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Translating Observed Weak Motion Site Response Into Predicted Strong Motion in Charleston, South Carolina, USA

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ABSTRACT

We model the response of the 850-meter thick coastal plain section beneath Charleston, South Carolina and compare this with observed site response. We find that impedance contrasts at 850 meters, 75 meters and 15-25 meters control the widely observed 1-2 Hz amplifications in our study area. We find that site response to moderate (0.1 g) strong motion most closely resembles the observed 1-2 Hz weak motion response, and that only frequencies <1 Hz are amplified for stronger (0.3 g) input motions. This implies that building damage in a future moderate magnitude earthquake may be very different from that observed during the large 1886 event.

Introduction

The Charleston, South Carolina region experienced the largest earthquake on the US East Coast, an M~7 event on August 31, 1886. This earthquake killed ~125 people (Coté, 2006), damaged thousands of mainly masonry buildings and caused widespread liquefaction. Paleoliquefaction evidence of previous large events (Talwani and Schaeffer, 2001) and continued seismicity in the epicentral region of the 1886 earthquake has lead to the greater Charleston region having the highest earthquake hazard on the US East Coast (Petersen et al., 2014).

The greater Charleston region is currently home to ~700,000 people and is the 8th largest port by volume in the United States. It has a thriving tourist economy (based in part on historic buildings that survived the 1886 earthquake) and also became a major assembly site for commercial airliners starting in 2011. The most recent estimates of the impact of a repeat of the 1886 earthquake project up to ~1500 deaths and US$32 billion in building damage in Charleston County (A. Braud, pers. comm.).

In this study we estimate strong motion site response by first using weak motion observations to constrain a geological model of the coastal plain sediment response in Charleston, and then “scale up” the input bedrock motion to those expected during a repeat of the 1886 earthquake. We can reproduce the main features of the observed weak motion response using both elastic wave modeling and strong motion modeling with a weak motion (0.01 g) input. We find, somewhat surprisingly, that the observed weak motion response is very similar to predicted strong motion response for moderately strong (0.1 g) input bedrock motions.

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Geological and Geotechnical Conditions of Charleston, South Carolina

One challenge to estimating seismic site response in Charleston is that it lies on a wide and deep coastal plain, where the nearest surface rock sites are ~150 km inland and bedrock lies at depths 750-900 meters below the surface (Figure 1). Observations from deep boreholes and seismic studies has established a sharp impedance contrast at the base of the sediments, followed by a gradual decrease in shear wave velocity to ~75 meters (Chapman et al., 2006), where a more rapid decrease in velocity occurs (Andrus et al., 2006; Figure 1). The average shear wave velocity of the coastal plain sediments beneath Charleston is ~700 m/sec (Chapman et al., 2003).

