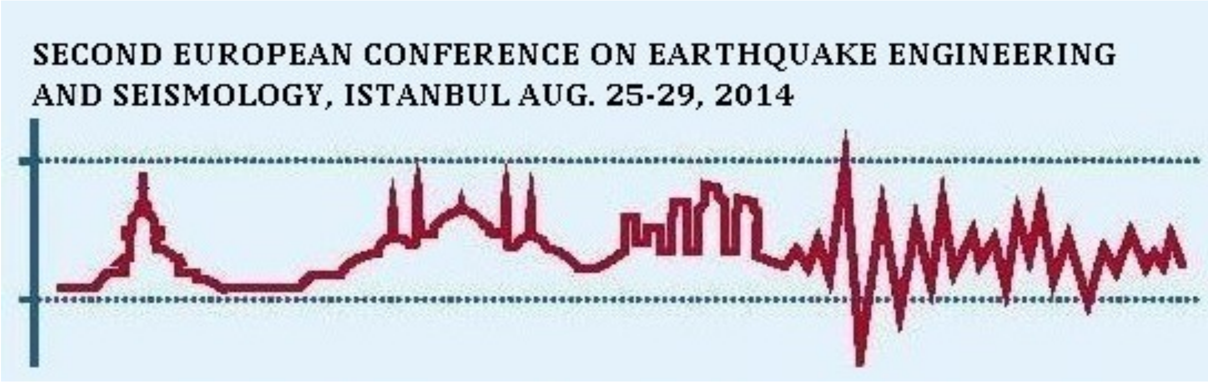

SITE EFFECTS ESTIMATION USING AMBIENT NOISE AND EARTHQUAKE DATA AT THE ICEARRAY II, NORTH ICELAND

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ABSTRACT

The town of Húsavík, in north Iceland is situated on Iceland's largest transform fault, the Húsavík-Flatey Fault, HFF, in the Tjörnes Fracture Zone, TFZ, one of Iceland's most seismically active and populated regions. Geologically, the town is characterized by lava rock overlain by several layers of soft sediments, which vary in depth across the town, thus increasing the potential damaging effects of earthquakes. In an attempt to assess conditions of high seismic risk arising from local site effects, Nakamura's (1989) H/V Spectral Ratio, HVSR, method was applied using both ambient noise data and earthquake recordings from seven ICEARRAY II (Halldorsson et al 2012) strong motion station sites in Húsavík. Comparison between HVSRs from both data sets reveals similarities in the estimated fundamental frequencies of the sites and in the estimated magnitudes of the site amplifications, which give credence to the use of the HVSR method for site characterization in the town of Húsavík.

Keywords: HVSR, site effects, ICEARRAY II

INTRODUCTION

Worldwide, earthquakes pose a great risk to the built environment and to life safety. While it is impossible to prevent earthquakes from occurring, it is possible to mitigate the effects of strong earthquake shaking to reduce loss of life, injuries, and damage. In general, when an earthquake occurs, seismic waves radiate away from the source and travel through the earth's crust. Although seismic waves travel through rock over the majority of their path from the source to the ground surface, they propagate up through near surface sediments and the characteristics of these sediments can greatly influence the nature of shaking at the ground surface. Soil deposits tend to act as "filters" to seismic waves by attenuating motions at certain frequencies and amplifying them at others. Since soil conditions can vary considerably over short distances, levels of ground shaking can vary significantly within a small area as a consequence. One important aspect of geotechnical earthquake engineering practice involves the evaluation of the effects of local soil conditions on strong ground motions.

