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Influence of gravel fill on the seismic response characteristics of sites in Iceland

Influence du remblai de gravier sur les caractéristiques de réponse sismique de sites en Islande

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ABSTRACT: Local geological, geotechnical and/or man-made site conditions can greatly increase the intensity and character of earthquake shaking and thus the extent and type of structural damage. Given the unique geologic/geotechnical conditions in Iceland and foundation construction methods, it is questionable whether the generic building code seismic site response coefficients apply. For example, man-made geotechnical foundations for buildings in the form of engineered fills made of compacted volcanic rock conglomerate has become prevalent in engineering practice in Iceland over the last decades. To gain insights into effects engineered fills have on seismic site response characteristics, horizontal-to-vertical spectral ratios (HVSR) are computed from microtremor measurements for a site in Kópavogur, Iceland, made at varying times during excavation and placement of the fill. Comparisons of the HVSR for the reference stratum and the surface of the gravel fill show that fill amplifies motions in the high- and middle-frequency band. Additionally, HVSR for points across the placed fill capture 3-D site effects, with the site's fundamental frequency increasing with fill thickness.

RÉSUMÉ: Les conditions géologiques, géotechniques, locales et/ou artificielles peuvent considérablement augmenter l'intensité et le caractère des secousses sismiques et donc l'ampleur et le type des dommages structurels. Compte tenu des conditions géologiques et géotechniques uniques en Islande ainsi que des méthodes de construction des fondations, il est crucial de savoir si les coefficients tirés du code générique pour les bâtiments s'appliquent à la réponse du site sismique. Pour mieux comprendre les effets des remblais artificiels sur les caractéristiques de réponse du site sismique, les rapports spectraux H/V sont calculés à partir de mesures de microséismes pour un site á Kópavogur, en Islande, effectuées à des instants variables pendant l'excavation et le placement du remblai. Les comparaisons des rapports spectraux H/V pour la strate de référence et la surface du remblai en gravier montrent que le remplissage amplifie les mouvements dans les bandes de fréquences aiguës et moyennes. De plus, les rapports spectraux H/V pour les points situés à travers le remblai capturent les effets tridimensionnels, tandis que la fréquence fondamentale du site augmente avec l'épaisseur du remplissage.

Keywords: seismic site effects; site response coefficients; HVSR; engineered fill, Iceland

1 INTRODUCTION

Worldwide, earthquakes pose a great risk to the built environment and to human safety. Moreover, historical accounts have shown that cities that have been exposed to multiple strong earthquakes over time often have areas where major damage to buildings and loss of life repeatedly tends to concentrate. Over the last few decades, researchers have correlated areas of observed damage concentration to the geological/geotechnical conditions in those areas. The results of these efforts have been adopted by building codes in the form of site response coefficients, which are used to modify the seismic design motions for various site conditions. However, given their unique characteristics, it is doubtful that the building code site response coefficients developed from generic profiles apply to sites of engineered fill in Iceland. Accordingly, the objective of the study presented herein is to gain insights into the seismic site response characteristics of engineered fills at building sites in Iceland.

To achieve the study objective, horizontal-to-vertical component spectral ratios are computed from microtremor measurements for a fill site in Iceland. The horizontal-to-vertical spectral ratio (HVSR) method (Nakamura 1989) is based on using time recordings of ambient vibrations (or microtremors) in the horizontal (H) and vertical (V) directions and calculating the amplitude of their ratio as a function of frequency. The HVSR calculated from microtremors provide valuable information regarding the site's fundamental frequency and amplification effects (e.g., Olivera et al. 2014). Furthermore, Halldórsson et al. (2016) and Rahpeyma et al. (2016) have found good agreement between HVSR derived from microtremors and from strong-motions in Iceland, implying that insights derived about site response characteristics from microtremors also apply to site effects during stronger, earthquake shaking. The HVSR method has several advantages over alternative approaches, but its greatest strength is that it is relatively inexpensive and an easy method for obtaining information needed in seismic hazard and risk analyses.

In the following, first, the fill study site is briefly discussed followed by a discussion of the microtremor recordings and analysis. The results are then presented and discussed.

