Soil Dynamics and Earthquake Engineering 89 (2016) 136–151

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Detailed site effect estimation in the presence of strong velocity reversals within a small-aperture strong-motion array in Iceland

Sahar Rahpeyma [a], Benedikt Halldorsson [a,*], Christian Olivera [b], Russell A. Green [c], Sigurjón Jónsson [d]

[a] Earthquake Engineering Research Centre & Faculty of Civil and Environmental Engineering, School of Engineering and Natural Sciences, University of Iceland, Selfoss, Iceland
[b] ECS Mid-Atlantic, LLC, 6710 Oxon Hill Road, Suite 101, National Harbor, MS 20745, USA
[c] Department of Civil & Environmental Engineering, Virginia Tech, Blacksburg, VA, USA
[d] King Abdullah University of Science and Technology (KAUST), Physical Science and Engineering Division (PSE), Thuwal 23955-6900, Saudi Arabia

ARTICLE INFO

Article history:
Received 11 March 2016
Received in revised form
5 July 2016
Accepted 7 July 2016
Available online 11 August 2016

Keywords:
Site effect
HVSR
SSR
Velocity reversal
Array
Iceland

ABSTRACT

The rock site characterization for earthquake engineering applications in Iceland is common due to the easily exposed older bedrock and more recent volcanic lava rock. The corresponding site amplification is generally assumed to be low but has not been comprehensively quantified, especially for volcanic rock. The earthquake strong-motion of the M_w6.3 Ölfus earthquake on 29 May 2008 and 1705 of its aftershocks recorded on the first small-aperture strong-motion array (ICEARRAY I) in Iceland showed consistent and significant variations in ground motion amplitudes over short distances (< 2 km) in an urban area located mostly on lava rock. This study analyses the aftershock recordings to quantify the local site effects using the Horizontal to Vertical Spectral Ratio (HVSR) and Standard Spectral Ratio (SSR) methods. Additionally, microseismic data has been collected at array stations and analyzed using the HVSR method. The results between the methods are consistent and show that while the amplification levels remain relatively low, the predominant frequency varies systematically between stations and is found to correlate with the geological units. In particular, for stations on lava rock the underlying geologic structure is characterized by repeated lava-soil stratigraphy characterized by reversals in the shear wave velocity with depth. As a result, standard modeling of HVSR using vertically incident body waves does not apply. Instead, modeling the soil structure as a two-degree-of-freedom dynamic system is found to capture the observed predominant frequencies of site amplification. The results have important implications for earthquake resistant design of structures on rock sites characterized by velocity reversals.

1. Introduction

Iceland is the largest subaerial part of the Mid-Atlantic Ridge where the North American and Eurasian crustal plates are drifting apart with an average rate of approximately 2 cm/year (Fig. 1) [1–3]. Passing across Iceland from south to north, the onshore part of the plate boundary is shifted eastward, resulting in two transform zones: the South Iceland Seismic Zone (SISZ) in the south and the Tjörnes Fracture Zone (TFZ) in the north. The largest and most populous agricultural region in Iceland is located in the SISZ for which the seismic potential and characteristics has been well documented on the basis of historical seismicity. It is known as a region in which destructive earthquakes occur, either as strong single earthquakes or in earthquake sequences of magnitude 6–7 events over a period lasting from weeks to years. The causative faults of strong earthquakes in the SISZ occur as parallel and near vertical north-south striking faults, which is perpendicular to the underlying east-west trending plate boundary [4–13].

Earthquake strong-motion in Iceland has been monitored over the last three decades by the Icelandic strong-motion network (ISMN) which is owned and operated by the Earthquake Engineering Research Centre of the University of Iceland. At present, the network consists of 40 free-field stations that are primarily located in the SISZ and the TFZ, along with several key strong-motion stations in urban centers and key infrastructures such as hydroelectric and geothermal powerplants, dams, hospitals, bridges etc. Additionally, the first Icelandic strong-motion array (ICEARRAY I) was deployed in 2007 in the town of Hveragerði in the SISZ. The ICEARRAY I consists of 13 strong-motion stations with interstation distances of only 50–1900 m [8], in contrast to the more typical ISMN interstation distances of 5–10 km in the

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[*] Corresponding author.
E-mail addresses: sahar@hi.is (S. Rahpeyma), skykkur@hi.is (B. Halldorsson), rugreen@vt.edu (R.A. Green), sigurjon.jonsson@kaust.edu.sa (S. Jónsson).

