Site Response Characteristics of Compacted Gravel Fill in Iceland

Thomas John Kennedy

Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

Master of Science
in
Civil Engineering

Russell A. Green
Adrian Rodriguez-Marek
Martin Chapman

May 15, 2019
Blacksburg, Virginia

Keywords: H/V Spectral Ratio, Site Effects, Site Response Characteristics, Microtremor, Iceland
Copyright© 2019, Thomas John Kennedy
ALL RIGHTS RESERVED

Site Response Characteristics of Compacted Gravel Fill in Iceland

Thomas John Kennedy

ABSTRACT

Local site conditions can greatly increase the intensity and character of earthquake shaking and, thus, the extent and type of structural damage. The removal and replacement of in-situ soils with compacted gravel-sized volcanic rock has been prevalent in the Icelandic foundation subgrade construction practice for decades, despite the unknown seismic site response characteristics of the fill (e.g., the predominant frequency and relative site amplification). To fill this knowledge gap, over 500 hours of microtremor measurements were made at six study sites located throughout the Reykjavík, Iceland, capital region. Measurements recorded at various construction stages (e.g., the in-situ or pre-excavation, post-excavation, intermediate grades, and final grade) reveal the change in site response characteristics before and after gravel fill placement. The data was analyzed using the horizontal-to-vertical spectral ratio (HVSR) technique over a bandwidth of 0.3 to 25 Hz. Generally, the pre-excavation condition had a predominant site frequency between 3.5 and 7 Hz with relative amplification between 3.8 and 3.9 times. The placement of gravel fill atop dense to very dense silty sand underlain by bedrock shifts the predominant frequency between 10 and 16 Hz with a relative peak amplification between 2.5 and 5.3 times, generally increasing with fill thickness. Fill underlain by undulating lava rock also results in a higher a predominant frequency between 9 and 10.5 Hz, but little change in relative site amplification occurred at these frequencies (between 0.95 and 1.2 times). This dissimilarity is due to the unique lava rock HVSR signatures which have large amplification values (between 2.6 to 3.9 times) throughout the high-band frequency range. Additional investigations of sites underlain by lava rock are required to draw stronger empirical trends. The data set produced by this study can serve as a useful tool for the local geotechnical and seismological communities to mitigate seismic risk for the capital region.

Site Response Characteristics of Compacted Gravel Fill in Iceland

Thomas John Kennedy

GENERAL AUDIENCE ABSTRACT

Problematic soil conditions can greatly increase the intensity and character of earthquake shaking and, thus, the extent and type of building damage. The removal of native soils and replacement with compacted gravel-sized fill has been the predominant building foundation subgrade construction method in Iceland for decades. The practice of removal and replacement is one of the oldest and conceptually simplest approaches of site improvement to reduce settlement and increase soil strength. However, the understanding of how compacted gravel fill responds to earthquake shaking was nonexistent in literature. To fill this knowledge gap, the response characteristics of compacted gravel fill were derived using the horizontal-to-vertical spectral ratio (HVSR) and standard spectral ratio (SSR) analysis techniques from a data set of over 500 hours of experimental in-field measurements. Measurements were recorded at various construction stages (e.g., pre-excavation or native soil, post-excavation, intermediate fill grades, and the final fill grade) to reveal the change in site response characteristics before and after gravel fill placement. The findings presented in this thesis can serve as useful information for the local geotechnical and seismological communities to mitigate seismic risk (e.g., the probability of building damage and/or loss of lives) of structures with compacted gravel fill subgrades in the Reykjavík, Iceland capital region.

Acknowledgments

A special thanks to the country of Iceland,
A very special place.

There are many people who I would like to thank that contributed in part to the successful competition of this thesis. However, first and foremost, I must express my boundless gratitude to Professors Russell A. Green and Benedikt Halldórsson for their indefatigable support and mentorship throughout my graduate studies. I place them both in high regard for their strong work ethic and ability to communicate effectively. Thank you for entrusting in me a unique opportunity to pursue a topic of international research in which I have a deep appreciation.

The work presented herein was based on an international research proposal written by Professors Green and Halldórsson and would not have been possible without the financial support of a graduate research fellowship awarded by the Leifur Eiríksson Foundation. I would like to acknowledge Professors Green, Adrian Rodriguez-Marek, and Ryan Kent Giles for their letters of recommendation during the application process – it was their support that endorsed this scholarly endeavor.

I would also like to thank Professors Green, Halldórsson, Rodriguez-Marek, and Chapman for their service as my thesis committee chairs/members. Professor Jónas Þór Snæbjörnsson of Reykjavík University and Dr. Saharalsadat Rahpeyma are also acknowledged for their support provided throughout this study.

Special thanks must be sent to the construction workers and supervisors that were responsible for the construction of all compacted gravel fill investigated. Specifically, Atli Gunnarsson and Guðjón Þór Ólafsson from the BYGG company and Guðmundur B Gunnarsson, Arnar Ármannsson, and Ágúst Sigurjónsson from the Jáverk company – your hard work and collaboration were essential to this study. Last but not least, Elli Alexandersson of the Alexander Ólafsson company is thanked for his time spent touring the Vatnskarðsnáma Quarry and for his wealth of knowledge regarding the manufacturing process of volcanic conglomerate rock.

Table of Contents

Chapter 1: Introduction 1

1.1. Thesis Objective 1
1.2. Organization 1
1.3. Attribution 2

Chapter 2: Site Response Characteristics of Compacted Gravel Fill in Iceland 3

2.1. Abstract 3
2.2. Introduction 3
2.3. Background 4

2.3.1. Estimating Site Effects 4
2.3.2. Gravel Fill 6

2.4. Approach 12

2.4.1. Site Locations and Stratigraphy 12
2.4.2. Data Collection and Analysis 21

2.5. Results and Discussion 26

2.5.1. Lundur Sites 1 and 2 (Events #1, 2, 3, 5, 6, 7, 8, 12, 15, 18, and 19) 26
2.5.2. The Nauthólsvegur 83 Site (Events #4, 9, 10, and 11) 30
2.5.3. Stuðlaskarð Sites 1 and 2 (Events #13, 14, 16, 20, 21, 22, and 23) 32
2.5.4. The Breidholt Site (Event #17) 34
2.5.5. Summary of Site Response Characteristics of Compacted Gravel Fill 35
2.5.6. Problematic Recording Conditions 36

2.6. Conclusion 41
2.7. References 42

Chapter 3: Thesis Conclusions 45

3.1. Summary and Conclusion 45
3.2. Recommendations for Future Work 46

Appendix A: The Influence of Gravel Fill on the Seismic Response Characteristics in Iceland 47

A.1. Abstract 47
A.2. Introduction 47
A.3. Fill Site 48
A.4. Microtremor Measurements 49
A.5. Results and Discussion 53
A.6. Conclusion 58
A.7. Acknowledgments 59
A.8. References 59

Appendix B: Additional Information Regarding the Vatnskarðsnáma Quarry 60
Appendix C: Additional Site Photographs 64

C.1. Lundur Sites 1 and 2 Located in Kópovogur 65
C.2. The Nauthólsvegur 83 Site Located in Reykjavík 67
C.3. Stuðlaskarð Sites 1 and 2 Located in Hafnarfjörður 69
C.4. The Breidholt Site Located in Reykjavík 73

List of Tables

Table 2.1. Site List and Event Recordings 22
Table 2.2. Summary of Site Response Characteristics 35

List of Figures

Figure 2.1. Microtremor velocity data of three components (two horizontal, x and y, and one vertical, z) taken atop a dense silty sand stratum at Lundur Site 1 in Kópavogur. 5
Figure 2.2. Panoramic view of the Vatnskarðsnáma Quarry. The flat terraces along the side of the mountain serve as areas from which volcanic conglomerate rock is mined. 8
Figure 2.3. The base of the mountain at Vatnskarðsnáma where mined gravel is collected. 8
Figure 2.4. Photographs showing gravel before (a, b) and after (c) compaction. 9
Figure 2.5. Compaction process for gravel fill in Iceland: dumping (a), spreading (b), and compacting (c) at Lundur Site 1 in Kópavogur. 11
Figure 2.6. The Volvo SD135B vibratory roller (a) used for gravel compaction and the real-time monitor (b) to measure relative density. 12
Figure 2.7. Map of the capital region of Iceland and relative locations of all sites encountered during the study, indicated by triangle markers. 13
Figure 2.8. Aerial and profile view of Lundur Site 1 in Kópavogur. Not drawn to scale. 15
Figure 2.9. Aerial and profile view of Lundur Site 2 in Kópavogur. Not drawn to scale. 16
Figure 2.10. Photograph of the dense SM – silty sand base layer at Lundur Site 1 in Kópavogur. 17
Figure 2.11. The particle-size distribution curve of a soil sample taken from the competent stratum on which the gravel fill was placed at Lundur Site 1 in Kópavogur. 17
Figure 2.12. Soil particles greater than 1 mm diameter (a) and soil retained on the #35 sieve (0.5 mm) that passed the #18 sieve (1 mm) (b). 17
Figure 2.13. Aerial view of the Nauthólsvegur 83 Site in Reykjavík. The proposed building footprint is outlined. Not drawn to scale. 18
Figure 2.14. Profile views of the Nauthólsvegur 83 Site in Reykjavík. Not drawn to scale. 19
Figure 2.15. Aerial and profile view of Stuðlaskarð Site 1 in Hafnarfjörður. Not drawn to scale. 20
Figure 2.16. Aerial and profile view of Stuðlaskarð Site 2 in Hafnarfjörður. Not drawn to scale. 21
Figure 2.17. Seismometer set-up before (a) and after (b) covering with nearby soil at Lundur Site 1 in Kópavogur. Note that the rock used to secure the cable was not in contact with the seismometer. 24
Figure 2.18. HVSR curves for MID at Lundur Site 2 before excavation (relative depth -1.5 m) for: (a) all ~60-minute intervals; and (b) the average of three ~20-minute segments with a shaded region representing ± one standard deviation of average. 25
Figure 2.19. Comparison of SSR (top) and HVSR (bottom) signatures for two locations atop gravel fill at Lundur Site 1 in Kópavogur. 28
Figure 2.20. Comparison of HVSR signatures for the in-situ (top-left), post-excavation dense to very dense silty sand reference (top-right), and the final gravel grade (bottom) for Site 2 at Lundur in Kópavogur. Note that for the in-situ condition, the seismometer was set up atop a thin layer (< 0.3 m) of compacted gravel underlain by in-situ soils. The gravel served as a temporary parking lot and, as a result, direct contact with the in-situ soil was not available. 29
Figure 2.21. Comparison of HVSR signatures for the in-situ soil (top-left), a nearby rock outcrop (top-right), and the final gravel grade (bottom) for the Nauthólsvegur 83 Site in Reykjavík. 31
Figure 2.22. Comparison of HVSR signatures taken post-excavation atop lava rock (left) and gravel fill (right) for two sites at Stuðlaskarð in Hafnarfjörður. 33
Figure 2.23. HVSR signature of the pre-excavation in-situ soil condition at Breidholt in Reykjavík. 34
Figure 2.24. The influence of the average and gust wind speed on HVSR signatures simultaneously recorded atop: (a) a rock outcrop, and (b) compacted gravel fill of three-meter thickness. 37
Figure 2.25. Poor surface conditions for Event #4 “base layer reference condition” recorded at the Nauthólsvegur 83 Site in Reykjavík. Seismometer location is highlighted by a red circle. 38
Figure 2.26. The influence of poor (a) and good (b) soil-sensor coupling on HVSR signatures. Measurements were taken atop a dense to very dense silty sand (SM) reference stratum. 39

Figure 2.27. The influence of frozen (a, b), thawing (c), and unfrozen (d) compacted gravel fill on HVSR signatures. Note that signatures a, c, and d were taken at the same location atop two-meter thick fill and signature b was taken nearby atop a three and one-half meter thick fill.....40
Figure A.1. Aerial-view and profile-view sketches of the fill study site in Kópavogur, Iceland. The black triangles are the approximate locations of the stations relative to the final fill height; start-date of recording and figure number is shown adjacently. Not drawn to scale.....50
Figure A.2. HVSR curves for MID before excavation for all ~60-minute intervals. Relative depth -1.5 m. 52
Figure A.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. 52
Figure A.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. 54
Figure A.5. 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. 55
Figure A.6. HVSR for the NW (deep) location and the average of three ~20-minute segments. The shaded region represents ± one std. deviation of average. 56
Figure A.7. HVSR for the MID (intermediate) location and the average of three ~20-minute segments. The shaded region represents ± one std. deviation of average. 57
Figure A.8. HVSR for the SE (shallow) location and the average of three ~20-minute segments. The shaded region represents ± one std. deviation of average. 58
Figure B.1. Panoramic view of the Vatnskarðsnáma Quarry. The flat terraces along the side of the mountain serve as areas from which volcanic conglomerate rock is mined.....61
Figure B.2. A 70-ton bulldozer tractor (a) with hook attachment (b) used to rip up the ground and push the resulting material off the mountainside.....62
Figure B.3. A mining terrace at Vatnskarðsnáma Quarry. The striations in the ground (a) are the result of the tractor hook ripping up the volcanic conglomerate rock. The mined rock is pushed off the mountainside (b) to be collected at the base.....63
Figure C.1. Photographs were taken at Lundur Site 1. The dense to very dense silty sand reference stratum (a), compacted gravel fill at an intermediate grade (b) and building foundation (c) are shown.....65
Figure C.2. Photographs were taken at Lundur Site 2. The in-situ condition with a temporary gravel parking lot (a), the dense to very dense silty sand reference stratum (b), and gravel fill at an intermediate grade (c) are shown. 66
Figure C.3. Photographs were taken at Nauthólsvegur 83 site. The Southwest (a) and Northwest (b) sections of the building foundation are shown.....67
Figure C.4. Photographs were taken at Nauthólsvegur 83 site. The positions of the rock outcrop (a, b), Northeast (b), and Northwest (b) seismometer locations are highlighted by circles in (b). Note that the seismometer stationed atop the rock outcrop was covered by nearby soil. 68
Figure C.5. Photographs were taken at Stuðlaskarð Site 1. The positions of West, MID, and East seismometer locations atop lava rock are highlighted by circles. Three lava rock undulations are pronounced.....69
Figure C.6. Photographs were taken at Stuðlaskarð Site 1. A seismometer set up at the West position is shown stationed atop compacted gravel fill at the final grade. 70
Figure C.7. Photographs were taken at Stuðlaskarð Site 2. The positions of West, MID, and East seismometer locations atop lava rock are highlighted by circles. Lava rock undulations are pronounced.....71
Figure C.8. The photograph was taken at Stuðlaskarð Site 2. The positions of West and East seismometer locations stationed atop compacted gravel fill at the final grade are highlighted by circles. 72
Figure C.9. Photographs were taken at Breidholt. A panoramic view of the site (a), the surface condition where the seismometer was in contact with the in-situ soils during measurements (b), and covered seismometer (c) are shown.....73

Chapter 1: Introduction

1.1. Thesis Objective

The primary objective of this thesis is to provide insights about the dynamic site response characteristics of compacted gravel fill in Iceland using the horizontal-to-vertical spectral ratio (HVSR) technique, a non-invasive surface wave method. Seismic hazard and risk analyses are based on the extent of and frequencies at which the geologic and geotechnical site conditions affect bedrock earthquake motions. The effect of local site conditions on bedrock ground motion characteristics are termed "site effects" and are quantified by site response characteristics (e.g., the predominant site frequency, the intensity of site amplification, etc.). Over 500 hours of microtremor measurements were recorded at six study sites located throughout the capital region of Iceland during various stages of gravel fill placement (e.g., the in-situ condition or pre-excavation, post-excavation, intermediate grades, and the finished grade). Each site presented unique stratigraphy and site conditions. As a result, the site response characteristics of multiple conditions are included herein.

This effort marks the beginning of microtremor microzonation mapping throughout the capital region of Iceland. A good agreement between HVSR from strong motions and microtremors has been established for Icelandic sites, implying that site response characteristics derived herein apply to stronger earthquake motions (Rahpeyma et al. 2016). Thus, microtremor analysis is an efficient and cost-effective way to map resonance frequencies and relative site amplification magnitudes in Iceland. A robust database of this kind will serve as a useful tool for urban planners and the local geotechnical and seismological communities to mitigate seismic risk for the capital region.

1.2. Organization

The thesis is organized in the following manner to achieve the primary objective stated above. *Chapter 2* presents a manuscript detailing typical site response characteristics of compacted gravel fill in Iceland. *Chapter 3* provides concluding remarks and offers recommendations for future work. Finally, three *Appendices* offer supplemental information: *A*) a manuscript wherein a single case study highlights 3-D site effects; *B*) a detailed account of Vatnskarðsnáma (a quarry from which most gravel in Iceland is sourced); and *C*) additional site photographs.

1.3. Attribution

This thesis contains two manuscripts. The first manuscript titled "Site Response Characteristics of Compacted Gravel Fill in Iceland" is located within *Chapter 2* and serves as the body of the thesis wherein a detailed account of the project is disclosed. The second manuscript titled "Influence of Gravel Fill on the Seismic Response Characteristics of Sites in Iceland" is located within *Appendix A* and was accepted for inclusion in the proceedings of the 17th European Conference on Soil Mechanics and Geotechnical Engineering (XVII ECSMGE). Manuscript 2 is located within the *Appendix* because its main findings were included in the body of this thesis. The co-authors and their contributions are listed below.

Benedikt Halldórsson, Ph.D., Research Professor at the Faculty of Civil and Environmental Engineering and Director of Research at the Earthquake Engineering Research Centre, University of Iceland, and Earthquake Engineering Seismologist, Icelandic Meteorological Office, Reykjavík, Iceland.

- A co-research advisor to the lead author who provided significant oversight and guidance to the thesis. Benedikt Halldórsson served as the main contact between the research team and contracting companies involved. He also provided the fundamental MATLAB scripts that enabled the lead author to process the microtremor data used in this study.

Russell A. Green, Ph.D., Professor at the Department of Civil and Environmental Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, U.S.A.

- A co-research advisor who provided exceptional expertise in all aspects of geotechnical and earthquake engineering. In addition, Russell Green took charge reformatting and structuring the first draft in an organized manner.

Jónas Þór Snæbjörnsson, Ph.D., Professor at the School of Science and Engineering, University of Reykjavík, Reykjavík, Iceland.

- Provided additional expertise related to the site effect conditions in Iceland and general earthquake engineering support.

Chapter 2: Site Response Characteristics of Compacted Gravel Fill in Iceland

2.1. Abstract

Local site conditions can greatly increase the intensity and character of earthquake shaking and, thus, the extent and type of structural damage. The removal and replacement of in-situ soils with compacted gravel-sized volcanic rock has been prevalent in the Icelandic foundation subgrade construction practice for decades, despite the unknown seismic site response characteristics of this fill material (e.g., the predominant frequency and relative site amplification). To fill this knowledge gap, over 500 hours of microtremor measurements were recorded at six study sites located throughout the Reykjavík, Iceland, capital region. Measurements recorded at various stages of site work (e.g., the in-situ or pre-excavation, post-excavation, intermediate grades, and final grade) reveal the change in site response characteristics before and after gravel fill placement. The data were analyzed using the horizontal-to-vertical spectral ratio (HVSR) technique over a bandwidth of 0.3 to 25 Hz. Generally, the pre-excavation condition had a predominant site frequency between 3.5 and 7 Hz with relative amplification between 3.8 and 3.9 times. The placement of gravel fill atop dense to very dense silty sand underlain by bedrock shifts the predominant frequency between 10 and 16 Hz and results in a relative peak amplification between 2.5 and 5.3 times, generally increasing with fill thickness. Compacted gravel fill underlain by undulating lava rock also results in a higher predominant site frequency between 9 and 10.5 Hz but has little effect on relative site amplification at these frequencies (between 0.95 and 1.2 times). This dissimilarity is due to the unique lava rock HVSR signatures having large amplification values throughout the mid- and high-band frequency range (4.1 to 5.7 and 2.6 to 3.9 times, respectively), which are unlike other reference conditions encountered.

