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Amplification of Earthquake Ground Motions in Washington, DC, and Implications for Hazard Assessments in Central and Eastern North America

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Key Points:
- Recordings from a temporary seismometer array document amplifications of earthquake ground motions in Washington, DC
- Damage in Washington, DC, during the 2011 M_w 5.8 Mineral, VA, earthquake was likely increased by these locally amplified ground motions
- Amplification of ground motions in other central and eastern North American cities could raise ground motions from moderate earthquakes to damaging levels

Supporting Information:
- Supporting Information S1

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Amplification of Earthquake Ground Motions in Washington, DC, and Implications for Hazard Assessments in Central and Eastern North America

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Abstract The extent of damage in Washington, DC, from the 2011 M_w 5.8 Mineral, VA, earthquake was surprising for an epicenter 130 km away; U.S. Geological Survey "Did-You-Feel-It" reports suggest that Atlantic Coastal Plain and other unconsolidated sediments amplified ground motions in the city. We measure this amplification relative to bedrock sites using earthquake signals recorded on a temporary seismometer array. The spectral ratios show strong amplification in the 0.7 to 4 Hz frequency range for sites on sediments. This range overlaps with resonant frequencies of buildings in the city as inferred from their heights, suggesting amplification at frequencies to which many buildings are vulnerable to damage. Our results emphasize that local amplification can raise moderate ground motions to damaging levels in stable continental regions, where low attenuation extends shaking levels over wide areas and unconsolidated deposits on crystalline metamorphic or igneous bedrock can result in strong contrasts in near-surface material properties.

Plain Language Summary Shaking during earthquakes in geologically older continental regions like central and eastern North America extends for much greater distances than in younger regions like much of western North America. We show that amplification of ground motions by shallow layers of sediment beneath Washington, DC, likely was responsible for amplifying moderate ground motions during the M_w 5.8 Virginia earthquake in 2011 to damaging levels, despite the earthquake being relatively distant and only moderate in size. This study thus emphasizes the importance of local amplification effects in causing damage to cities in stable continental regions, where there can be strong contrasts in material properties between shallow sediments and underlying igneous or metamorphic bedrock.

1. Introduction

Washington, DC, had surprisingly high intensities of ground shaking during the 2011 M_w 5.8 Mineral, VA, earthquake given the earthquake's moderate size and epicentral distance (Hough, 2012; McNamara et al., 2014). The city is 130 km from the epicenter (Figure 1a), and the peak horizontal ground acceleration of 0.11 g on bedrock at nearby Reston, VA (Wells et al., 2015), would normally not be expected to cause significant damage. Nonetheless, the earthquake caused much-publicized damage to the Washington Monument (Nikolaou et al., 2011; Wells et al., 2015), the Washington National Cathedral (http://cathedral.org/earthquake/eq2/), the Sherman building at the Armed Forces Retirement Home (Swift, Daw, & Burgess, 2015, Swift, Daw, & Burke, 2015), the main building ("Castle") of the Smithsonian Institution (Clough, 2014), and other buildings (Horton et al., 2015). Minor damage in the city included rotated or toppled gravestones, cracked masonry and chimneys, and broken architectural elements such as facing stones. It was fortunate that no serious injuries or deaths occurred in the city from broken and falling masonry.

The 2011 earthquake damage in Washington, DC, highlights three factors that make cities in central and eastern North America vulnerable to moderately large earthquakes (M~5.5–6.5), which are a more common hazard than large earthquakes like the 1811–1812 M~7–7.5 Mississippi Valley earthquakes (e.g., Hough & Page, 2011; Johnston & Schweig, 1996; Nuttli, 1973; Tuttle et al., 2002) or the 1886 M~7 Charleston, SC, earthquake (Dura-Gomez & Talwani, 2009; Dutton, 1889; Wong et al., 2005). First, low seismic attenuation in central and eastern North America causes earthquakes to expose much wider areas to potentially damaging ground motions than in geologically young regions like much of western North America (e.g., Bockholt et al., 2015; Frankel et al., 1990; McNamara et al., 2014; Nuttli, 1973). Second, many older buildings there were constructed before modern seismic building codes were in effect.

