

## **Fundamental Resonance Frequencies in a Region with Gradually “Varying” Sediment Thickness**

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### **ABSTRACT**

Teleseismic records were collected along a NW-SE transect across residual soils-marine sediments of coastal plain of South Carolina in the eastern United States of America. Regional geology indicates sediment thickness increases seaward. The fundamental resonance frequencies at selected seismic monitoring stations were estimated based on the Nakamura's H/V ratio (HVR), classical spectra ratio (CSR), and one-dimensional equivalent linear analysis methods. In this geological region with gradually “varying” sediment thickness, it is observed that fundamental resonance frequency becomes lower as the sediment becomes thicker. This preliminary observation, therefore, suggests that fundamental resonance frequencies appear to be an effective gauge in reflecting local instead of regional phenomenon. When comparing estimates from the HVR and the CSR methods, the former appears to provide more consistent results with the increasing thickness of sediment. Practice wise, this article provides an empirical alternative to guide the determination of sediment thickness for a site specific seismic design.

Keywords: fundamental resonance frequency, weak motion, H/V, spectral ratio, sediment thickness

### **INTRODUCTION**

It has long been understood that fundamental resonance is an effective parameter in reflecting the geological contribution to ground motion during seismic events. Basically, the greater the sediment thickness is, the lower the observed fundamental resonance frequency becomes. The coastal regions of the eastern United States of America provide an ideal geological setup for verifying this concept. Basically, the sediment (i.e., non-bedrock) becomes thicker seaward and some regions appear simpler than others. For example, the sediment thickness in South Carolina has an approximate increase of 5 meters per 1 km horizontal distance seaward along the section starting from Piedmont Fall Line crossing Columbia to Charleston. Geotechnical and geological data are bountiful for this area, such as velocity profiles and depth of bedrock, and provide an ideal environment for further analysis.

In this article of our preliminary investigation, we collected weak ground motion records along NW-SE section crossing the residual-marine sediments in South Carolina. The fundamental resonance frequencies at selected seismic monitoring stations, which are located at Aiken, Orangeburg, Summerville, and James Island, were estimated based on the Nakamura's H/V ratio (HVR), classical spectra ratio (CSR), and one-dimensional equivalent linear analysis methods. Of general importance to ground motion analysis are the classical spectral ratio technique by using records from the sediment site and a reference bedrock site and the Horizontal versus Vertical (H/V) technique (Nakamura, 1989) by using records from the sediment site. In contrast to the well established classical spectral ratio technique, the H/V technique has proved to be convenient, cost efficient, and less affected by ambient

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noises. Basically, the H/V technique has a relatively robust reputation of estimating the resonant frequency of the subsurface sediment, which can be used to interpret the thickness of the sediment. For comparison, one-dimensional (1D) equivalent linear analysis was used for calculating the theoretical fundamental resonance frequencies at the locations where the seismic records were collected.

Our goal in this article is to infer the general variation of fundamental resonance frequencies along the selected section so that a detailed study is warranted in the future.

## GEOLOGICAL AND SEISMOLOGICAL SETTING

The surficial geology of South Carolina can be divided into two major regions, an inland zone of Paleozoic igneous and metamorphic rocks of the Appalachian Orogen and a coastal plain consisting of unconsolidated and semi-consolidated Cretaceous through Recent sediments (SCDNR, 2005; Figure 1). Beneath the coastal plain these sediments lay upon Mesozoic flood basalts and rift basin sedimentary rocks related to the opening of the Atlantic Ocean (e.g., Lanphere, 1983; Gohn et al., 1983). The thickness of the coastal plain sediments increases going towards the Atlantic coast of South Carolina, reaching a maximum thickness >1000 meters in the southeast corner of the state.

Earthquakes in South Carolina occur primarily in the Middleton Place-Summerville Seismic Zone (Madabhushi and Talwani, 1993; near SUMMR, Figure 1) and include a destructive  $M = 7$  earthquake on August 31, 1886. However, in recent years no events larger than  $M = 4.2$  have occurred in the state of South Carolina, thus making it impossible to use strong motion records of local large earthquakes to characterize seismic ground motions.