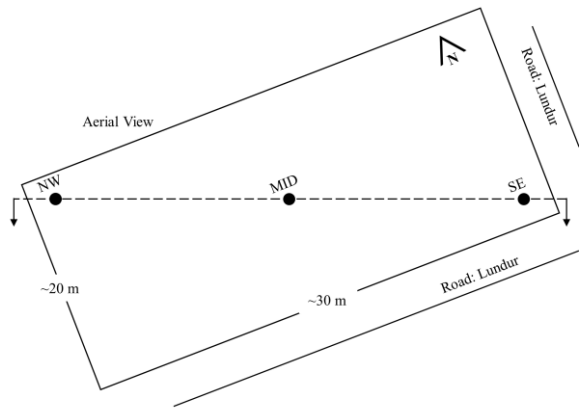
2 FILL SITE

The removal and replacement method is one of the oldest, and conceptually the simplest approaches to improve site properties for static loading (e.g., reduce settlement and increase bearing capacity) and, in addition, for leveling the site. The method involves the removal of in-situ soils and replacement with a stronger soil, such as gravel or sand. Gravel manufactured in Iceland from volcanic conglomerate is often compacted in ≤ 70 cm thick lifts to ensure uniform compaction throughout the fill.

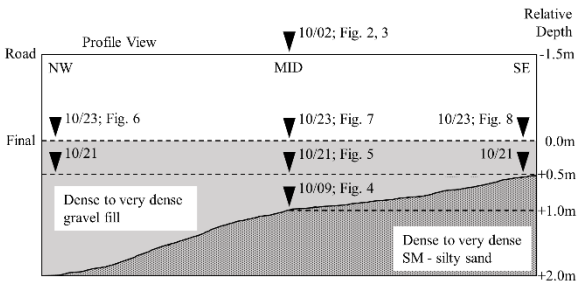
The fill site examined in this study is in an apartment complex in Kópavogur, Iceland. Kópavogur is Iceland's second largest municipality by population and lies immediately south of Reykjavík. The apartment complex has structures ranging from three to ten stories and new buildings are being constructed in the eastern and western sections of the complex. The coordinates for the site are 64º 06' 57" N, 21º 53' 26" W.

The contractor excavated the in-situ soft marine sedimentary soils down a dense to very dense silty sand stratum. This stratum was used as the reference stratum in this study, and the gravel fill was placed on this stratum and compacted in lifts. The contractor used a Volvo SD135B vibro-roller to compact the gravel fill. The machine travels at ~2.5 km/h when compacting gravel and weighs 12,728 kg (~28,000 lb). The operator can change the amplitude and frequency at which the roller vibrates; a high amplitude mode with 26 Hz is used for the first pass and a low amplitude mode with 27 Hz for subsequent passes. The gravel fill was compacted to 60-65% relative compaction, with the compaction being monitored in real-time by the vibro-roller.

Figure 1 shows aerial- and profile-view sketches of the site. As may be observed from this figure, the site's dense reference stratum varies in elevation. Accordingly, the gravel fill varies in thickness, being the thinnest in the SE corner of the site (~0.5 m thick) and the thickest in the NW corner (~2.0 m thick). The compacted fill will serve as the foundation subgrade for a new apartment building.



(a)



(b)

Figure 1. Aerial-view (a) and profile-view (b) sketches of the fill study site in Kópavogur, Iceland. The black triangles in (b) are the approximate locations of the stations relative to the final fill height; start-date of recording and figure number is shown adjacently.

3 MICROTREMOR MEASUREMENTS

Microtremor measurements were made on four occasions during the excavation of the in-situ soil and compaction of the fill: (1) 10/02 before excavation; (2) 10/09 after excavation down to the reference stratum; (3) 10/21 after placement and compaction of the second-to-last gravel lift; and (4) 10/23 after placement and compaction of the last gravel lift (i.e., after site was brought to its final elevation). Figure 1 shows the dates when microtremor recordings were performed and the approximate seismometer locations relative to the final gravel fill height. As shown in this figure, the recording stations were set up collinearly on 10/21 and 10/23 to measure the effect that the variation of the fill thickness across the site had on site response.

The microtremor recordings were performed overnight using tridirectional Lennartz LE-3D/5s seismometers and REF TEK 130-01 broadband seismic data acquisition systems. Each axis had the same set parameters. The sensor was collecting data at a rate of 100 Hz with high gain. The seismometers were placed level atop the surface of interest and, to minimize the influence of wind gusts, covered with nearby shoveled soil.

Velocity spikes were filtered from raw data to eliminate irregular excitations. Prior to computing the HVSR, the horizontal and vertical components were smoothed using the Konno and Ohmachi (1998) smoothing function with a smoothing coefficient of 20. The recordings were split into ~60-minute time windows, delineated by each hour.