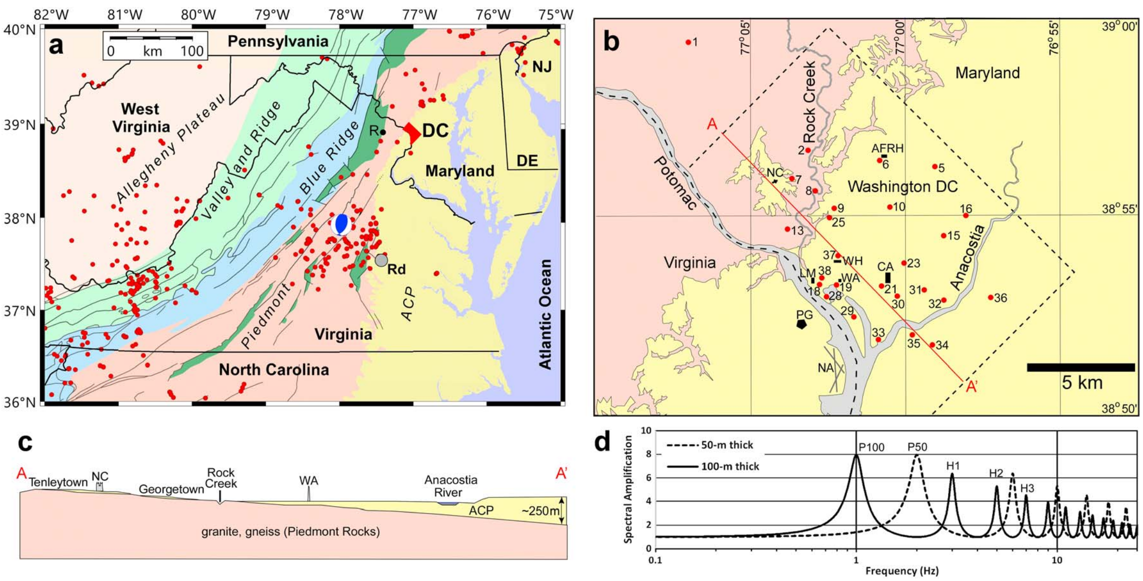

Figure 1. (a) Map of east-central U.S. showing Washington, DC (DC), and labeled geologic provinces (Bailey et al., 2016), including the Atlantic Coastal Plain (ACP) in yellow and green denoting Mesozoic rift basins. The blue focal mechanism is the M_W 5.8 Mineral, VA, earthquake of 2011, and the red dots are other earthquakes. Earthquakes west of Richmond, VA (Rd), form the Central Virginia seismic zone, from which three earthquakes were used in our analysis. R = Reston, VA. (b) Map of Washington, DC, showing Piedmont rocks (pink) and ACP strata and other unconsolidated deposits (yellow) (Darton, 1950; Southworth & Denenny, 2006; Powars, Catchings et al., 2015, Powars, Edwards et al., 2015). The red dots show seismometer sites, the black shapes show major buildings, and the rivers are gray. AFRH = Armed Forces Retirement Home (Sherman building); CA = Capitol; LM = Lincoln Memorial; NA = National Airport; NC = Washington National Cathedral; PG = Pentagon; WA = Washington Monument; WH = White House. The red line A-A′ locates the A-A′ cross section. (c) Cross section A-A′ showing ACP strata and unconsolidated deposits increasing in thickness from near Rock Creek to about 250 m thick at the southeast edge of the city. A thin layer of unconsolidated deposits is also present near the Washington National Cathedral. (d) Model of the amplification effects due to thin layers. The two models assume layers with velocities of 400 m/s and thicknesses of 100 m and 50 m. Each layer produces a primary resonance peak (P100 and P50) and higher-frequency peaks at multiples of the primary frequency (e.g., H1, H2, and H3 for the 100 m thick layer) as predicted by equation (1).

A third factor, investigated here, is that shallow sediments and unconsolidated deposits often overlie high-velocity Mesozoic or older rocks in central and eastern North America, which creates large velocity and density contrasts that contribute to amplification of ground shaking (e.g., Baise et al., 2016; Field et al., 1990; Fischer et al., 1995; Motazedian et al., 2011; Yilar et al., 2017). This is the case in parts of Washington, DC, and in other central and eastern U.S. cities situated on Atlantic Coastal Plain (ACP) and Mississippi Embayment (ME) strata (e.g., Bodin & Horton, 1999; Jaumé & Ghanat, 2015). This amplification effect also applies to eastern U.S. and Canadian cities outside of the extent of the ACP and ME strata but situated on other low velocity sediments (e.g., Baise et al., 2016; Field et al., 1990; Fischer et al., 1995; Motazedian et al., 2011). This local amplification can raise widespread, moderate ground motions from modest-sized earthquakes to damaging levels. Amplified ground motions in Washington, DC, during the 2011 earthquake are suggested by the anomalously high intensities in "Did-You-Feel-It" reports (Hough, 2012) and the significant damage in the city. The 1988 M_W 5.9 Saguenay earthquake in southern Canada likewise caused damages in distant cities, with amplification by shallow soils contributing to damages in Quebec city about 150 km from the epicenter and in Montreal about 340 km from the epicenter (Mitchell et al., 1990).

Most of Washington, DC, is underlain by ACP and other unconsolidated deposits overlying metamorphic and igneous basement rocks (Fleming et al., 1994; Southworth & Denenny, 2006). ACP strata in the city begin near Rock Creek and gradually thicken to about 250 m at the southeast edge of the city (Figures 1b and 1c; Darton, 1950; Powars, Catchings et al., 2015; Powars, Edwards et al., 2015). Sedimentary deposits also underlie the area around the Washington National Cathedral (Figure 1b), and parts of the city are on man-made fill (Fleming et al., 1994; Southworth & Denenny, 2006; Wells et al., 2015).

