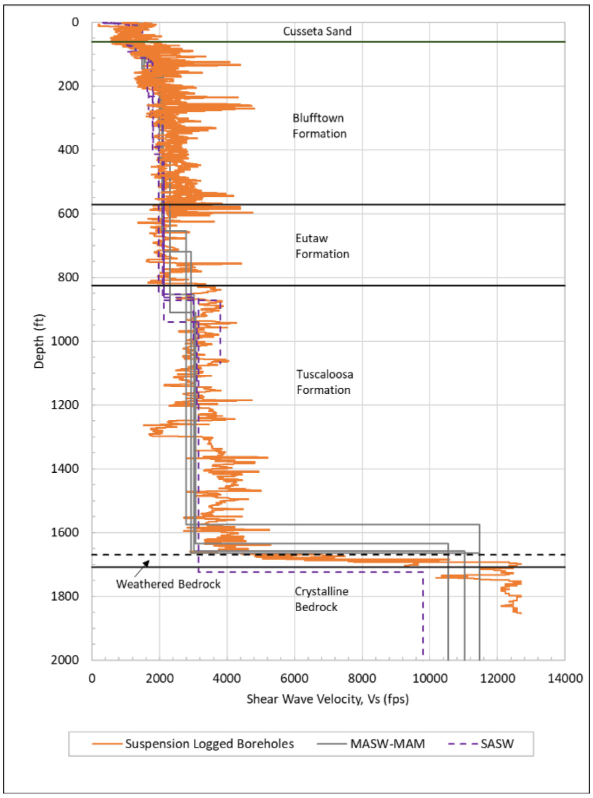

Figure 15- Compiled Shear Wave Velocity Data

Observations of the data reveal that the Vs values in the Coastal Plain sediments, above the crystalline bedrock, generally range between 2,000 to 4,000 fps, increasing with depth. While the downhole and surface methods are in good agreement with these values, the depth at which strata interfaces occur do not align well. This is particularly evident between the Eutaw and Tuscaloosa Formations and the Tuscaloosa Formation and the crystalline bedrock. This misalignment may be attributed to the velocity contrast between layers, as well as the overall variation across the site given that the stratigraphy show is from one deep borehole (B-1023).

5. Conclusions

Five methods were used to evaluate the shear wave velocity profile of a greenfield site located in the Coastal Plain physiographic province in southwest Georgia. Two of these methods were conducted downhole and three methods were conducted on the surface. The data show excellent agreement between all methods. Note that the project was terminated before the Vs data were fully interpreted to account the variability within the profile. A final site shear wave velocity profile was not developed.

In considering the collection of Vs data for site characterization, this project demonstrates the value of gathering data using multiple methods. However, the importance of experience cannot be overemphasized. Each of the methods utilized for this study was conducted by an experienced contractor who specializes in that particular test or survey method. Each method requires a significant amount of data processing and interpretation of dispersion data.

Acknowledgements

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