All ~60-minute time windows were further split into three equal ~20-minute segments to determine the stability of the HVSR curve for each hour (Olivera et al. 2014). The average HVSR of the three segments and the standard deviation were compared to the HVSR computed over the ~60-minute time window. A case with an overall low standard deviation was considered to be stable and used as the representative HVSR curve for that respective site condition and location. Stable HVSR were mostly obtained during times

when transient noise was low and regular (e.g. during the night time). This process is illustrated in Figures 2 and 3. Figure 2 shows the separate HVSR curves for all ~60-minute time windows for the microtremor data recorded at the center of the site (MID), prior to excavation. Figure 3 shows the representative HVSR curve for the same location and site condition, selected due to the coincidence of the HVSR curve for the ~60-minute time window and the average of the three HVSR curves for ~20-minute time windows, and the low standard deviation of the HVSR curves for ~20-minute time windows.

4 RESULTS AND DISCUSSION

Figures 3 and 4 show the representative HVSR curves at the MID location before excavation of the site (in-situ condition) and after excavation down to the dense reference stratum (reference condition), respectively. There is a noticeable decrease in HVSR amplitude after the in-situ soil was removed. However, the fundamental frequency of the site (~13 Hz) did not change due to the excavation, despite the amplitude differences in the HVSR curves.

Figures 5 and 7 show the HVSR curves at MID for a fill thickness of ~0.5 m and ~1 m, respectively. As may be observed from these figures, the placement of the fill resulted in an amplification of ~2.5 times in the HVSR curves, relative to the reference site conditions (Figure 4), in the middle- and high-frequency band.

For the final site conditions (i.e., compacted fill at the final elevation across the site), the fundamental frequency varies across the site, due to differences in the thickness of the fill. Three stations were set up collinearly to identify the influence of the difference in fill thicknesses. Figures 6, 7, and 8 show HVSR curves for the deep (NW corner of the site: ~2 m), intermediate (MID: ~1 m), and shallow (SE corner: ~0.5 m) fill thicknesses, respectively. There are marked differences in these HVSR curves.

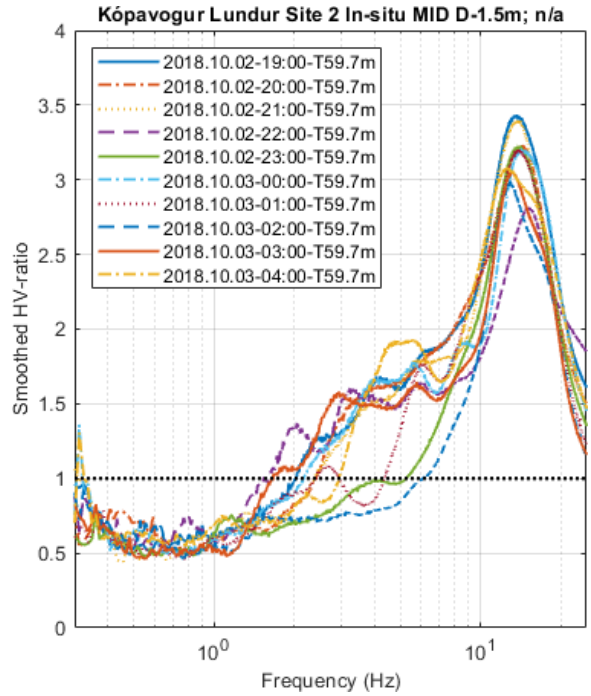


Figure 2. HVSR curves for MID before excavation for all ~60-minute intervals. Relative depth -1.5 m.

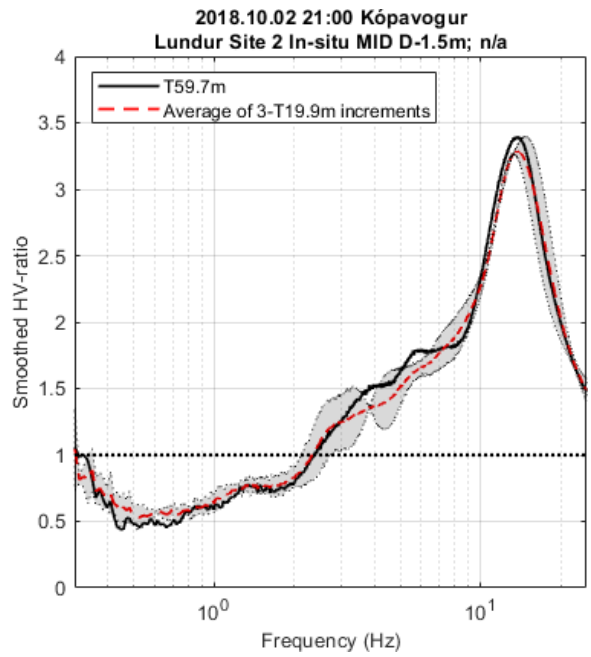


Figure 3. Representative HVSR curve for a ~60-minute interval for MID and the average of three ~20-minute segments. The shaded region represents ± one standard deviation of average.