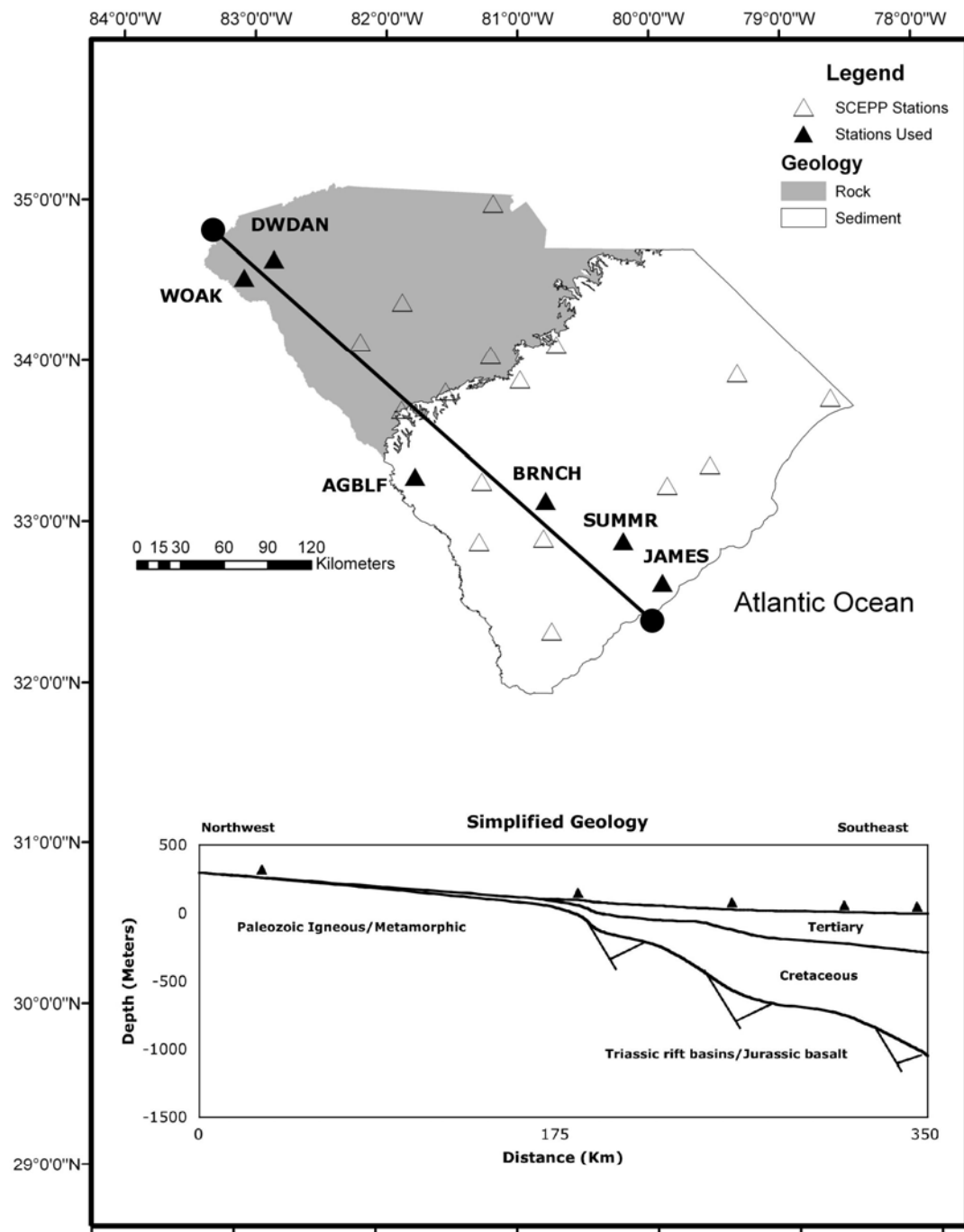
## FIELD DATA

The seismic ground motions used in this study were recorded by stations of the South Carolina Earth Physics Project (SCEPP), a network of educational seismometers installed in high schools throughout South Carolina (Figure 1). This network utilized three-component digital seismometers with a response flat to ground velocity between 0.1 and 10 Hz. Although not installed for the purpose of characterizing ground motion in South Carolina, examination of earthquakes recorded by the SCEPP network revealed considerable variation in ground motion site response across the state of South Carolina. This paper represents our initial attempt to utilize this data to examine the variation in site response across the state.