One common procedure for estimating site effects is the Standard Spectral Ratio, SSR, method (Borcherdt 1970). The SSR method is based on the comparison of earthquake recordings obtained

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simultaneously on a site and nearby reference site (Borcherdt 1970). Unfortunately, it is not always easy to gather sufficient data to apply this technique because of high instrumentation costs and the need for long duration experiments, especially in regions of low seismicity. An alternative approach to estimate site effects was put forth by Nakamura (1989). The H/V Spectral Ratio, HVSR, method is based on recordings of ground shaking as a function of time in the horizontal, H, and vertical, V, directions, respectively, and calculating their Fourier amplitude as a function of frequency. Analyzing their ratio, H/V, as a function of frequency allows one to capture the characteristics of the site conditions that may amplify earthquake shaking. Since initially being proposed by Nakamura (1989), the HVSR method has been widely used. Although the method's physical basis and theoretical background have come into question (Lachetl and Bard 1994, Mucciarelli 1998, among others), the advantages of the approach are several fold, foremost being that it is a relatively inexpensive and easy method for obtaining information needed in seismic hazard and risk analyses (e.g., Atakan et al 1997, Bessason and Kaynia 2002).

The presented study aims at providing the first quantitative estimates regarding the characteristics of site response in the town of Húsavík, north Iceland using ambient noise and earthquake data. To assess conditions of high relative differences in seismic hazard arising from local site effects, the HVSR method was applied using single station ambient noise measurements and earthquake data recorded at seven ICEARRAY II strong motion stations (Halldorsson et al 2012), shown in Figure 1. The study intends to demonstrate the applicability of Nakamura's method in estimating local site effects and provide a reliable estimation of the predominant frequencies at several sites throughout the town of Húsavík.

LOCAL SITE EFFECTS AND THEIR METHODS OF ESTIMATION

The Evidence for site effects and their influence on damage distribution have been observed and investigated over the past few decades with the progression of various instruments and their availability for measuring ground motions. In general, the methods used to estimate site effects can be categorized into two major groups: the theoretical (numerical) and the experimental methods. The theoretical calculations of site response are based on the available geotechnical information pertaining to physical parameters of a site's sub-surface structure (Idriss and Seed 1968), while the experimental methods are somewhat more effective in the sense that they are based on calculating the frequency spectrum directly from recorded ground motions. The two widely used experimental methods are the SSR (Borcherdt 1970) and HVSR (Nakamura 1989).

In Borcherdt's (1970) SSR method, the horizontal records at each studied site are compared with the horizontal records for the same event at a nearby bedrock site (or reference site) through spectral ratios. The ratio of the response spectrum of a record at a given site divided by the response spectrum of the record (for the same event) at the reference site is considered to be a measure of the site effects on ground motion, if the following two assumptions are valid (Bonilla et al 1997, Borcherdt 1970): (1) the reference site is free or almost free from local amplification effects and can be used at least for relative estimates of the local amplification, which is the case when the reference site is located on unweathered bedrock, and (2) the distance between the source and the receivers is much greater than the distance between the receivers themselves. Despite its effectiveness in estimating site amplification, concerns with the method's definition of a reference site have been raised. Studies have shown that the simple geological identification of stiff-soil/rock-mass outcrops do not warrant, by itself, the absence of site effects (Pileggi et al 2011).

Despite the SSR method's ability to estimate site amplification, the method's dependance on the availability of an adequate reference site (one with negligible site response) and earthquake data pleads for an alternative non reference site method. Unlike the SSR method, the Nakamura (1989) HVSR method is a single station approach for estimating site effects. The HVSR method uses three component single station ground motion records, and involves the ratio of the combined horizontal Fourier amplitude spectrum, H, to vertical, V, Fourier amplitude spectrum at the studied site. This spectral ratio, H/V, usually shows a peak, which closely corresponds to the predominant frequency (frequency at which maximum ground amplification occurs) of the investigated site. Though most of the method's applications have used ambient noise data, Nakamura's (1989) HVSR method has also

