Soil Dynamics and Earthquake Engineering 97 (2017) 143–154

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

Directional effects of tectonic fractures on ground motion site amplification from earthquake and ambient noise data: A case study in South Iceland

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ARTICLE INFO

Keywords:
Wavefield polarization
Amplification
Spectral ratios
Shear wave splitting

ABSTRACT

The geology of SW-Iceland is characterized by alternating basaltic lava units, hyaloclastite formations, postglacial sedimentary filled valleys and alluvial plains, as well as highly fractured bedrock within the Reykjanes Peninsula volcanic rift zone and the South-Iceland transform fault system. Historic earthquakes within this region reach magnitudes 6.5–7. Using earthquake and ambient noise recordings from 15 seismic stations within the rift and transform zones we compared wavefield polarization and seismic site response in order to assess characteristics of local amplification of ground motion. Ambient noise and earthquake ground motion spectral ratios are comparable in frequency and can qualitatively be subdivided into three groups: one with a spectral ratio characterized by a single predominant frequency of horizontal amplification, one with a bi- or multimodal and one characterized by a relatively constant amplitude across the frequency range. Seismic wavefield polarization within the transform zone has a prevailing direction of amplification towards 110°–150°N in the frequency range 1.0–3.0 Hz, having a *quasi*-perpendicular relationship with mapped faults and fractures. Shear wave splitting results show that the wavefield polarization and fast S wave directions tend to be orthogonal, i.e. highly dependent on the anisotropy of the medium.

1. Introduction

Local geological, geotechnical and/or man-made site conditions can amplify earthquake vibrations and thus the extent of damage. These conditions give rise to what is generally referred to as seismic site effects caused by significant contrasts in wave impedance, stratigraphic discontinuities and/or irregular geometry of the surface from the presence of canyons, valleys or hills [25,41]. The site effects are manifested as variations in frequency and amplitude content of seismic waves that need to be accounted for as they ultimately affect earthquake hazard estimates, and play an important role in evaluating seismic risk. Moreover, from an engineering seismology point of view, it is also important to evaluate the role of near surface geology compared to the morphological setting (e.g. [51]). Site effects can be estimated in the frequency domain using various spectral ratio methods, thus effectively revealing how near surface geological structures modify the seismic waves. The most common site response estimation technique is the standard spectral ratio (SSR) which compares earthquake recordings at two sites, one of which is a “reference site” that is believed to be devoid of significant site effects, usually located on solid bedrock [9]. Selecting a reference site however is not trivial. Another widespread technique that does not need a reference station is based on the horizontal-to-vertical spectral ratio (HVSR) using noise recordings (i.e., microseismic or ambient vibrations) (for clarity referred to here as HVNR). This method was originally introduced by Nakamura [40] to characterize the transfer function of subsurface geological units. Over the past two decades it has become widely used since it has been shown to provide a reliable estimate of the predominant frequency of ground motion response at the surface of soft soil deposits [36,43,60]. This method applied to horizontal shear wave recordings (for clarity referred to here as HVSR) by Lermo and Chavez-Garcia [36] was shown to be consistent with results obtained using the SSR technique, especially in the frequency range around the predominant frequency of response (resonant peaks) [14,50]. In recent years, many authors have tested the reliability of both methods (HVSR and/or HVNR) with good results on the surface of different morphological conditions, such as faults, topography, landslides etc (e.g. [56,47,42,12]). In particular, results from studies on the seismic site response in fault zones have been shown to have important implications on earthquake hazard on a local scale, indicat-