2.2. Introduction

Worldwide, earthquakes pose a great risk to the built environment and to human safety. Over the last decades, the degree of building damage during earthquakes has been correlated to the local geological and geotechnical soil conditions (e.g., Seed and Idriss 1971; Seed et al. 1972). Unfavorable site conditions can result in an increased intensity of ground shaking and a higher seismic hazard. The influence of local soil conditions on ground motions are quantified by site response characteristics (e.g., the predominant site frequency, relative amplification magnitudes,

etc.) determined by site investigation analysis techniques, such as the horizontal-to-vertical spectral ratio (HVSR) and the standard spectral ratio (SSR). Accordingly, seismic risk (e.g., the probability of damage and/or loss of lives) can be mitigated to some degree if the influence of the geological and geotechnical site conditions can be quantified and accounted for in the design of infrastructure and/or in urban planning.

In an effort to improve the engineering properties of a site, for both static and dynamic conditions, the removal of in-situ soils and replacement with compacted gravel-sized volcanic conglomerate rock (i.e., the removal and replacement method) has been performed in Iceland for decades as the primary foundation subgrade construction method. This method 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 a site. The method in Iceland involves the removal of in-situ soft marine sedimentary soils down a firm stratum and the replacement of excavated soils with a compacted sand or gravel fill. However, while the site improvement aspects of compacted gravel fill for static loading are well understood, less is known about the dynamic site response characteristics of this fill. Accordingly, the objective of the study presented herein is to provide insights about the typical site response characteristics of compacted gravel fill used in Iceland.

This chapter is organized into three sections, followed by a summary of the conclusions. First, background information is provided about estimating site effects using the SSR and HVSR methods, and about the placement and compaction of fill. This is followed by brief descriptions of the study sites and approach to characterizing their dynamic response characteristics. Finally, the results of the field measurements and data analyses are presented and discussed.

2.3. Background

2.3.1. Estimating Site Effects

One of the most common procedures 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 simultaneously on a soil site and a nearby reference site located on rock (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, i.e. the "H/V Spectral Ratio" (HVSR) method, to estimate site effects was proposed by Nogoshi and Igarashi (1971) and Nakamura (1989, 2000). This method is based on recordings of ambient noise or microtremors as a function of time in the horizontal, H, and vertical, V, directions (e.g., **Figure 2.1**), and calculating their amplitude as a function of frequency via Fourier amplitude spectra (FAS). The ratio of the FAS of the combined microtremor horizontal components and the vertical component produces a curve, as a function of frequency, which allows an understanding of how earthquake motions are amplified/deamplified by the site.

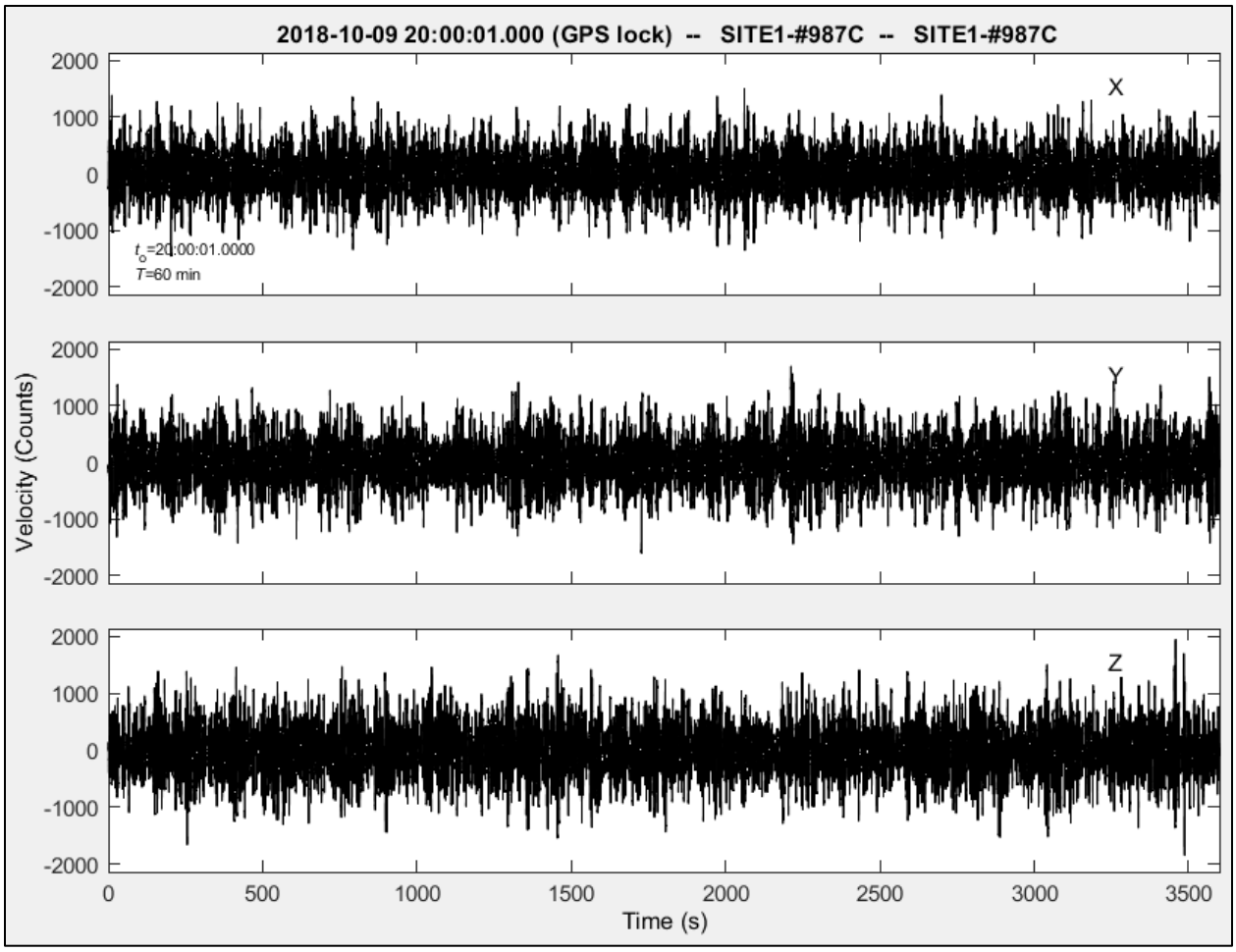

Figure 2.1. Microtremor velocity data of three components (two horizontal, x and y, and one vertical, z) taken atop a dense silty sand stratum at Lundur Site 1 in Kópavogur.

Although the HVSR technique has gained in popularity because it is relatively inexpensive and easy to implement, the validity and underlying basis of the procedure have come into question. Bonnefoy-Claudet et al. (2006b) outline two contradictory propositions that explain the geophysical basis of the technique. First, the "body-wave" interpretation proposed by Nakamura (1989, 2000) considers HVSR as a filtering technique that directly provides the secondary (S) wave transfer function, and thus the peak HVSR corresponds to the S-wave resonance amplitude and frequency. However, others (e.g., Lachet and Bard 1994; Kudo 1995; Fäh et al. 2001) question the efficacy of the technique's ability to estimate site amplification and demonstrate that the peak HVSR can be explained by the ellipticity of fundamental-mode Rayleigh waves. Lermo and Chávez-García (1994) and many others (e.g., Field and Jacob 1993; Lachet and Bard 1994; Tokeshi and Sugimura 1998; Bonnefoy-Claudet et al. 2006a) have shown by numerical simulations that the HVSR can be used to determine the site's predominant frequency, despite providing no clear theoretical background for this.

The study performed by SESAME (2004) revealed that HVSR and SSR techniques provide similar predominant frequencies. However, SESAME (2004) also showed that the HVSR amplitude generally underestimates site amplification, which provides some justification for using the HVSR peak amplitude as a first-order approximation of site amplification. There are many accounts (e.g., Ohmachi et al. 1994; Field et al. 1995; Kudo 1995; Theodulidis and Bard 1995; Lachet et al. 1996; Wakamatsu and Yasui 1996; Bour et al. 1998; Konno and Ohmachi 1998; Mucciarelli 1998; Seht and Wohlenberg 1999; Al Yuncha and Luzón 2000; Maresca et al. 2003; Zhao et al. 2006) that accept the abovementioned tenets of HVSR and have demonstrated that the technique is an effective and affordable method for seismic microzonation.

2.3.2. Gravel Fill

As stated in the *Introduction*, the removal and replacement method is commonly used in Iceland to improve the engineering properties of a site. The method involves the removal of in-situ soils and replacement with a compacted fill composed of gravel and/or sand, much of which originates from Vatnskarðsnáma, a quarry located south of the Reykjavík capital region. **Figure 2.2** shows a panoramic view of the quarry, which began operations in the 1950s and significantly increased production in the early 1980s. Since then, Vatnskarðsnáma has become the largest manufacturer

of sand- and gravel-sized volcanic conglomerate rock in Iceland, with an output of over 800,000 m^3 of aggregate during 2018, with an expected increase of 20% in 2019. The quarry operates year-round, but the highest demand is during September and October.

The material produced at Vatnskarðsnáma has many uses. It is estimated that 50% of the aggregate mined from the quarry is subsequently sorted and shaped (e.g., cubic, spherical, angular, smooth, etc.). Sorted aggregates are used in asphalt or concrete mixtures and as road underlayment. The second half of the mined aggregate is not sorted and is used as fill to support building structures. The mining process begins at the top of the mountain. Fifty- and seventy-ton bulldozer tractors rip up the underlying ground with a large hook and push the resulting material off of the mountainside, as shown in **Figure 2.3**. Drilling and blasting occur in areas with hard rock. It is estimated that the material at this stage ranges between 0 and 300 mm in diameter. It is important to note, therefore, that the aggregate used as gravel fill includes cobble-sized particles. However, the supervisors at each study site discussed herein said their preferred fill is comprised of angular gravel-sized particles. More information about Vatnskarðsnáma and the gravel manufacturing process in Iceland is provided in *Appendix B*.

Figure 2.2. Panoramic view of the Vatnskarðsnáma Quarry. The flat terraces along the side of the mountain serve as areas from which volcanic conglomerate rock is mined.

Figure 2.3. The base of the mountain at Vatnskarðsnáma where mined gravel is collected.

Figure 2.4a shows a load of gravel dumped at one of the study sites and **Figures 2.4b** and **2.4c** show another load of gravel before and after compaction. From these figures, it is clear that some particles are cobble-sized and particle crushing is likely to occur during the compaction process.

Figure 2.4. Photographs showing gravel before (a, b) and after (c) compaction.

Figure 2.5 illustrates the approach commonly used to place and compact fill in Iceland. Contractors excavate in-situ soils, which are typically composed of marine sediments, down to either bedrock, lava rock, or a competent reference stratum (i.e., a firm glacial deposit; jökulaur). The excavation depth ranged between 0.5 to 5 m across sites encountered. The gravel is dumped on the competent stratum by a truck (**Figure 2.5a**), spread by an excavator in ≤ 70 cm thick lifts (**Figure 2.5b**), and then compacted by a vibro-roller (**Figure 2.5c**). Because at most sites, the base layer is not level, fill with varying thickness is required to level the site at the desired elevation.

These cases allowed the effect of fill thickness to be assessed by placing seismometers collinearly along the fill surface.

At the study sites discussed herein, the fill thicknesses ranged between 0.5 to 4 m across sites. The gravel fill was compacted using a Volvo SD135B vibro-roller (or equivalent) that travels at ~2.5 km/h and weighs 12,600 kg (~27,750 lb). For this model, the operator can change the amplitude and frequency at which the roller vibrates; a high amplitude mode (1.87 mm) at 33.8 Hz is used for the first pass and a low amplitude mode (1.38 mm) at 30.8 Hz for subsequent passes. The author estimates that each site was compacted to 60-65% relative density, with the density estimated by the vibro-roller's built-in continuous compaction control system (i.e., Compactometer®). The continuous compaction control system estimates the underlying material density in real-time by correlating the ratio of the measured vertical drum acceleration amplitude at the fundamental and first harmonic frequencies to the underlying soil stiffness (Adam and Pistrol 2016). **Figure 2.6** shows the vibro-roller used at two of the study sites (i.e., at Lundur and Stuðlaskarð) and the monitor that displays the estimated relative density and the frequency and amplitude of vibration.

Figure 2.5. Compaction process for gravel fill in Iceland: dumping (a), spreading (b), and compacting (c) at Lundur Site 1 in Kópavogur.

Figure 2.6. The Volvo SD135B vibratory roller (a) used for gravel compaction and the real-time monitor (b) to measure relative density.

2.4. Approach

2.4.1. Site Locations and Stratigraphy

Six sites located throughout the Reykjavík capital region in Southwest Iceland were studied during this project. Most of the sites are being developed to support multiple-story residential or dormitory buildings. The relative locations of sites are indicated by triangle markers in **Figure 2.7**. At the time of the investigation, numerous buildings were being constructed throughout the area, most atop compacted gravel fill, similar to the six study sites. From north to south, the study sites encountered were: the Nauthólsvegur 83 Site located in Reykjavík; Lundur Sites 1 and 2 located in Kópavogur; the Breidholt Site located in Reykjavík; and Stuðlaskarð Sites 1 and 2 in Hafnarfjörður. Each site is discussed in the following, with the Lundur Sites discussed first because of the more detailed site characterization and recordings performed at these sites (e.g., Kennedy et al. 2019; *Appendix A*). In a similar vein, the Breidhold Site is discussed last because it was the least well-characterized site.

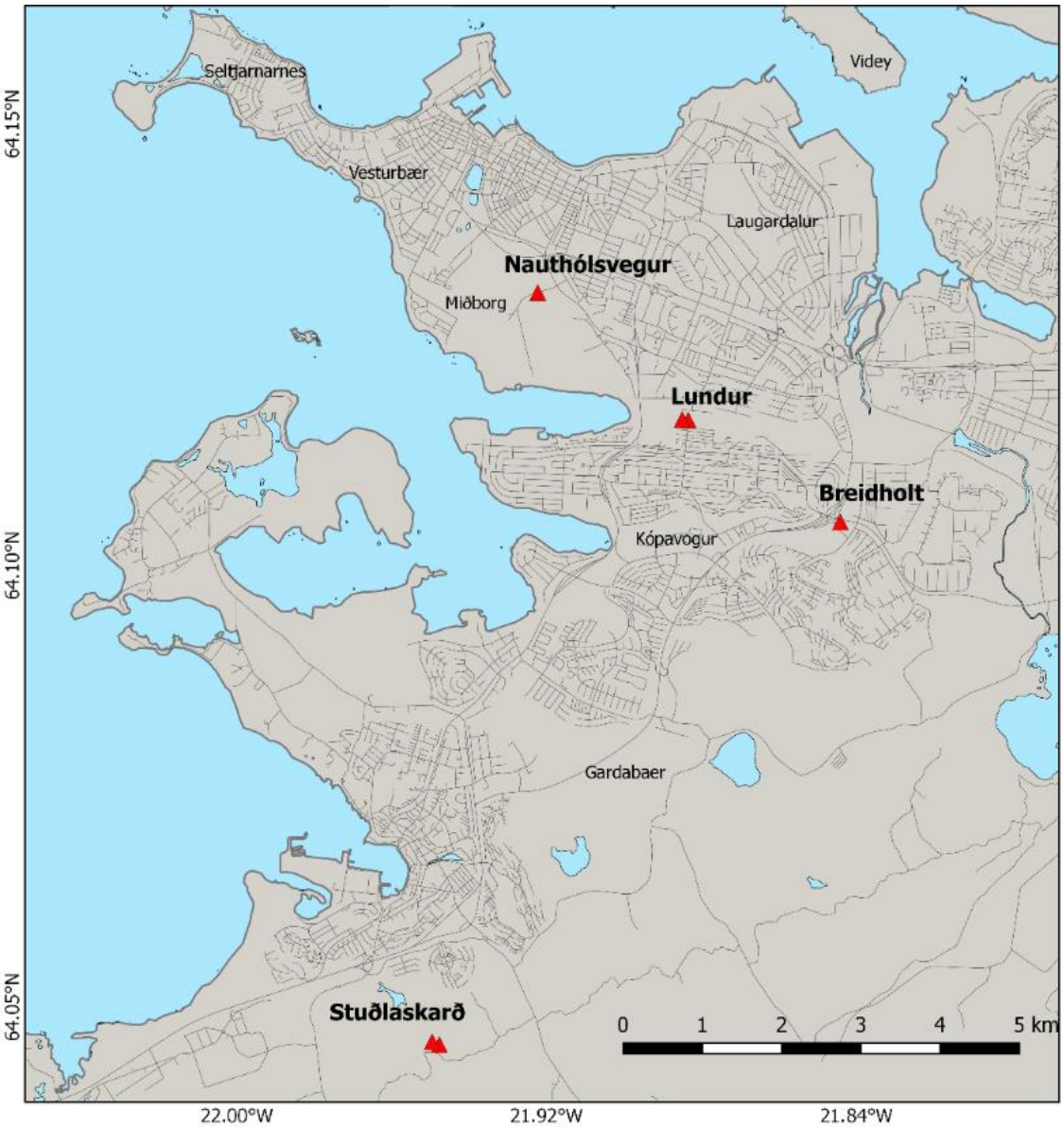

Figure 2.7. Map of the capital region of Iceland and relative locations of all sites encountered during the study, indicated by triangle markers.

Figures 2.8 and **2.9** are sketches of Lundur Sites 1 and 2, respectively, located in Kópavogur. The in-situ soils were excavated down to a competent reference stratum (**Figure 2.10**), which was comprised of dense to very dense SM – silty sand (ASTM D2487 2017), underlain by bedrock. The stratum's particle-size distribution is presented in **Figure 2.11**. As shown in **Figure 2.12**, the stratum's coarse grains have an overall well-rounded shape; **Figure 2.12a** illustrates the shape of soil particles larger than 1 mm diameter (with a maximum particle diameter of ~15 mm) and **Figure 2.12b** shows soil retained on the #35 sieve (0.5 mm) that passed the #18 sieve (1 mm). ASTM D4318 (2017) was used to determine the Atterberg limits for the portion of soil finer than the #35 sieve. (Note that ASTM D4318 calls for testing of soil passing the #40 sieve (0.425 mm), but unfortunately this sieve size was not available and thus the tests were performed on the soil passing the #35 sieve.) Due to the nonplastic nature of the soil, the liquid limit for the soil could not be determined, negating the need to perform the plastic limit test. In addition, the soil finer than the #35 sieve exhibited no cohesion in an oven dried state, thus corroborating the conclusion that the fines are predominantly non-plastic silt and a negligible amount of clay exists.

The black circles and triangles presented in **Figures 2.8** and **2.9** illustrate the relative horizontal and vertical positions of recordings made at Lundur. The recording dates are listed next to the black triangles. The first microtremor measurements recorded at Lundur Site 1 was of the dense to very dense silty sand base layer. Gravel fill was then placed, and measurements were recorded atop an intermediate fill grade (~1.5 m thick). Measurements at three locations (West, MID, and East) atop the final gravel fill grade (~2 m thick) were recorded together with simultaneous measurements of a nearby base layer reference condition. Unlike Lundur Site 1, the adjacent base layer at Lundur Site 2 varied in elevation and thus presented a case where the effect of fill thickness could be measured directly. Seismometers were placed collinearly across Lundur Site 2 to measure the effect of gravel fill thickness. Refer to *Appendix A* for more details about Lundur Site 2. *Appendix C.1* contains site photographs of Lundur.