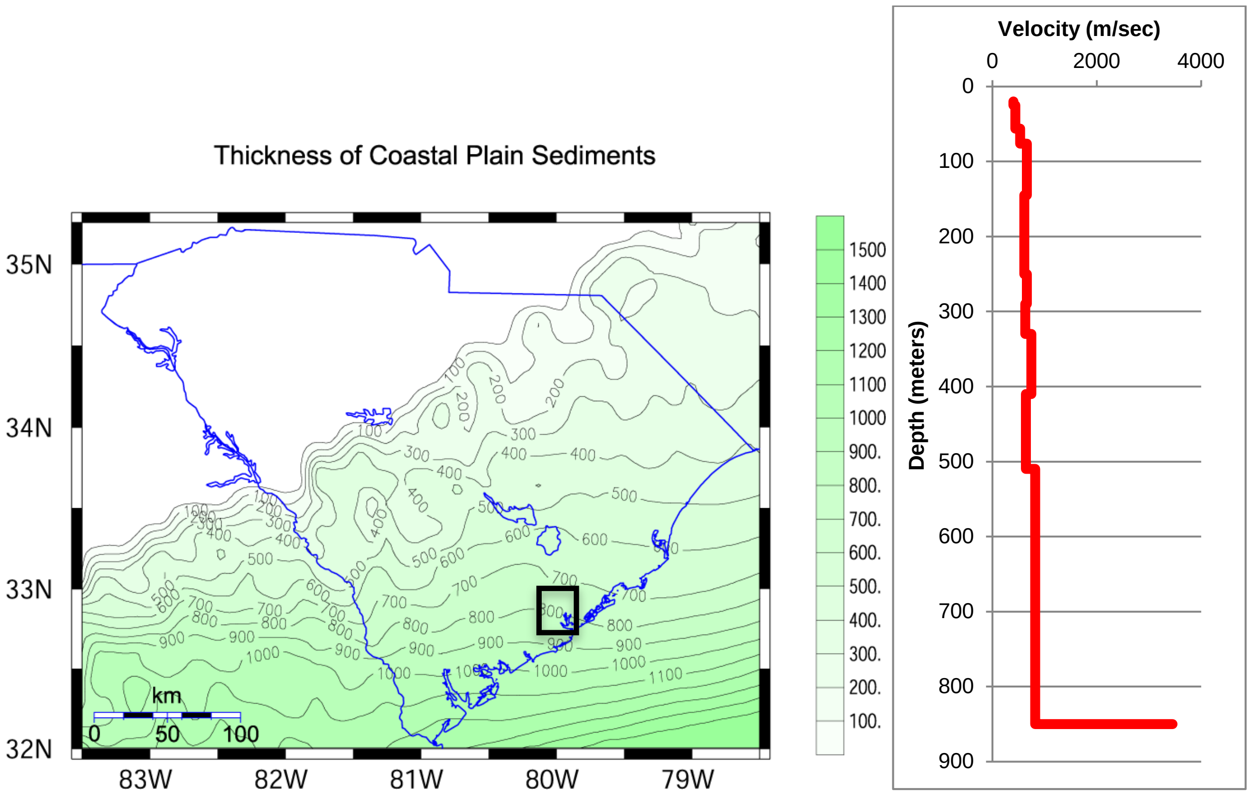

Figure 1. Left: Thickness of coastal plain sediments derived from borehole and geophysical data (Figure 6 from Chapman and Talwani, 2006; used with permission.). Black box is our study area. Right: Shear wave velocity from the top of bedrock to the base of the Tertiary section.

The next significant velocity decrease occurs at the top of the Tertiary section (locally known as the "Cooper Marl"). Figure 2 gives examples of shear wave velocities from two geotechnical boreholes that penetrate this boundary. Shear velocities drop from ≥400 m/sec to below 300 m/sec, with local variation depending upon the nature of the surficial deposits. In general, sites with artificial fill (e.g., C98706-C15) and recent marsh deposits have lower near surface velocities than sites on older surfaces (e.g., C98706-C4). The depth of this boundary varies from 3 to 26 meters across our study region (Levine et al., 2014).

