Strong ground motion in the epicentral area of the 2020-2021 earthquake swarm in the Reykjanes Peninsula, Iceland

Victor M. Hernandez – Earthquake Engineering Research Centre – University of Iceland, Selfoss, Iceland, e-mail: vmh5@hi.is

Rajesh Rupakhety – Earthquake Engineering Research Centre – University of Iceland, Selfoss, Iceland, e-mail: rajesh@hi.is

Simon Ólafsson – Earthquake Engineering Research Centre – University of Iceland, Selfoss, Iceland, e-mail: rajesh@hi.is

Bjarni Bessason – Faculty of Civil and Environmental Engineering – University of Iceland, Reykjavík, Iceland, e-mail: bb@hi.is

Sigurður Erlingsson – Faculty of Civil and Environmental Engineering – University of Iceland, Reykjavík, Iceland, e-mail: sigger@hi.is

Abstract: The Geldingadalur eruption in the Reykjanes Peninsula on 19 March 2021 was preceded by several earthquakes of volcano-tectonic origin throughout 2020 and 2021. Seven earthquakes with magnitude M≥5 took place during the swarm, all of them recorded by the Icelandic Strong Motion Network operated by the Earthquake Engineering Research Centre of the University of Iceland. In this paper we present salient features of strong ground motion in the epicentral area caused by the swarm. Interestingly, earthquakes as small as M5.0 caused peak ground acceleration (PGA) larger than the 475-year return period PGA at a town near the epicentral area. At two recording stations, unusually high energy content at vibration periods <0.3s was detected, with spectral accelerations exceeding the design values. The largest recorded horizontal PGA was ~0.4g at Krýsuvík, station, which is the strongest PGA recorded in Iceland since the M_W6.3 2008 Ölfus Earthquake. For this station we present horizontal-to-vertical spectral ratios indicating likely site-effects. We also compare the attenuation of PGA of the largest event of the sequence with two ground-motion prediction equations (GMPEs). The recorded PGA attenuation is well captured by a local GMPE.

Keywords: ICESMN; Fagradalsfjall; Volcano-tectonic earthquake; Site-effects; Peak ground acceleration.

1. Introduction

The effusive eruption in Geldingadalir that began on 19 March 2021 is the first to occur on the Reykjanes Peninsula since the 13th century episode that affected both the Reykjanes and Svartsengi volcanic systems (Sæmundsson et al., 2020). This eruption is the first in the Fagradalsfjall system in at least 6000 years (Sæmundsson et al., 2016). In the Reykjanes Peninsula, periods of rifting and volcanism occur at intervals of 800–1000 years (Sæmundsson et al., 2020) alternating with periods of predominant transcurrent motion manifested as high seismicity episodes occurring at intervals of a few tens of years (Einarsson, 2008).

Unrest in the Reykjanes Peninsula was first identified in Mt. Þorbjörn-Svartsengi in mid-January 2020, when inflation of about 3-4 mm/day was detected in automated GNSS and InSAR results, coinciding with the onset of an earthquake swarm with magnitudes M<4 (Geirsson et al., 2021). In the Krýsuvík volcanic system, inflation started in mid-July 2020, leading to a M5.6 earthquake on 20 October 2020.

The dike formation in Geldingadalir caused 6 earthquakes of Magnitude M≥5 between 24 February and 14 March 2022. The largest earthquake of the sequence was a M5.7 on 24 February 2022 and occurred in the eastern half of the top part of the magma reservoir. This is the largest recorded earthquake in the Peninsula since 2000 (Jónasson et al., 2021). The injected dike segment following the M5.4 earthquake on 14 March 2021 eventually resulted in the dike propagating to the surface to feed the Geldingadalur eruption.

The Icelandic Strong Motion Network (IceSMN) operated by the Earthquake Engineering Research Centre (EERC) of the University of Iceland recorded ground accelerations caused by these events. Stations as close as ~4km and as far as ~200km were triggered by these events. This paper presents a summary of ground shaking at the stations closest to the epicentres of some of the earthquakes in the Peninsula between 20 October 2020 and 14 March 20021. Horizontal peak ground acceleration (PGA) as large as 0.4g (g being acceleration due to gravity) was recorded at one station, Krýsuvík, during these events. This is the strongest recorded shaking in Iceland since the 2008 Ölfus Earthquake.

