On the seismic response of lava-layers as foundations for roads and bridges from microseismic recordings

Annual project report for 2019

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EARTHQUAKE ENGINEERING RESEARCH CENTRE
UNIVERSITY OF ICELAND

Project's details

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On the seismic response of lava-layers as foundations for roads and bridges from microseismic recordings
Flokkun:
Mannvirki/Structures

umsækjanda

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1. Introduction

One of the important lessons learned from catastrophic earthquakes (San Francisco,1906; Mexico City, 1985; and Loma Prieta, 1989) is that the seismic waves can significantly change over relatively small areas because of variation in localized geological conditions (Seed et al. 1988; Aki 1993). Since the spatial variability of strong ground motions can significantly affect the response of lifeline and service networks (e.g., electricity transmission networks, power grids, pipelines, water supply, and sewage systems), local and site-specific characteristics should be considered as a critical factor in earthquake-resistant design and studies of where earthquake ground motion may be systematically higher than in other areas.

In Iceland, high seismic background as well as fast-growing population and an increasing number of infrastructures and critical lifeline networks pose a high potential of seismic risk (Einarsson 1991; Stefánsson et al. 1993; Sigbjörnsson et al. 2006). Hence, ongoing research efforts on understanding the seismic activity characteristics and regional site-effects are required in order to mitigate earthquake disasters and early-stage damages. The near-surface amplification of seismic waves (i.e., “site-effects”) on what is called “rock” in Iceland is typically assumed to be negligible. While this may be the case for old bedrock, it is not the case for young lava-rock layers when softer sedimentary layers lie underneath (creating a phenomenon known as “shear wave velocity reversal” with depth). This is a very common site condition in Iceland on, or in the vicinity of the volcanic zones, and lava-rock is generally classified simply as “rock” and is not considered specifically in seismic design. This needs to change as recent site-effect investigations have shown that lava-rock shows significantly different site response than bedrock, and is also variable even over relatively short distances on the lava-rock itself (Bessason and Kaynia 2002; Rahpeyma et al. 2016, 2017, 2018, 2019a, 2020b) are present on the surface of lava-rock. This research thus suggests a detailed investigation of site-effect characterization employing comprehensive physical modeling within a rigorous statistical framework to develop site amplification factors for profiles characterized as lava-rock. The results of this study will find direct practical applications in seismic microzonation, earthquake-resistant design of pipeline systems and urban planning.

In this study, therefore, we investigate (1) how and to what extent, we can identify the underlying site conditions from Icelandic recordings; (2) how and to what extent, we can mitigate seismic risk and improve aseismic design criteria, for key energy and service infrastructures as well as lifeline networks.

2. Summary of Project Results

2.1. Influence of Gravel fill on the seismic site response characteristics

Man-made geotechnical foundations for structures in the form of engineered fills made of compacted volcanic rock conglomerate has largely become prevalent in engineering practice in Iceland over the last decades. In this project, we aim to shed light on the effects engineered fills on seismic site response characteristics. To do so, horizontal-to-vertical spectral ratios (HVSR) were computed from microtremor measurements recorded at different sites in Reykjavik, made at varying times during excavation and placement of the fill (see Figure 1). Furthermore, over 500 hours of microtremor measurements were recorded in South Iceland and analyzed, prepared for further investigations.