Seismic wave amplitudes can increase substantially as they pass from relatively high-impedance (velocity × density) basement rocks into low-impedance shallow layers (Borcherdt, 1970; Haskell, 1960; Shearer & Orcutt, 1987; Singh et al., 1988). Reverberations in shallow strata further increase amplitudes and durations of ground shaking at specific resonant frequencies (F_n) defined by the thickness (h) and shear wave velocity (V_s) of the shallow strata:

$$F_n = (2n + 1)V_s/4h \quad (1)$$

where n is the harmonic number (0 = primary peak; 1 = first harmonic, etc.) (e.g., Shearer & Orcutt, 1987; van der Baan, 2009). Thin surface layers can therefore cause a series of resonance peaks that decrease in amplitude at higher frequencies because of frequency-dependent attenuation (Figure 1d).

2. Measuring Amplification Effects

We deployed 27 seismometers throughout Washington, DC, between November 2014 and September 2015 to measure seismic wave amplifications caused by the shallow sedimentary deposits (Figure 1b and Table S1 in the supporting information). We computed spectral ratios of ground shaking relative to the average at four bedrock sites northwest of downtown, thus using the seismic waves reaching the bedrock sites as a proxy for the seismic waves entering the base of the shallow deposits. Identical 2 Hz sensors recorded at 100 samples/s produced usable signals from about 0.1 Hz (10 s period) to 25 Hz or more. Sensor response is reduced at low frequencies, but recordings with adequate signal-to-noise ratios are still useable. The response of the instruments was removed by dividing each site's Fourier frequency spectrum by the average spectrum at the reference sites. Instruments were located in open areas using battery power (e.g., graveyards) or at small buildings for power and security but away from large structures that would introduce significant building vibrations. Most sensors were buried in soil next to buildings, but a few sensors were placed inside small buildings on concrete floors with sand bags on top.

The relative lack of seismicity near Washington, DC, required us to rely on weak ground motions from distant earthquakes. We are not aware of reported liquefaction or pronounced ground settlement in Washington, DC, that indicates strong nonlinear effects in the city during the 2011 earthquake. However, small amounts of nonlinear soil response could reduce the peak amplifications from what we document using weak motions (e.g., Banab et al., 2012) and could slightly shift the frequency of the resonance peaks. Our results nonetheless identify the frequency range of amplification effects and highlight their importance, even if strong amplifications are partially mitigated by some nonlinearity in the soil response.

We analyzed recordings from 30 earthquakes having high signal-to-noise ratios (Figure 2 and Table S2), with low frequencies (0.1 to ~3 Hz) coming from teleseisms, middle frequencies (~0.5 to ~7 Hz) from regional earthquakes, and high frequencies (~1 to 25 Hz) from local earthquakes. We used 100 s windows for teleseisms and 50 or 25 s time windows for regional or local earthquakes (Figure 2). Some teleseisms with long durations allowed for analysis of several consecutive time windows. To provide adequate signal-to-noise ratios in this noisy urban area, we used time windows that spanned the strongest recorded ground motions from each event (e.g., Figure 2).

We applied a cosine taper to 10% of each end of the analysis windows, computed the Fourier spectrum of each component of ground motion, smoothed the spectra over 2.5 Hz, and then used the vector sum of the N and E spectra to produce a single horizontal spectrum. We removed frequency components with amplitudes less than twice that of a preearthquake noise window processed in an identical manner. The frequencies used from each earthquake at a site thus depended on the signal-to-noise ratio. Each data point on the spectra (Figures 3 and S1 in the supporting information) is the spectral ratio relative to the average of the four bedrock sites of a single frequency component during one earthquake, with the geometric mean of these points providing the summary amplification function at each site. The bedrock sites show spectral ratios near 1 between frequencies of 0.1 and about 5 Hz, above which each site shows some variation (Figure S1). We used the average signal from four reference sites to minimize the influence of a single site. We required two or more bedrock sites to be operating during any earthquake we analyzed, with few earthquakes having less than three reference sites operating.

3. Amplifications in Washington, DC

Inspection of the seismograms shows that sites on ACP strata had larger amplitudes and longer durations of ground shaking than bedrock sites in some frequency ranges (Figure 2). Nearly all sites on 15 m or more of ACP strata show large fundamental amplification peaks in the 0.7 to 4.0 Hz frequency range and little or