Peak ground accelerations, and elastic response spectra of ground motion recorded at four stations during 5 earthquakes with M≥5 are discussed in Section 3, while in Section 4 the attenuation with distance of the recorded PGA for the largest event of the swarm is compared with two ground motion prediction equations. Finally, a plausible explanation for the unusually large PGA recorded at Krýsuvík is given.

2. Tectonic framework

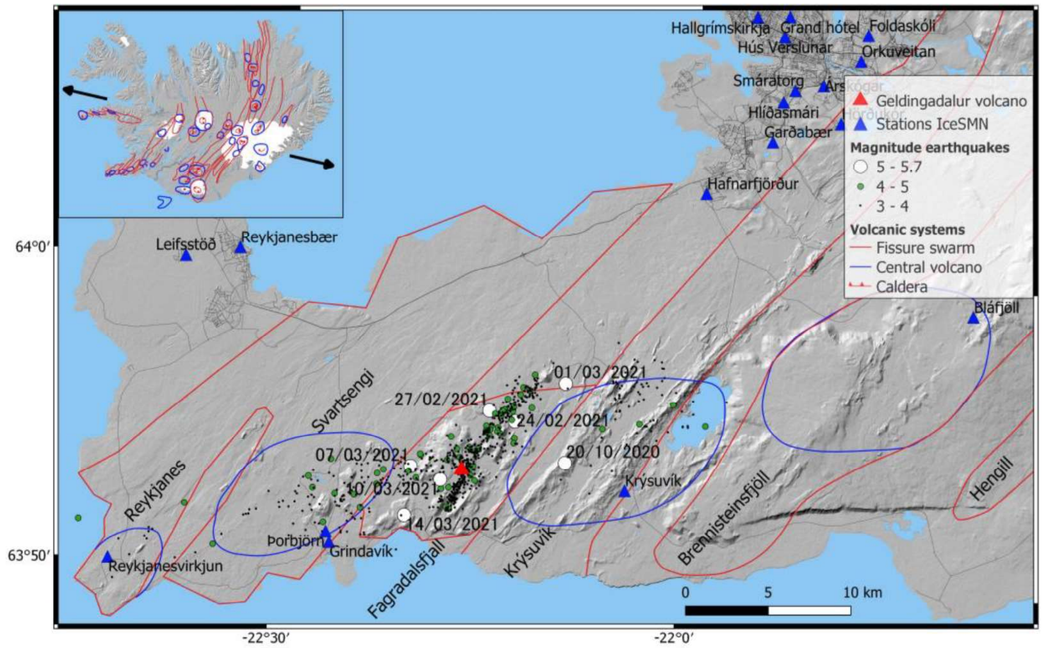


Fig. 1. Map of the Reykjanes Peninsula with its 6 volcanic systems highlighted. The location of the Geldingadalur eruption of 19 March 2021 is shown, along with the location of the earthquakes with M>3 from the precursor swarm that started in January 2020. The accelerometric stations of the IceSMN network are also presented. The Iceland inset shows the volcanic systems (modified from Johannesson & Sæmundsson, 2009) and the location of the study area (black square). The arrows show the direction of the spreading between the North American and Eurasian tectonic plates.

The Reykjanes Peninsula rift (Fig. 1) is a segment of the mid-Atlantic plate boundary and forms a transition between the Reykjanes Ridge off shore to the west and the Western Volcanic Zone and the South Iceland Seismic Zone to the east (Einarsson, 1991). The plate boundary as shown by the epicentral zone of earthquakes runs along the peninsula in the direction of about N(70-80)°E (Björnsson et al., 2020; Keiding et al., 2009), whereas the relative spreading of the North American and Eurasian Plates is about ~18–19 mm/year in direction ~N(100–105)°E, as measured from a global plate motion model, MORVEL2010 (DeMets et al., 2010), and GNSS geodesy (Sigmundsson et al., 2020). The oblique spreading leads to extensive volcanism and large earthquakes (Einarsson, 2008).