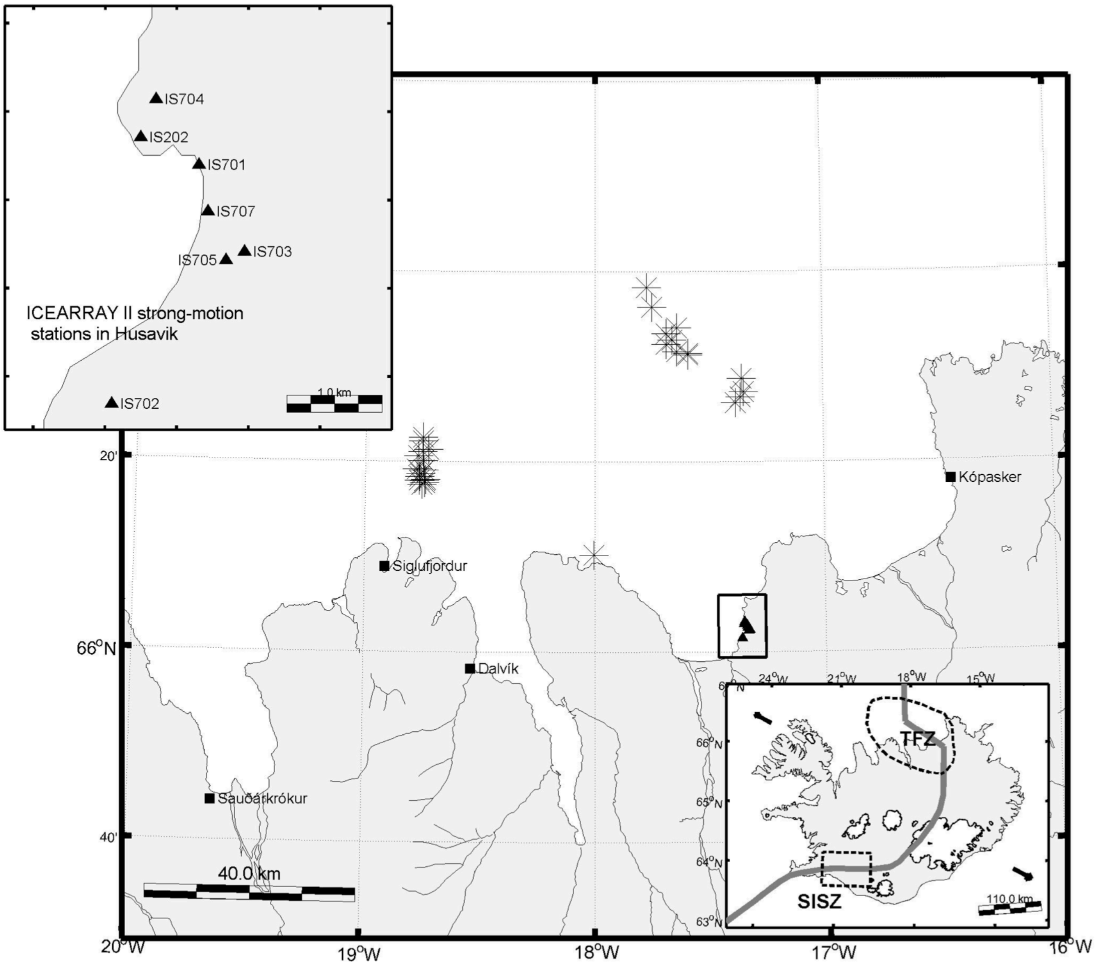

Figure 1: The seismic distribution (represented by black stars) for the duration of September 19, 2012 to April 4, 2013 in the Tjörnes Fracture Zone, TFZ, in north Iceland, including the strongest earthquake swarm to hit north Iceland in over 30 years. The inset picture at the bottom right shows Iceland with respect to the Mid-Atlantic Ridge, the South Iceland Seismic Zone, SISZ, in the lowlands of south Iceland, and the Tjörnes Fracture Zone, TFZ, in north Iceland, outlined by the dashed areas. The outlined area in north Iceland indicates the area shown in the main picture. The inset picture at the top left shows the seven ICEARRAY II strong motion stations (represented by black triangle symbols, along with station ID-codes) in Húsavík, north Iceland where single station ambient noise measurements were performed and earthquakes recorded.