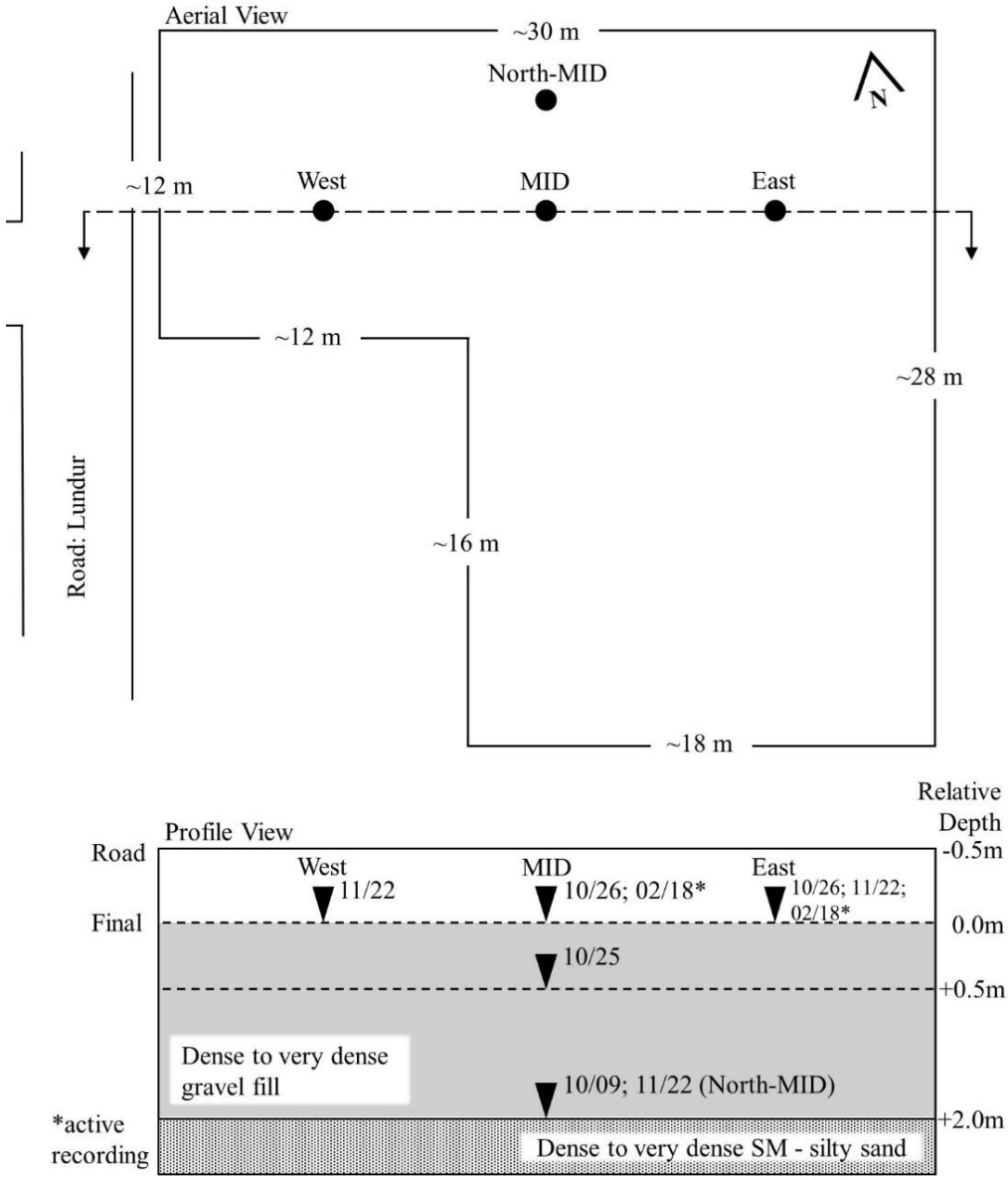

Figure 2.8. Aerial and profile view of Lundur Site 1 in Kópavogur. Not drawn to scale.

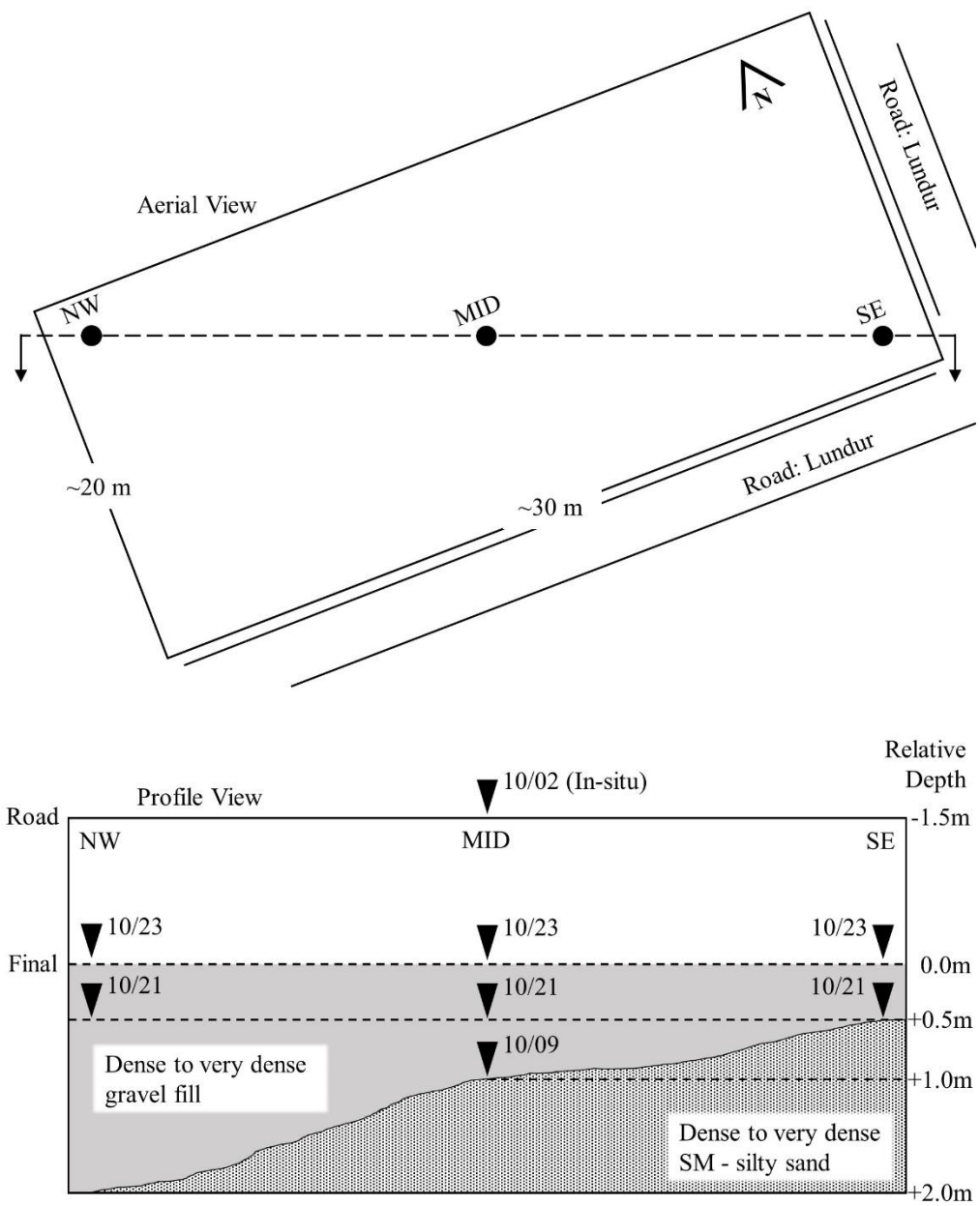

Figure 2.9. Aerial and profile view of Lundur Site 2 in Kópavogur. Not drawn to scale.

Figure 2.10. Photograph of the dense SM – silty sand base layer at Lundur Site 1 in Kópavogur.

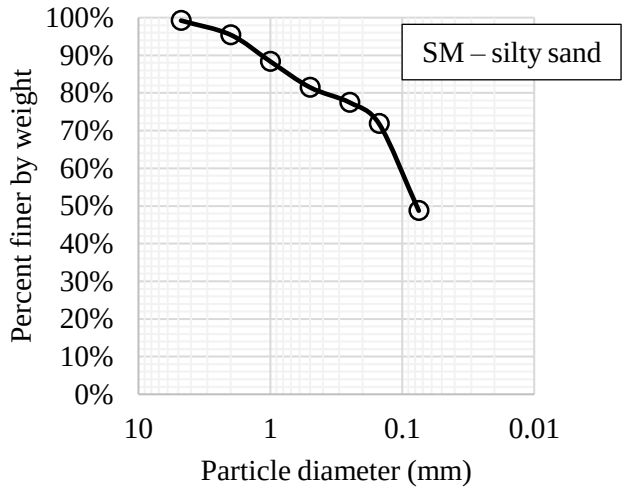

Figure 2.11. The particle-size distribution curve of a soil sample taken from the competent stratum on which the gravel fill was placed at Lundur Site 1 in Kópavogur.

Figure 2.12. Soil particles greater than 1 mm diameter (a) and soil retained on the #35 sieve (0.5 mm) that passed the #18 sieve (1 mm) (b).

Aerial and profile sketches of the Nauthólsvegur 83 Site located in Reykjavík are shown in **Figures 2.13** and **2.14**. The Nauthólsvegur 83 Site had a base layer that varied in elevation across the site. The final fill thickness increased southwesterly. The site presented a unique case where simultaneous recordings atop gravel fill and a nearby rock outcrop could be performed. In addition, the in-situ soil condition was measured pre-excavation. Site photographs taken at Nauthólsvegur 83 are included in *Appendix C.2*.

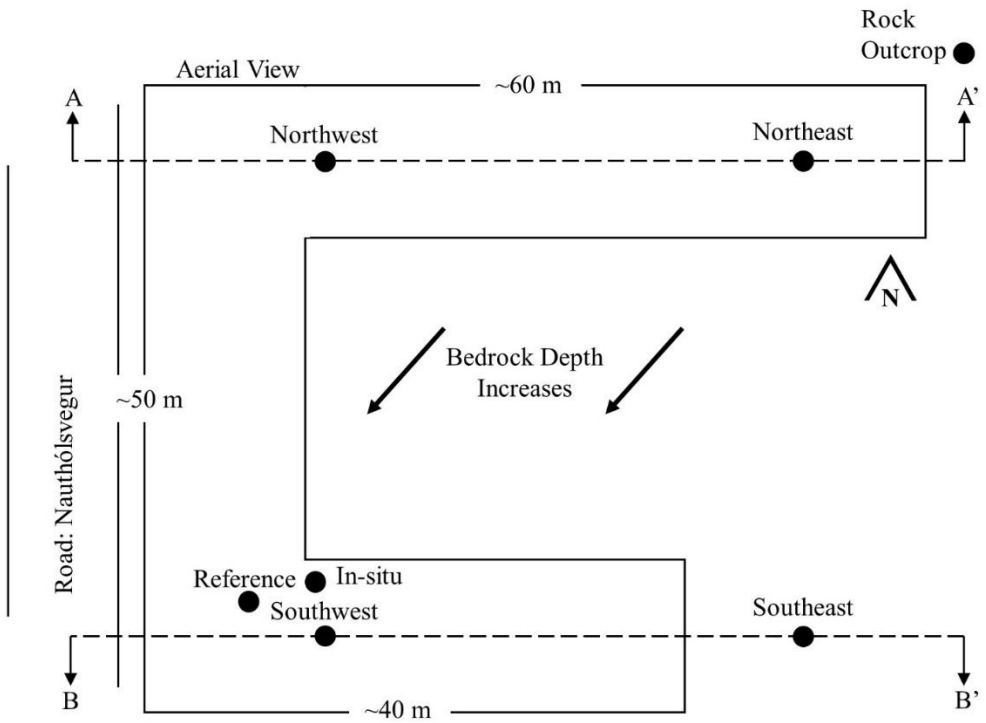

Figure 2.13. Aerial view of the Nauthólsvegur 83 Site in Reykjavík. The proposed building footprint is outlined. Not drawn to scale.

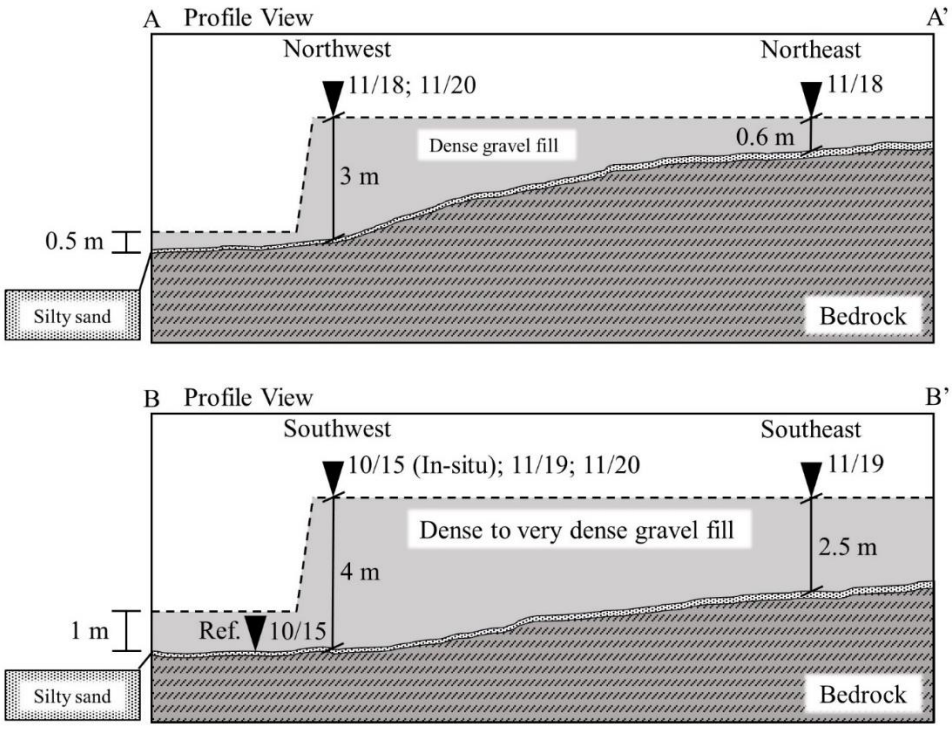

Figure 2.14. Profile views of the Nauthólsvegur 83 Site in Reykjavík. Not drawn to scale.

Sketches of Stuðlaskarð Sites 1 and 2 in Hafnarfjörður are shown in **Figures 2.15** and **2.16**, respectively. Both sites were underlain by lava rock formations and presented a unique case where microtremor measurements could be recorded directly atop lava rock base layers and after gravel fill placement. The effect that conditions of frozen, thawing, and unfrozen gravel fill had on site response characteristics were also conducted at Stuðlaskarð Site 1. Site photographs for both sites are illustrated in *Appendix C.3*.

The Breidholt Site was not sketched due to inadequate site investigation (resulting from schedule conflicts to access the site). The only measurements taken at the Breidholt Site were recordings of the in-situ soil condition. The site area at Breidholt was the largest of all sites encountered. Approximately 20,000 m^3 of in-situ soils were to be removed before replacement with compacted gravel fill. Site photographs of Breidholt are shown in *Appendix C.4*.

The data collection and analysis methodologies are described in the *following section*.

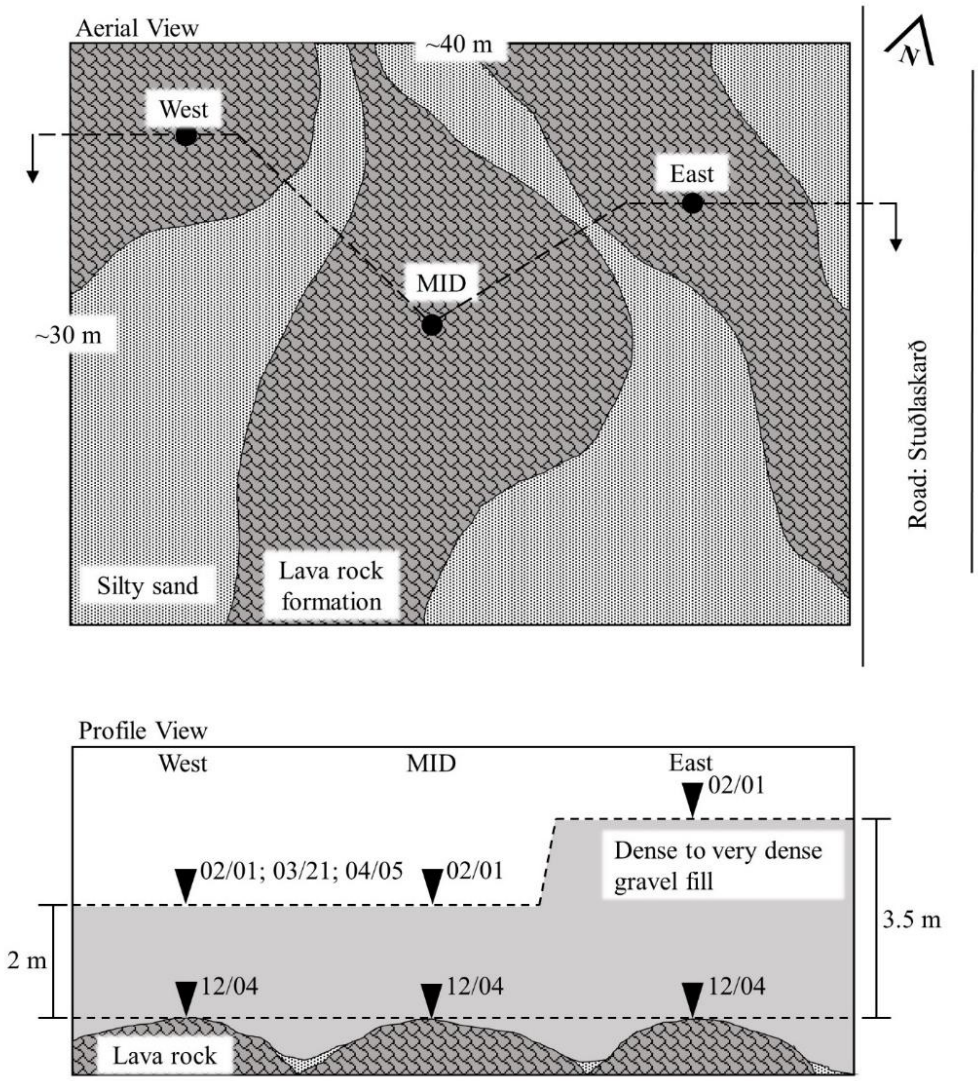

Figure 2.15. Aerial and profile view of Stuðlaskarð Site 1 in Hafnarfjörður. Not drawn to scale.

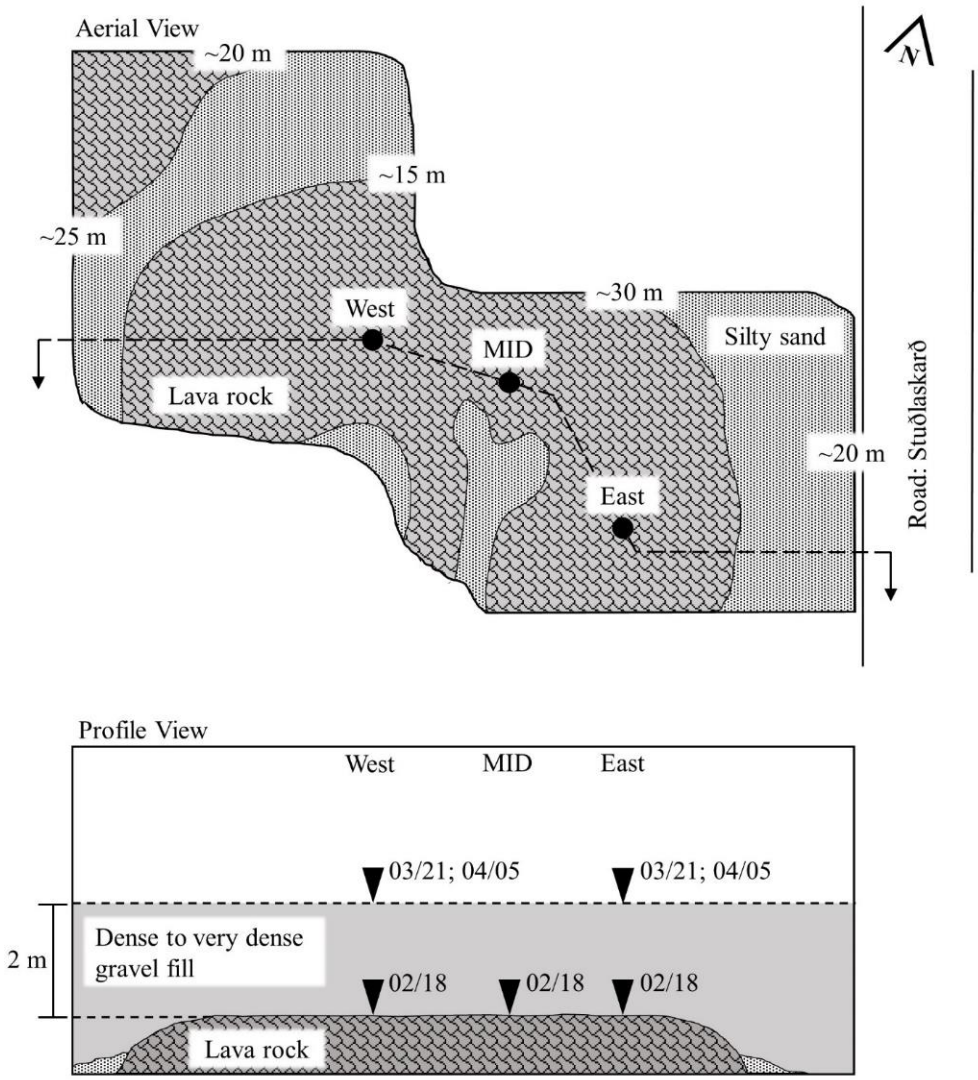

Figure 2.16. Aerial and profile view of Stuðlaskarð Site 2 in Hafnarfjörður. Not drawn to scale.