The main tectonic features on the peninsula are a large number of NE-SW trending volcanic fissures and normal faults and a series of N-S oriented right-lateral strike-slip faults (Clifton & Kattenhorn, 2006). As shown in Fig. 1, there are six volcanic systems in the peninsula according to Sæmundsson et al. (2020), namely: Reykjanes, Svartsengi, Fagradalsfjall, Krýsuvík, Brennisteinsfjöll and Hengill. The fissure swarms of the volcanic systems extend a few tens of kilometres into the plates on either side, have a trend of about N35°E, and are thus arranged en echelon with respect to the plate boundary (Einarsson, 2008).

Seismic activity on the peninsula is episodic. Recent high activity periods took place at the beginning of the last century, in 1929–1935, 1967–1975, and 2000–2004 (Björnsson et al., 2020; Einarsson, 2008). The largest earthquakes in the latest episodes were associated with strike-slip faulting (Árnadóttir et al., 2004; Einarsson, 1991). Hreinsdóttir et al. (2001) suggests that transcurrent motion is taken up by right-lateral motion on N-S trending strike-slip faults (bookshelf faulting, Einarsson et al., 1981) while extension perpendicular to the fissure swarms takes place during magmatic periods by dyke injection. In the period 1900-2019, in total 25 earthquakes of M≥5 have occurred on the Peninsula, west of −22°0′ (Fig. 1), i.e. on average one earthquake every fifth year (Jónasson et al., 2021).

3. Strong-motion recordings

During the 2020-2021 Reykjanes swarm, seven earthquakes with a magnitude 5 or larger were reported by the Icelandic Meteorological Office (IMO). Their epicentres are marked in Fig. 1 with white circles. These events were recorded by the IceSMN.

3.1. Peak ground accelerations

PGA recorded at 4 stations of the ICESMN in the Reykjanes Peninsula are presented in Table 1. Components X and Y are horizontal, close to the E-W and N-S directions, respectively. The largest PGA was recorded in the X direction at Krýsuvík station, where it reached ~0.4g, which is almost twice the 475-year return period PGA used for seismic design in Grindavík and the surrounding area, which is 0.2g. Peak ground accelerations close to or exceeding the 475-year design PGA in Grindavík are highlighted in the table. It is interesting to note that even earthquakes as small as M5.0 caused PGA close to or more than 475-year design PGA.

Table 1. PGA in g's recorded at 4 of the stations of the IceSMN during five events with M≥5.

Station	Component	20/10/2020 M5.6	24/02/2021 M5.7	01/03/2021 M5.0	07/03/2021 M5.1	14/03/2021 M5.4
Grindavík	X	0.033	0.052	0.010	0.073	0.121
	Y	0.020	0.057	0.010	0.041	0.214
	Z	0.015	0.047	0.008	0.065	0.076
Þorbjörn	X	0.050	0.103	0.011	0.144	0.273
	Y	0.051	0.092	0.018	0.196	0.276
	Z	0.023	0.046	0.009	0.122	0.139
Krýsuvík	X	0.327	0.405	0.207	0.028	0.044
	Y	0.206	0.283	0.118	0.030	0.051
	Z	0.167	0.220	0.067	0.014	0.019
Reykjanesbær	X	0.020	0.018	0.012	0.011	0.025
	Y	0.015	0.023	0.010	0.020	0.018
	Z	0.011	0.017	0.007	0.018	0.017

3.2. Elastic response spectra

Elastic response spectra (5% damped) of some of the recorded ground motions are presented in this section. Response spectra of ground motion recorded at the Krýsuvík station during the 24 February 2021 M5.7 earthquake are shown in Fig. 2. For comparison, Eurocode 8 Type 1 elastic spectrum on rock site and corresponding to a PGA of 0.2g is also shown. The response spectra of recorded motion are greatly under-estimated by the EC8 spectra for vibration periods less than ~0.15s. This is the case even when the PGA of recorded motion is similar to the PGA used to scale the EC8 spectrum, for example the Y component of recorded motion.

