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Soil amplification with a strong impedance contrast: Boston, Massachusetts

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ABSTRACT

In this study, we evaluate the effect of strong sediment/bedrock impedance contrasts on soil amplification in Boston, Massachusetts, for typical sites along the Charles and Mystic Rivers. These sites can be characterized by artificial fill overlying marine sediments overlying glacial till and bedrock, where the depth to bedrock ranges from 20 to 80 m. The marine sediments generally consist of organic silts, sand, and Boston Blue Clay. We chose these sites because they represent typical foundation conditions in the City of Boston, and the soil conditions are similar to other high impedance contrast environments. The sediment/bedrock interface in this region results in an impedance ratio on the order of ten, which in turn results in a significant amplification of the ground motion. Using stratigraphic information derived from numerous boreholes across the region paired with geologic and geomorphologic constraints, we develop a depth-to-bedrock model for the greater Boston region. Using shear-wave velocity profiles from 30 locations, we develop average velocity profiles for sites mapped as artificial fill, glaciofluvial deposits, and bedrock. By pairing the depth-to-bedrock model with the surficial geology and the average shear-wave velocity profiles, we can predict soil amplification in Boston. We compare linear and equivalent-linear site response predictions for a soil layer of varying thickness over bedrock, and assess the effects of varying the bedrock shear-wave velocity (V_{Sb}) and quality factor (Q). In a moderate seismicity region like Boston, many earthquakes will result in ground motions that can be modeled with linear site response methods. We also assess the effect of bedrock depth on soil amplification for a generic soil profile in artificial fill, using both linear and equivalent-linear site response models. Finally, we assess the accuracy of the model results by comparing the predicted (linear site response) and observed site response at the Northeastern University (NEU) vertical seismometer array during the 2011 M 5.8 Mineral, Virginia, earthquake. Site response at the NEU vertical array results in amplification on the order of 10 times at a period between 0.7–0.8 s. The results from this study provide evidence that the mean short-period and mean intermediate-period amplification used in design codes (i.e., from the F_a and F_v site coefficients) may underpredict soil amplification in strong impedance contrast environments such as Boston.

1. Introduction

Recent earthquakes such as the 2011 M 5.8 Mineral, Virginia, earthquake have focused attention on seismic hazards and risk in the Central and Eastern United States (CEUS), especially in regions with moderate seismic activity and high population density (e.g., Hough, 2012). In the CEUS, where bedrock is harder and less fractured than in the Western U.S., strong bedrock/soil seismic impedance contrasts are common, and the resulting soil amplification can play a major role in damage patterns over large areas even due to a moderate sized event. When evaluating seismic hazard in regions such as Boston, Massachusetts, where artificial fill and marine soils are underlain by hard, competent bedrock—resulting in a strong impedance contrast—particular attention should be paid to site effects, and the influence of the impedance contrast on ground motions.

Strong impedance contrasts have played a role in soil amplification for other regions in the CEUS as well as in other tectonically active regions. Banab et al. (2012) analyzed soil amplification in Ottawa, Canada. The geology of Ottawa consists primarily of soft clay sediments with low shear-wave velocity ($V_S \sim 150$ m/s), underlain by hard bedrock with high shear-wave velocity ($V_S \sim 2700$ m/s), resulting in an impedance ratio of at least 18. The impedance ratio is calculated as $\rho_2 V_{S2}/(\rho_1 V_{S1})$, where ρ_1 and ρ_2 are the densities of the upper and lower layer, respectively, and V_{S1} and V_{S2} are the corresponding shear-wave velocities. Other examples of soil amplification at soft clay sites with a strong impedance contrast at the bedrock interface include the 1985 M 8.1 Mexico City earthquake (Seed et al., 1988; Kramer, 1996) and the 2001 M 6.8 Nisqually earthquake (Molnar et al., 2004). The damage in Mexico City was attributed in part to the strong impedance contrast between the lake deposits ($V_S \sim 75$ m/s) and the underlying

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cemented sand and gravel (V_S ~500–900 m/s), resulting in amplification ratios near 10 at periods of approximately 2 s (Kramer, 1996). The 2001 Nisqually earthquake caused noticeable soil amplification in Victoria, British Columbia, which has similar geology to the Boston area: bedrock overlain by glacial deposits, marine clay, and organic material. The clay consists of an overconsolidated layer ("brown Victoria clay") on top of a normally consolidated layer ("gray Victoria clay"), not unlike typical sites in Boston underlain by the Boston Blue Clay. Shear-wave velocity measurements in the brown Victoria clay (~164–262 m/s) are low compared to bedrock (~2000–3500 m/s), and bedrock depth ranges from 0 to 30 m. In Victoria, observed peak accelerations at soil sites were up to six times those of observed peak accelerations at bedrock sites at periods between 0.2–0.5 s.

In this paper, we explore the effect of the observed strong impedance contrasts for soil profiles in Boston, where the stratigraphy includes artificial fill over marine clay (V_S ~200–400 m/s) over glacial till over hard bedrock (V_S >2000 m/s); the bedrock depth is generally between 5 and 50 m but can reach 80 m at some locations. Our objective is to develop region-specific models for use in site response estimation and to characterize the influence of a strong impedance contrast on site effects. We are interested in evaluating the predicted mean short-period (0.1–0.5 s) amplification and the mean intermediate period (0.5–1.5 s) amplification for Boston against code-based coefficients: F_a and F_v (Dobry et al., 2000; BSSC, 2009). In this study, we develop a generic velocity profile for sites based on the surficial geologic unit (artificial fill, glaciofluvial deposits, and glacial till/bedrock defined in Brankman and Baise, 2008), which can be paired with a depth-to-bedrock model for the region. We validate the methodology by comparing the 1D predicted site response at the Northeastern University (NEU) vertical seismometer array in Boston to the observed site response during the 2011 Mineral, Virginia, earthquake. Because the expected ground motions and resulting soil strains in the Boston area are relatively low and near the linear/nonlinear soil behavior boundary, we evaluate site response using both linear and equivalent linear methods. As discussed in Kaklamanos et al. (2015) and Zalachoris and Rathje (2015), nonlinear methods may result in improved performance over equivalent-linear models for short periods (<1 s) and maximum shear strains above 0.1%; however, these strain levels are not expected for design ground motions in Boston.