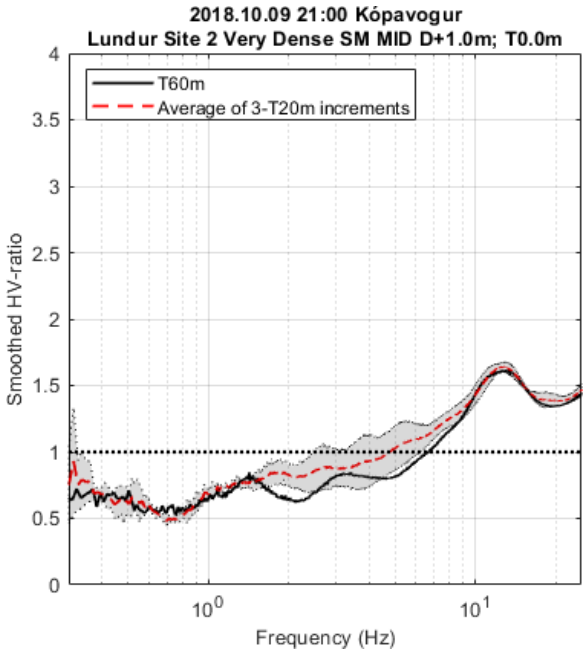


Figure 4. Representative reference HVSR curve for a ~60-minute interval for MID and the average of three ~20-minute segments. The shaded region shows ± one standard deviation of average.

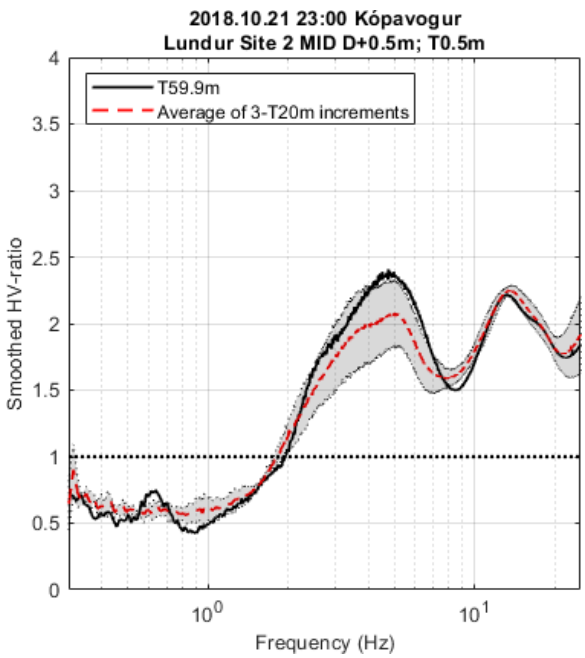


Figure 5. Representative HVSR curve for a ~60-minute interval for MID and the average of three ~20-minute segments. The shaded region shows ± one standard deviation of average.

The deep condition resulted in a peak HVSR in the high-frequency band at ~15 Hz, which is comparable to the in-situ and reference conditions. However, the location with the shallow and intermediate fill thicknesses have similar fundamental frequencies of ~4 to 5 Hz. Whereas the amplitude of the H/V ratio changes from 2 at 0.5 m thickness to 5 at 2 m thickness. This implies that 3-D effects will potentially influence the site response of the site during future earthquakes.

5 CONCLUSION

The purpose of this study was to gain insights into the effects of engineered fills on seismic site response characteristics of building foundations in Iceland. Towards this end, horizontal-to-vertical spectral ratios were computed from microtremor recordings performed at a study fill site in Kópavogur, Iceland, where the microtremor data was recorded on-site at varying times during excavation and placement of the fill. Changes in the HVSR were observed as a result of constructing the fill, especially in the middle- and high-frequency parts of the frequency range covered (0.3-25 Hz). The results indicate that the engineered fill has a marked HVSR signature that is different in amplitude and frequency content compared to the dense silty sand reference condition, and it becomes more pronounced with increasing fill thickness. Namely, the amplitudes of the horizontal component of motion increase relative to the vertical component in a relatively narrow frequency range around a specific predominant frequency. Stations set up in a collinear fashion show the same signature around the same predominant frequency, except the amplitude is shown to be dependent on fill thickness. Additional case studies involving compacted gravel fill with different thicknesses and geometries, and on different reference strata, are required to draw more evident observational trends (these are currently in progress), followed by numerical modeling of fill response including the buildings it will support.