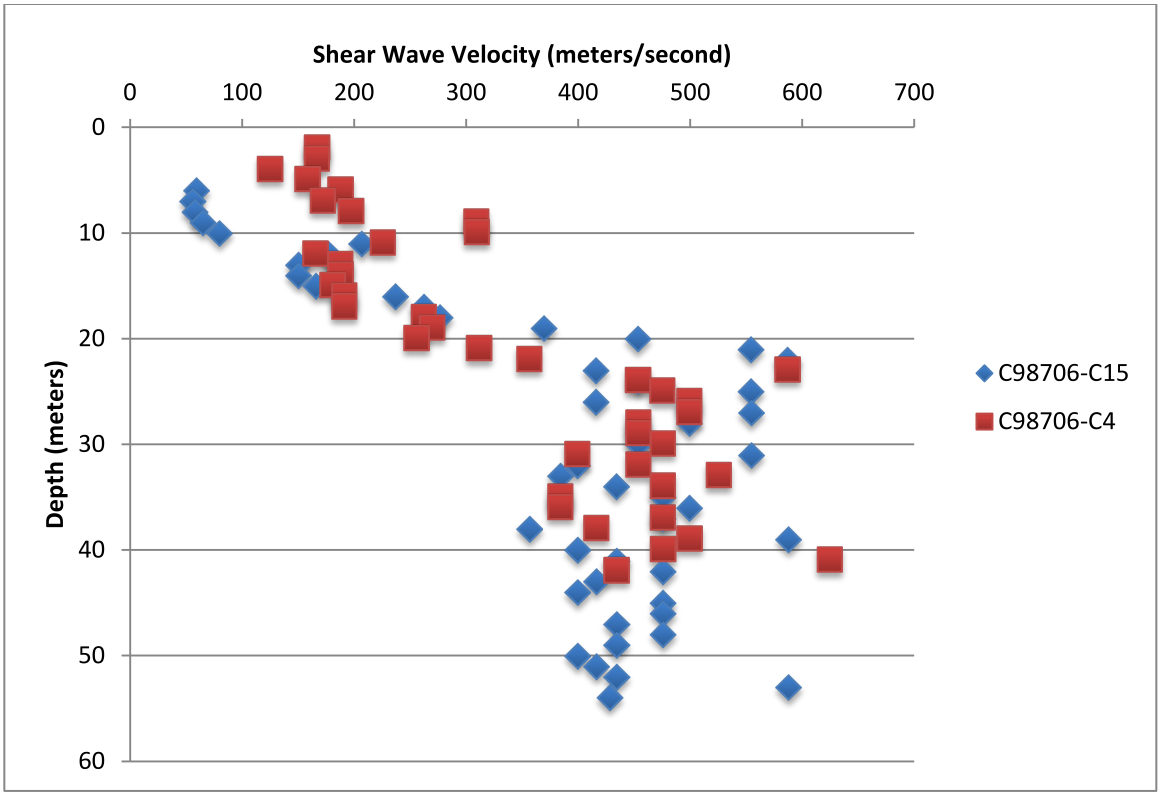

Figure 2. Example shallow shear wave velocity profiles derived from seismic cone penetrometer tests in Charleston. C98706-C15 is located on artificial fill above marsh deposits; C98706-C4 is located on an ~100,000 year old near shore deposit (Wando Formation).

Weak Motion Observations and Modeling

Because of the lack of nearby rock sites and recorded strong ground motions, we rely primarily on site response estimates derived by determining the horizontal-to-vertical spectral ratio (HVSR) of ambient seismic noise (Lachet and Bard, 1994) to help constrain site response in Charleston. We observe very little variation in the frequencies of amplification in our study area, with peaks at 0.2 Hz and 1-2 Hz (Figure 3). The amplitude of the 0.2 Hz peak, which corresponds to the resonance of the entire sedimentary section, is very consistent. We find, however, there is significant variation in the amplitude of the 1-2 Hz resonance, which is strongly correlated with the thickness and velocity of the surficial deposits (Miner, 2014). In general, sites with thicker and slower near surface materials (i.e., Mason, Figure 3) show a stronger 1-2 Hz amplification than sites on thinner, faster materials (i.e., Blacklock, Figure 3).

We are able to model this weak motion site response by creating synthetic seismograms using vertical and horizontal forces at the surface of an attenuating elastic medium (Hermann, 2002) with shear wave velocities corresponding to the geological column in Figure 1, with variations in the near surface velocity structure at individual sites (e.g., Figure 2). While we generally do not match the exact frequency and amplitude of these resonances, the elastic models do capture the major features and their variation, giving us confidence our geological model is correct. In particular, a thicker section of lower velocity (i.e., artificial fill) near surface material produces a strongly-peaked high amplitude resonance at 1-2 Hz; thinner, higher velocity (i.e., Wando Formation) surface material produces a broader, lower amplitude 1-2 Hz peak, consistent with observations. We note, however, that these elastic models also predict resonances at higher frequencies (>2 Hz), which are not observed in the field data.