**Table 1. Source parameters of earthquakes used in this study. Distance is relative to station AGBLF**

DATE	TIME (UTC)	LATITUDE	LONGITUDE	DEPTH (KM)	MAGNITUDE	DISTANCE (KM)
2001/06/23	20:33	-16.14	-73.31	33	8.4 $M_w$	5555
2001/06/26	04:18	-17.73	-71.28	33	6.7 $M_s$	5766
2001/11/13	09:45	22.27	-106.95	33	6.1 $M_w$	2761
2002/11/03	22:12	63.74	-147.69	10	8.5 $M_s$	5558

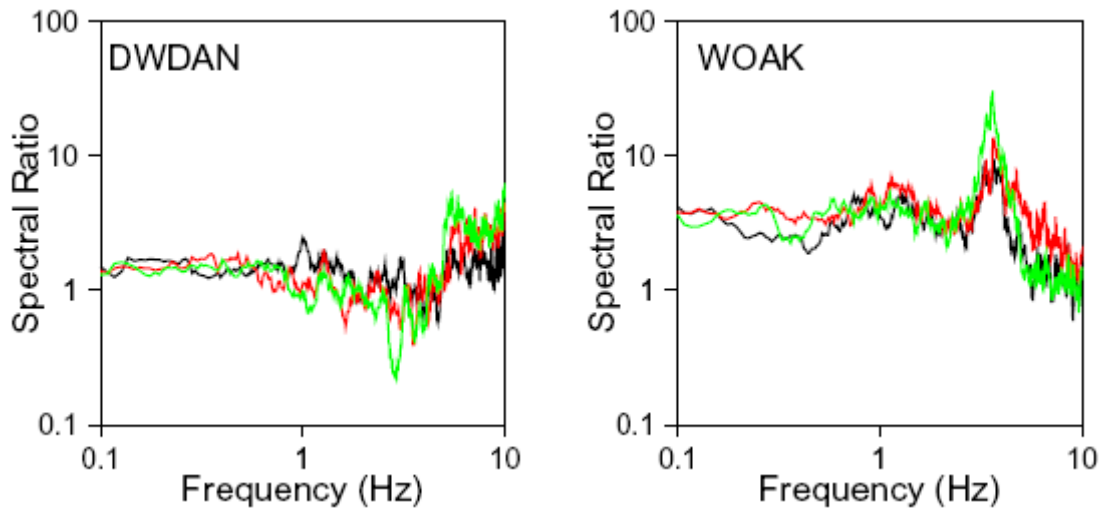
We analyzed the ground motion from a selection of SCEPP stations (Figure 1) in two ways: 1) by calculating horizontal/vertical (H/V) spectral ratios (Nakamura, 1989) using 60 seconds of ambient ground motion (microtremor) and 2) by calculating sediment/rock spectral ratios (CSR) using 60 seconds of transverse (SH) ground motion from four teleseismic events (Table 1). In all cases the 60 second data samples were demeaned and tapered before performing a Fast Fourier Transform. The resulting spectra were then smoothed using the mean of a sliding 15 point window. In the case of the H/V ratios the spectra of the two horizontal components were added and then divided by  $\sqrt{2}$  before dividing by the vertical spectra. For the sediment/rock spectral ratios we first rotated the horizontal components into a source-receiver coordinate system, then selected data windows starting with the



**Figure 1. Top: Simplified geologic map of South Carolina (SCDNR, 2005) showing locations of SCEPP seismic stations (triangles). The filled and labeled triangles are those stations used in this study. Bottom: Cross-section across the state of South Carolina showing the increasing depth of coastal plain sediments as one approaches the Atlantic coast.**

direct S arrival on the transverse component. The signals used in this study have threshold accelerations in the range of  $4 \times 10^{-6}$  to  $1.5 \times 10^{-4}$  cm/s<sup>2</sup>.

Figures 2a and 2b shows the results of the HVR method using three arbitrarily selected 60-second time windows. Of the two stations on metamorphic rock, DWDAN shows little apparent site response below 5 Hz. Conversely, horizontal ground motion at WOAK is strongly peaked between 3 and 4 Hz, indicative of some local site response. Therefore we decided to use station DWDAN as our reference site for the sediment/rock spectral ratios, with the caveat that there can be some local site response at that station above 5 Hz.