2.4.2. Data Collection and Analysis

At least two microtremor measurements were made at each study site to identify differences in site response characteristics before and after gravel fill placement. At some sites, recordings were taken with multiple stations during the intermediate and final stages of gravel fill placement to measure the change across the site; this was especially opportune for conditions where the underlying base layer (e.g., bedrock, lava rock, or dense silty sand stratum) was not level to highlight 3-D site response effects. Most recordings took place during quiet hours overnight (i.e., "passive times"). However, recordings during the daytime with identifiable excitation sources, e.g., a nearby jackhammer, were also made (i.e., "active times").

Table 2.1 lists all recordings made during this study and delineates recording events by start date and time, location name, recording duration (in hours), number of seismometer stations, and ground conditions. A total of 531 hours of microtremor measurements were recorded for 23 unique start times (referred to herein as an "event").

Table 2.1. Site List and Event Recordings

#	Start Date and Time	Location	Recording Duration	Number of Stations	Condition
1	2018-10-02; 18:00	Kópavogur, Lundur Site 2	12:00	2	I-s, I-s
2	2018-10-09; 18:00	Kópavogur, Lundur Site 1	12:00	2	SM, SM
3	2018-10-09; 18:00	Kópavogur, Lundur Site 2	13:00	1	SM
4	2018-10-15; 16:00	Reykjavík, Nauthólsvegur 83 Site	16:30	2	I-s, SM
5	2018-10-21; 18:00	Kópavogur, Lundur Site 2	13:00	3	SM, G, G
6	2018-10-23; 18:00	Kópavogur, Lundur Site 2	12:00	3	G, G, G
7	2018-10-25; 18:00	Kópavogur, Lundur Site 1	12:00	1	G
8	2018-10-26; 18:00	Kópavogur, Lundur Site 1	13:00	2	G, G
9	2018-11-18; 18:00	Reykjavík, Nauthólsvegur 83 Site	11:00	3	RO, G, G
10	2018-11-19; 19:00	Reykjavík, Nauthólsvegur 83 Site	11:00	3	RO, G, G
11	2018-11-20; 21:00	Reykjavík, Nauthólsvegur 83 Site	07:00	3	RO, G, G
12	2018-11-22; 20:00	Kópavogur, Lundur Site 1	09:00	3	SM, G, G
13	2018-12-04; 18:00	Hafnarfjörður, Stuðlaskarð Site 1	10:00	3	LR, LR, LR
14	2019-02-01; 21:00	Hafnarfjörður, Stuðlaskarð Site 1	11:00	3	G, G, G
15	2019-02-18; 12:00	Kópavogur, Lundur Site 1	04:00	3	RO, G, G
16	2019-02-18; 20:00	Hafnarfjörður, Stuðlaskarð Site 2	12:00	3	LR, LR, LR
17	2019-03-04; 19:00	Reykjavík, Breidholt	12:00	1	I-s
18	2019-03-07; 11:00	Kópavogur, Lundur	07:00	1	RO
19	2019-03-07; 19:00	Kópavogur, Lundur	14:00	1	RO
20	2019-03-21; 20:00	Hafnarfjörður, Stuðlaskarð Site 1	11:00	1	G
21	2019-03-21; 20:00	Hafnarfjörður, Stuðlaskarð Site 2	11:00	2	G
22	2019-04-05; 21:00	Hafnarfjörður, Stuðlaskarð Site 1	11:00	1	G
23	2019-04-05; 21:00	Hafnarfjörður, Stuðlaskarð Site 2	11:00	2	G

I-s: in-situ soils; SM: dense silty sand; G: gravel fill; RO: rock outcrop; LR: lava rock

All events were measured using tridirectional Lennartz LE-3D/5s seismometers (5-s period) and recorded by REF TEK 130-01 high-resolution broadband seismic data acquisition systems. The sensors collected data at a rate of 100 Hz with high gain. Note that SESAME (2004**)** guidelines state that HVSR results are independent of the gain used and a sampling rate of at least 50 Hz suffices because the maximum frequency of engineering significance is ~25 Hz and the Nyquist frequency is one-half the sampling rate. Each axis had the same set parameters. Seismometers were set up with great care to ensure proper contact with the ground and were leveled using three thumbscrew feet protruding from the base and a bullseye-type spirit level. In cases where recordings were made at the same location but at different times of site preparation (e.g., before and after fill placement), the onboard REF TEK GPS system was used to identify the seismometer's location. In addition, the GPS system guaranteed time synchronization between stations.

During set up, the seismometers were covered with nearby soil to reduce the chance and extent of unwarranted perturbations. **Figure 2.17** shows the seismometer before and after covering. Although SESAME (2004**)** guidelines state that sensors need not be covered, the author deemed it necessary to cover the instruments with nearby soil given the harsh and unpredictable weather conditions in Iceland and based on the sensor setup recommendations outlined in Foti et al. (2018). The SESAME 2004 guidelines also note that wind has the most influence on instrument disturbance. Therefore, weather data (e.g., average wind velocity, wind gust velocity, precipitation rate, etc.) were collected for all events to retrospectively identify time periods when wind or rain may have affected measurements. This is discussed in more detail in the *Results and Discussion* section, along with soft soil and frozen ground conditions that influenced measurements.

Figure 2.17. Seismometer set-up before (a) and after (b) covering with nearby soil at Lundur Site 1 in Kópavogur. Note that the rock used to secure the cable was not in contact with the seismometer.

After microtremor measurements were recorded, PASSCAL software was used to convert the data type to ASCII format. The PASSCAL software and information required to convert to this data type can be found at the website: <https://www.passcal.nmt.edu/>. The ASCII format contained velocity time histories and station information (e.g., GPS and sensor parameter values). Velocity spikes were filtered from raw ASCII velocity data to eliminate irregular excitations. This process involved an iterative procedure wherein the velocity time histories were viewed, and if apparent spikes were present, the section of data that included the spike was deleted (usually ~5 seconds of velocity data would be deleted to remove a spike). Velocity spikes were uncommon during times of passive recording (i.e., during quiet hours overnight). After the raw velocity data have been checked for and filtered of spikes, the FAS of horizontal and vertical components were calculated and 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 over a frequency bandwidth of 0.3 to 25 Hz 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 **Figure 2.18**. **Figure 2.18a** shows the separate HVSR curves for all ~60-minute time windows for the microtremor data recorded at the center (MID) of Lundur Site 2, prior to excavation. **Figure 2.18b** 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.

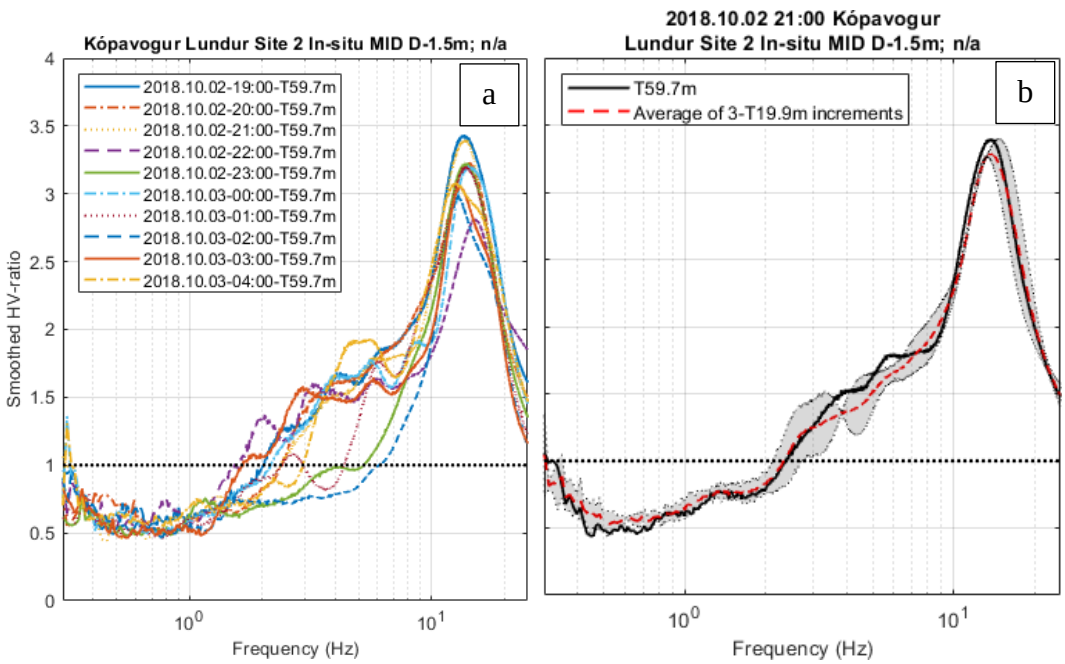

Figure 2.18. HVSR curves for MID at Lundur Site 2 before excavation (relative depth -1.5 m) for: (a) all ~60-minute intervals; and (b) the average of three ~20-minute segments with a shaded region representing ± one standard deviation of average.

In addition to the HVSR method, the microtremor velocity data was also used to implement the SSR technique, proposed by Borcherdt (1970). As stated previously, the SSR is the ratio of the site's combined horizontal motion FAS to the combined horizontal reference motion FAS over the desired frequency bandwidth of engineering significance (e.g., 0.3 – 25 Hz).

The *following section* presents the results obtained from the HVSR and SSR analyses.

2.5. Results and Discussion

The three main site conditions studied were: (1) in-situ soils, (2) a competent reference stratum, and (3) compacted gravel fill. In a few cases, measurements were made on intermediate fill grades. In addition, when either a nearby rock outcrop or reference stratum was accessible while recording atop a gravel surface, simultaneous measurements were made atop the fill and the rock outcrop/competent stratum so that the standard spectral ratio (SSR) technique could be used to assess site effects. At most sites, the competent reference condition was dense to very dense SM underlain by bedrock. However, as mentioned previously, lava rock undulations were discovered beneath in-situ soils at two sites in Hafnarfjörður, which presented a unique opportunity to measure the response characteristics of this reference stratum directly.

2.5.1. Lundur Sites 1 and 2 (Events #1, 2, 3, 5, 6, 7, 8, 12, 15, 18, and 19)

The sites at Lundur were the most visited during this study. As a result, measurements were made on various site conditions. The sites were excavated down to a dense to very dense silty sand reference stratum (of unknown thickness) underlain by bedrock. Both HVSR and SSR techniques were used to assess the site effects at Lundur Site 1. **Figure 2.19** shows a comparison of the HVSR and SSR signatures at two locations (West and East) atop 2 m thick gravel fill at Lundur Site 1. The reference condition was a nearby simultaneously measured dense to very dense silty sand stratum. From **Figure 2.19**, it is clear that the HVSR mean amplitudes underestimate site amplification (3.5 and 4.4) compared to values obtained from SSR analyses (4.7 and 6). However, both techniques resulted in a similar predominant frequency between 15 to 19 Hz, with SSR being slightly higher in frequency and amplitude. These findings are in accord with the SESAME (2004) investigation comparing the techniques. It is worthwhile to note that the SSR analyses result in a ratio near unity across the low- and mid-band frequency range whereas HVSR result in values of less than unity across this bandwidth.

Figure 2.20 shows the HVSR signatures for the in-situ condition, the dense silty sand reference stratum, and two final grade thicknesses recorded at Lundur Site 2. Recall that **Figure 2.9** illustrates the sketch of all locations and site conditions where recordings were made. It is worthwhile to note that the seismometer for the in-situ condition was placed atop a thin layer (<

0.3 m) of compacted gravel underlain by in-situ soils. The gravel served as a temporary parking lot and, as a result, direct contact with in-situ soils was not available.

It is clear from the signatures shown in **Figure 2.20** that the site's HVSR amplitude increases as a result of gravel fill placement and that the predominant frequency is similar for all site conditions (between 13 and 15 Hz). This trend was also observed at Lundur Site 1 (less the in-situ condition). Note, however, that the HVSR signature for the MID condition (1 m gravel thickness) also had a broad peak at mid-band frequencies (~3 to 8 Hz) that were not present in the in-situ or reference site conditions. A broad local peak at mid-band frequencies with similar amplitudes also exists for the NW condition (2 m gravel thickness). Nevertheless, the consistent presence of a peak at 13 Hz for all site conditions provides justification to assume the fundamental frequency at MID is 13 Hz, despite the broad local peak with slightly higher amplitude in the mid-band frequency range.

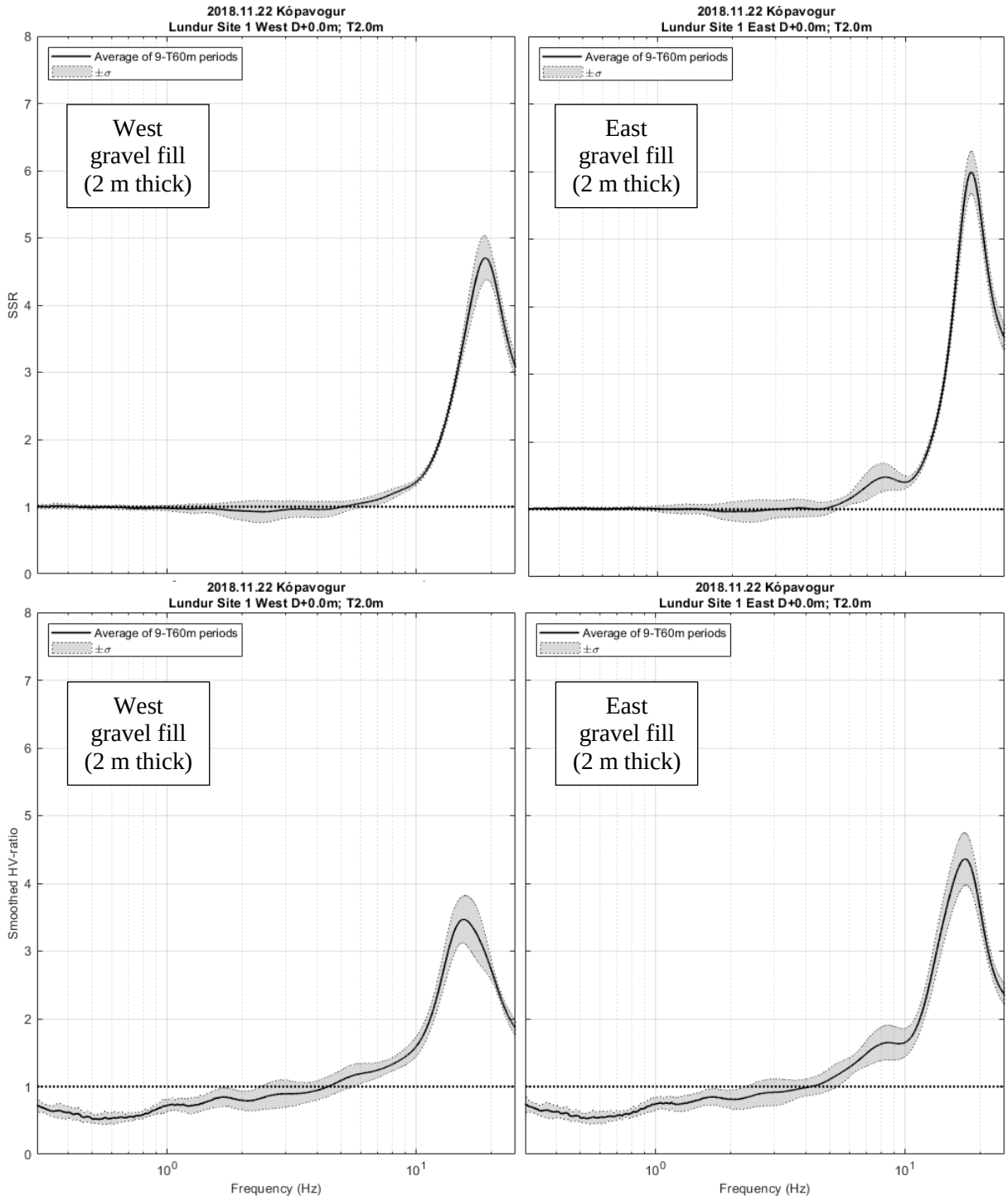

Figure 2.19. Comparison of SSR (top) and HVSR (bottom) signatures for two locations atop gravel fill at Lundur Site 1 in Kópavogur.

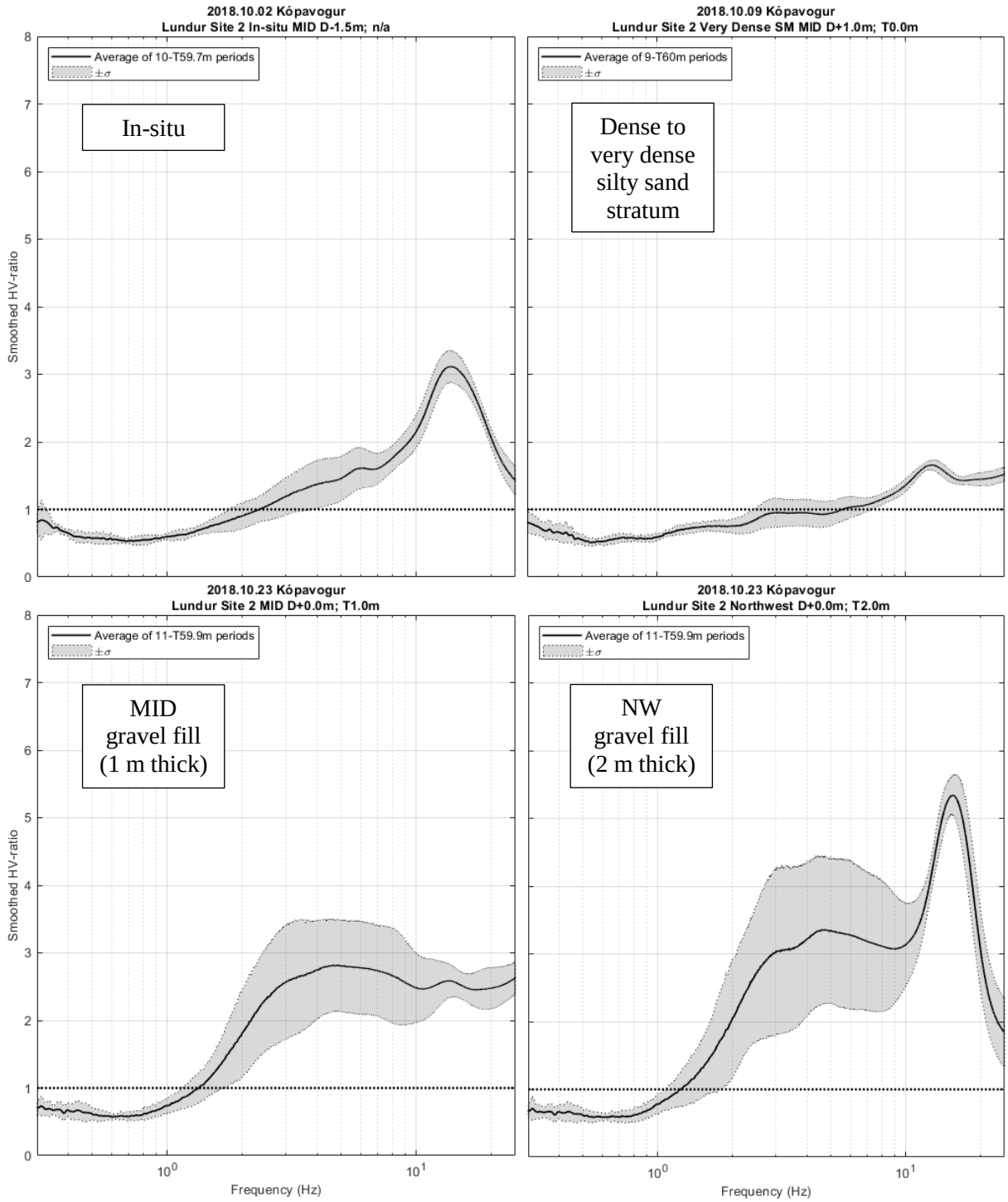

Figure 2.20. Comparison of HVSR signatures for the in-situ (top-left), post-excavation dense to very dense silty sand reference (top-right), and the final gravel grade (bottom) for Site 2 at Lundur in Kópavogur. Note that for the in-situ condition, the seismometer was set up atop a thin layer (< 0.3 m) of compacted gravel underlain by in-situ soils. The gravel served as a temporary parking lot and, as a result, direct contact with the in-situ soil was not available.