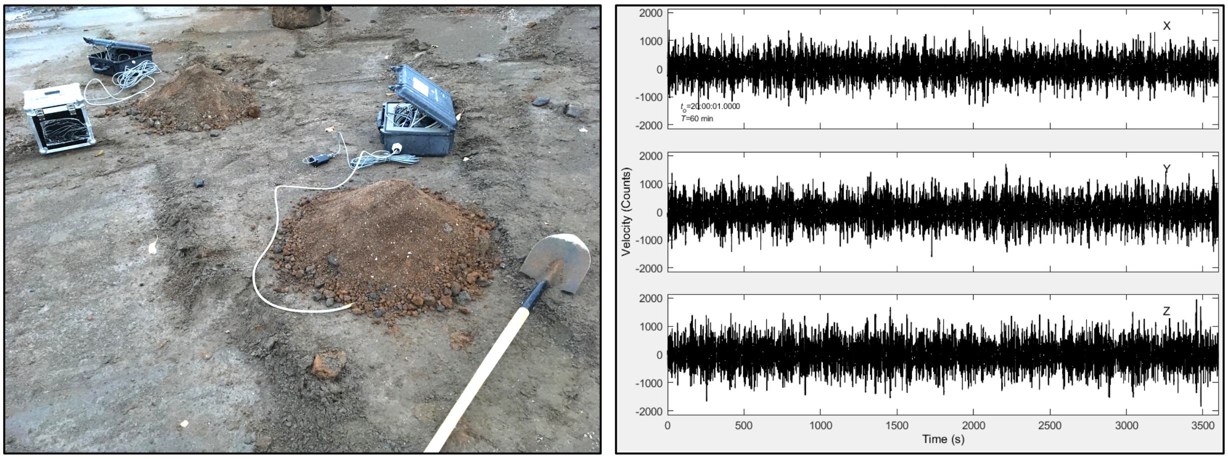

Figure 1. Instrument set up and example velocity time histories of microseismic noise.

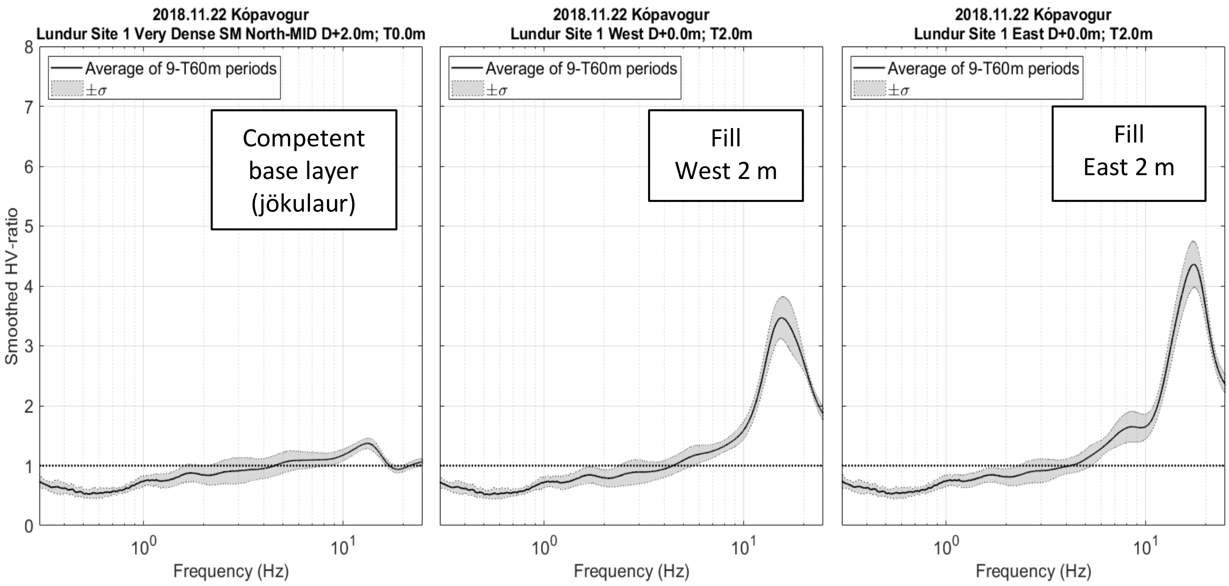

Figure 2. Representative mean HVSR curve for two sites with different geological conditions. The shaded region represents ± one standard deviation of average.

As one can see in Figure 2, 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 captures 3-D site effects, with the site's fundamental frequency increasing with fill thickness (Kennedy et al. 2019).