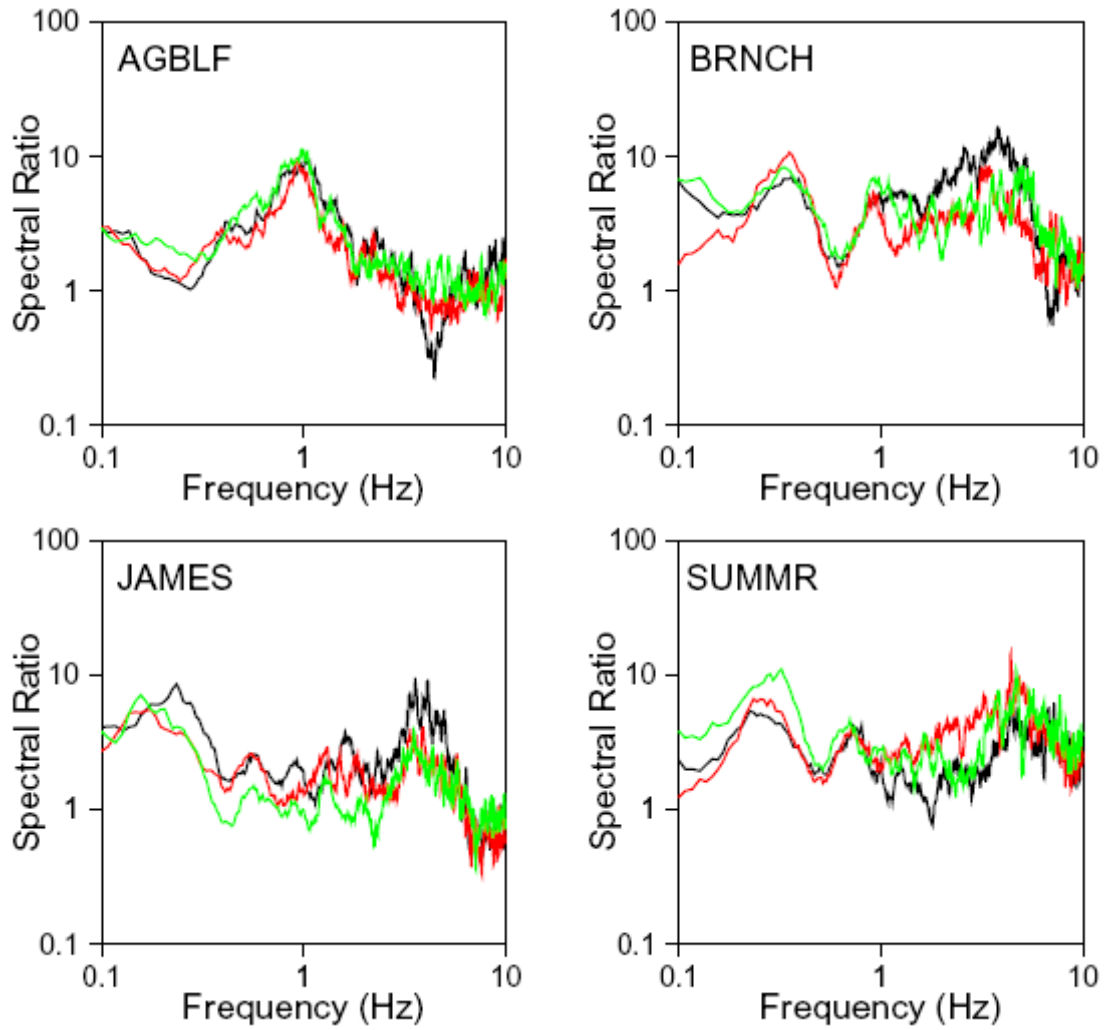


**Figure 2a. Horizontal versus Vertical (H/V) spectral ratios for selected SCEPP stations (filled triangles in Figure 1). Colored (red, green, black) lines represent H/V ratios using three different 60-second time windows.**