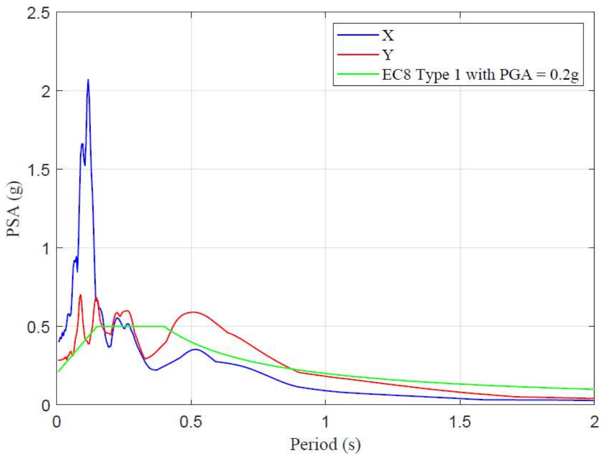
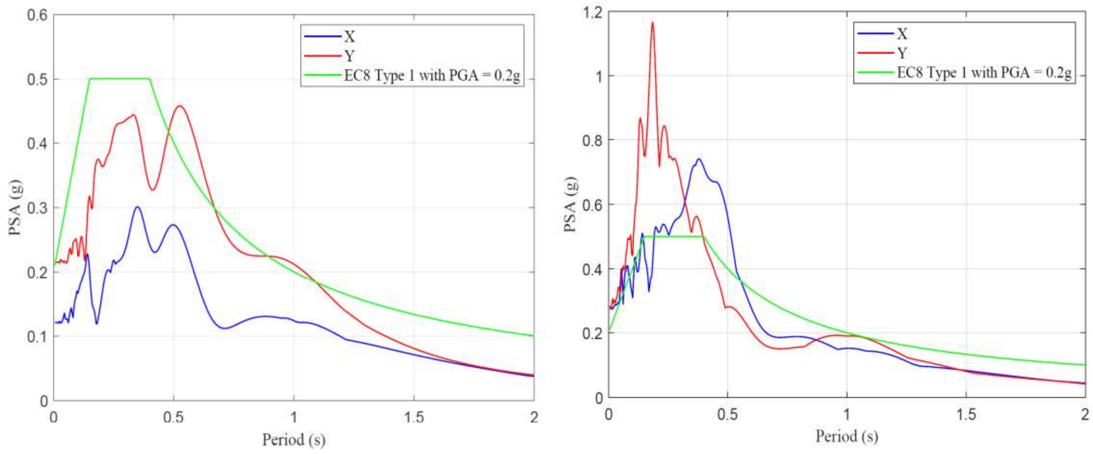


Fig. 2. Elastic pseudo-spectral acceleration (5% damping) of the ground motion recorded at Krýsuvík during the 24 February 2021 M5.7 earthquake.

Response spectra of ground motion recorded at the Grindavík station during the 14 March 2021 M5.4 event are well captured by the EC8 spectrum as shown in Fig. 3a. Response spectra recorded at Þorbjörn station for the same event are shown in Fig. 3b. The response spectrum for X direction at Þorbjörn has unusually high ordinates at vibration periods less than ~0.15s. The shapes of response spectra at Grindavík are very different from those at Krýsuvík and Þorbjörn.



a) Grindavík b) Þorbjörn

Fig. 3. Elastic pseudo-spectral acceleration (5% damping) of the ground motion recorded at Grindavík (a) and Þorbjörn (b) during the 14 March 2021 M5.4 earthquake.

It is worth nothing that stations Grindavík and Þorbjörn are separated just ~650 m (see Fig. 1), hence, they have similar hypocentral distances and azimuth from the source, however, their ground motion characteristics are contrasting. One possibility for the large spectral accelerations at station Þorbjörn at low periods might be that the station is affected by site-effects, however, according to the Geological map of SW Iceland (Sæmundsson et al., 2016) both stations are located on postglacial lavas. To elucidate the reason of the ground motion differences between these stations further study is required.

4. Ground-motion attenuation and site effects

Attenuation of the geometric mean PGA of the two horizontal components recorded during the largest event is shown in Fig. 4. Two ground-motion prediction equations (GMPEs) are compared with the recorded PGA. The model of Akkar et al. (2014), hereafter called as Ak2014, was derived based on data from Europe and the Middle East. The second model employed is that of Rupakhety et al. (2016), referred as Ru2016, which was calibrated from ground-motion data recorded in Iceland. Both models are presented for rock-site conditions, and a strike-slip faulting was used considering the focal mechanism reported by the U.S. Geological Survey. It is evident that the model Ru2016 fits better the recorded data. In fact, it has been previously reported that GMPEs calibrated on data outside Iceland tend to under-predict ground motion at short distances and overpredict further away from the source (Ólafsson & Sigbjörnsson, 2006).