2.5.2. The Nauthólsvegur 83 Site (Events #4, 9, 10, and 11)

The Nauthólsvegur 83 Site presented a case where the in-situ soil condition, a nearby rock outcrop, and gravel fill of various thicknesses were available. **Figure 2.21** illustrates the HVSR signatures for these conditions. The in-situ soil condition had a clear peak with a predominant frequency of 3.5 Hz and a mean amplitude of 3.8. The placement of gravel fill (with thicknesses of 3 and 4 m) shifted the site's predominant frequency to higher frequencies (between 10.5 and 11 Hz) with larger mean amplitudes (4.8 and 4.9, respectively). Meanwhile, measurements atop a nearby rock outcrop reveal a flat HVSR signature consistent with a reference condition relatively free of any amplification.

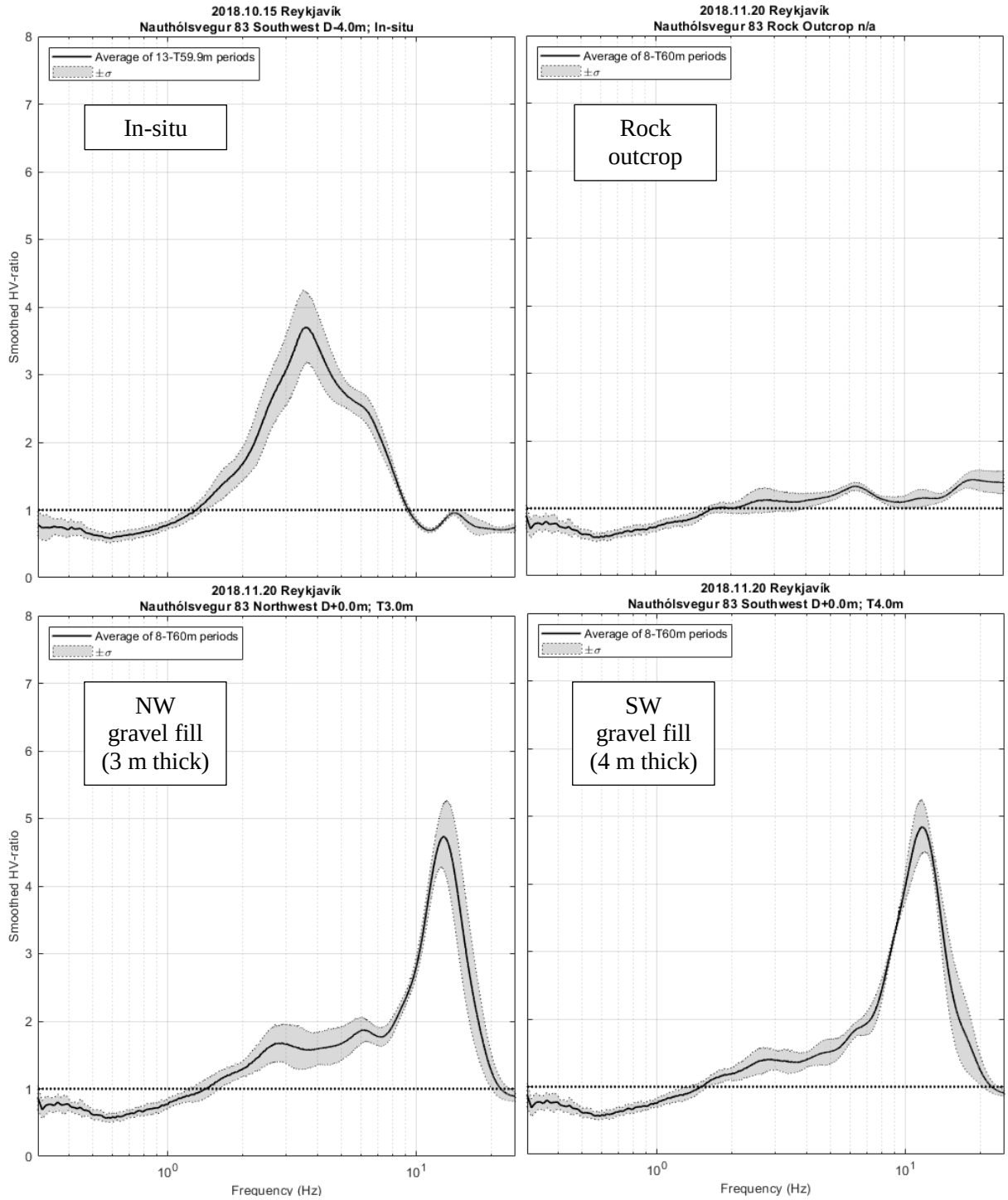

Figure 2.21. Comparison of HVSR signatures for the in-situ soil (top-left), a nearby rock outcrop (top-right), and the final gravel grade (bottom) for the Nauthólsvegur 83 Site in Reykjavík.

2.5.3. Stuðlaskarð Sites 1 and 2 (Events #13, 14, 16, 20, 21, 22, and 23)

Both sites at Stuðlaskarð were underlain by undulating lava rock formations. Lava rock resulted in HVSR signatures unlike any other reference condition encountered where the relative amplification decreased as a result of gravel fill placement. **Figure 2.22** shows a comparison of lava rock HVSR signatures measured at two sites to compacted gravel (2 m thick) at final grade. Lava rock measured at both sites had similar predominant frequencies (between 4 and 4.4 Hz) with high mean amplitudes (4.1 and 5.7). The addition of compacted gravel fill shifted the predominant frequency to values between 9 and 10.5 Hz with relative mean peak amplification values of 3.1 and 3.7. HVSR amplitudes were suppressed in the mid-band frequencies by 0.35 to 0.5 times. It is worth noting that lava rock HVSR signatures contain local peaks at higher frequencies with similar amplitudes found in gravel fill signatures.

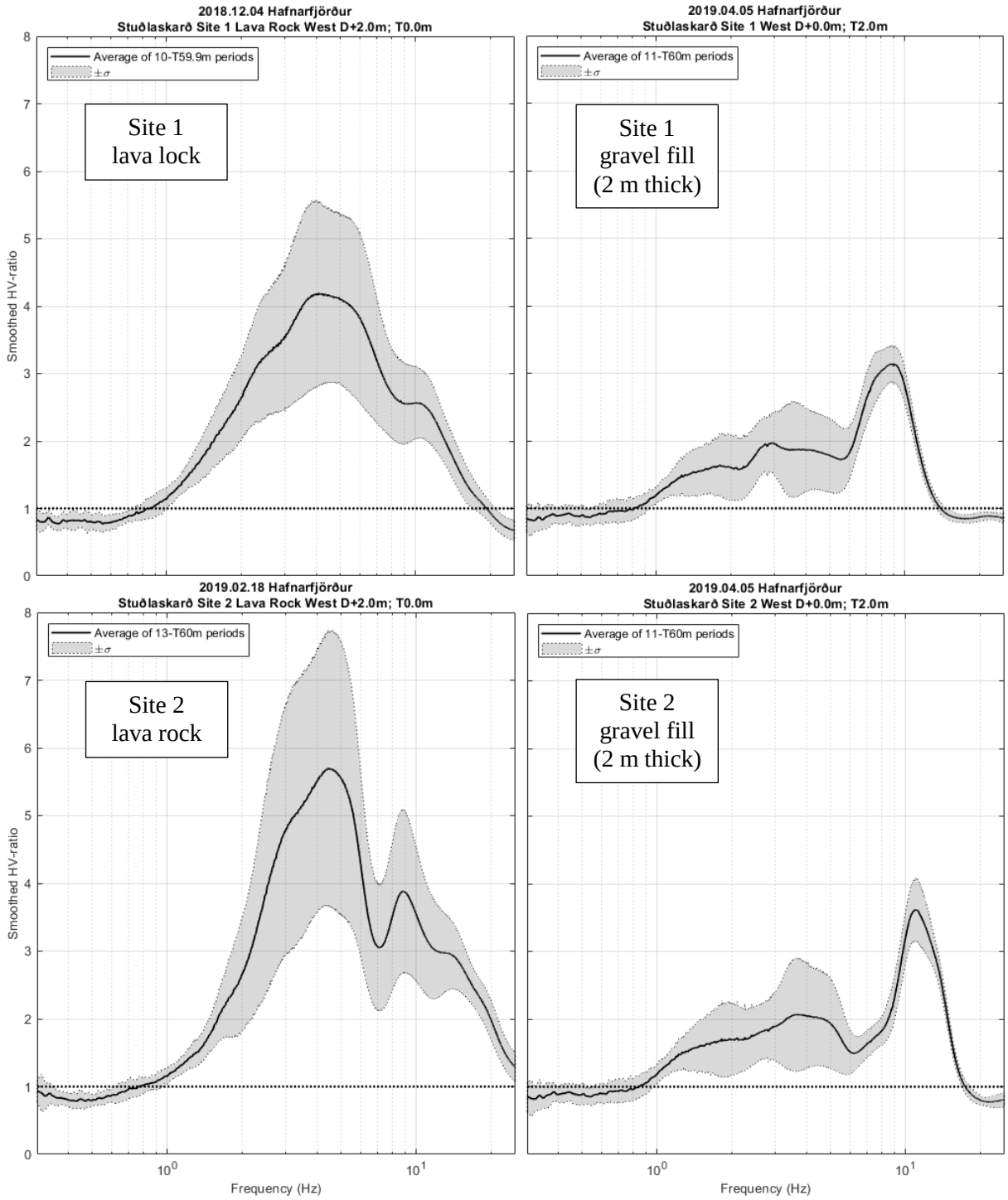

Figure 2.22. Comparison of HVSR signatures taken post-excavation atop lava rock (left) and gravel fill (right) for two sites at Stuðlaskarð in Hafnarfjörður.

2.5.4. The Breidholt Site (Event #17)

The in-situ site condition at the Breidholt Site was measured by one seismometer set up directly atop the in-situ soil overnight. The weather conditions were within acceptable ranges (i.e., wind velocity less than 5 m/s and negligible precipitation; SESAME 2004). The HVSR signature for the in-situ soil condition at Breidholt is illustrated in **Figure 2.23**. A clear peak exists at a predominant frequency of 7 Hz with a mean amplitude of 3.9.

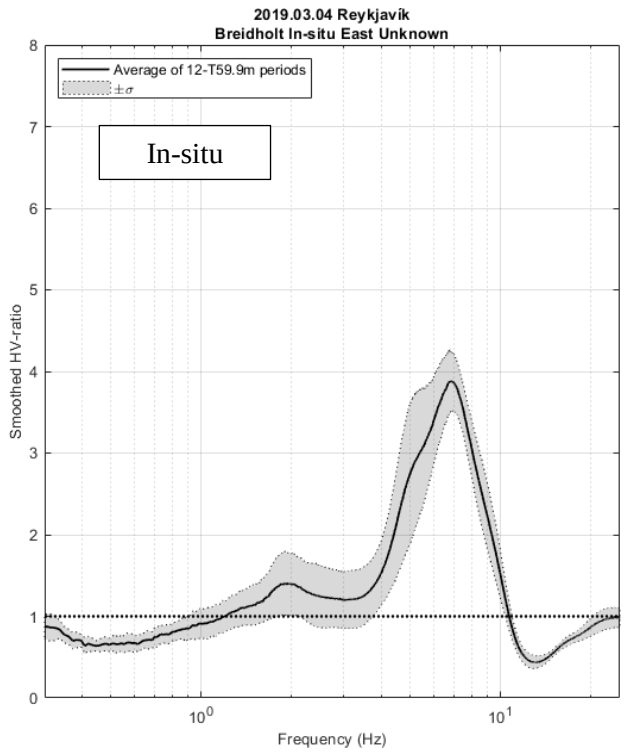

Figure 2.23. HVSR signature of the pre-excavation in-situ soil condition at Breidholt in Reykjavík.

2.5.5. Summary of Site Response Characteristics of Compacted Gravel Fill

Table 2.2 lists the predominant frequency, mean peak amplitude, and signature shape for each site and condition. It may be observed that the placement of compacted gravel fill results in a higher predominant frequency compared to the in-situ soil condition.

Table 2.2. Summary of Site Response Characteristics

Site	**Site Condition**	**Predominant Frequency, f_0 (Hz)**	**Mean Peak Amplitude, A_0**	**SESAME (2004) Classification**
Breidholt	In-situ soil	7	3.9	Clear peak
Lundur Site 1	W. gravel (2 m thick)	15 (19 from SSR)	3.5 (4.7 SSR)	Clear peak
	E. gravel (2 m thick)	16 (19 from SSR)	4.4 (6 SSR)	Clear peak
Lundur Site 2	In-situ*	13	3	Clear peak
	MID gravel (1 m thick)	13	2.6	Broad or multiple peaks: f_1 = 4.8 Hz, A_1 = 2.9; f_2 = 13 Hz, A_2 = 2.6
	NW gravel (2 m thick)	15	5.3	Broad or multiple peaks: f_1 = 4.8 Hz, A_1 = 3.3; f_2 = 15 Hz, A_2 = 5.3
Nauthólsvegur	In-situ soil	3.5	3.8	Clear peak
	NW gravel (3 m thick)	11	4.8	Clear peak
	SW gravel (4 m thick)	10.5	4.9	Clear peak
Stuðlaskarð Site 1	Lava rock	4	4.1	Broad or multiple peaks: f_1 = 4 Hz, A_1 = 4.1; f_2 = 10 Hz, A_2 = 2.6
	W. gravel (2 m thick)	9	3.1	Broad or multiple peaks: f_1 = 3 Hz, A_1 = 2; f_2 = 9 Hz, A_2 = 3.1
Stuðlaskarð Site 2	Lava rock	4.4	5.7	Broad or multiple peaks: f_1 = 4.4 Hz, A_1 = 5.7; f_2 = 9 Hz, A_2 = 3.9
	W. gravel (2 m thick)	10.5	3.7	Broad or multiple peaks: f_1 = 3.4 Hz, A_1 = 2; f_2 = 10.5 Hz, A_2 = 3.7

*The seismometer was set up atop a thin layer (< 0.3 m) of compacted gravel underlain by in-situ soils. The gravel served as a temporary parking lot. Direct contact with in-situ soils was not available.

2.5.6. Problematic Recording Conditions

The HVSR signatures presented above were the result of good set-up and measurement conditions. However, there were cases when measurement conditions were poor. As first introduced in *Section 2.4.2 Data Collection and Analysis*, the following paragraphs present the poor results of three unique cases when poor microtremor measurements were recorded due to: (1) wind gusts (**Figure 2.24**); (2) poor soil-sensor coupling due to soft soil (**Figure 2.26**); and (3) frozen ground (**Figure 2.27**). Recordings impacted by these conditions were not included in the data analyses presented above.

Strong wind can potentially perturb seismometers while measuring microtremors. According to SESAME (2004), even a slight wind (approximately > 5 m/s) may influence HVSR results. However, covering the sensor may increase the perturbation threshold for wind and rain (Foti et al. 2018). **Event #9** (**Figure 2.24**) illustrates the effect that strong average and gust wind speeds have on HVSR signatures measured simultaneously atop a rock outcrop and a compacted gravel fill (3 m thick) at the Nauthólsvegur 83 Site in Reykjavík. In both cases, there are two distinct signature groups that diverge at the same time. Weather data was used retrospectively to identify that by 22:00 the average and gust wind speeds increased from 1 m/s and 4 m/s to 8 m/s and 16 m/s, respectively. These high wind speeds sustained throughout the night. The weather data and grouped HVSR signatures served as evidence to conclude that the seismometers were disturbed by a significant increase in wind speed.

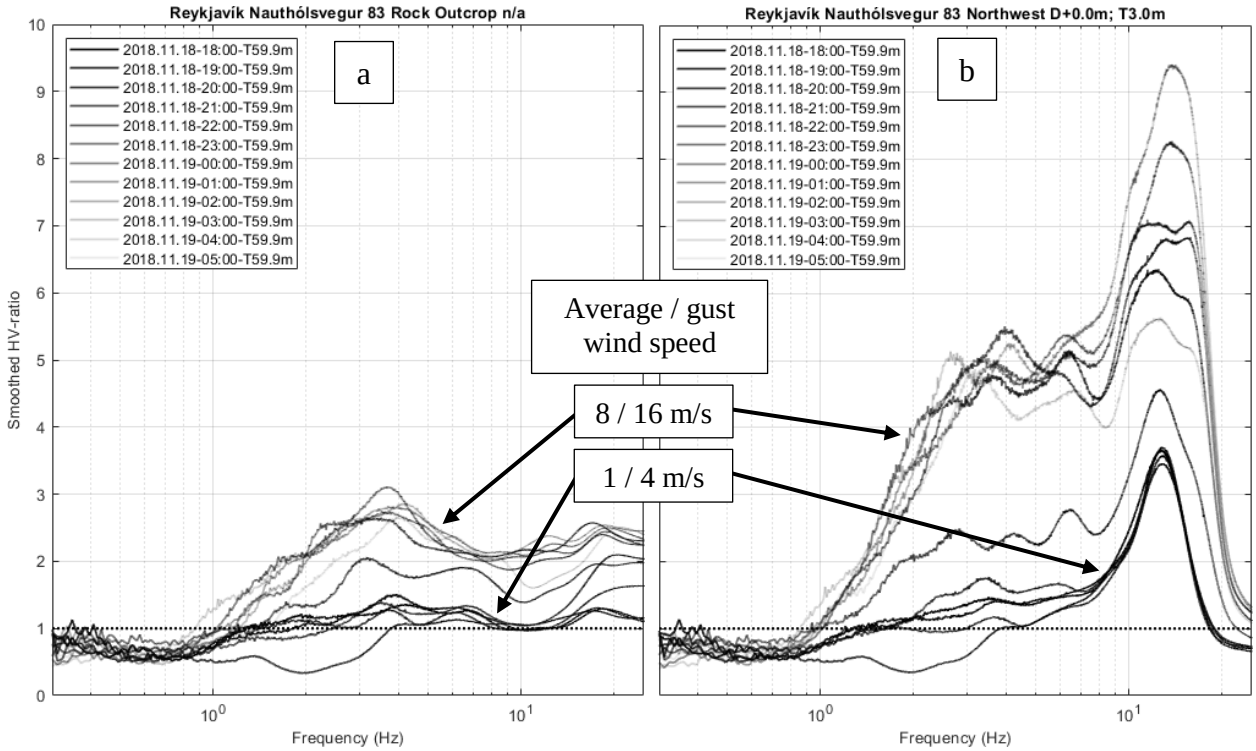

Figure 2.24. The influence of the average and gust wind speed on HVSR signatures simultaneously recorded atop: (a) a rock outcrop, and (b) compacted gravel fill of three-meter thickness.

