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# On the Characterization of Strong-motion Site Effects in the Presence of Strong Velocity Reversals

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Site effects in Iceland are generally assumed to be low and uniform due to the prevalence of rock, typically under a relatively thin and easily removable top soil, and the lack of densely sampled data on site response characterized by different geological profiles. It is noteworthy that in geologically younger parts of Iceland, which generally coincide with or are in the proximity of the seismically active regions, the interplay of repeated glaciation/deglaciation and fluctuation sea levels with primary basaltic volcanism has resulted in the geological profiles consisting of recurring layers of basaltic lavas, as well as tuff layers, often with intermediate layers of sediments. In such cases the lack of consolidation of the sedimentary deposits between the layers of lava rock causes reversal in the velocity profile with depth, which may lead to significant differences in site response relative to the older bedrock or sites with the traditional velocity profiles without reversals, and should therefore not be ignored. In fact, on a lava rock site in Iceland the presence of noticeable site effects has been reported relative to the nearby bedrock response (Bessason and Kaynia 2002; Rahpeyma et al. 2016).

To shed more light on the relative site response over short distances we used in this study the data set of more than 1705 aftershock recordings of the earthquake strong-motion of the $M_w 6.3$ Ölfus earthquake on 29 May 2008, recorded on the first small-aperture strong-motion array (ICEARRAY I) in south Iceland. The site effect investigations showed consistent and significant variations in ground motion amplitudes over short distances in an urban area located mostly on lava rock (see Figure 1). We analyzed the aftershock recordings to quantify the local site effects using the Horizontal to Vertical Spectral Ratio (HVSR) and Standard Spectral Ratio (SSR) methods. Additionally, microseismic data has been collected at array stations and analyzed using the HVSR method. The results reveal the strong variation in site response within a relatively small area of ICEARRAY I. In particular, some stations exhibit bimodal amplification curves with one mode being more dominant and of relatively larger amplitude than the other while other stations have a single narrow-band peak of relatively low amplitudes or a broad amplification curves of relatively high amplitude, or even very low and uniform amplification curves across the frequency range. Nevertheless, the results between the different methods and data sets are consistent and show that while the amplification levels remain relatively low, the predominant frequency varies systematically between stations and is found to correlate with the geological units.

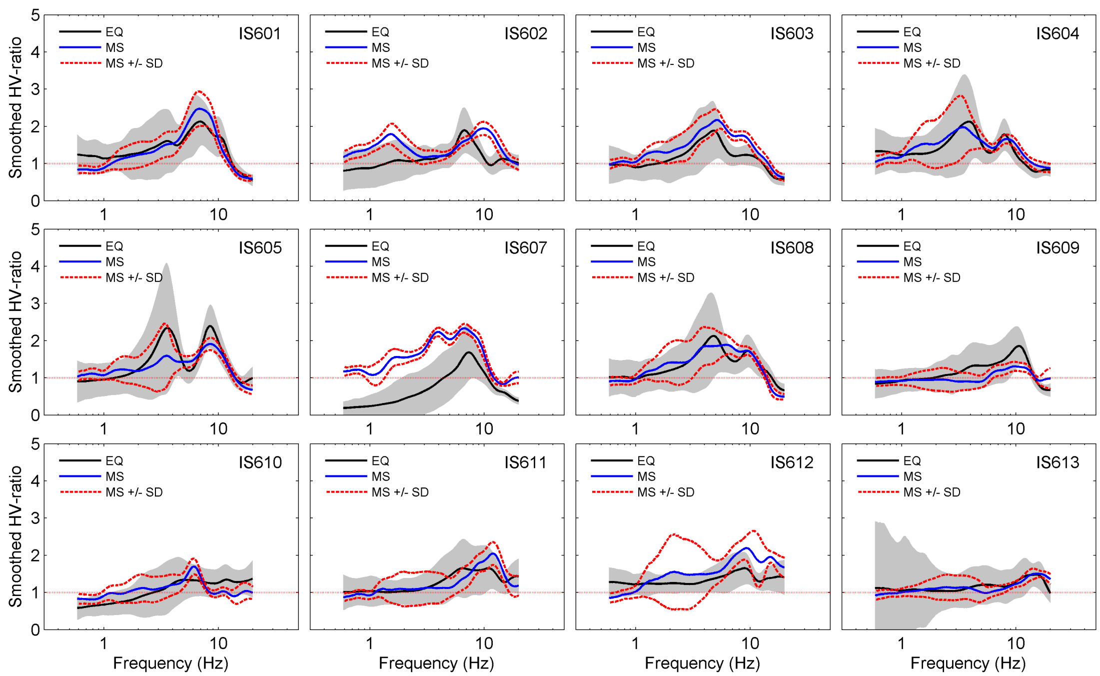


*Figure 1. Comparison of the mean HVSR estimated from earthquake (black lines) and microseismic (blue lines) data for the twelve ICEARRAY I stations. Standard deviations $\pm 1\sigma$ are shown with gray shaded areas (earthquake HVSR) and red dashed lines (microseismic HVSR).*