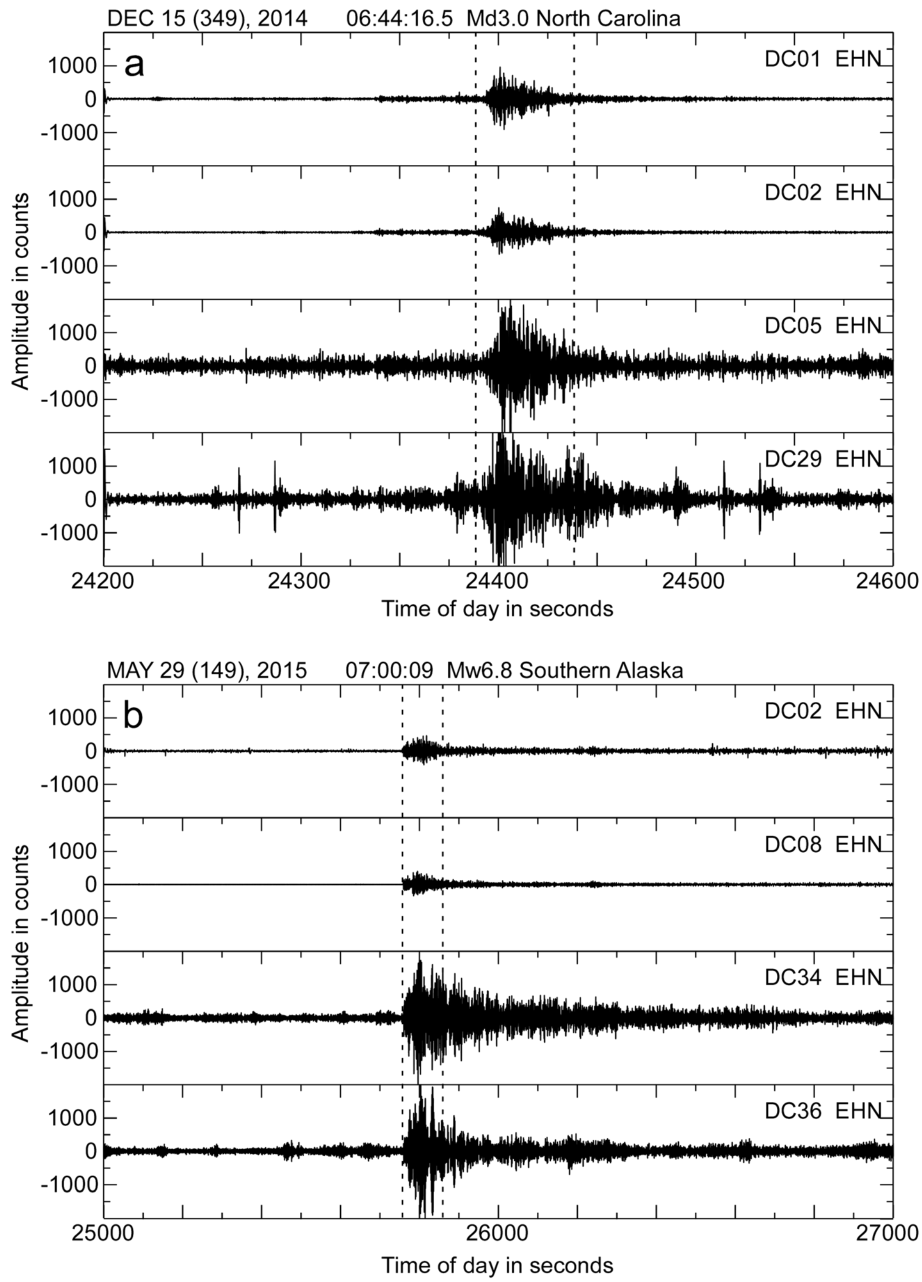

Figure 2. (a) Recordings of a M_d 3.0 earthquake beneath western North Carolina at two of our bedrock sites (DC01 and DC02) and two of our sites on moderately thick ACP strata (DC05 and DC29; ~61 and ~32 m, respectively). Note the larger amplitudes and longer durations of the recordings at sites on the ACP strata. The dashed lines show the 50 s analysis window used for this earthquake. Data have a 0.6 to 3 Hz band-pass filter for display. Amplitudes are raw data (counts) from the recording instrument. (b) Records from a M_w 6.8 earthquake from southern Alaska at two of our bedrock sites (DC02 and DC08) and at two sites on thick ACP strata (DC34 and DC36; ~169 m and ~150 m of ACP, respectively). The dashed lines show the 100 s analysis window encompassing the strongest shaking. Note the larger amplitudes and longer durations of the recordings made on ACP strata. Data have a 0.1 to 1 Hz band-pass filter for display.

no amplification at lower frequencies (Figure 3). Higher-frequency resonance peaks generally show decreasing amplifications with increasing frequency. Sites on thicker strata (>130 m) show a low-frequency, fundamental peak caused by resonance between the surface and the bedrock interface, and sometimes larger higher-frequency peaks presumably due to harmonics of the main peak and resonances from reflective layers within the ACP strata. Sites with less than ~15 m of ACP strata show flat responses similar to bedrock sites, with only minor amplification peaks at high frequencies caused by thin layers or