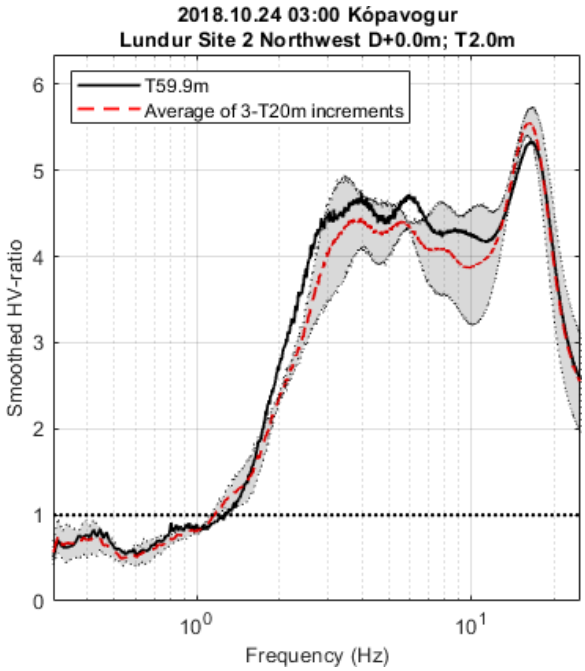


Figure 6. HVSR for the NW (deep) location and the average of three ~20-minute segments. The shaded region represents ± one std. deviation of average.

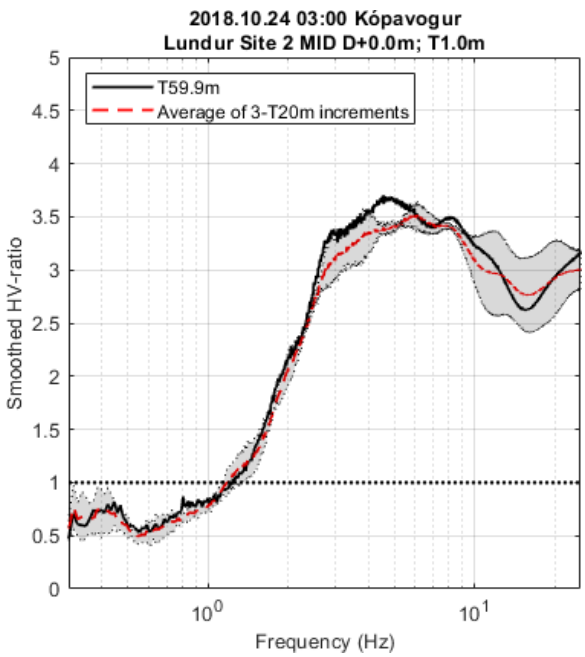


Figure 7. HVSR for the MID (intermediate) location and the average of three ~20-minute segments. The shaded region represents ± one std. deviation of average.

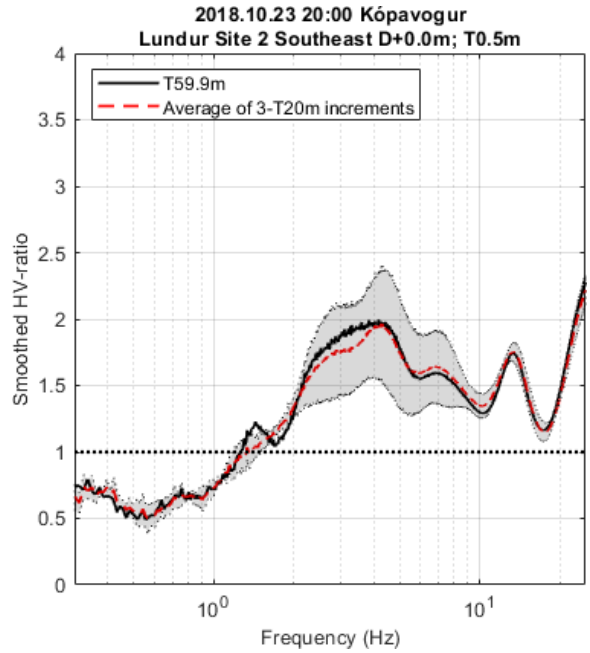


Figure 8. HVSR for the SE (shallow) location and the average of three ~20-minute segments. The shaded region represents ± one std. deviation of average.

6 ACKNOWLEDGMENTS

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