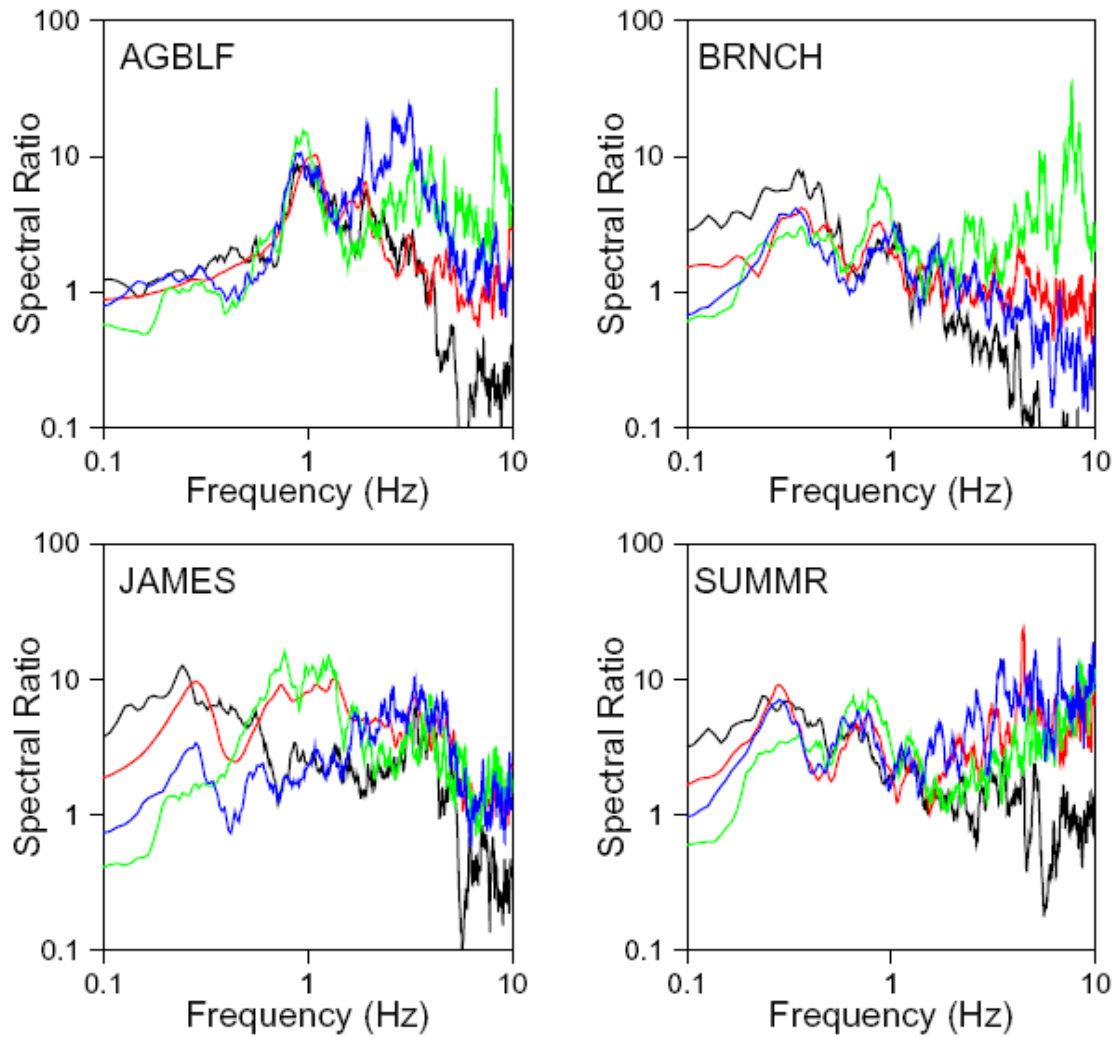
The four stations located on the South Carolina coastal plain (Figure 1) all show a strong peaks in the HVR (Figure 2b). We interpret the lowest of these spectral peaks to represent the fundamental resonance frequency of the site. We note that the frequency of the fundamental resonance decreases as it approaches the coast of South Carolina, consistent with the increasing thickness of coastal plain sediments (Figure 2b).

Figure 3 shows the CSR at the four coastal plain stations. The response at stations AGBLF, BRNCH and SUMMR show the same fundamental resonance frequency as in the H/V spectral ratios, although for only three of the four events at SUMMR. However, at station JAMES the fundamental resonance appears to be shifted to higher frequencies in the CSR as opposed to the H/V ratio. Also note that the fundamental resonance is very weak at both SUMMR and JAMES for the event on 2001/11/13, suggesting that this source did not appear to excite the fundamental resonance mode of the very thick sediments.