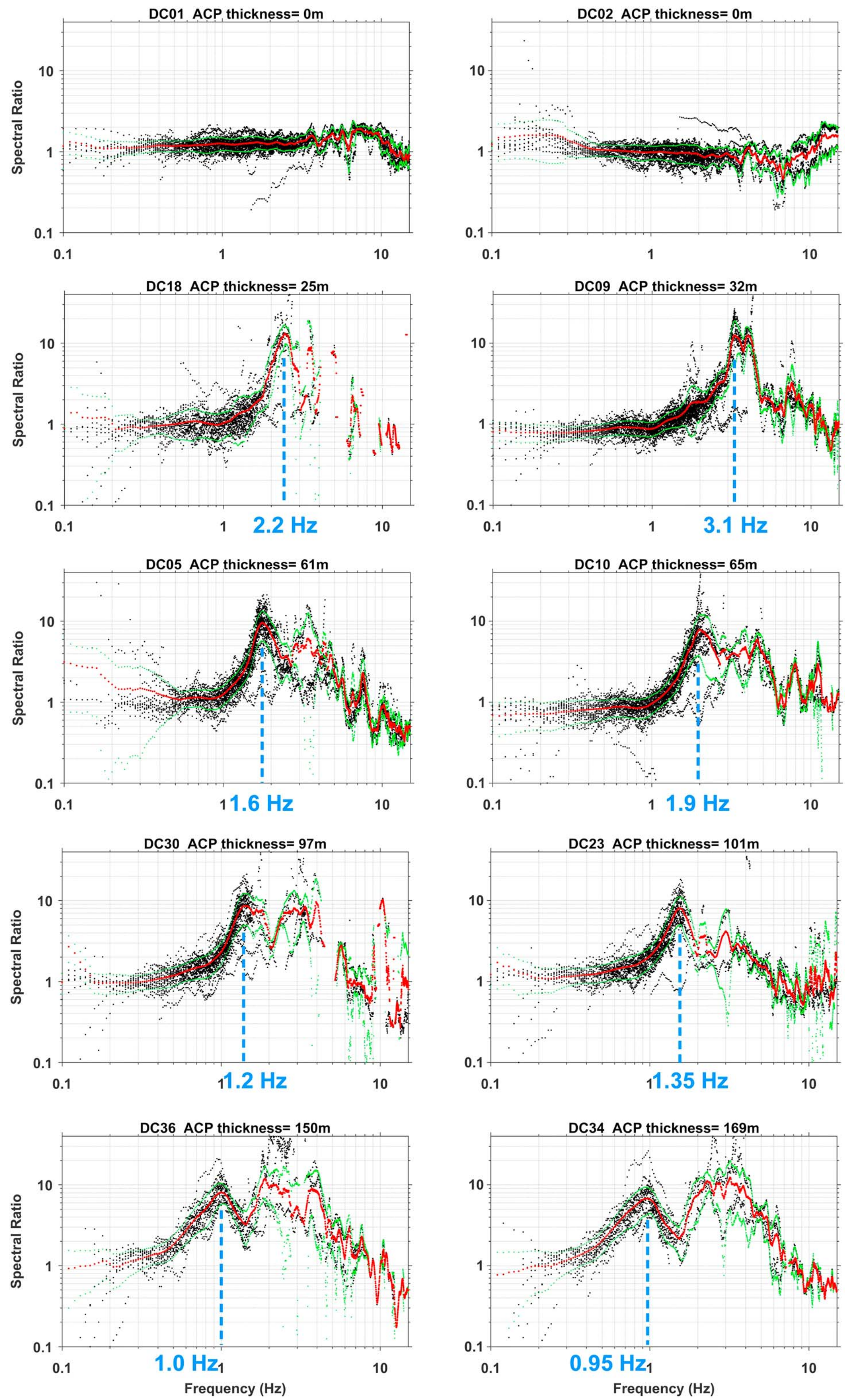

Figure 3. Spectral ratios at sites with well-defined resonance peaks, arranged by increasing thickness of ACP strata and unconsolidated deposits (i.e., depth to bedrock). The site number and depth to bedrock are listed above each graph. Each black dot represents the spectral ratio of a single frequency during a single earthquake, the red dots are the geometric mean of the data points at each frequency component, and the green dots show one standard deviation from the mean. Strong resonance peaks occur at nearly all sites on ACP strata, and the frequency of the primary resonance peak decreases with increasing ACP thickness as expected from equation (1).