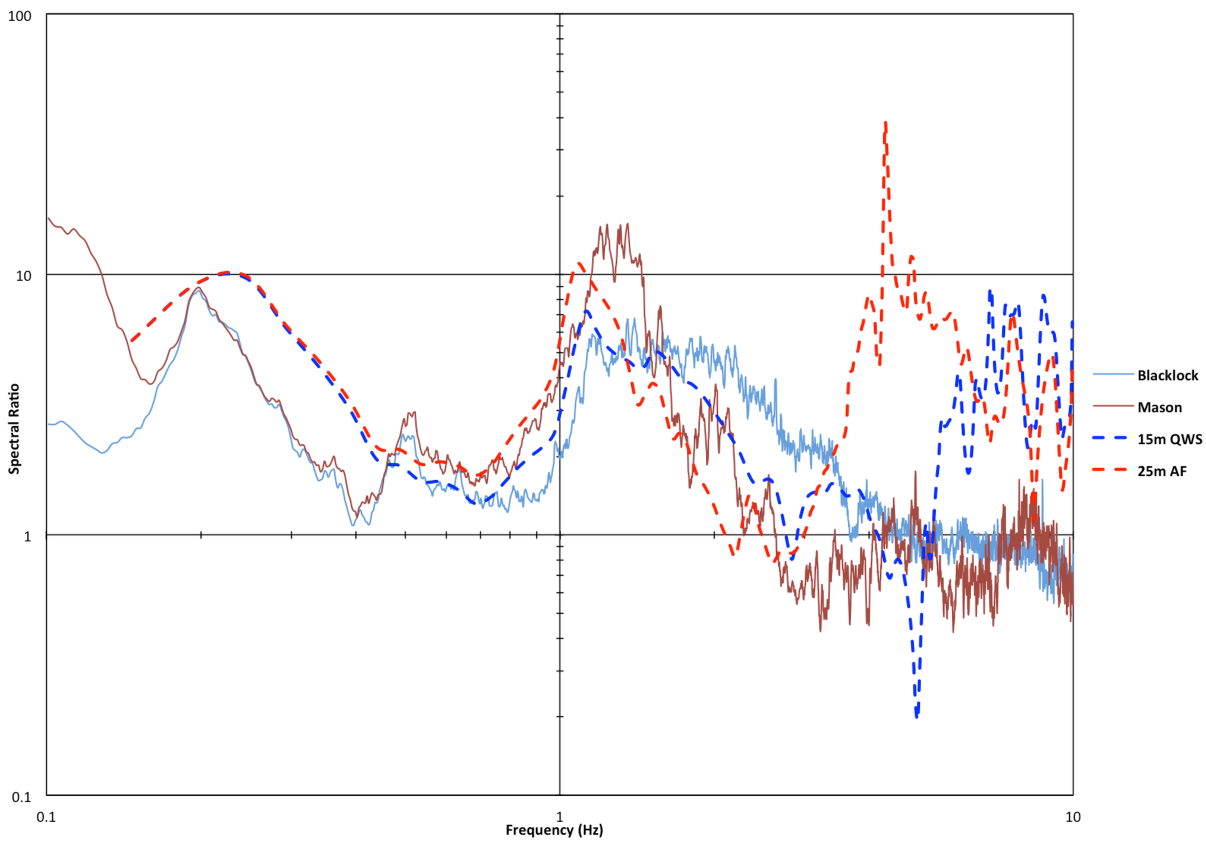

Figure 3. Observed (solid) and modeled (dashed) HVSR at 2 sites on the Charleston Peninsula. Red - site on artificial fill above marsh deposits; blue – site on Quaternary Wando Formation.

Strong Motion Modeling

Equivalent linear seismic response analyses are performed using the computer program SHAKE 2000 (Ordonez, 2007), a commercial version of the widely used computer program SHAKE (Schnabel, 1972). These seismic response analyses are performed for a representative 850 m soil column overlying a bedrock half space. Equivalent linear seismic response analyses are conducted for the representative column using six-time histories selected to characterize the design earthquake. The selected time histories are three synthetic motions taken from New Madrid Seismic Zone (Silva et al., 1989) and three strong ground motions taken from 2011 Christchurch event.