Figure 2.25 illustrates the ponding of water at the excavated Nauthólsvegur 83 Site in Reykjavík, which resulted in soft-ground conditions. SESAME (2004) experimental condition guidelines regarding in-situ soil-sensor coupling state that such conditions (e.g., mud or soil saturated after rain) should be avoided due to the potential for poor soil-sensor coupling.

Proper seismometer contact with the soil surface (i.e., good soil-sensor coupling) is required for accurate measurements. The HVSR signatures of two dense to very dense silty sand reference conditions are shown in **Figure 2.26**. **Figure 2.26a** shows HVSR signatures resulting from poor soil-sensor coupling at the Nauthólsvegur 83 Site (**Event #4**) due to soft ground conditions. The poor signatures were compared to those recorded atop a similar reference condition at Lundur Site 1 shown in **Figure 2.26b** where there was good soil-sensor coupling. The comparison provides a clear distinction between good and poor soil-sensor coupling by highlighting the erroneous amplification values throughout the mid-band frequency range in **Figure 2.26a** and the flat HVSR near unity in **Figure 2.26b**.

Figure 2.25. Poor surface conditions for Event #4 "base layer reference condition" recorded at the Nauthólsvegur 83 Site in Reykjavík. Seismometer location is highlighted by a red circle.

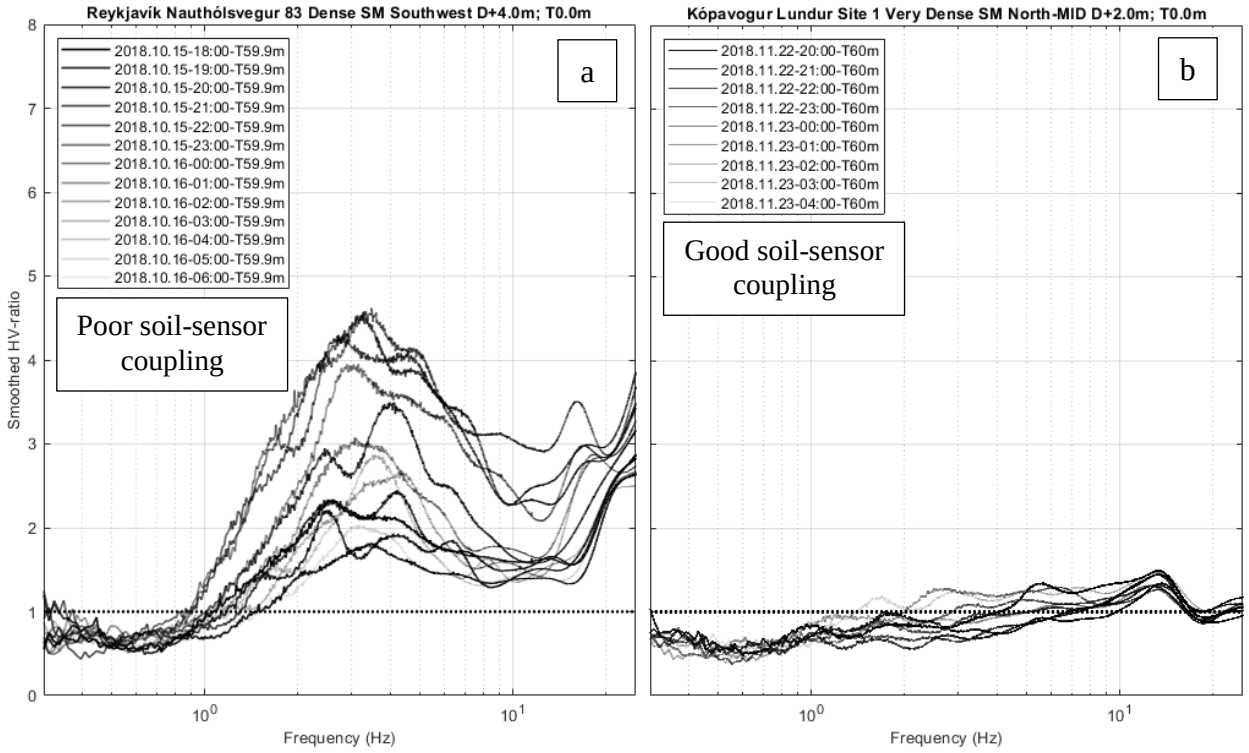

Figure 2.26. The influence of poor (a) and good (b) soil-sensor coupling on HVSR signatures. Measurements were taken atop a dense to very dense silty sand (SM) reference stratum.

Frozen ground conditions were also found to influence microtremor measurements. **Event #14** performed on 1 February 2019 at Stuðlaskarð Site 1 in Hafnarfjörður was recorded on frozen compacted gravel fill (of unknown frost depth). Two frozen conditions were measured at this date, West and East, and both resulted in similar HVSR signatures in frequency content and amplitude, despite having different fill thicknesses, 2 and 3.5 m, respectively (**Figure 2.27a,b**). The site was revisited on 21 March 2019 and additional measurements were made at the West location. The author noted that during set-up he heard trickling noises as a result of ice-melt seepage through the gravel fill and refers to this condition as "thawing." The change in HVSR signature from the frozen condition to the thawing condition is apparent throughout the mid-band frequency range, as shown in **Figure 2.27c**. The broad peak in mid-band frequencies is due to the thawing of the fill. This signature is not apparent in the unfrozen (or thawed) condition, measured on 5 April 2019 at the same location. Instead, a clear predominant frequency at 9 Hz exists with a mean amplitude of 3.1, as shown in **Figure 2.27d**. It is important to note that the predominant frequency is similar between the frozen and unfrozen conditions (~9 Hz) despite the suppression of HVSR amplitudes in frozen ground.

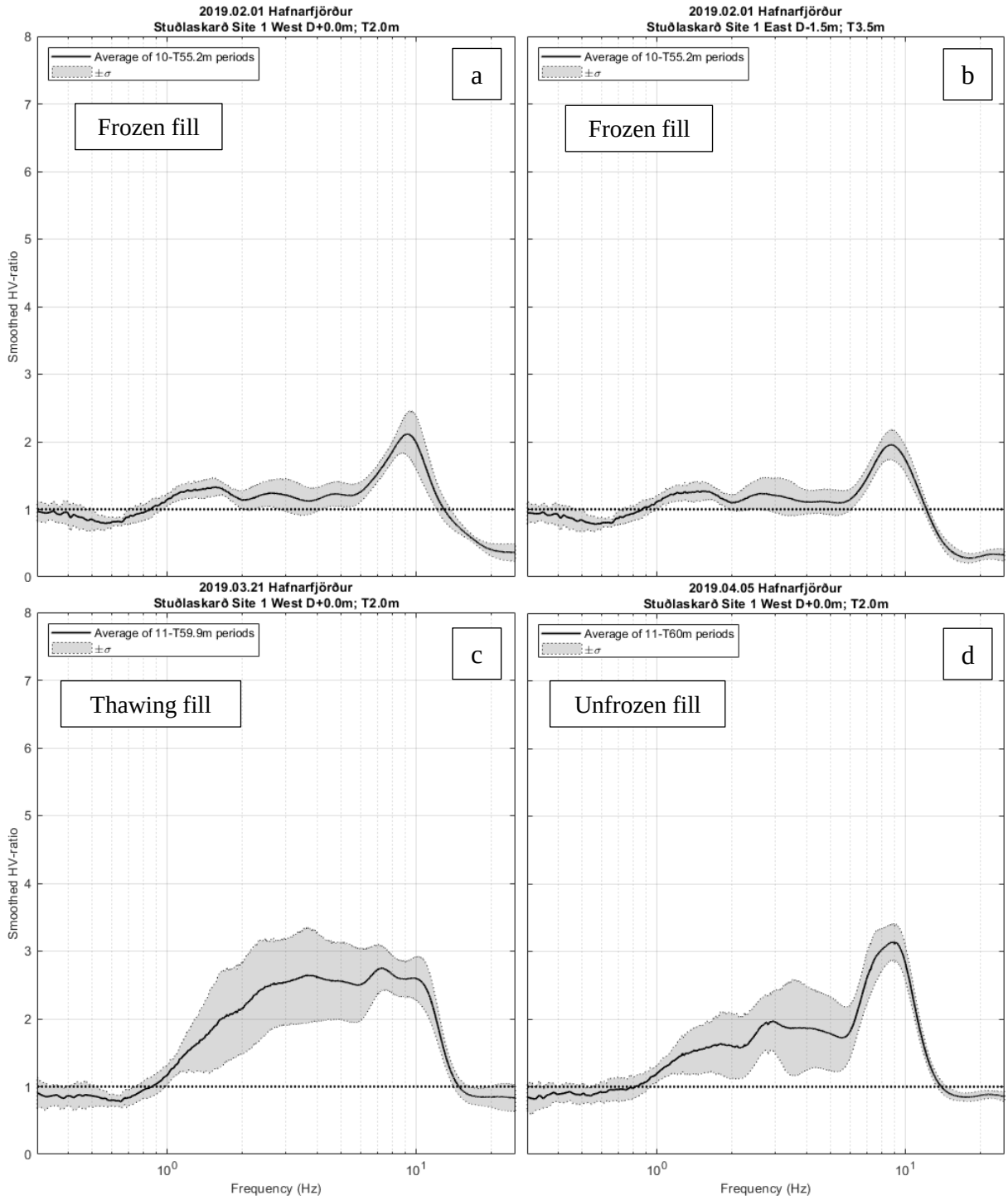

Figure 2.27. The influence of frozen (a, b), thawing (c), and unfrozen (d) compacted gravel fill on HVSR signatures. Note that signatures a, c, and d were taken at the same location atop two-meter thick fill and signature b was taken nearby atop a three and one-half meter thick fill.

2.6. Conclusion

In order to perform thorough seismic hazard and risk analyses, information pertaining to the site effects of the soil underlying the building foundation is required. Most buildings in Iceland are constructed atop compacted gravel fill after the complete removal of in-situ soils to a competent stratum. This manuscript presented the site response characteristics of compacted gravel fill and other site conditions (e.g., the in-situ or pre-excavation, post-excavation, and nearby rock outcrop) from six study sites located throughout the Reykjavík capital region. This objective was achieved by recording microtremor measurements at these sites and calculating the corresponding HVSR and SSR signatures over a bandwidth of 0.3 to 25 Hz. The key findings are summarized below.

The pre-excavation condition was measured at three sites (Breidhold, Lundur Site 2, and Nauthólsvegur 83). Two in-situ soil HVSR signatures revealed predominant frequencies within the mid-band frequency range (3.5 and 7 Hz). One condition measured atop a thin layer (< 0.3 m) of compacted gravel underlain by in-situ soils resulted in a high predominant frequency value (13 Hz). The predominant relative mean amplification values were similar for the pre-excavation condition from site to site (between 3 and 3.9).

The HVSR signature of compacted gravel fill was obtained at all sites except for the Breidholt Site (due to a schedule conflict). At all sites, the predominant frequency shifted to a higher frequency value (between 10 and 16 Hz) relative to the in-situ soil condition after gravel fill placement. The amplification values ranged between 2.6 and 5.3, generally increasing with fill thickness. SSR signatures of compacted gravel relative to a dense silty sand reference condition provided slightly higher site response characteristics derived from HVSR signatures. While a similar shift of predominant frequencies occurred at lava rock sites, a notable reduction of relative amplification by 0.35 to 0.5 times occurred over mid-band frequencies.

An important note should be made regarding careful set-up conditions for microtremor measurements. This manuscript identified surface and weather conditions that resulted in poor quality measurements. It is recommended that weather data (e.g., average wind velocity, wind gust velocity, precipitation rate, etc.) be collected after measurements to retrospectively identify the potential source of unwarranted perturbations.

2.7. References

Adam, D., and Pistrol, J. (2016). "Dynamic Roller Compaction for Earthworks and Roller-Integrated Continuous Compaction Control: State of the Art Overview and Recent Developments." *Proceedings of the 24th Geotechnical Conference of Torino*, Turin, Italy.

Al Yuncha, Z., and Luzón, F. (2000). "On the Horizontal-to-Vertical Spectral Ratio in Sedimentary Basins." *Bulletin of the Seismological Society of America*, 90(4), 1101–6.

ASTM D2487. (2017). "Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)." ASTM International, West Conshohocken, PA.

ASTM D4318. (2017). "Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils." ASTM International, West Conshohocken, PA.

Bonnefoy-Claudet, S., Cornou, C., Bard, P.-Y., Cotton, F., Moczo, P., Kristek, J., and Fäh, D. (2006a). "HV Ratio: A Tool for Site Effects Evaluation. Results from 1-D Noise Simulations." *Geophysical Journal International*, 167(2), 827–37.

Bonnefoy-Claudet, S., Cotton, F., and Bard, P.-Y. (2006b). "The Nature of Noise Wavefield and its Applications for Site Effects Studies: A Literature Review." *Earth-Science Reviews*, 79(3–4), 205–27.

Borcherdt, R. D. (1970). "Effects of Local Geology on Ground Motion Near San Francisco Bay." *Bulletin of the Seismological Society of America*, 60(1), 29–61.

Bour, M., Fouissac, D., Dominique, P., and Martin, C. (1998). "On the Use of Microtremor Recordings in Seismic Microzonation." *Soil Dynamics and Earthquake Engineering*, 17, 465–74.

Cadet, H., Bard, P.-Y., and Duval, A.-M. (2008). "A New Proposal for Site Classification Based on Ambient Vibration Measurements and the KiK-net Strong Motion Data Set." *Proceedings of the 14th World Conference on Earthquake Engineering*, Beijing, China.

Fäh, D., Kind, F., and Giardini, D. (2001). "A Theoretical Investigation of Average HV Ratios." *Geophysical Journal International*, 145(2), 535–49.

Field, E. H., Clement, A. C., Jacob, K. H., Aharonian, V., Hough, S. E., Friberg, P. A., Babaian, T. O., Karapetian, S. S., Hovanessian, S. M., and Abramian, H. A. (1995). "Earthquake Site-Response Study in Giumri (Formerly Leninakan) Armenia, Using Ambient Noise Observations." *Bulletin of the Seismological Society of America*, 85(1), 349–53.

Field, E., and Jacob, K. (1993). "The Theoretical Response of Sedimentary Layers to Ambient Seismic Noise." *Geophysical Research Letters*, 20(24), 2925–28.

Foti, S., Hollender, F., Garofalo, F., Albarello, D., Asten, M., Bard, P.-Y., Comina, C., Cornou, C., Cox, B., Di Giulio, G., Forbriger, T., Hayashi, K., Lunedei, E., Martin, A., Mercerat, D., Ohrnberger, M., Poggi, V., Renalier, F., Sicilia, D., and Socco, V. (2018). "Guidelines for the Good Practice of Surface Wave Analysis: A Product of the InterPACIFIC Project." *Bulletin of Earthquake Engineering*, 16(6), 2367–420.

Halldórsson, B., Olivera, C. I., Rahpeyma, S., Ólafsson, S., Green, R. A., and Snæbjörnsson, J. Þ. (2016). "On the HVSR Estimation at Icelandic Strong-Motion Stations." *Proceedings of the 17th Nordic Geotechnical Meeting*, Reykjavík, Iceland, 1243–52.

Kennedy, T. J., Halldórsson, B., Snæbjörnsson, J. Þ., and Green, R. A. (2019). "Influence of Gravel Fill on the Seismic Response Characteristics of Sites in Iceland." *Proceedings of the XVII European Conference on Soil Mechanics and Geotechnical Engineering*, Reykjavík, Iceland.

Konno, K., and Ohmachi, T. (1998). "Ground-Motion Characteristics Estimated from Spectral Ratio Between Horizontal and Vertical Components of Microtremor." *Bulletin of the Seismological Society of America*, 88(1), 228–41.

Kudo, K. (1995). "Practical Estimates of Site Response State-of-Art Report." *Proceedings of the 5th International Conference on Seismic Zonation*, Nice, France.

Lachet, C., and Bard, P.-Y. (1994). "Numerical and Theoretical Investigations on the Possibilities and Limitations of Nakamura's Technique." *Journal of Physics of the Earth*, 42(4), 377–97.

Lachet, C., Hatzfeld, D., Bard, P.-Y., Theodulidis, N., Papaioannou, C., and Savvaidis, A. (1996). "Site Effects and Microzonation in the City of Thessaloniki (Greece) Comparison of Different Approaches." *Bulletin of the Seismological Society of America*, 86(6), 1692–1703.

Lermo, J., and Chávez-García, F. J. (1994). "Are Microtremors Useful in Site Response Evaluation?" *Bulletin of the Seismological Society of America*, 84(6), 1350–64.

Maresca, R., Castellano, M., De Matteis, R., Saccorotti, G., and Vaccariello, P. (2003). "Local Site Effects in the Town of Benevento (Italy) from Noise Measurements." *Pure and Applied Geophysics*, 160(9), 1745–64.

Mucciarelli, M. (1998). "Reliability and Applicability of Nakamura's Technique Using Microtremors: An Experimental Approach." *Journal of Earthquake Engineering*, 2(4), 625–38.

Mucciarelli, M., and Gallipoli, M. R. (2001). "A Critical Review of 10 Years of Microtremor HVSR Technique." *Bollettino di Geofisica Teorica ed Applicata*, 42(3–4), 255–66.

Nakamura, Y. (1989). "A Method for Dynamic Characteristics Estimation of Subsurface Using Microtremor on the Ground Surface." *Quarterly Report of Railway Technical Research Institute*, 30(1), 25–30.

Nakamura, Y. (2000). "Clear Identification of Fundamental Idea of Nakamura's Technique and its Applications." *Proceedings of the 12th World Conference on Earthquake Engineering*, Auckland, New Zealand.

Nogoshi, M., and Igarashi, T. (1971). "On the amplitude characteristics of microtremor (Part 2)." *Journal of Seismological Society of Japan*, 24, 26–40.

Ohmachi, T., Konno, K., Endoh, T., and Toshinawa, T. (1994). "Refinement and Application of an Estimation Procedure for Site Natural Periods Using Microtremor." *Japan Society of Civil Engineers*, 489(1–27), 251–61.

Olivera, C. I., Halldórsson, B., Ólafsson, S., Green, R. A., and Sigbjörnsson, R. (2014). "A First Look at Site Effects at Icelandic Strong-Motion Stations Using Microseismic Data." *Proceedings of the 2nd European Conference on Earthquake Engineering*, Istanbul, Turkey.

Rahpeyma, S., Halldórsson, B., Olivera, C. I., Green, R. A., and Jónsson, S. (2016). "Detailed Site Effect Estimation in the Presence of Strong Velocity Reversals within a Small-Aperture Strong-Motion Array in Iceland." *Soil Dynamics and Earthquake Engineering*, 89, 136–51.

Rodriguez-Marek, A., Bray, J. D., and Abrahamson, N. A. (2001). "An Empirical Geotechnical Seismic Site Response Procedure." *Earthquake Spectra*, 17(1), 65–87.

Seed, H. B., and Idriss, I. M. (1971). "Influence of Soil Conditions on Building Damage Potential During Earthquakes." *Journal of the Structural Division, Proceedings of the American Society of Civil Engineers*, 97(ST2), 639–63.

Seed, H. B., Whitman, R. V., Dezfulian, H., Dobry, R., and Idriss, I. M. (1972). "Soil Conditions and Building Damage in 1967 Caracas Earthquake." *Journal of the Soil Mechanics and Foundations Division, Proceedings of the American Society of Civil Engineers*, 98(SM8), 787–806.

Seht, M. I., and Wohlenberg, J. (1999). "Microtremor Measurements Used to Map Thickness of Soft Sediments." *Bulletin of the Seismological Society of America*, 89(1), 250–59.

SESAME. (2004). "Guidelines for the Implementation of the HV Spectral Ratio Technique on Ambient Vibrations; Measurements, Processing, and Interpretation." European Project n° EVG1-CT-2000-00026.

Theodulidis, N. P., and Bard, P.-Y. (1995). "Horizontal to Vertical Spectral Ratio and Geological Conditions: An Analysis of Strong Motion Data from Greece and Taiwan (SMART-1)." *Soil Dynamics and Earthquake Engineering*, 14(3), 177–97.