been shown to be applicable to strong ground motions (e.g., Wood et al 2011). Furthermore, studies described in Nakamura (2000, 2008), Lermo and Chávez-García (1993), and Sato et al. (2004), among others, have shown that HVSRs of ambient noise and strong ground motions are similar to each other. However, despite it being a relatively inexpensive and easy approach for obtaining information useful for seismic hazard and risk analysis, the method's theoretical background has come into question, particularly in regards to the source of ambient noise and the method's inability of estimating the ground amplification. Additionally, questions have been raised about the method's ability of estimating the predominant frequency of complex multi-layer systems (Cid et al 2001). Nevertheless, the method has successfully been used to estimate predominant frequencies, and its use of ambient noise data makes it even more desirable as it can be practically applied at any time and place.

THE TJÖRNES FRACTURE ZONE AND THE ICEARRAY II

The Iceland is located on the Mid-Atlantic Ridge, the diverging plate boundary of the North American and Eurasian plates in the North Atlantic Ocean. Crossing the island from southwest to north, the onshore part of the plate boundary shifts eastward, resulting in two transform zones: the completely onshore, South Iceland Seismic Zone, SISZ, and the largely offshore Tjörnes Fracture Zone, TFZ (Figure 1). The SISZ, located in the lowlands of south Iceland, and the TFZ in north Iceland are the regions of Iceland where earthquake hazard is the highest and have the greatest potential for the occurrence of large earthquakes. The surface geology of Iceland was formed during and after the last Ice Age and is generally described as a pile of basaltic lavas, as well as tuff layers, often with intermediate layers of sediments or alluvium (Einarsson and Douglas 1994).

In the TFZ, earthquakes mainly occur along two seismic faults: the Húsavík-Flately Fault, HFF, and the Grimsey Oblique Rift, GOR. Although mostly offshore, a part of the HFF system extends through the coastal town of Húsavík, inducing a seismic risk to its inhabitants (Sæmundsson 1974, Rögnvaldsson et al 1998, Sæmundsson and Karson 2006, Gudmundsson 2007, Metzger et al 2011) and has the potential to host a M6.8 earthquake (Metzger et al 2013). Earthquake induced effects are increased by the varying and complex geological profiles throughout the TFZ, and in particular, the town of Húsavík. The oldest rock present in Húsavík is a 8.5-10 Ma old basalt and can only be found north of the HFF, where the basalt are cut at the fault; and are known to not be present south of the HFF (Rögnvaldsson et al 1998). Most of the lowest strata in Húsavík is of young Quaternary basalt, originating from a series of eruptions from the nearby Grjothals shield volcano (Gudmundsson 2007). However, at relatively low elevations, the lava rock is superseded by hyalochlastite, a volcanic breccia, indicating that the Grjothals lava had flowed into the sea (Gudmundsson 2007). The town of Húsavík itself is generally characterized by several sedimentary layers, which generally overlay the Grjothals lava rock and hyalochlastite and vary in depth across the town (Gudmundsson 2007, Sæmundsson and Karson 2006). The oldest sediments are glacial deposits and have, over time, altered to solid Tillite rock, which also underlay parts of Húsavík (Rögnvaldsson et al 1998).

The ICEARRAY II is a relatively new (since 2012) small aperture array of accelerographs and high sampling rate GPS instruments located in the town of Húsavík and is operated by the Earthquake Engineering Research Centre, EERC, of the University of Iceland, UI, since 2012 (Halldorsson et al 2012). The results and new research opportunities created by the ICEARRAY I, located in the town of Hveragerði in the SISZ, and its globally unique and high quality recordings of the M_w6.3 Olfus earthquake of 29 May 2008 and its aftershocks (Halldorsson et al 2009, Halldorsson and Sigbjörnsson 2009, Halldorsson and Avery 2009, Sigbjörnsson et al 2009, Halldorsson et al 2010), provided the impetus to establish the ICEARRAY II to monitor strong motions from earthquakes in the TFZ and to map the characteristics of the relative levels of strong motion across Húsavík (Halldorsson et al 2012).