Material properties required for the equivalent linear site response analysis include unit weight, shear wave velocity, and modulus reduction and damping curves for the soil column and unit weight and shear wave velocity for the underlying bedrock half space. These material properties are estimated based upon available boring logs and typical soil properties. The unit weight for the soil column is 18.2 KN/m^3 immediately below the ground surface and increases linearly to 22.5 KN/m^3 to just above half space, 850 m below ground surface. The shear wave velocity profile ranges from 155 m/s immediately below the surface (for the artificial fill site) to 800 m/s, just above of the bedrock half space. The bedrock "half space" is assigned a constant shear wave velocity of 3500 m/s and a unit weight of 23 KN/m^3. The modulus reduction and damping model of Ishibashi and Zhang (1993) for sand is used at shallow depths. Overburden pressure-dependent modulus reduction and damping model of Assimaki et al. (2000) with reduced damping and modulus degradation at higher overburden pressure are employed to compensate for the tendency of SHAKE to damp out higher frequency motions in deeper soil deposits.

The results of the equivalent linear seismic response analyses are in the form of 5% damped spectral acceleration response spectral ratios for ground surface motion to that of an outcrop basement rock. We use a bedrock input acceleration of 0.01 g, 0.1 g and 0.3 g to simulate the weak motion response (0.01 g), response for a moderate earthquake (0.1 g) and for a repeat of the 1886 earthquake (0.3 g). We present the equivalent linear results for the artificial fill site, together with the observed and modeled weak motion response, in Figure 4.

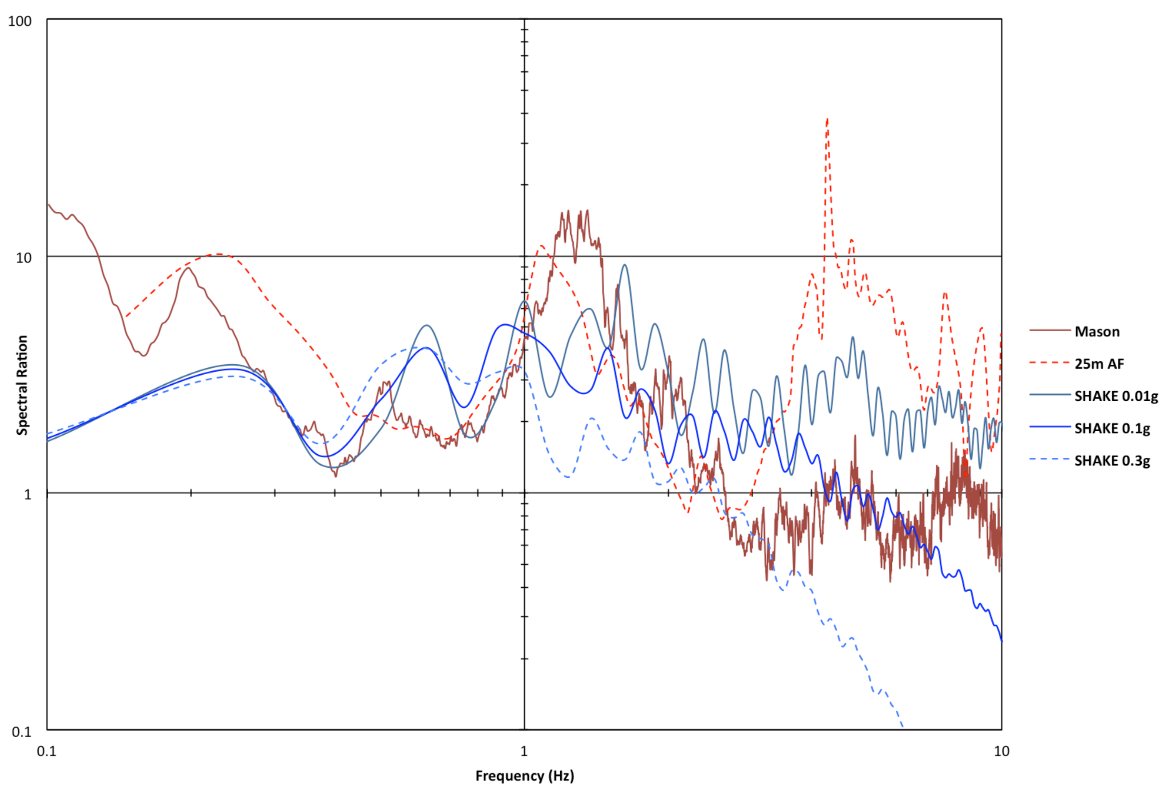

Figure 4. Weak and strong motion response models using SHAKE (blue) versus observed weak motion observation and elastic model for an artificial fill site (red).