Tokeshi, J. C., and Sugimura, Y. (1998). "On the Estimation of the Natural Period of the Ground Using Simulated Microtremors." *Proceedings of the 2nd International Symposium on the Effects of Surface Geology on Seismic Motion*, Yokohama, Japan, 651–53.

Wakamatsu, K., and Yasui, Y. (1996). "Possibility of Estimation for Amplification Characteristics of Soil Deposits based on Ratio of Horizontal to Vertical Spectra of Microtremors." *Proceedings of the 11th World Conference on Earthquake Engineering*, Acapulco, Mexico.

Zhao, J. X., Irikura, K., Zhang, J., Fukushima, Y., Somerville, P. G., Asano, A., Ohno, Y., Oouchi, T., Takahashi, T., and Ogawa, H. (2006). "An Empirical Site-Classification Method for Strong-Motion Stations in Japan Using HV Response Spectral Ratio." *Bulletin of the Seismological Society of America*, 96(3), 914–25.

Chapter 3: Thesis Conclusions

3.1. Summary and Conclusion

This thesis revealed the site response characteristics of six sites located throughout the Reykjavík, Iceland, capital region. While the primary objective was to determine the site response characteristics (e.g., the predominant frequency and site amplification effects) of compacted gravel fill using microtremor measurements, multiple site conditions (e.g., the pre-excavation and reference conditions) were also determined to quantify the change in site response characteristics as a result of gravel fill placement. The HVSR technique was the main analysis method used in this study and proved to be a relatively easy-to-perform and affordable means to achieve this study's objective. The data collected during this study has advanced the understanding of the dynamic site response characteristics of compacted gravel fill used in Iceland, which is necessary for seismic hazard and risk analyses.

The site response characteristics of gravel fill depend on the competent stratum beneath the gravel fill and the impedance contrast between the two. The placement of compacted gravel fill on sites underlain by dense to very dense silty sand and bedrock results in a predominant frequency shift to higher frequencies (between 10 and 16 Hz) and, at these frequencies, an increase of relative site amplification (by 2.5 to 5 times) as fill thickness increases. Fill underlain by lava rock also results in a shift of the predominant frequency to a higher frequency (between 9 and 10.5 Hz). However, little change in relative site amplification occurs at high frequencies (0.95 to 1.2 times). Compacted gravel placed atop lava rock revealed a case where the relative amplification decreased (by 0.35 to 0.5 times) in the mid-band frequency range (between 3.5 and 4.5 Hz) as a result of gravel fill placement, unlike any other reference condition encountered.

3.2. Recommendations for Future Work

This thesis has shown the effectiveness of HVSR to characterize site effects throughout the Reykjavík capital region. However, the data set is limited. The four recommendations listed below would either advance or pair well with the results presented herein. Recommendations for future work include:

1. Continue microtremor microzonation throughout the Reykjavík, Iceland, capital region to increase the resolution of mapped site response characteristics. Additional microtremor measurements collected atop compacted gravel fill and lava rock will increase the reliability of trends observed during this study.
2. Record microtremor measurements at the top and bottom floor of the building constructed on compacted gravel fill to determine the building's fundamental frequency and the site response after building construction (Mucciarelli and Gallipoli 2001). From these measurements, the effect of building construction on the site response characteristics can be determined. Moreover, the building's fundamental frequency can be compared to that of the underlying compacted gravel fill. If these values match, an undesired resonance phenomenon may occur during earthquake shaking and cause larger forces upon the structure.
3. Develop a two-parameter characterization seismic site classification scheme (Cadet et al. 2008) in Iceland based on the results from non-invasive survey techniques (e.g., HVSR, MASW, SASW; Foti et al. 2018) to reduce site class variability. The site's natural period obtained from the HVSR provides one important parameter used in many multiparameter classification schemes (e.g., Zhao et al. 2006). Rodriguez-Marek et al. (2001) show a decrease in site class variability when two parameters (dynamic soil stiffness and depth to bedrock) were used in site classification compared to one parameter (e.g., average small-strain shear wave velocity over 30 m depth).
4. Compare popular ground improvement methods used in other countries to the removal and replacement method used in Iceland. Alternative methods (e.g., rammed aggregate piers and stone columns) may save time and construction costs due to their faster application and smaller carbon-footprint because fewer truckloads of soil are required. However, additional soil and site investigations are required to assess the applicability of these methods in Iceland.

Appendix A: The Influence of Gravel Fill on the Seismic Response Characteristics in Iceland

A.1. 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.

A.2. 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.

A.3. 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 33.8 Hz is used for the first pass and a low amplitude mode with 30.8 Hz for subsequent passes. The gravel fill was compacted to 60-65% relative density, with the compaction being monitored in real-time by the vibro-roller.

Figure A.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.4. 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 A.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.

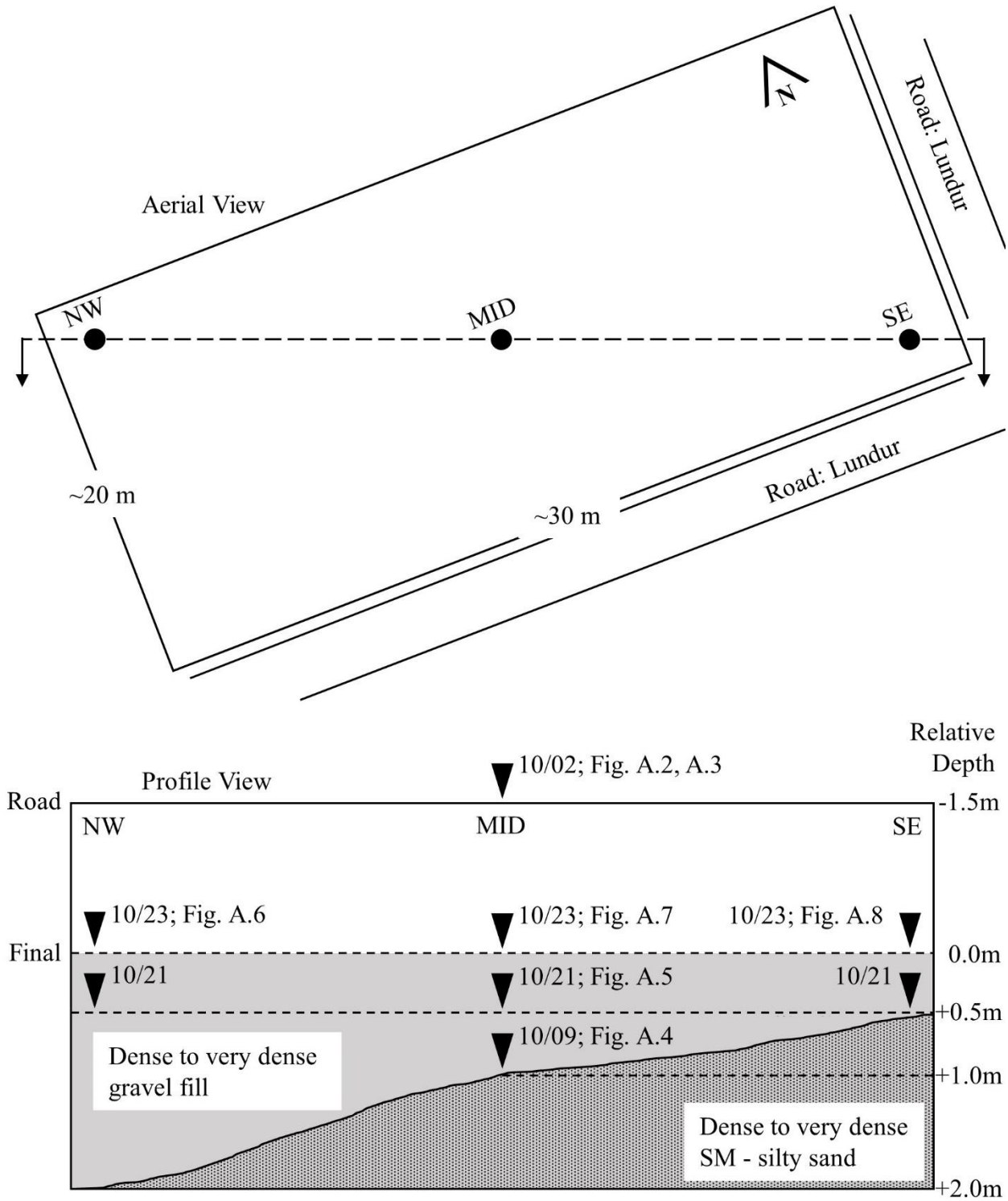

Figure A.1. Aerial-view and profile-view sketches of the fill study site in Kópavogur, Iceland. The black triangles are the approximate locations of the stations relative to the final fill height; start-date of recording and figure number is shown adjacently. Not drawn to scale.

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 A.2** and **A.3**. **Figure A.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 A.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.

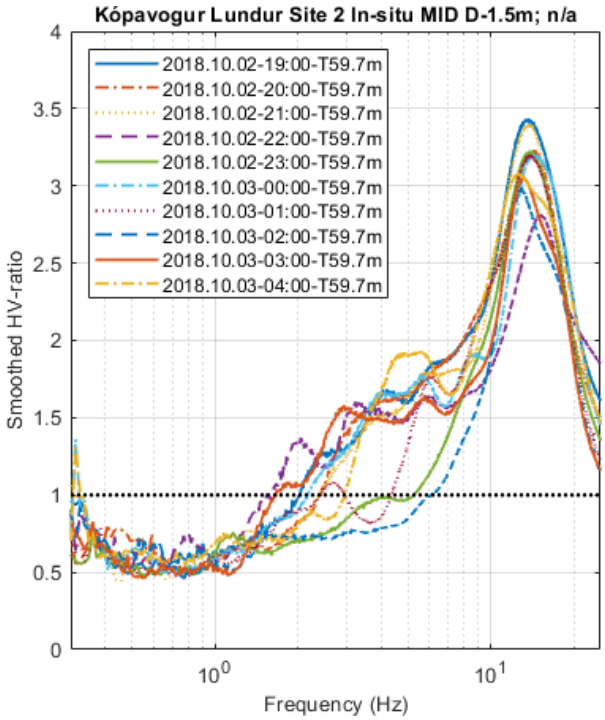

Figure A.2. HVSR curves for MID before excavation for all ~60-minute intervals. Relative depth -1.5 m.

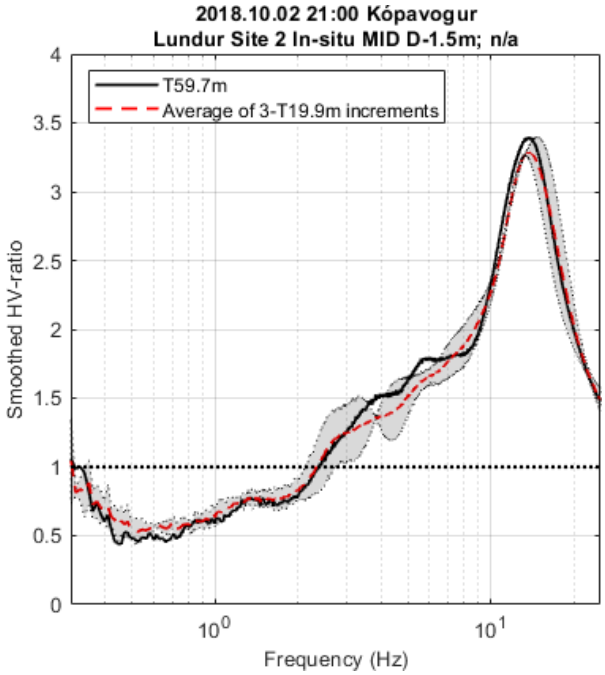

Figure A.3. Representative HVSR curve for a ~60-minute interval for MID and the average of three ~20-minute segments. The shaded region represents ± one standard deviation of average.

A.5. Results and Discussion

Figures A.3 and **A.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 A.5 and **A.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 A.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 A.6**, **A.7**, and **A.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.

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 mean 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.

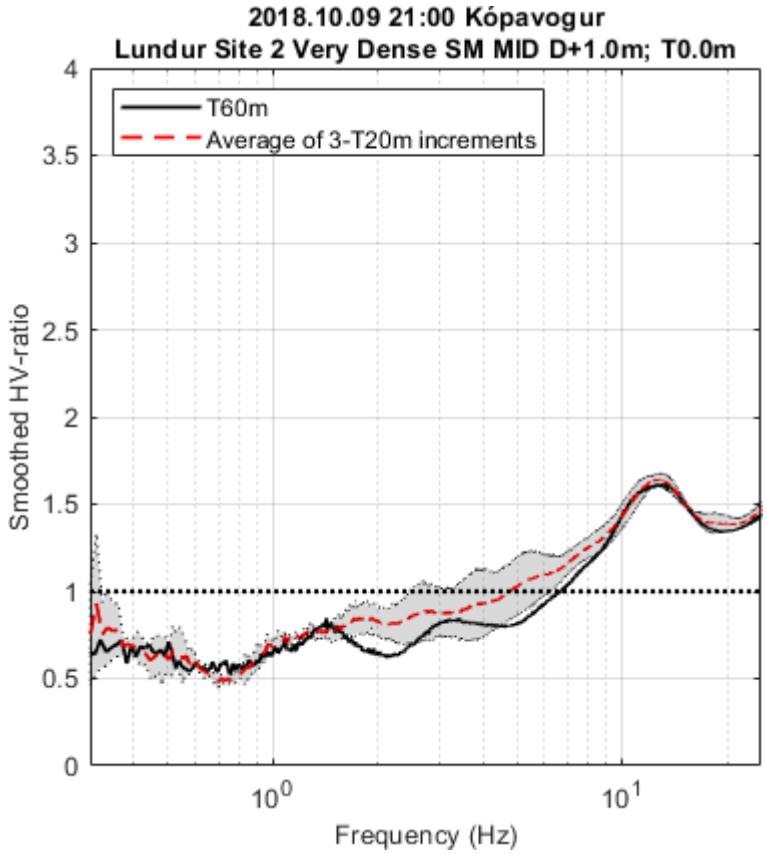

Figure A.4. Representative reference HVSR curve for a ~60-minute interval for MID and the average of three ~20-minute segments. The shaded region shows ± one standard deviation of average.

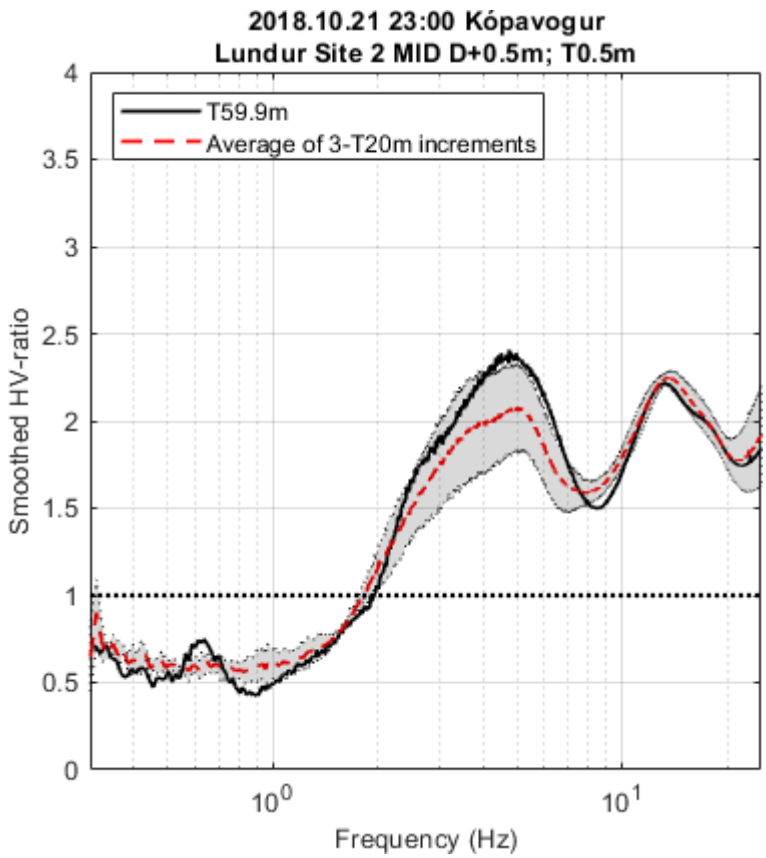

Figure A.5. Representative reference HVSR curve for a ~60-minute interval for MID and the average of three ~20-minute segments. The shaded region shows ± one standard deviation of average.

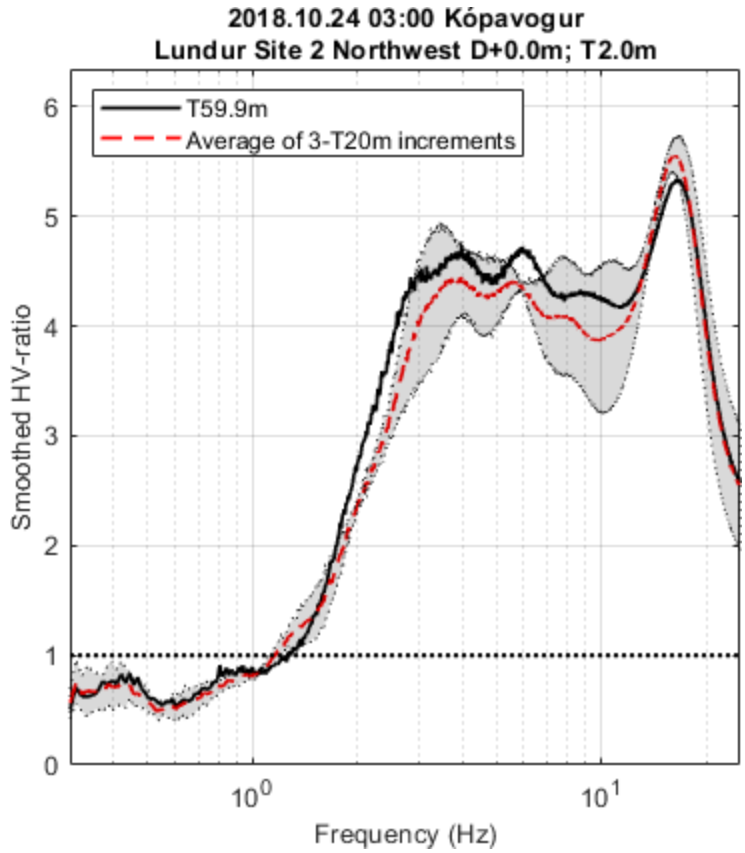

Figure A.6. HVSR for the NW (deep) location and the average of three ~20-minute segments. The shaded region represents ± one std. deviation of average.

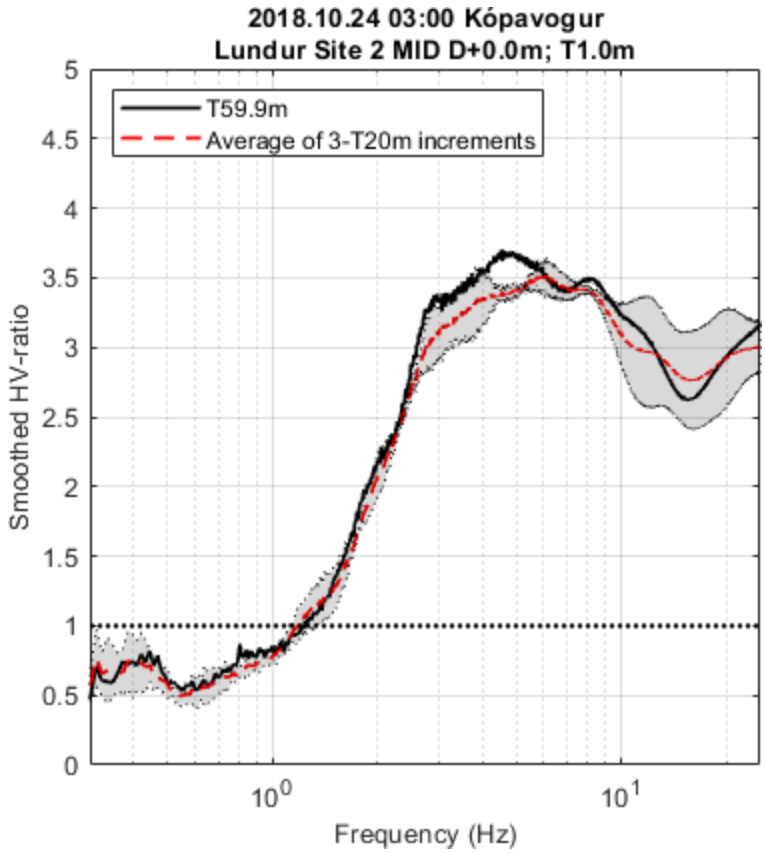

Figure A.7. HVSR for the MID (intermediate) location and the average of three ~20-minute segments. The shaded region represents ± one std. deviation of average.