DATA AND METHODS

Ambient noise is defined as low amplitude vibrations generated by natural disturbances such as wind, sea tides, or of man-made origins such as traffic, industrial machinery, household appliances, etc. (Triantafyllidis et al., 2006). Continuous measurements of ambient noise, with minimum one-hour recordings, were performed at seven ICEARRAY II strong motion stations using a REF TEK 130-01 Broadband Seismic Recorder and Lennartz LE-3D/5s Seismometer from the Icelandic instrument bank, Loki, which is operated through the Icelandic Meteorological Office, IMO.

The strong motion dataset was made up of earthquake events recorded by the ICEARRAY II using single CUSP-3Clp strong motion accelerograph units manufactured by Canterbury Seismic Instruments, Ltd. Since its deployment, the ICEARRAY II has recorded twenty-nine earthquakes, including the strongest earthquake swarm since the January 1976 Kopasker earthquake to hit north Iceland, in October 2012 and April 2013. The first swarm, in October 2012, occurred on the Eyjafjardarall rift and HFF, while the swarm in 2013 took place on the GOR. On 20 October, seismicity began just before midnight in the southern part of the Eyjafjardarall rift and continued into the following day, 21 October, when magnitude 5.3 and 5.6 earthquakes occurred at approximately 00:10 and 00:25, respectively (Guðmundsson et al. 2013; Jónsson et al. 2013). The April 2013 earthquake swarm started with a magnitude 5.3-5.5 earthquake on 2 April at 00:59 and continued into the morning and evening with several earthquakes of magnitudes 4.0-4.7 (Guðmundsson et al. 2013; Jónsson et al. 2013). Clusters of aftershocks were ongoing through the next few days and continued throughout April.

A unified procedure was implemented, using an in-house code written in Matlab, to consistently process ambient noise data and earthquake recordings so that any similarities or differences observed could be attributed to factors other than data processing itself. For ambient noise data, 20 minute time windows were selected for HVSR analysis, whereas for strong motion data, the entire earthquake recording was selected as the time window for HVSR analysis. The following procedure was applied to both ambient noise data and earthquake recordings: (a) calculating the Fourier amplitude spectra for the selected time window and computing the geometric mean for both horizontal components, (b) applying the Konno and Ohmachi (1998) smoothing function with a smoothing coefficient of B=20, and (c) computing the horizontal to vertical spectral ratio for the selected time window. The final mean HVSR for each site was determined by computing the geometric mean of the HVSRs from all the individual time windows, from step (c) above.

RESULTS

In Figure 2 results are shown for the HVSR method applied to ambient noise data from the seven ICEARRAY II strong motion stations and reflect the geological profiles underlying the respective sites. Geological maps and studies conducted of the town of Húsavík have described the ground in the northwest part of town, underlying IS202 and IS704 as Pleistocene Tillite. The uniform amplification of approximately one across a wide range of frequencies for site IS202 is characteristic of the Tillite rock sites; stiff sediments and hard rock sites generally tend to result in little to no significant ground motion amplification. Although IS704 is also a stiff sediment/hard rock site, topographical effects might be the cause of the amplification shown in the HVSRs (e.g., Sepúlveda et al. 2005, among others). Similarly, the geological maps produced by Waltl (2013) have also described the material underlying stations IS701, IS703, IS705, and IS707 in the center of the town of Húsavík as Lateglacial sediments. Although predominant frequencies and their respective amplification vary between sites, all the sites on these sediments are characterized by amplifications of approximately 2 or more in the 1-3 Hz range, with the exception of IS701 as its predominant frequency is approximately 6 Hz with amplification greater than 2. Although all the sites in this part of town are underlain by the same material, the varying thicknesses of the sedimentary layers could explain the slight difference in predominant frequencies, and the Grjothals lava rock laying beneath the sedimentary layers serve to somewhat clarify the fluctuation between their respective amplification. In addition to these stations, IS702, southwest of the center of town, is underlain by hyaloclastites (Waltl 2013) and is characterized by two slight amplified peaks at approximately 1 Hz and 10 Hz. The intertwining sedimentary layers of varying thicknesses within the lava rock can serve as an explanation for the slight amplification, whereas the multiple peaks can be interpreted as a characteristic of a more complex sub-surface model, as was observed in Sivaram et al. (2012) where one layer corresponds to the first peak and another shallow layer beneath the surface corresponding to the second peak.