There is considerable variation in the excitement of higher mode resonances in the HVR versus CSR. At stations AGBLF and SUMMR the earthquake events appear to excite the first higher mode resonance to a greater degree than seen in the HVR. At BRNCH both the HVR and CSR show peaks at the fundamental and first resonance mode frequencies. At JAMES only two of the earthquake events appear to excite higher modes of resonance, and both the HVR and CSR show an apparent resonance between 3 and 4 Hz.



**Figure 2b. Horizontal versus Vertical (H/V) spectral ratios for selected SCEPP stations (filled triangles in Figure 1). Note that the resonant frequency shifts towards lower frequencies with increasing coastal plain sediment thickness. Colored (red, green, black) lines represent H/V ratios using three different 60-second time windows.**

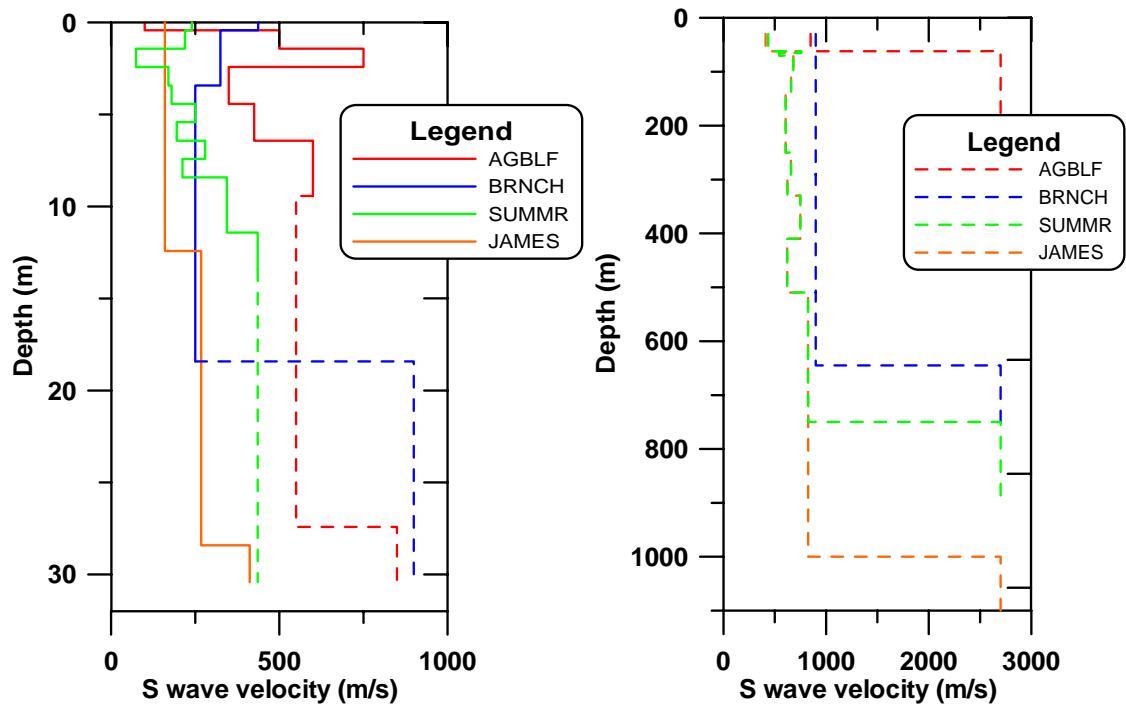


**Figure 3. Sediment versus rock spectral ratios using DWDAN as the reference site. Colored lines represent the different events in Table 1: Black – earthquake on 2001/06/23, red – 2001/06/26, green – 2001/11/13, blue – 2002/11/13. Compare to H/V ratios in Figure 2.**

### ONE-DIMENSIONAL EQUIVALENT LINEAR ANALYSIS

To quantitatively demonstrate the sediment thickness effect on the shift of the fundamental resonance, the transfer functions of one-dimensional (1D) modeling of the four sites are calculated by using the one-dimensional equivalent linear analysis program, ProShake. Site specific surface profiles (including soil type and shear wave-velocity) were determined from adjacent geotechnical investigations in the upper 30 m and geological findings by others (Chapman, et al., 2006 and Odum, et al., 2003) in the 30+ m range. The embedment depths of the bedrock were estimated from well (Colquhoun et al., 1983; Gohn et al., 1983) and geophysical data (Marine and Siple, 1974) to be 150, 645, 750, and 1000 m at ABGLF, BRNCH, JAMES, AND SUMMER, respectively. Shear wave velocity profiles for each site are compiled and shown in Figure 4.