The PGA recorded at Krýsuvík is highlighted in Fig. 4. This was the largest PGA recorded during the earthquake swarm and the low period peaks in the elastic response spectra (Fig. 2) are way beyond the spectral accelerations of the Eurocode 8 Type 1 elastic design spectrum. Unusually high PGAs at Krýsuvík were also recorded during other earthquakes, so we hypothesize that this station might be affected by site-effects. Detailed site characterization for this site is not available, however, a Geological map (Sæmundsson et al., 2016) for this area shows tephra deposits**.**

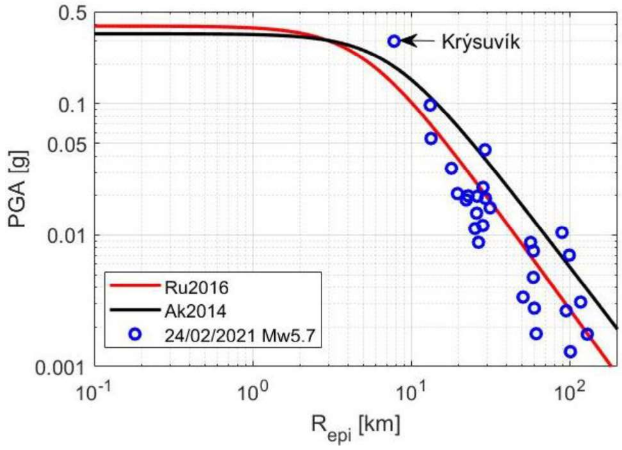


Fig. 4. Geometric mean of horizontal peak ground accelerations recorded by the IceSMN network during the 24 February 2021 M5.7 earthquake (circles), compared to the GMPEs Ru2016 and Ak2014.

The horizontal-to-vertical spectral ratios (HVSR, Nakamura, 1989) for six earthquakes with M≥5 recorded at Krýsuvík are presented in Fig. 5. The strong motion section of each record was windowed and cosine tapered (5%). A bandpass filter between 0.05 and 50 Hz was used before computing Fourier Amplitude Spectra (FAS). Then spectral amplitudes were smoothed and the HVSR computed as the root mean square of the horizontal spectral amplitudes divided by the vertical spectral amplitude. The results show a broad-band amplification, with a value as large as 9 at ~8 Hz for the average HSVR. While the HVSR technique was initially proposed to interpret microtremor measurements, it has been shown that the HVSR for earthquake recordings gives a good approximation of the dominant site frequencies (e.g., Lermo & Chavez-Garcia, 1993; Mucciarelli et al., 2003).

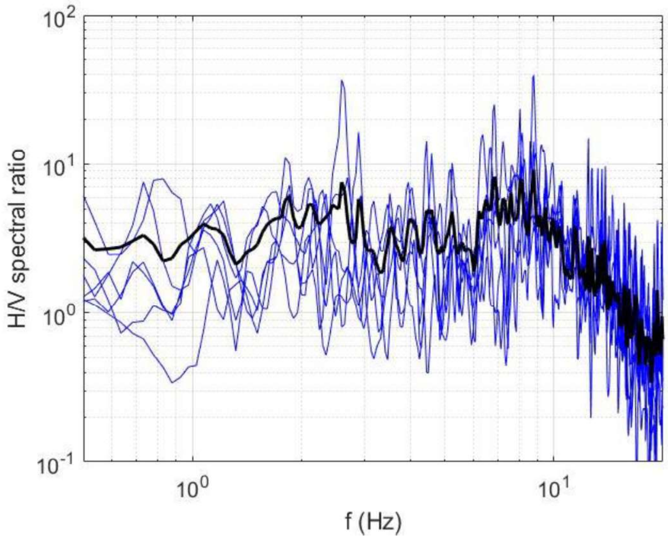


Fig. 5. Horizontal-to-vertical spectral ratios for six earthquakes with M≥5 recorded at station Krýsuvík. The average HSVR is shown with a thick black line.