http://dx.doi.org/10.1016/j.soildyn.2016.07.001
0267-7261/

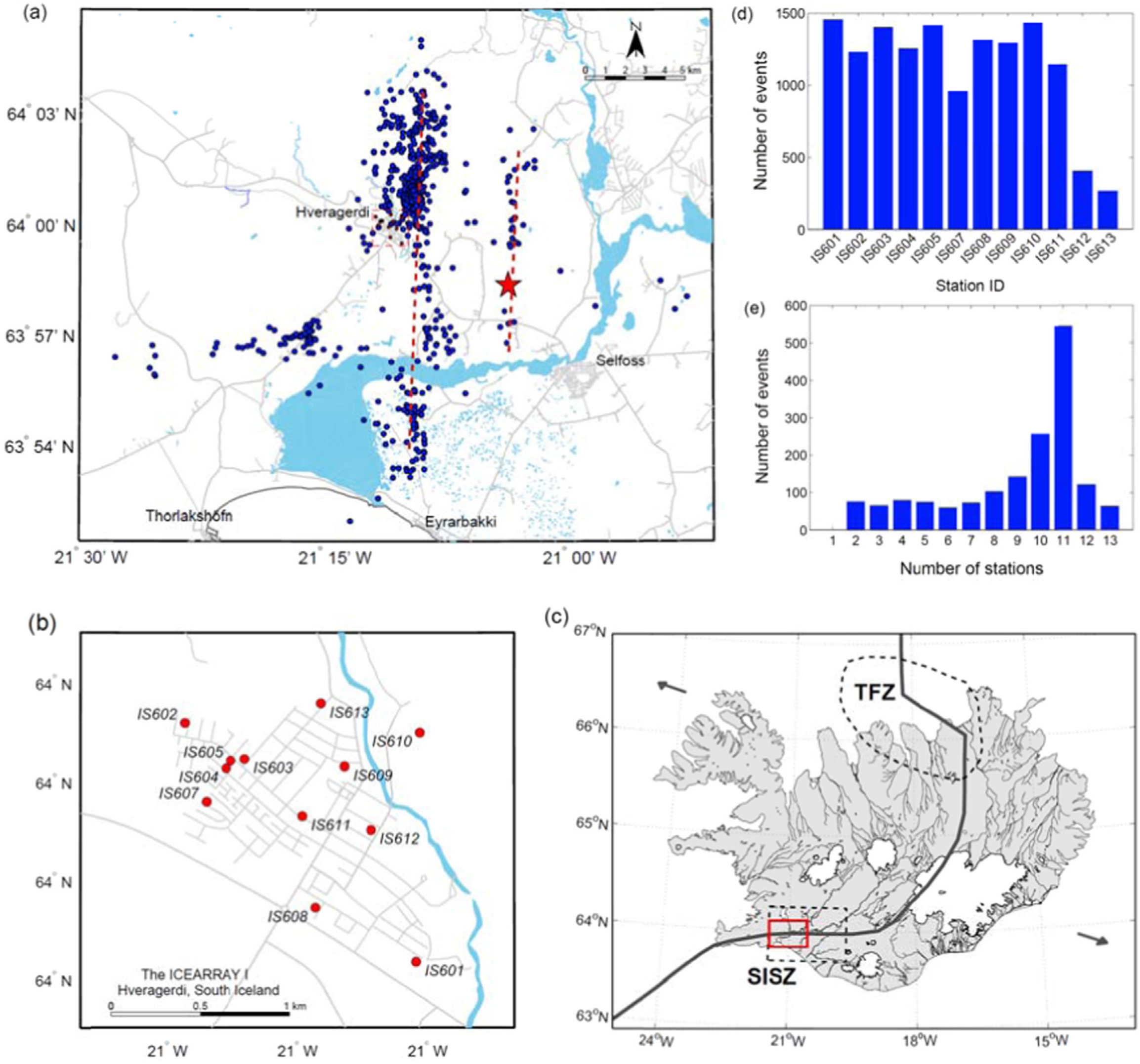

Fig. 1. (a) North–south trending alignments of aftershock locations (blue circles) recorded by ICEARRAY I after the 29 May 2008 Ölfus earthquake (red star) in southwest Iceland indicate the location of the causative faults (approximated by the red dashed lines), The ICEARRAY I stations (red dots) are located within the town of Hveragerði (red dashed rectangle). (b) Map of Hveragerði showing the locations of the twelve ICEARRAY I strong motion stations (red circles) (c) Map of Iceland showing the rough location of the present-day Mid-Atlantic plate boundary (dark solid line), the Tjörnes Fracture Zone (TFZ) and South Iceland Seismic Zone (SISZ). Histograms show (d) the number of recordings at each ICEARRAY I station and (e) the number of events recorded by a given number of stations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

SISZ [14]. During the 29 May 2008 M_w6. 3 Ölfus earthquake and its aftershock sequence, the ICEARRAY I recorded the strong-motions of the mainshock and 1705 of its aftershocks [8,15]. The main shock recordings were characterized by intense ground accelerations of relatively short durations (5–6 s) and large amplitude near-fault velocity pulses. Despite the relatively small interstation distances of the array considerable variations of earthquake ground motion amplitudes and frequency content were observed. The geometric mean of the horizontal peak ground acceleration (PGA) varied from about 44% to 88% of the acceleration of gravity (g) and peak ground velocity (PGV) from 26 to 62 cm/s [8]. Similar variations of relative amplitudes of the recorded aftershocks have also been reported but not yet fully investigated [15].

The spatial variation in amplitude and frequency content of earthquake ground motions can be attributed to wave propagation effects and localized site effects. During recent decades, it has been recognized that propagation of seismic waves may vary significantly due to local geological and geostructural settings, even over relatively small distances [16,17]. In general, motions recorded on sites classified as "soil" are larger in amplitude relative to those recorded on "rock" sites [18,19]. This is due to impedance contrast where soil deposits acting as filters to incoming seismic waves and amplifying motions at certain frequencies. Consequently, site effects is a major aspect of geotechnical earthquake engineering and has a major influence on seismic hazard [e.g., 20,21–25]. It is noteworthy that in earthquake engineering practice in Iceland, site effects are generally not considered to be a key factor, presumably due to the relatively thin topsoil which is in most cases is easily removed from the uppermost competent rock (e.g., lava rock, hyaloclastite, dolerite, etc.). However, for lava rock the presence of pronounced site effects has been reported [17]. Namely, in geologically younger parts of Iceland the interplay of repeated glaciation/deglaciation and fluctuating sea levels with the primary basaltic volcanism has resulted in the geological profiles consisting of recurring layers of basaltic lavas, as well as tuff layers, often with intermediate layers of sediments or alluvium [26]. This is especially true in the SISZ where the topography is approximately flat and of low elevation, and largely covered with postglacial lava flows underlain by Quaternary sediments of mainly fluvial, glacial, and glaciofluvial origin [27]. In such cases