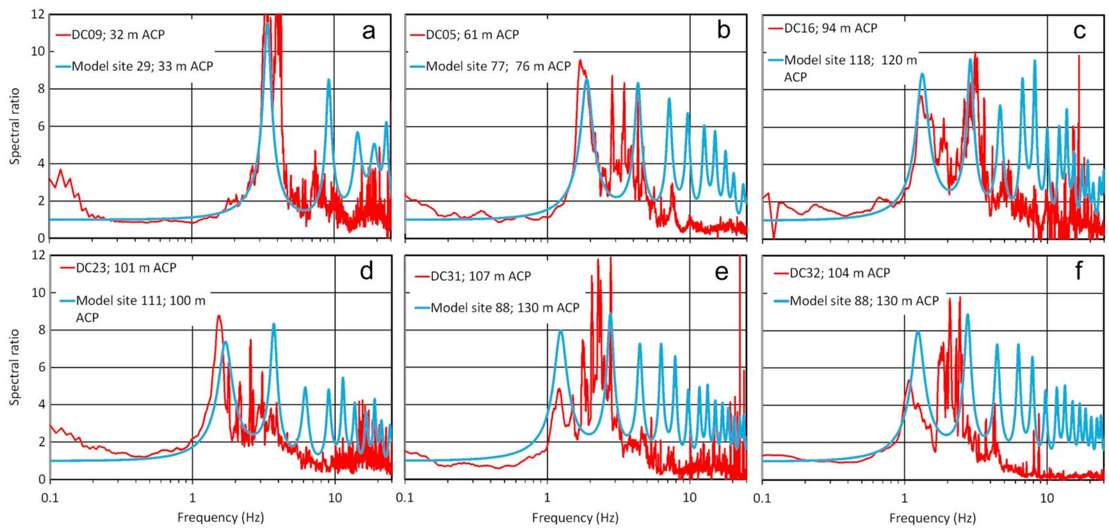

Figure 4. (a–f) Comparison of observed site responses over a range of ACP thicknesses (red lines) compared to modeled site responses from Tilashalski et al. (2015) (blue lines). Note that the models predict well the primary and first resonance peaks, suggesting that ACP strata are the primary cause of the amplification peaks. The best matches often are with modeled responses that have 10 to 25 m greater thickness of ACP strata because the thick layer of weathered bedrock (saprolite) causes bedrock velocities to be reached at depths below the lithologic boundary. A model with thicker ACP strata might fit the observed data better in Figure 4f, but 130 m was the thickest model for which there was geotechnical data.

vibrations of adjacent small buildings. The frequencies of the primary resonance peaks decrease with increasing thickness of ACP strata (Figure 3), as predicted by equation (1).

Comparisons with 1-D site response models indicate that ACP strata are responsible for most of the observed amplifications, without requiring 3-D effects such as surface waves or basin edge effects (e.g., Bard & Bouchon, 1985; Frankel et al., 1991, 2009; Kawase, 1996). Tilashalski et al. (2015) modeled amplification effects at 122 sites in Washington, DC, using depth to bedrock (Darton, 1950; Powars, Catchings et al., 2015; Powars, Edwards et al., 2015), measured shear wave velocities (Kayen et al., 2015), and unpublished geotechnical data. The geotechnical data were collected primarily near large buildings in busy parts of the city, whereas our instruments were in quieter areas away from large buildings. The modeled site responses are thus at different sites than our seismometers, and they showed some variation even for similar ACP thicknesses. The ACP thicknesses also have some uncertainty because they are based on extrapolation of relatively sparse drill hole data (Darton, 1950; Powars, Edwards et al., 2015). Nonetheless, models with similar ACP thicknesses as our sites match well the primary and next higher frequency resonance peaks and the flat responses at lower frequencies (Figures 4a–4f). Peaks between the first two major resonance peaks likely originate from reverberations from reflective layers within the ACP strata.

The best matches to observed site responses often are from models with ACP thicknesses 10 to 25 m greater than at the site (Figures 4a–4f), presumably due to thick saprolite (decomposed bedrock from chemical weathering) causing bedrock velocities to be reached at depths below the lithologic surface determined from drill holes. Saprolite in the Washington, DC, area has been observed with thicknesses up to 50 m on exposed bedrock (e.g., Froelich, 1975), and thicknesses of 15 m are common on bedrock beneath ACP sediments (e.g., Pavich & Obermeier, 1985).

Measured site responses above about 7 Hz generally show smaller spectral ratios than modeled responses (Figures 4a–4f), likely because scattering of high-frequency seismic waves by shallow structures and uneven interfaces is not accounted for in the 1-D site response models. This observation suggests that in areas with thick ACP strata the attenuation effect is greater than the amplification effect and the strata could reduce ground motions at high frequencies. However, this effect in the Fourier domain may not always indicate decreased response spectra, which are influenced by a broader frequency range of ground motions.

We computed an average shear wave velocity for the ACP strata beneath each site by using equation (1), the observed frequency of the main resonance peak, and the ACP thicknesses estimated from the drill hole data (but shifted to 10 m greater depth because of the saprolite). Using the average velocities for ACP strata of