5. Conclusions

This work presents salient features of strong ground motion recorded during the earthquake swarm in 2020-2021, preceding the 2021 Geldingadalur eruption in the Reykjanes Peninsula, Iceland. One very important observation is that earthquakes as small as M5.0 caused PGA larger than the 475-year return period PGA at towns near the epicentre. Furthermore, spectral accelerations at low periods (T<0.4 Hz) were extremely large at two stations near the epicentre. Large spectral accelerations in this frequency range could be damaging because the Icelandic building tradition consists of low-rise buildings made of concrete, masonry and timber, with fundamental natural frequencies usually larger than 5 Hz (Sigbjörnsson et al., 2009). However, only few minor damages have been reported for these events. The largest recorded PGA was ~0.4g at Krýsuvík, which is around twice the PGA estimated from GMPEs. Large PGAs at this station were recorded also during other events. Site-effects at Krýsuvík are a plausible explanation for the unusually large PGAs and spectral accelerations at low periods. Further geotechnical investigation is required to better understand local site effects at this station.

Acknowledgements

This work was partly financed by the SERICE project funded by a Grant of Excellence from the Icelandic Centre for Research (RANNIS), Grant Number: 218149-051. We also acknowledge support from the University of Iceland Research Fund. The authors wish to thank the Icelandic Meteorological Office for the access to the earthquake catalogue.

References

Akkar, S., Sandıkkaya, M. A., & Bommer, J. J. (2014). Empirical ground-motion models for point- and extended-source crustal earthquake scenarios in Europe and the Middle East. *Bulletin of Earthquake Engineering*, *12*(1), 359–387. https://doi.org/10.1007/s10518-013-9461-4

Árnadóttir, T., Geirsson, H., & Einarsson, P. (2004). Coseismic stress changes and crustal deformation on the Reykjanes Peninsula due to triggered earthquakes on 17 June 2000. *Journal of Geophysical Research: Solid Earth*, *109*(9). https://doi.org/10.1029/2004JB003130

Björnsson, S., Einarsson, P., Tulinius, H., & Hjartardóttir, Á. R. (2020). Seismicity of the Reykjanes Peninsula 1971–1976. *Journal of Volcanology and Geothermal Research*, *391*, 106369. https://doi.org/10.1016/j.jvolgeores.2018.04.026

Clifton, A. E., & Kattenhorn, S. A. (2006). Structural architecture of a highly oblique divergent plate boundary segment. *Tectonophysics*, *419*(1–4), 27–40. https://doi.org/10.1016/j.tecto.2006.03.016

DeMets, C., Gordon, R. G., & Argus, D. F. (2010). Geologically current plate motions. *Geophysical Journal International*, *181*(1), 1–80. https://doi.org/10.1111/j.1365-246X.2009.04491.x

Einarsson, P. (1991). Earthquakes and present-day tectonism in Iceland. *Tectonophysics*, *189*(1–4), 261–279. https://doi.org/10.1016/0040-1951(91)90501-I

Einarsson, P. (2008). Plate boundaries , rifts and transforms in Iceland. *Jokull*, *58*, 35–58.

Einarsson, P., Bjornsson, S., Foulger, G., Stefansson, R., & Skaftadottir, T. (1981). Seismicity pattern in the South Iceland Seismic Zone. *In Earthquake Prediction (Eds D.W. Simpson and P.G. Richards)*, *March 2016*, 141–151. https://doi.org/10.1029/me004p0141

Geirsson, H., Parks, M., Vogfjörd, K., Einarsson, P., Sigmundsson, F., Jónsdóttir, K., Drouin, V., Ófeigsson, B. G., Hreinsdóttir, S., Ducrocq, C., Geirsson, H., Parks, M., Vogfjörd, K., Einarsson, P., Sigmundsson, F., Jónsdóttir, K., Drouin, V., Ófeigsson, B. G., Hreinsdóttir, S., & Ducrocq, C. (2021). The 2020 volcano-tectonic unrest at Reykjanes Peninsula, Iceland: stress triggering and reactivation of several volcanic systems. *EGU General Assembly 2021, Online, 19–30 Apr 2021*, EGU21-7534. https://doi.org/https://doi.org/10.5194/egusphere-egu21-7534, 2021

Gudmundsson, A., Bazargan, M., Hobé, A., Selek, B., & Tryggvason, A. (2021). Dike-Segment Propagation, Arrest, and Eruption at Fagradalsfjall, Iceland. *Earth and Space Science Open Archive*, 1. https://doi.org/10.1002/essoar.10508827.3