We observed that for stations located on lava rock, which are characterized by strong velocity reversals with depth, individual amplification curves exhibit different trends in the amplification and predominant frequency, warranting further inspection of the HVSR curves for each event for azimuthal, distance, and magnitude dependence. Accordingly, for stations with bimodal peaks we clustered the aftershock recordings into two groups, those associated with the peak amplification at low and higher predominant frequencies (lower or higher than 5 Hz). The results reveal that the two groups of aftershocks are distributed more or less evenly between the fault structures. In more quantitative terms, there is no azimuthal dependence of predominant frequency exists. Similarly, no correlation was found between predominant frequency and earthquake depth, and both groups of earthquakes have similar coverage of hypocentral distances. On the other hand, there is clearly a strong correlation between earthquake magnitude and the associated predominant frequency; this is in turn reflected in a strong correlation with peak ground acceleration. Thus, larger magnitude earthquakes appear to produce a bimodal amplification curve at station with bimodal peaks, where the lower predominant frequency dominates the higher predominant frequency. It is therefore likely that for station with bimodal peaks the velocity reversal is considerable and abrupt and that the earthquake waves are sampling deeper parts of the subsoil layers which microseismic wave field generated on or near the surface is not able to reach (see Figure 2).

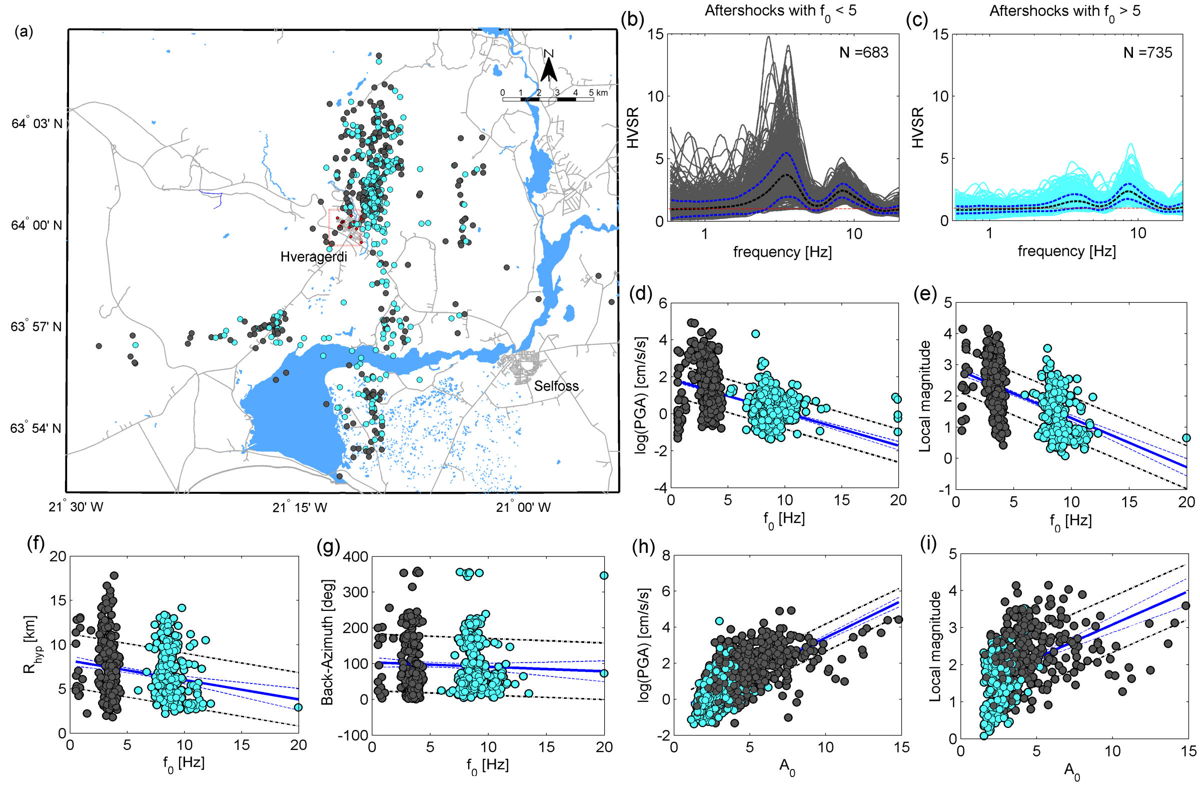


*Figure 2. Map of ~630 aftershock locations recorded by ICEARRAY I grouped according to the predominant frequency range above (blue) and below (gray) 5Hz, using station IS605 located in the town of Hveragerði (red dashed rectangle). The HVSR for two groups of the aftershocks is shown in (b) and (c) as well as the mean HVSR $\pm 1\sigma$ with N the number of available earthquake. Also shown (d) PGA, (e)$M_L$, (f)$R_{hyp}$, (g) Back-Azimuth vs. $f_0$, and (h) PGA (i) $M_L$ vs. $A_0$.*

Furthermore, focusing on the spatial distribution of predominant frequency show a general northeast-southwest trend of decreasing peak predominant frequency which is in agreement with geological transition in the area. As a result, standard modeling of HVSR using vertically incident body waves does not apply. Instead, modeling the soil structure as a two-degree-of-freedom dynamic system is found to capture the observed predominant frequencies of site amplification. The results of this study have important implications for earthquake resistant design of structures on rock sites characterized by velocity reversals (*Yoshida 2015; Rahpeyma et al. 2016*).

## References:


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