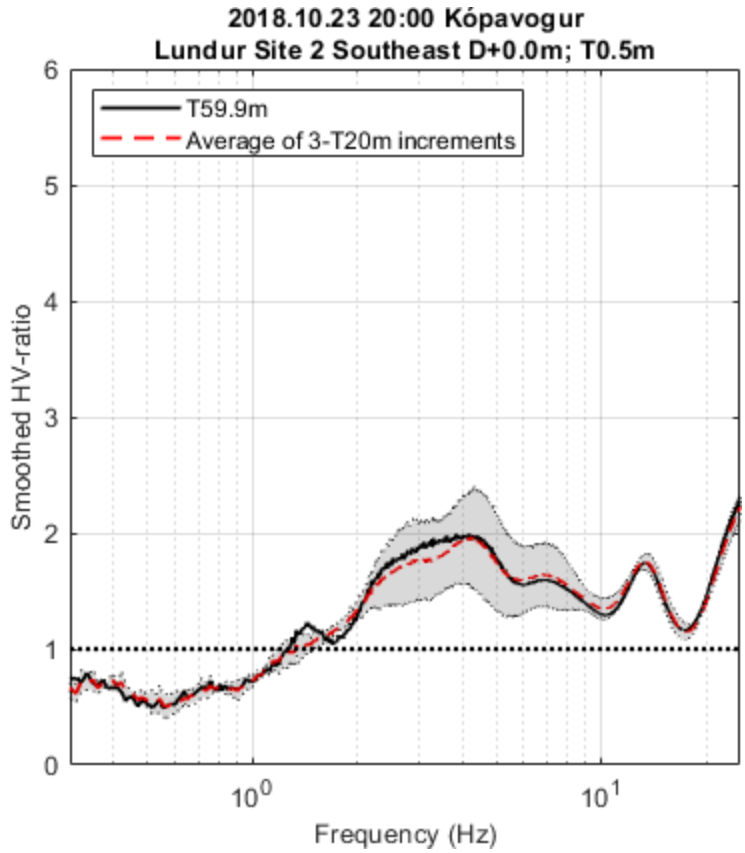

Figure A.8. HVSR for the SE (shallow) location and the average of three ~20-minute segments. The shaded region represents ± one std. deviation of average.

A.6. 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.

A.7. Acknowledgments

This work would not have been possible without the financial support provided by the Leifur Eiríksson Foundation. The seismometers were rented from the LOKI instrument bank at the Icelandic Meteorological Office. In addition, the Office provided transportation support. The authors thank Guðjón þór Ólafsson and Atli Gunnarsson from the BYGG company – your creative collaboration, time, and assistance were crucial for this study.

A.8. References

Halldórsson, B., Olivera, C. I., Rahpeyma, S., Ólafsson, S., Green, R. A., and Snæbjörnsson, J. Þ. (2016). "On the HVSR Estimation at Icelandic Strong-Motion Stations." *Proceedings of the 17th Nordic Geotechnical Meeting*, Reykjavík, Iceland, 1243–52.

Konno, K., and Ohmachi, T. (1998). "Ground-Motion Characteristics Estimated from Spectral Ratio Between Horizontal and Vertical Components of Microtremor." *Bulletin of the Seismological Society of America*, 88(1), 228–41.

Olivera, C. I., Halldórsson, B., Ólafsson, S., Green, R. A., and Sigbjörnsson, R. (2014). "A First Look at Site Effects at Icelandic Strong-Motion Stations Using Microseismic Data." *Proceedings of the 2nd European Conference on Earthquake Engineering*, Istanbul, Turkey.

Rahpeyma, S., Halldórsson, B., Olivera, C. I., Green, R. A., and Jónsson, S. (2016). "Detailed Site Effect Estimation in the Presence of Strong Velocity Reversals within a Small-Aperture Strong-Motion Array in Iceland." *Soil Dynamics and Earthquake Engineering*, 89, 136–51.

Appendix B: Additional Information Regarding the Vatnskarðsnáma Quarry

The Vatnskarðsnáma Quarry is located south of the Reykjavík capital region. **Figure B.1** shows a panoramic view of the site. The quarry began in the 1950s and was popularized in the early 1980s. Since then, Vatnskarðsnáma has been the largest manufacturer of sand and gravel-sized volcanic conglomerate rock in Iceland, with an output of over 800,000 m^3 of aggregate during 2018, with an expected increase of 20% in 2019. The quarry operates year-round, but the highest demand is during September and October.

The material produced at Vatnskarðsnáma has many uses. It is estimated that 50% of the aggregate mined from the quarry is subsequently sorted and shaped (e.g., cubic, spherical, angular, smooth, etc.). Sorted aggregates are used as a component of asphalt or concrete mixtures and as road underlayment. The second half of the mined aggregate is not sorted and is used as fill to support building structures.

The mining process begins at the top of the mountain. Fifty- and seventy-ton bulldozer tractors rip up the underlying ground with a large hook and push the resulting material off of the mountainside (as shown in **Figures B.2** and **B.3**). Drilling and blasting occur in areas with hard rock. It is estimated that the material at this stage ranges between 0 and 300 mm in diameter. It is important to note, therefore, that the aggregate used as gravel fill includes cobble-sized particles. However, the supervisors at each construction site have said their highest choice when choosing material for fill contains mostly gravel-sized particles.

Figure B.1. Panoramic view of the Vatnskarðsnáma Quarry. The flat terraces along the side of the mountain serve as areas from which volcanic conglomerate rock is mined.

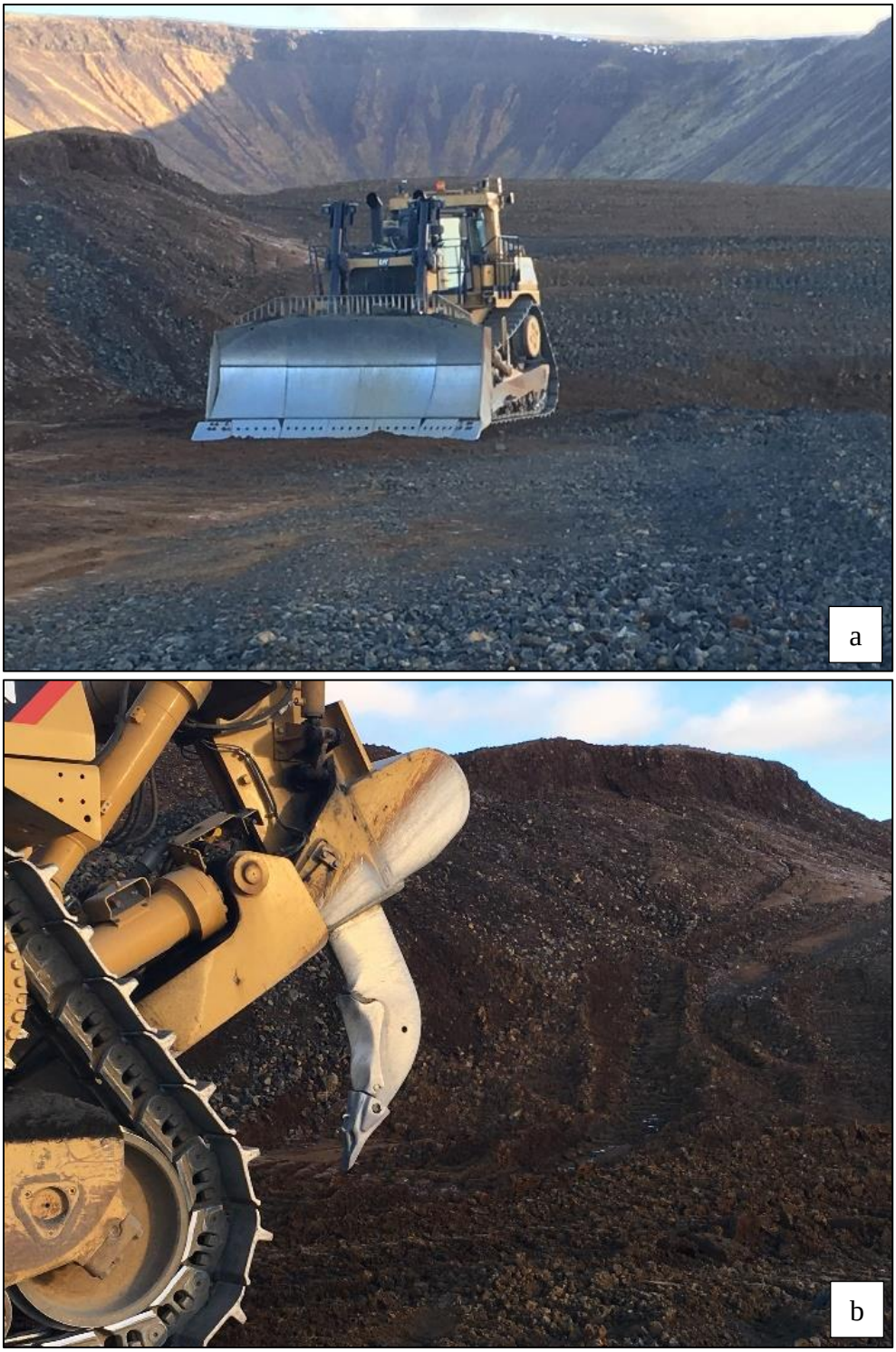

Figure B.2. A 70-ton bulldozer tractor (a) with hook attachment (b) used to rip up the ground and push the resulting material off the mountainside.

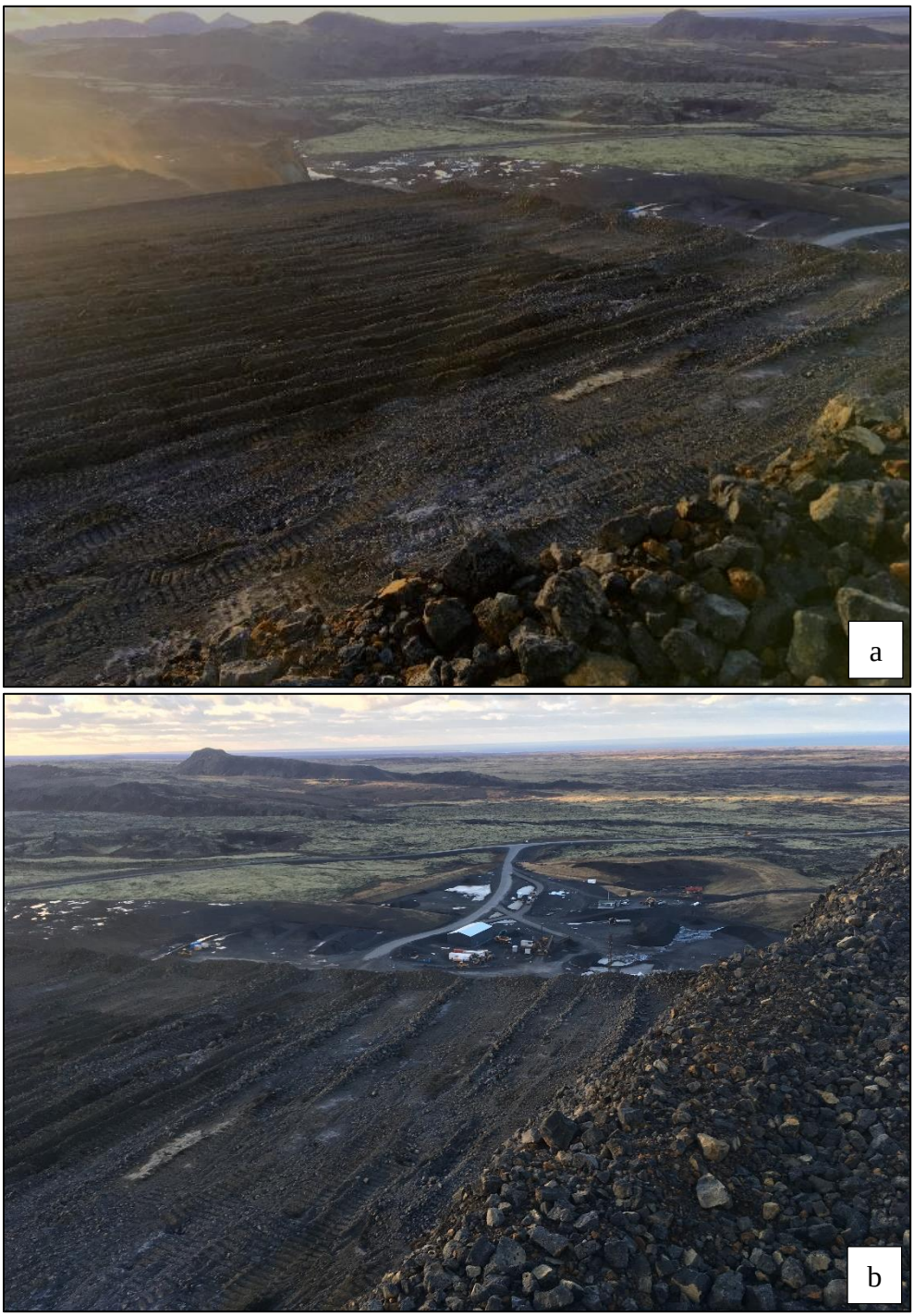

Figure B.3. A mining terrace at Vatnskarðsnáma Quarry. The striations in the ground (a) are the result of the tractor hook ripping up the volcanic conglomerate rock. The mined rock is pushed off the mountainside (b) to be collected at the base.

Appendix C: Additional Site Photographs

Appendix C presents photographs taken at all sites encountered during this study. The photographs are organized by site location. Sites are presented in the same order as *Section 2.5. Results and Discussion*.

C.1. Lundur Sites 1 and 2 Located in Kópovogur

Figure C.1. Photographs were taken at Lundur Site 1. The dense to very dense silty sand reference stratum (a), compacted gravel fill at an intermediate grade (b) and building foundation (c) are shown.

Figure C.2. Photographs were taken at Lundur Site 2. The in-situ condition with a temporary gravel parking lot (a), the dense to very dense silty sand reference stratum (b), and gravel fill at an intermediate grade (c) are shown.

C.2. The Nauthólsvegur 83 Site Located in Reykjavík

Figure C.3. Photographs were taken at Nauthólsvegur 83 site. The Southwest (a) and Northwest (b) sections of the building foundation are shown.

Figure C.4. Photographs were taken at Nauthólsvegur 83 site. The positions of the rock outcrop (a, b), Northeast (b), and Northwest (b) seismometer locations are highlighted by circles in (b). Note that the seismometer stationed atop the rock outcrop was covered by nearby soil.

C.3. Stuðlaskarð Sites 1 and 2 Located in Hafnarfjörður

Figure C.5. Photographs were taken at Stuðlaskarð Site 1. The positions of West, MID, and East seismometer locations atop lava rock are highlighted by circles. Three lava rock undulations are pronounced.

Figure C.6. Photographs were taken at Stuðlaskarð Site 1. A seismometer set up at the West position is shown stationed atop compacted gravel fill at the final grade.

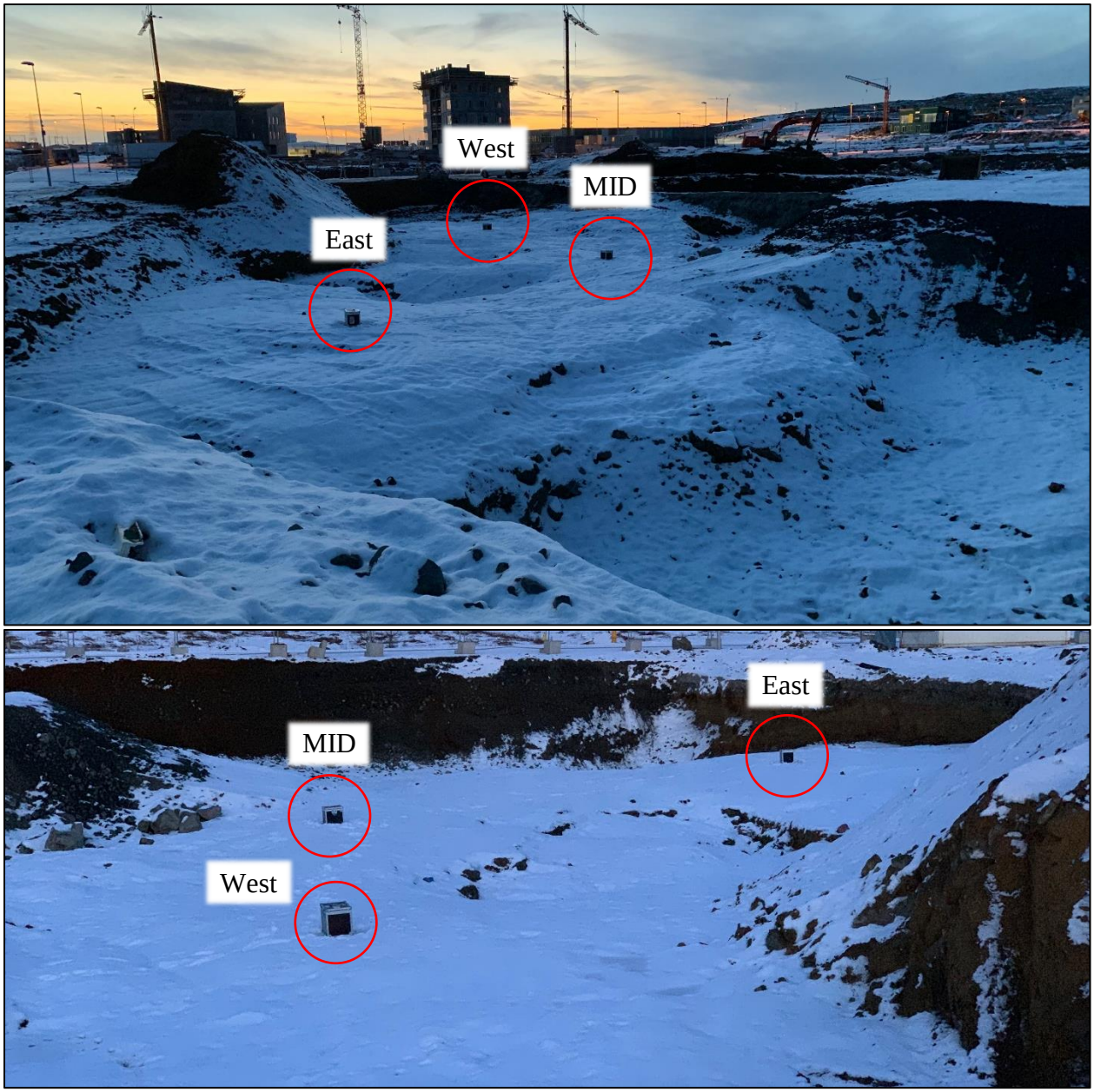

Figure C.7. Photographs were taken at Stuðlaskarð Site 2. The positions of West, MID, and East seismometer locations atop lava rock are highlighted by circles. Lava rock undulations are pronounced.

Figure C.8. The photograph was taken at Stuðlaskarð Site 2. The positions of West and East seismometer locations stationed atop compacted gravel fill at the final grade are highlighted by circles.

C.4. The Breidholt Site Located in Reykjavík

Figure C.9. Photographs were taken at Breidholt. A panoramic view of the site (a), the surface condition where the seismometer was in contact with the in-situ soils during measurements (b), and covered seismometer (c) are shown.