The 0.01 g equivalent linear site response shows similarities to the elastic wave modeling, having the strongest amplifications near 1-2 Hz, a 0.2 Hz peak and considerable amplification at frequencies >2 Hz. It differs, however, in that it shows strong amplification between 0.5-1 Hz, i.e., considerably stronger than observed or predicted from the elastic modeling. The 0.1 g equivalent linear site response is most similar to the observed weak motion response, with amplification peaks at 0.2 and 1-2 Hz and deamplification at >2 Hz. The 0.3 g equivalent linear seismic response only shows amplifications at frequencies <1 Hz and deamplification >1 Hz.

Discussion

We can compare the observed amplification peaks with those expected given the thickness and velocity of the coastal plain sediments beneath Charleston using the quarter wavelength law (1)

$$f_N = (2N + 1)\, V_S / 4\, H \qquad (1)$$

Where f_N is the frequency of resonance, V_S is the average shear wave velocity of the sedimentary layer and H is the thickness of the sediments. Using V_S = 700 m/s and H = 850 m (i.e., values for the entire coastal plain section), for N =0 f_N is 0.20 Hz, for N = 1 f_N is 0.62 Hz and for N = 2 f_N is 1.03 Hz. Two of these resonances (0.2 and 1 Hz) consistently show up in both observations and weak motion modeling, but only the SHAKE results show the 0.62 Hz peak. Considering only the section above 75 m depth (i.e., where there is a significant velocity decrease), Eqn. (1) predicts (V_S = 370-410 m/s and H = 75 m) f_N = 1.2-1.4 Hz for N=0; and considering only the Quaternary section (V_S = 160-190 m/s and H = 15-25 m) f_N = 1.6-3.1 Hz for N=0. These simple considerations suggest that the consistent strong 1-2 Hz amplification observed throughout our study area is actually a convergence of amplifications from three different impedance contrasts beneath Charleston, with the strength of this amplification controlled by how closely the individual amplifications match.

This does not, however, explain the lack of higher frequency amplifications in the HVSR observations. Both the elastic and "weak motion" SHAKE modeling predict some amplification at frequencies above 3 Hz, but this is rarely if ever observed (Miner, 2014). If anything, the moderately strong input (0.1 g) equivalent linear results look the most like our observed weak motion amplifications. The greatest amplifications occur near 1-2 Hz and there is a strong decrease in amplification at higher frequencies. It is unlikely the near surface sediments are behaving nonlinearly under these weak motions (which are what is happening in the strong motion models); a more probable explanation is the rapid variation in the thickness and velocity of near surface materials (Levine et al., 2014) is preventing a true 1D response.

A final observation is that our strong motion modeling suggests the frequencies of site amplification in Charleston will change dramatically with the strength of the input strong motion. For very strong motions (i.e., a repeat of the 1886 earthquake) the strongest amplifications are predicted to occur at frequencies below 1 Hz. This is consistent with damage to 2-3 story masonry buildings in 1886, which shows little difference in damage ratios for buildings on artificial fill versus older, firmer materials (Robinson and Talwani, 1983). However, our results suggest this would not be true for a moderate-sized earthquake, which would likely create a strong variation in amplification at 1-2 Hz. This would not only influence damage to the historic masonry buildings, but also more strongly impact the modern 5-10 story reinforced concrete buildings in the region. Given that a moderate earthquake is more likely in the near future, damage patterns in such an event would be substantially different than in 1886.

Conclusions

We find that observed weak motion amplifications and their variation in Charleston, South Carolina are explained by resonances associated with 3 different impedance contrasts in the 850 meters of coastal plain sediment beneath the city. We can reproduce the main features of this observed amplification using both elastic wave modeling and the strong motion response model SHAKE using a weak motion input. Surprisingly, we find an equivalent linear model response with a moderate (0.1 g) input most closely matches our observed weak motion response. Results using an even stronger input (0.3 g) only show amplification at frequencies lower than the peak amplifications seen in observed data.

Acknowledgments

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