2.2. Estimating shear-wave velocity profiles in the presence of velocity reversals

It has been well investigated that the inversion of physical parameters of the subsoil structure provides reliable results around the resonance frequency on the basis of the HVSR method using the body-wave approximation (Tsai 1970; Herak 2008; Albarello and Lunedei 2010). However, we showed that the body-wave approximation is relatively insensitive to velocity reversals that are highly common in Iceland and fails to reproduce the observed fundamental frequencies (Rahpeyma et al. 2016). Therefore, due to the obvious mechanical similarities to that of a dynamic structural system, we modeled the geologic profile as a classically damped dynamic system subjected to base excitation. The Geological evidence and borehole records of our case study in the town of Hveragerði show the existence of two lava layers and for that reason, a two-degree of freedom (2DOF) system was assumed to model the bimodal HVSR amplification (Rahpeyma et al. 2016, 2017) (see Figure 3).

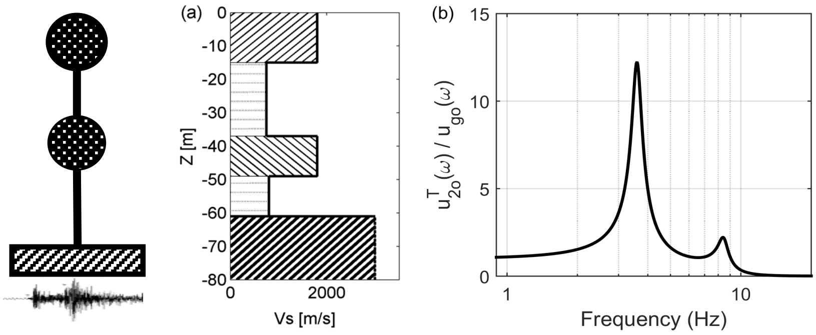

Figure 3. (a) Shear-wave velocity profile obtained by modal analysis (hatched and dotted areas denote lava and sedimentary layers, respectively); (b) The total displacement transfer function corresponding to the soil structure in (a) exhibiting two fundamental modes at the predominant frequencies (Rahpeyma et al. 2016).

In this project, we set up the inversion scheme in the context of the Bayesian statistical framework (Berger 2013; Congdon 2014) using the Markov Chain Monte Carlo (MCMC) technique (Brooks 1998) along with the Metropolis step algorithm (Metropolis et al. 1953) to explore the model parameters space and find the best fitting family of subsoil properties. The Bayesian methodology provides a robust statistical structure for making inference on different independent variables in the light of observations using an underlying probability statement. Figure 4 shows the posterior histograms for thickness and S-wave velocity for a 4-layer subsoil structure over the half-space along with the mean and 16-84% posterior percentile of shear-wave velocity profile beneath station IS605 in Hveragerði, South Iceland (Rahpeyma et al. 2019b, 2020c).

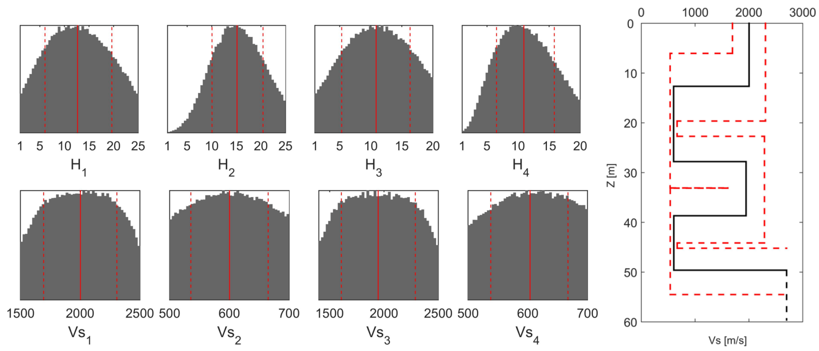

Figure 4. (left) Posterior histograms for thickness and S-wave velocity. The thick red line shows the posterior median and the dotted red lines indicate 16-84% posterior percentile; (Right) (b) S-wave velocity profile for the posterior (solid black) model along with its 16-84% posterior percentile (dashed red) for a 4-layer subsoil structure under station IS605 in Hveragerði, South Iceland (Rahpeyma et al. 2019b).