2. Data resources

2.1. Geology

The City of Boston is located in a shallow sedimentary basin within the fault-bounded Boston Basin, which is defined by north-dipping faults that separate granitic and volcanic rocks from meta-sedimentary rocks (Cambridge Argillite and Roxbury Conglomerate). The shape of bedrock in the basin is the result of preferential erosion of weaker rock during repeated glaciation throughout the Pleistocene (Barosh and Woodhouse, 2011/2012). The location and geometry of present river channels as well as previous paleochannels are largely a function of the bedrock shape (FitzGerald et al., 2005). Boston soil conditions can be summarized generally in the following manner (Woodhouse and Barosh, 2011/2012):

1. The area of Boston has been extensively filled, resulting in a layer of miscellaneous, often non-engineered fill overlying organic materials. The artificial fill is usually underlain by the marine clay unit (called the Boston Blue Clay), and is often coincident with the deepest soil sites in the region.
2. Boston Harbor includes the mouths of two major rivers: the Charles and Mystic Rivers. Both these river channels are underlain by marine clay.
3. The area of Boston was heavily glaciated and is surrounded by glacial drumlins. In general, bedrock is overlain by glacial till in the region, and both materials exhibit high shear-wave velocities.

A surficial geology map for greater Boston is shown in Fig. 1. Note that glacial till and bedrock are simplified to a single unit in this map and also include glacial ground and end moraines. The glaciofluvial deposits include glacial outwash plains, eskers, kames, and kame fields (Brankman and Baise, 2008).

2.2. Geotechnical data

The map in Fig. 1 includes borehole locations where soil stratigraphy is known, as well as locations where spectral analysis of surface waves (SASW) and seismic cone penetration testing (sCPT) velocity measurements are available. The 500+ boreholes shown in Fig. 1 include stratigraphic layer boundaries and were collected from numerous projects in the region (Boston Society of Civil Engineers logs; Central Artery/Tunnel (CA/T) Project; Massachusetts Water Resources Authority) (BSCE, 1961; Haley, and Aldrich, Inc., 1991). SASW velocity profiles were available at 27 locations (Thompson et al., 2014) and the sCPT were available at 3 locations (Santagata and Kang, 2007).

We grouped the 30 shear-wave velocity (V_S) profiles by surficial geology unit: artificial fill, glaciofluvial deposits, and bedrock, as summarized in Fig. 2. Drumlins, glacial till, and bedrock were grouped together as one unit because the velocity profiles were consistent and the sediments are generally shallow (bedrock). The V_S profiles in the artificial fill indicate a gradient of low V_S (~200–400 m/s) down to 30–50 m depth. The V_S profile in the glaciofluvial deposit also indicates low V_S in the shallow sediments (<10 m); however, the available boreholes with stratigraphic information indicate that the glaciofluvial unit is relatively shallow and underlain by bedrock. The V_S profiles in glacial till and bedrock indicate that the near-surface bedrock sites have a thin soil cover or weathered layer but reach V_S typical for bedrock (>2000 m/s) at depths between 1 and 10 m.

To characterize the stratigraphy in Boston, we used information from the borehole logs, V_S profiles, and the literature. The generalized soil properties are provided in Table 1. The height of the soil column (H) varied between 10 and 80 m. The shear-wave velocity of the soil (V_{Ss}) measurement ranged from 100 to 500 m/s, and the shear-wave velocity of the bedrock (V_{Sb}) measurement ranged from 1750 m/s to 2250 m/s. The density of the soil (ρ_s) was calculated as a function of V_S, following Brocher (2005). Hashash et al. (2014) defined a reference rock unit weight for Eastern North America (ENA) of 27 kN/m^3, corresponding to a density of 2.75 g/cm^3, which we used as the density of the bedrock (ρ_b). For linear site response, we assumed a soil quality factor (Q) range of 10 to 30, which is equivalent to a damping ratio (ξ) range of 1.67% to 5% ($\xi = 1/(2Q)$).

2.3. Ground motion data

Using recorded ground motions from the 2011 M 5.8 Mineral, Virginia, earthquake, we validate site response models at a vertical seismometer array in Boston. The Northeastern University (NEU) site is located in the Charles River basin and represents a typical artificial fill site with a thick layer of marine clay (Johnson, 1989). The NEU vertical seismometer array consists of both a surface accelerometer at 0 m depth (NEU00) and a downhole accelerometer at 51 m depth (NEU51). The epicentral distance for the 2011 Mineral earthquake is 760 km and the recorded peak ground acceleration (PGA) at the site is 0.004 g (NEU00), which is within the linear range of soil behavior. The stratigraphy at NEU is 2.5 m of fill, 2.5 m of sand, 43 m of clay, and 2 m of till (Yegian, 2014). The downhole recorded ground motions at NEU51 are compared with those recorded at the Jamaica Pond (JP) bedrock site (2 km away), which is assumed to behave as a bedrock outcrop site.

3. Results and discussion

This study was subdivided into three phases. The first phase involved the development of average soil profile models for sites