In Figure 3, results are shown for the HVSR method applied to earthquake events recorded by the seven ICEARRAY II strong motion stations. Similar to ambient noise data, the HVSRs from earthquake recordings reflect the influence of the geological profiles beneath each of the respective sites. The sites on Tillite rock, IS202 and IS704, northwest of the center of town, show little to no amplification across a range of frequencies, except for IS704, which shows amplification at high frequencies as a result topographical effects. Stations IS701, IS703, IS705, and IS707, on lateglacial sediments, at the center of town, show amplification in the 2-4 Hz range, with the exception of IS705, which is characterized by a second peak at 6 Hz. Southwest of the center of town, IS702 is underlain by hyaloclastites. And, as was the case when interpreting the HVSRs from ambient noise data, the hyaloclastites and intertwining sediments serve to explain amplification at the site.

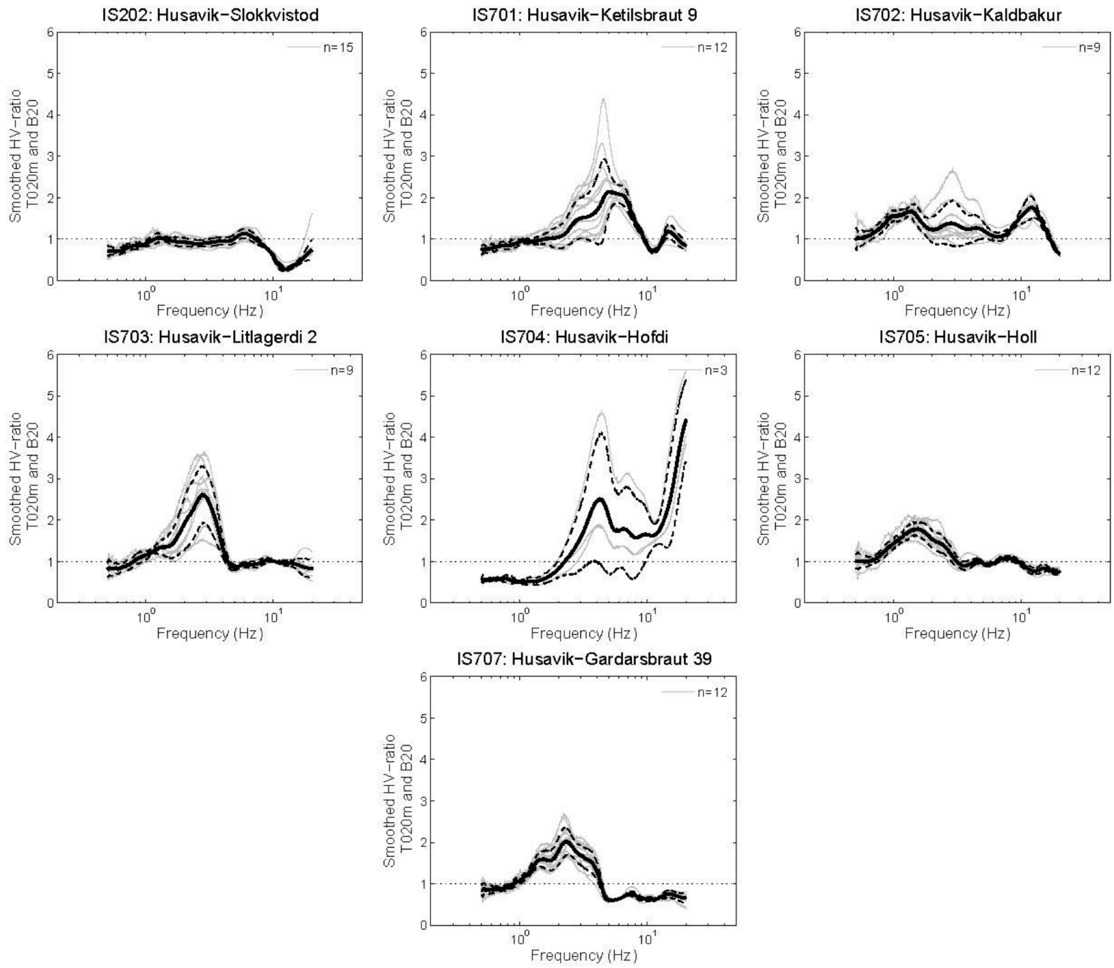

Figure 2: Mean HVSR +/- one standard deviation form ambient noise measurements with a Konno and Ohmachi smoothing coefficient, B=20 where n is the number of available 20-min ambient noise windows used to derive the mean HVSR for each of the seven ICEARRAY II strong motion stations in Húsavík, north Iceland.

DISCUSSION

As a result of the consistency in the HVSRs computed for the sites using ambient noise (Figure 2) and multiple earthquake strong ground motions (Figure 3), and the relationship between the HVSRs and the sites' geological and topographical characteristics, the following trends in dynamic site response are expected:

(1) Sites that have a pronounced peak in their HVSRs are anticipated to amplify ground motions in the frequency range around that of the peak.

(2) Sites that have relatively flat HVSRs are anticipated to amplify motions uniformly across a wide range of frequencies. Furthermore, in cases where the HVSRs are relatively flat and have an amplitude of approximately one, characteristic of stiff sediment/hard rock sites, no significant ground amplification is expected.

(3) Sites that have HVSRs with broad or multiple peaks are characteristic of a more complex geologic profile. As was observed by Sivaram et al. (2012), such HVSRs could imply sub-