2.3. A quantitative estimate of the earthquake source, path, and site-effects on ground motion variability

The earthquake ground motions of over earthquakes of $M_w 6.3$ recorded on a small aperture strong-motion array in south Iceland (the ICEARRAY I) that is situated on a relatively uniform site condition characterized as rock exhibit a statistically significant spatial variation of earthquake peak ground amplitudes across the array. In the current project, we implemented a Bayesian hierarchical model (BHM) of the seismic ground motions that partitions the model residuals into three distinct effects: an earthquake event term, station term, and event-station term, respectively (Rahpeyma et al. 2018).

Later, Rahpeyma et al. (2019) implemented the BHM to investigate site-effects on two Icelandic strong-motion arrays in the south (ICEARRAY I) and north (ICEARRAY II) of Iceland with totally different geological settings. The results highlighted that although the site conditions across ICEARRAY I have been classified as uniform (i.e., “rock”, and with a relatively flat topography) station terms contribute around to the total variability in the amplitudes of predicted ground motions across the array. On the other hand, the contribution of site effect variability across ICEARRAY II was found to be larger up to, consistent with the observation that it is built on top of much more variable subsoil structure and topography. In the current study, we extended the BHM model for the earthquake peak ground acceleration, PGA i.e. the peak acceleration response of an “infinitely stiff“ Single-Degree-of-Freedom, SDOF, oscillator and pseudo-spectral acceleration, PSA i.e. the maximum response amplitude of a 5% damped SDOF oscillator with a fundamental resonance period to seismic ground motion at oscillator periods of interest recorded by ICEARRAY I strong-motion stations (Rahpeyma et al. 2020b, a).

The station terms are important since they are a practical tool to show how larger or smaller, compared to the array average, the ground motions at those stations tend to be, and thus act as proxies for localized site effects and amplification factors. The findings of this study indicate that the station terms tend to increase in the period range of 0.1-0.3 s on most stations and to different extents, leading to an increase in the overall variability of ground motions at those periods, captured by a larger inter-station standard deviation. Comparing the findings of this study with recent site-effect investigation results (Rahpeyma et al. 2016) revealed that high variability in the period range of 0.1-0.3 s is largely due to a considerable increase in the inter-station variability. In other words, the individual station terms all increase considerably for those stations residing on lava-rock but do so to different extents. Another important finding of the current study is presented in Figure 5 showing the relative ratio of station terms between strong-motion stations located on lave-rock and the reference station (i.e., the average station terms of stations IS609, IS611, and IS612 which are not considered as typical lava-rock stations). The results of this project provide an important contribution to our improved understanding of the key factors that affect the variation of seismic ground motions across a relatively small area of ICEARRAY I.

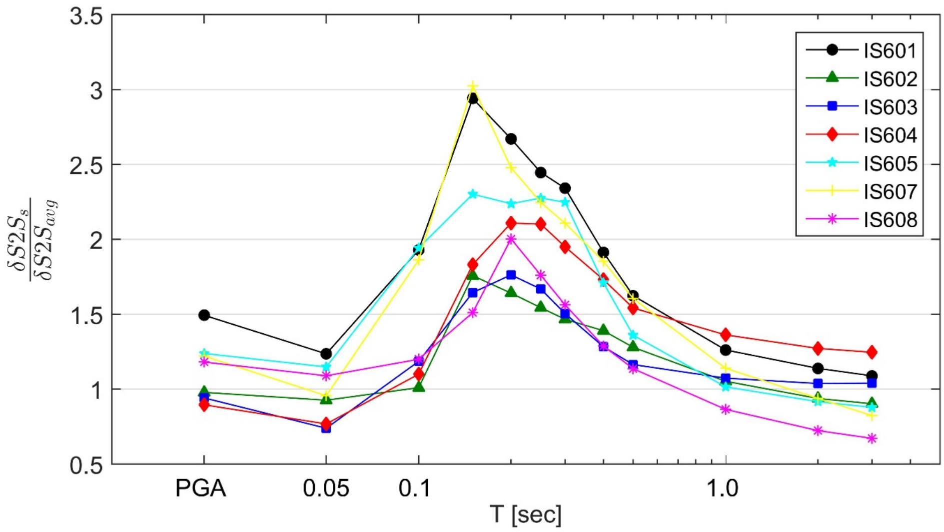

Figure 5. The relative ratio between ICEARRAY I stations located on lava-rock and the average of station terms located on the rock (i.e., IS609, IS611, and IS612) (Rahpeyma et al. 2020b).