The collected signals have a threshold acceleration of  $4 \times 10^{-6} \text{ cm/s}^2$ , which is less than 100 gal and can be considered in the soils linear response range (Beresnev and Wen, 1996). For the ProShake analyses, “linear” modulus degradation curves were used and constant damping ratios of 2%, 1%, and 0.5% were assumed for clays, sands, and rocks, respectively.



**Figure 4. Upper 30 m (left) and deeper (right) shear wave velocity profiles obtained in the vicinity of the seismic stations. The solid lines are from geotechnical investigations. The dashed lines represent velocity information obtained by others from deep borehole and geophysical investigations (Chapman, et al., 2006 and Odum, et al., 2003)**

The transfer functions from the 1D modeling are presented in Figure 5. The fundamental resonance frequencies at stations ABGLF, BRNCH, SUMMR, and JAMES are 1.34, 0.33, 0.24, and 0.19 Hz, respectively.

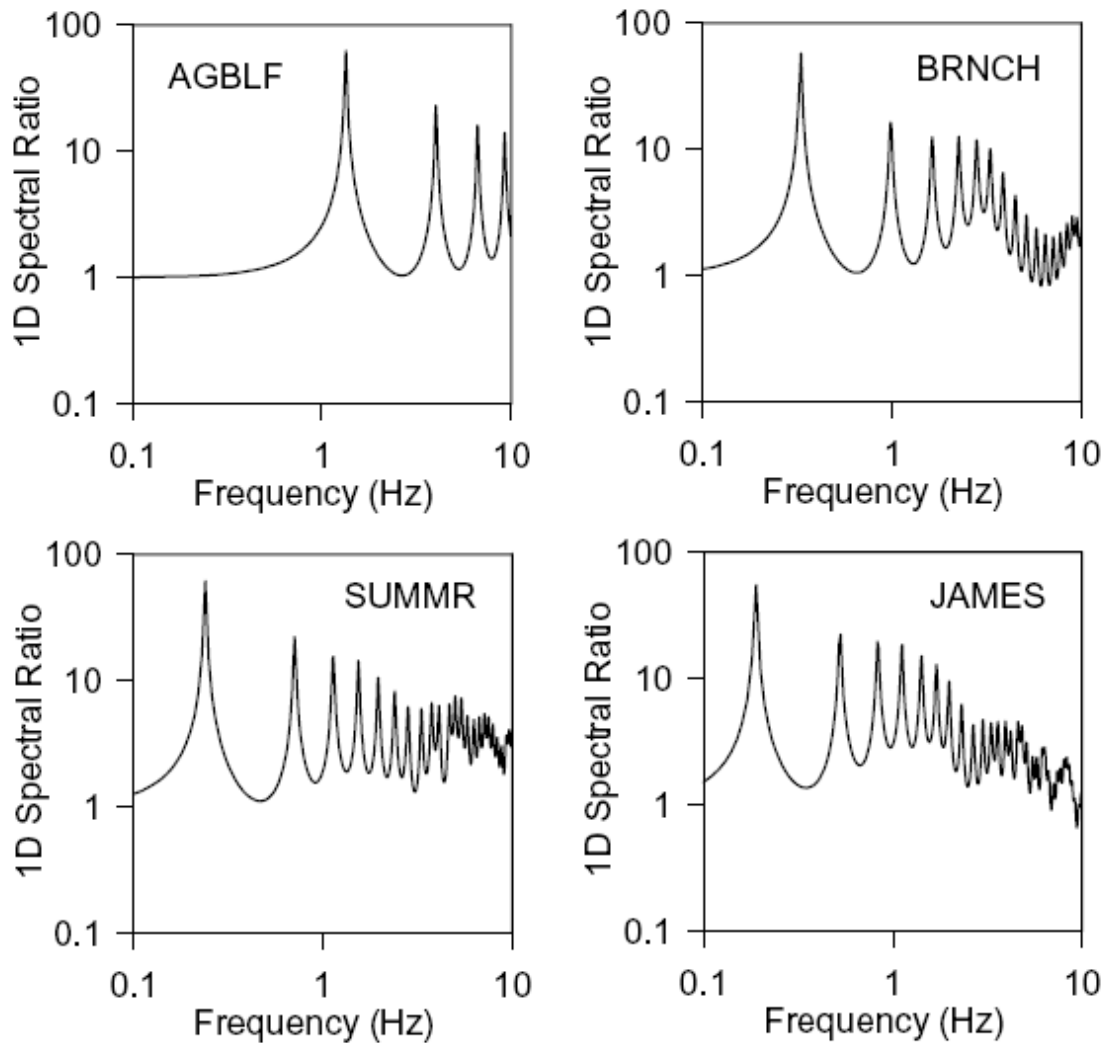
#### **FUNDAMENTAL RESONANCE FREQUENCY VS. SEDIMENT THICKNESS**

Table 2 compares the fundamental resonance frequencies of the coastal plain sediments versus their thickness for the three methods used in this study. For station ABGLF the two observational techniques agree well with each other but are lower than the resonance frequency derived from the 1D modeling. This suggests that the sediment thickness at ABGLF may be greater than what we have used in the 1D modeling.

It is at stations BRNCH and SUMMR that the resonance frequencies derived from the three methods agree the best. However, we find that the 1D modeling results tend to most closely match the lower range of frequencies estimated from the H/V and CSR spectral ratio methods. At station JAMES we find that the H/V spectral ratios and 1D modeling resonance frequencies match well, but that the CSR method suggests the fundamental resonance frequency at JAMES is similar to that at SUMMR.

**Table 2. Comparison of fundamental resonance frequencies (Hz) estimated for the seismic stations on the South Carolina coastal plain. HVR = Horizontal/Vertical spectral ratio method; CSR = Classical Sediment/Rock spectral ratio method**

STATION	SEDIMENT THICKNESS (meters)	HVR	CSR	1D MODELING
AGBLF	150	0.908-1.065	0.859-1.123	1.34
BRNCH	645	0.313-0.391	0.332-0.430	0.33
SUMMR	750	0.225-0.322	0.234-0.302	0.24
JAMES	1000	0.137-0.244	0.234-0.303	0.19