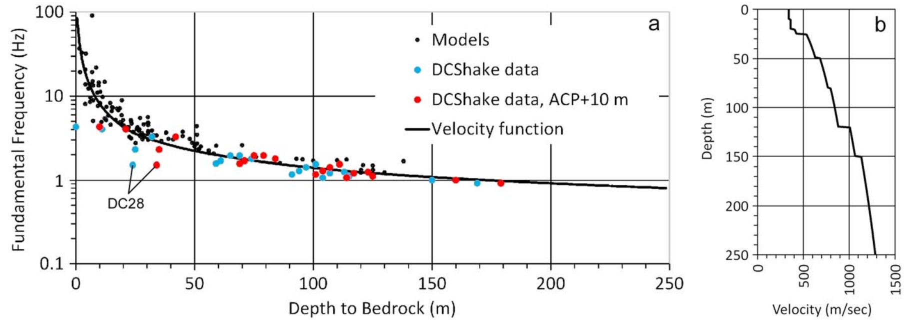

Figure 5. (a) Graph of the frequency of the primary resonance peak versus thickness of ACP strata, with the predicted values from equation (1) and our derived velocity function shown as a black line. The blue dots are the observed data, the red dots are the observed data with 10 m added to the ACP thickness because of saprolite (see text), and the black dots are from the models based on geotechnical data (Tilashalski et al., 2015). The anomalously low-resonant frequency at site DC28 is likely because it is on man-made fill with an anomalously low velocity. (b) The velocity function for ACP strata was derived by matching the predicted resonant frequencies based on ACP thickness (black line in part Figure 5a) using equation (1).

different thicknesses, we computed a velocity function for the ACP strata that provided a good fit to the observations and models (Figures 5a and 5b). Polynomial equations, even to sixth order, did not fit the data well, so we used trial and error to modify the velocities at different depths to match the data. The resulting velocity function is 350 m/s in the upper 20 m, increases to 760 m/s at about 75 m depth, and reaches 1,000 m/s below about 120 m (Figure 4h). We emphasize that this velocity function is only loosely constrained and is nonunique, with trade-offs between the shallow and deeper velocities. Variations in ACP velocities across the city also make use of our velocity function problematic at any specific site. Nevertheless, the frequency of the primary resonance peak throughout the city can be estimated based on the thickness of the ACP strata (Figure 5a), or vice versa.

While amplification peaks reach factors of 10 or more at some sites, our results are derived using only weak motion data. Strong motion amplifications could be lowered by pervasively nonlinear response (e.g., Banab et al., 2012; Chin & Aki, 1991; Seed et al., 1976). While clear nonlinear effects such as liquefaction were not reported in Washington, DC, during the 2011 earthquake, sediments can experience significant nonlinear effects even at low to moderate accelerations (e.g., Banab et al., 2012; Chin & Aki, 1991; Rubinstein, 2011). "Did-You-Feel-It" intensity data suggest that local amplifications in the Washington, DC, area in 2011 were generally less than about 1.5 MMI units, corresponding to a peak acceleration amplification of about 3 (Hough, 2000). A nonlinear response of ACP strata in the region could explain why this factor was not as high as we measured from weak motions. Nonetheless, although pervasive nonlinearity could slightly shift and decrease the fundamental resonance peak, our results make it clear that amplification effects contribute significantly to hazard.

4. Discussion

4.1. Resonant Frequencies and Building Heights

A major factor in a building's resistance to earthquake damage is the relationship between the resonant frequencies of a building and the ground shaking, with a matching of frequencies increasing the chances of damage. An extreme example was the 1985 earthquake in Mexico City, where shallow sediments and trapping of surface waves in the underlying basin caused large amplifications of ground motions (summary in Flores-Estrella & Lomnitz, 2007). The matching of resonant frequencies during the earthquake was cited as contributing to severe damage to 5- to 15-story buildings while buildings of other heights sustained less damage (e.g., Flores et al., 1987; Seligman et al., 1989; Singh et al., 1988).

Our results suggest a matching of the resonant frequencies of buildings and amplified ground shaking in Washington, DC. Resonant frequencies of buildings are approximately inversely proportional to their height (Chopra & Goel, 2000; Dym & Williams, 2007; Ellis, 1980; Goel & Chopra, 1997, 1998). Two- to five-story houses and small commercial buildings are prevalent in Washington, DC, and height restrictions limit most buildings in the downtown business district to heights less than about 40 m. Empirical studies of concrete shear-wall and steel-frame buildings suggest resonant frequencies in the 0.4 to 5 Hz range for the 6 to 40 m tall buildings that dominate the city (Chopra & Goel, 2000; Dym & Williams, 2007; Goel & Chopra, 1997, 1998). These likely resonant frequencies overlap with the frequency range of amplified ground motions documented here. This matching of frequencies suggests that the amplified ground motions likely contributed to building damages during the 2011 earthquake and to the anomalously high perceived shaking reflected in the USGS "Did-You-Feel-It" intensity reports (Hough, 2012). There were no building collapses in Washington, DC, during the 2011 earthquake, but even without building collapse, amplified shaking in future earthquakes or in other cities makes it more likely that poorly attached veneers or architectural elements will sustain damage or fail, as happened to some buildings in Washington, DC, during the 2011 earthquake.