Hreinsdóttir, S., Einarsson, P., & Sigmundsson, F. (2001). Crustal deformation at the oblique spreading Reykjanes Peninsula, SW Iceland: GPS measurements from 1993 to 1998. *Journal of Geophysical Research: Solid Earth*, *106*(B7), 13803–13816. https://doi.org/10.1029/2001jb000428

Johannesson, H., & Sæmundsson, K. (2009). *Geological Map of Iceland, 1:600 000, Tectonics*. Icelandic

Institute of Natural History.

Jónasson, K., Bessason, B., Helgadóttir, Á., Einarsson, P., Guðmundsson, G. B., Brandsdóttir, B., Vogfjörd, K. S., & Jónsdóttir, K. (2021). A harmonised instrumental earthquake catalogue for Iceland and the northern Mid-Atlantic Ridge. *Natural Hazards and Earth System Sciences*, *21*(7), 2197–2214. https://doi.org/10.5194/nhess-21-2197-2021

Keiding, M., Lund, B., & Árnadóttir, T. (2009). Earthquakes, stress, and strain along an obliquely divergent plate boundary: Reykjanes Peninsula, southwest Iceland. *Journal of Geophysical Research: Solid Earth*, *114*(9), 1–16. https://doi.org/10.1029/2008JB006253

Lermo, J., & Chavez-Garcia, F. J. (1993). Site effect evaluation using spectral ratios with only one station. *Bulletin of the Seismological Society of America*, *83*(5), 1574–1594.

Mucciarelli, M., Gallipoli, M. R., & Arcieri, M. (2003). The stability of the horizontal-to-vertical spectral ratio of triggered noise and earthquake recordings. *Bulletin of the Seismological Society of America*, *93*(3), 1407–1413. https://doi.org/10.1785/0120020213

Nakamura, Y. (1989). A Method for Dynamic Characteristics Estimation of Subsurface using Microtremor on the Ground Surface. *Q. Rep. Railway Tech. Res. Inst.*, *30*(1), 25–33.

Ólafsson, S., & Sigbjörnsson, R. (2006). Attenuation in Iceland compared with other regions. *First European Conference on Earthquake Engineering and Seismology (1ECEES)*, *September*, Paper no. 1157.

Rupakhety, R., Ólafsson, S., & Sigurðsson, G. (2016). Site response analysis and near-fault effects for seismic resistant design of wind turbine towers in the Búrfellslundur area. *Landsvirkjun Report Number LV-2016-040*.

Sæmundsson, K., Sigurgeirsson, M. Á., Hjartarson, Á., Kaldal, I., Kristinsson, S. G., & Víkingsson, S. (2016). *Geological map of Southwest Iceland, 1: 100 000 (2nd edition)*. Reykjavík: Icelandic Energy Research.

Sæmundsson, K., Sigurgeirsson, M., & Friðleifsson, G. Ó. (2020). Geology and structure of the Reykjanes volcanic system, Iceland. *Journal of Volcanology and Geothermal Research*, *391*, 106501. https://doi.org/10.1016/j.jvolgeores.2018.11.022

Sigbjörnsson, R., Snæbjörnsson, J. T., Higgins, S. M., Halldórsson, B., & Ólafsson, S. (2009). A note on the M w 6.3 earthquake in Iceland on 29 May 2008 at 15:45 UTC. *Bulletin of Earthquake Engineering*, *7*(1), 113–126. https://doi.org/10.1007/s10518-008-9087-0

Sigmundsson, F., Einarsson, P., Hjartardóttir, Á. R., Drouin, V., Jónsdóttir, K., Árnadóttir, T., Geirsson, H., Hreinsdóttir, S., Li, S., & Ófeigsson, B. G. (2020). Geodynamics of Iceland and the signatures of plate spreading. *Journal of Volcanology and Geothermal Research*, *391*, 106436. https://doi.org/10.1016/j.jvolgeores.2018.08.014

U.S. Geological Survey. (2022). *Earthquake Catalog*. accessed February 1, 2022 at URL https://earthquake.usgs.gov/earthquakes/eventpage/us6000dkmk/moment-tensor.