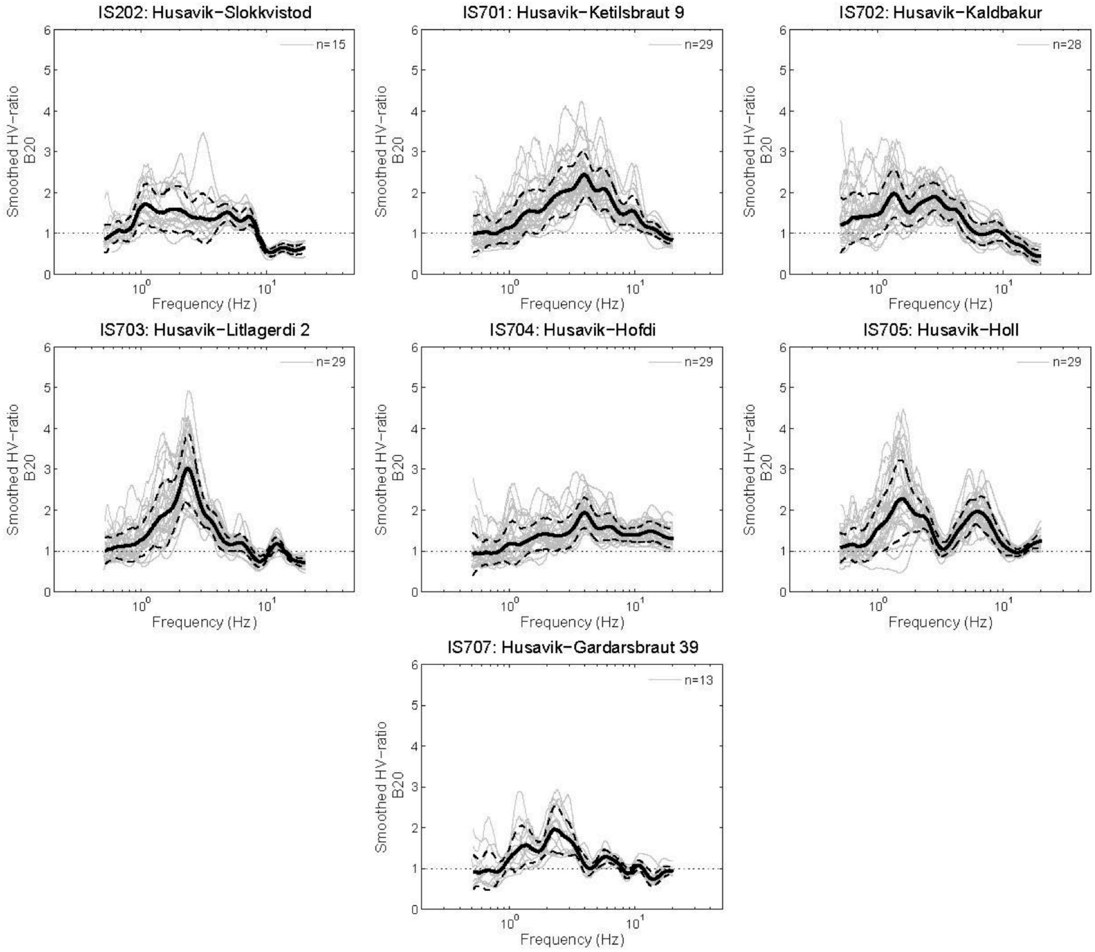

Figure 3: Mean HVSR +/- one standard deviation from earthquake recordings with a Konno and Ohmachi smoothing coefficient, B=20 where n is the number of available earthquake events used to derive the mean HVSR for each of the seven ICEARRAY II strong motion stations in Húsavík, north Iceland.

surface topography with two horizontal layers, where the deeper layer results in the lower frequency peak and the shallow layer results in the higher frequency peak.

As a result of little to no studies on the sub-surface conditions in the TFZ, there in a general lack of understanding of the dynamic response characteristics of this region. However, to help fill this knowledge gap, the HVSRs computed herein and the relationship between the computed HVSRs and the geological and topographical characteristics of the sites provide insights about the expected dynamic site response characteristics of Húsavík. .

This study has also served to provide significant information regarding the application of the HVSR method using earthquake recordings. Despite the earthquake motions originating from different sources (i.e. different epicenters, depths, etc.), the HVSRs computed using the strong motion data (Figure 3) were consistent for each of the seven strong motion station sites. This consistency shows that the HVSR method can be used with earthquake recordings, in addition to ambient noise data, to provide insights into dynamic site characteristics. Furthermore, the comparison between HVSRs computed using ambient noise data and earthquake recordings are generally consistent..

CONCLUSIONS

In the absence of well-studied site response in the town of Húsavík, north Iceland, this study provides new and valuable information from HVSRs computed using long duration ambient noise data and earthquake recordings. The stability of the estimated predominant frequencies and the consistency of the shapes of the HVSRs for each site using both datasets, give credence to the use of the method for estimating local site effects. In particular, the method shows potential for estimating the fundamental frequency of the geologic profiles (which is the frequency at which maximum amplification occurs). However, further research could help verify the validity and usefulness of the HVSR method for use in seismic risk analyses, specifically comparing the method to results from numerical analyses using detailed geotechnical data and to other experimental techniques such as the SSR. Nevertheless, the results from the HVSRs from ambient noise and strong motion data recorded in Húsavík provides the first estimates of the dynamic site response characteristics across the town, which is a prerequisite for its detailed earthquake hazard and risk analyses.

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