**Figure 5. Calculated One-dimensional modeling transfer functions at the four stations on the South Carolina coastal plain.**

It is instructive to compare our results with those of Bodin et al. (2001), who determined site resonance of unconsolidated sediments of the Mississippi Embayment using the HVR method. Like the findings presented here, they found that the frequency (period) of site resonance decreases (increases) as the thickness of the unconsolidated sediments increases. Using the relationship they derived between sediment thickness and site frequency (period), we would expect a narrower range of resonance frequencies at our three deepest sediment sites (BRNCH – 0.29 Hz; SUMMR – 0.26 Hz; JAMES – 0.23 Hz). This suggests that one cannot simply take the results from a different region with similar sediment thickness and apply it to South Carolina and vice versa.



Finally, by looking at Figures 3 and 4, we can make some remarks about the effectiveness of the HVR and CSR methods. The observed fundamental resonance frequency at thicker sediment locations, such as SUMMR and JAMES, appears more distinctively from the former method. As mentioned earlier, the fundamental resonance mode could be either have no response or is submerged in the environmental noise. This observation may suggest alternatively that the HVR method is less sensitive to local noise and therefore is more robust in estimating the fundamental resonance frequency (Ibs-von Seht and Wohlenberg, 1999).

## CONCLUSIONS

Our preliminary study using the Horizontal versus Vertical, Classical Spectral Ratio, and One-dimensional equivalent linear methods confirms that the fundamental resonance frequency is a rather local phenomenon. It has been demonstrated successfully that in a “varying” geological region, fundamental resonance frequency shifts sensitively with its immediate sediment thickness underneath.

Practice wise, this article provides an empirical alternative to guide the determination of sediment thickness for a site specific seismic design. It appears necessary to include both the unconsolidated and semi-consolidated Cretaceous through Recent sediments in ground motion analyses. For example, when deaggregation data obtained from the United States Geological Survey (USGS) are used as input for a site specific seismic analysis according to the International Building Code, Edition 2003, both the geotechnical and geological information is needed for performing a one-dimensional ground motion analysis.

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