3. **Summary of** Publications

The ***results*** and their dissemination have exceeded the original expectations. The results have in part been published and presented at scientific conferences in Iceland during 2019:

1- Rahpeyma S., Halldorsson B., Hrafnkelsson B., Jónsson S. (2019) "Site Effect Estimation on two Icelandic Strong-motion Arrays Using a Bayesian Multi-level Model for the Spatial Distribution of Earthquake Ground Motion Amplitudes" *Proceedings of the 3rd international workshop on earthquakes in North Iceland*, 21-24 May 2019, Húsavík, Iceland.
2- Rahpeyma S., Kennedy T. J., Halldorsson B., Hrafnkelsson B., Green, R. A., and Snæbjörnsson J. Þ. (2019) "On the Microseismic Response of Lava Layers as Road and Bridge Foundations" Vegagerðin Annual Meeting, 01 November 2019, Reykjavik, Iceland (Poster)
3- Kennedy T. J., Halldorsson B., Snæbjörnsson J. Þ., Green, R. A., and Rahpeyma S. (2019) "Microseismic response characteristics of typical gravel fills in Iceland using HVSR and SSR techniques". In: *Proceedings of the 3rd International Workshop on Earthquake Engineering in North Iceland*, 21-24 May 2019, Húsavík, Iceland.
4- Kennedy T.J., Halldorsson B., Snæbjörnsson J. Þ., Green R.A. (2019) "Influence of gravel fill on the seismic response characteristics of sites in Iceland". In: *Proceedings of the XVII European Conference on Soil Mechanics and Geotechnical Engineering*. Reykjavik, Iceland, 1-6 September 2019, 7p.

The following conference papers have been submitted, and have been accepted, for presentation and publication at two major international conferences in 2020:

5- *Rahpeyma S., Halldorsson B., Hrafnkelsson B. (2020) "Detailed site-effect estimation using multi-level modeling of earthquake strong-motion amplitudes and uncertainties" 6th International Conference on Geotechnical and Geophysical Site Characterization, 7-11 September, Budapest, Hungary (Accepted)*
6- *Rahpeyma S., Halldorsson B., Hrafnkelsson B. (2020) "Subsoil structure estimation in the presence of multiple strong velocity reversals" 17th World Conference on Earthquake Engineering, 13-18 September 2020, Sendai, Japan (Accepted)*

The following manuscripts have been prepared for publication in ISI journals in 2020:

7- *Scientific paper on the shear wave velocity profile estimation of reverse sites i.e., in the presence of multiple strong velocity reversals (manuscript almost ready, in review by coauthors)*
8- *Scientific paper on the Bayesian hierarchical modeling of earthquake ground motion amplitudes and their variabilities in a reverse-sites region (manuscript almost ready, in review by coauthors)*

4. Disclaimer

The authors of the present report are responsible for its contents. The report and its findings should not be regarded as to reflect the Icelandic Road Authority's guidelines or policy, nor that of the respective author's institutions.

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Rahpeyma S, Halldorsson B, Hrafnkelsson B, et al (2020b) Bayesian hierarchical modeling of earthquake ground motion amplitudes and their variabilities over a strong-motion array in Iceland. manuscript in preparation

Rahpeyma S, Halldorsson B, Hrafnkelsson B (2020c) Subsoil Structure Estimation in the presence of Multiple strong velocity reversals. In: 17th World Conference on Earthquake Engineering. Sendai, Japan

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