The buildings in Washington, DC, with the most damage during the 2011 earthquake, however, were mostly larger, historic buildings that likely have fundamental frequencies lower than the resonance peaks documented here. The Washington Monument provides a singular but important case study. Wells et al. (2015) concluded after an engineering analysis that the 169 m tall structure has a fundamental resonance mode of about 0.3 Hz (2.8–3.2 s period) and a second-order (S-shape) resonance mode of about 1.11 Hz (0.9 s period). However, damage was prevalent at the pyramidion top of the monument, the components of which have resonant frequencies in the 2.5 to 5 Hz range (0.2 to 0.4 s periods). Wells et al. (2015) found that shallow deposits beneath the monument amplified ground motions in a frequency range of 2.5 to 5 Hz (0.2 to 0.4 s periods), which overlaps the resonant frequencies of the pyramidion. They concluded that resonance of the upper elements of the building (pyramidion) in these amplified ground motions likely caused the concentration of damage there. It thus appears that amplification by shallow deposits was a significant factor contributing to the damage to the Washington Monument in the 2011 earthquake.

Matching of frequencies of amplified seismic waves with the resonant frequencies of specific building components may hold true for other large buildings in the city. In particular, the National Cathedral had damage concentrated in the flying buttresses and the relatively small, unreinforced spires and towers in the upper parts of the building (http://cathedral.org/earthquake/eq2/). Amplified ground motions were also suggested as contributing to the damage primarily to chimneys and other small elements at the Smithsonian "Castle" (Clough, 2014). Both the cathedral and the Smithsonian "Castle" are on thin layers of sediment (e.g., Clough, 2014; Mark et al., 2001) consistent with high frequencies of ground shaking being amplified. We can only speculate, but the pattern of damage in these buildings may be similar to the Washington Monument, with damage to the smaller architectural elements being exacerbated by amplification of high-frequency ground shaking caused by thin layers of sediment.

In contrast to these buildings, the badly damaged Sherman Building at the Armed Forces Retirement Home may have been shaken by ground motions amplified near its fundamental resonant frequency. This was among the most badly damaged buildings in the Washington-Baltimore area during the 2011 earthquake (Swift, Daw, & Burgess, 2015, Swift, Daw, & Burke, 2015). The building is masonry with a ~37 m tall tower and a main building a little more than half that height. Given the heights of the building and tower, their resonant frequencies are likely in the 1 to 3 Hz range. The building sits on about 89 m of ACP strata above crystalline bedrock, and the seismometer we located 280 m southwest of the building on about 73 m of strata showed a strong amplification peak at a frequency of about 1.8 Hz (site DC06 in Figure S1). These numbers suggest that the building was shaken by ground motions that were amplified substantially at about the resonant frequency of the building.

4.2. Implications for Central and Eastern North America Earthquake Hazards

Damages in Washington, DC, during the Mineral earthquake and to eastern Canadian cities in the Saguenay earthquake demonstrate that moderate ground motions can be locally amplified to damaging levels, with implications for many cities in central and eastern North America. Our results show that ACP sediments and other unconsolidated deposits are the dominant factor in amplifying ground shaking in Washington, DC, and likely contributed to the damages there. Strong resonance effects (reverberations) are created by the large contrast in material properties between the unconsolidated shallow deposits and the underlying metamorphic or igneous basement rocks. Similar amplification effects have been documented in other central and eastern North American cities such as Boston, MA, New York City, Providence, RI, Charleston, SC, and

Ottawa, Canada (e.g., Baise et al., 2016; Banab et al., 2012; Braganza et al., 2017; Field et al., 1990; Fischer et al., 1995; Jaumé & Ghanat, 2015; Motazedian et al., 2011; Yilar et al., 2017), and presumably would be a factor in other central and eastern North American cities built entirely or partially on shallow ACP and other sedimentary deposits overlying crystalline rocks, such as Trenton, NJ, Wilmington, DE, Baltimore, MD, Richmond, VA, and Columbia, SC. Deposits similar to the ACP strata also underlie cities in the Mississippi Valley and Gulf Coast of the U.S., notably Memphis, TN (Bodin & Horton, 1999). Our sites had a maximum ACP thickness of about 200 m, but we can infer that thicker ACP strata will cause resonance peaks at lower frequencies, as well as high-frequency peaks caused by layering within the ACP strata (e.g., Jaumé & Ghanat, 2015; Pratt & Magnani, 2017).

Local amplification by unconsolidated strata is a special concern for cities located in stable continental interiors and passive margin settings. Low attenuation of seismic energy in these settings can extend similar levels of ground shaking to much greater distances than in geologically younger areas like parts of western North America (e.g., Frankel et al., 1990; Horton & Williams, 2012; McNamara et al., 2014; Nuttli, 1973). The 2011 Mineral and 1988 Saguenay earthquakes show that moderate ground motions can be locally amplified to levels that can cause substantial damage, even if the epicenter was in a rural area distant from major cities. A larger earthquake, or a moderate earthquake near a major metropolitan area, could produce much greater damage if local amplifications like we document in Washington, DC, substantially increase the strength of shaking. Furthermore, the increasing seismicity due to induced earthquakes like the M_w 5.8 Pawnee, OK, earthquake (e.g., Chen & Nakata, 2017) suggests that moderate ground shaking may be more common in the future. Our results in Washington, DC, thus highlight the importance of local amplification of ground motions leading to future earthquake damages in central and eastern North American cities and in passive margin and midplate regions in general.

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