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http://dx.doi.org/10.1016/j.soildyn.2017.03.024
Received 14 October 2016; Received in revised form 14 March 2017; Accepted 15 March 2017
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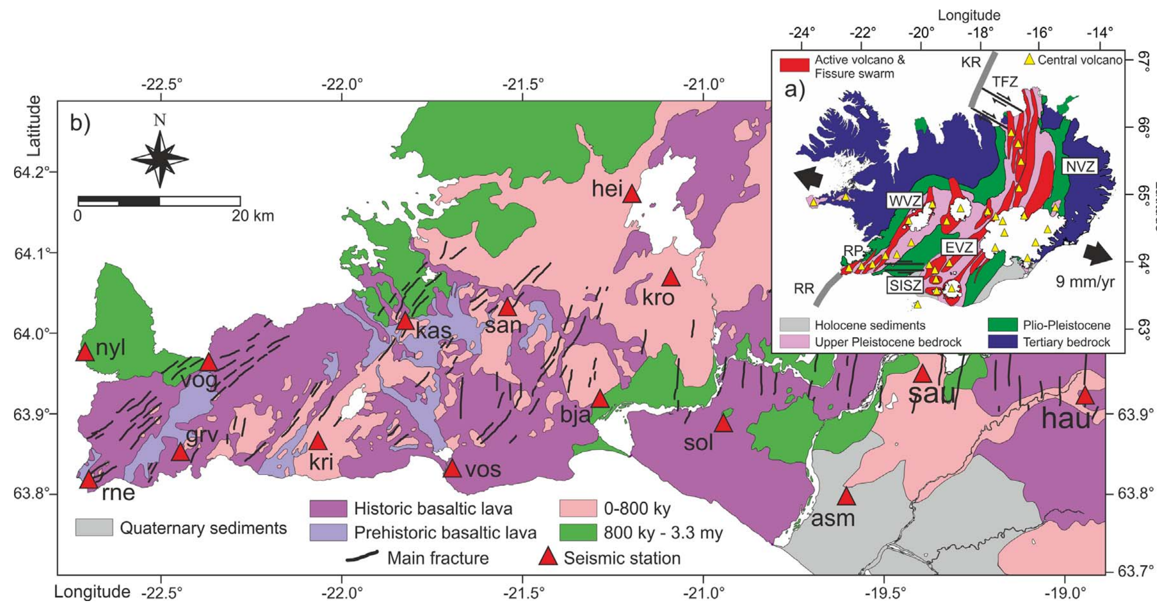

Fig. 1. a) The geometry of the plate boundary across Iceland: WVZ=Western Volcanic Zone; EVZ=Eastern Volcanic Zone; KR=Kolbeinsey ridge; RR=Reykjanes ridge (RR); TFZ=Tjörnes Fracture Zone; SISZ=South Iceland Seismic Zone (modified from Einarsson and Sæmundsson [23]). b) Simplified geological map of the study area showing the major lava rock units and mapped faults (modified from Geological Map of Southwest Iceland 1:100,000). Red triangles show the location and name of the seismic stations in study area.

ing that amplified motions near faults with a high angle to the fault strike, travel in a way different from trapped waves. The directional amplification of the horizontal ground motion observed in many fault zones is interpreted as being due to the crack orientation causing a larger ground motion transversal to fractures [52,53,49,44]. Shear-wave anisotropy, inferred from shear-wave splitting in a fault zone [54], indicates an orthogonal relation between the horizontal polarization and fast shear wave direction, suggesting that wavefield polarization and fast velocity direction in fractured medium originate from the same source mechanism.

In the present study, we report variations in site response along the highly fractured plate boundary in Southwest Iceland, which is characterized by tectonic extension (Reykjanes Peninsula) and transform motion (South Iceland Seismic Zone) (see Fig. 1). However, using both ambient noise and earthquake recordings we attempt to verify the correlation between directional amplification and the predominant direction of tectonic fractures, the primary factor contributing to seismic anisotropy in the region. The effects of the strong heterogeneities on the seismic response of the study area were investigated by adopting the most commonly used techniques to evaluate the site response properties, such as the horizontal to vertical shear wave ratio and the horizontal to vertical noise ratio. Techniques evaluating directional effects and polarization of the wavefield are also used as a procedure for identifying the presence of directional effects.

2. Tectonic setting and geology

The complex tectonic setting of Iceland is due to the gradual westward motion of the Mid-Atlantic Ridge causing it being offset eastward across Iceland in response to the presence of a hotspot situated under the Vatnajökull glacier in eastern Iceland [21]. This movement gives rise to two sub-parallel volcanic zones in southern Iceland (Fig. 1a). The divergent plate boundary of the Mid-Atlantic Ridge continues subaerially along the Reykjanes peninsula (RP) and the Western Volcanic Zone (WVZ). The plate boundary shifts eastward along the South Iceland Seismic Zone (SISZ) forming the Eastern Volcanic Zone (EVZ), which continues north known as the Northern Volcanic Zone (NVZ). The plate boundary rift then shifts back westward along the Tjörnes fracture zone (TFZ) and joins the Kolbeinsey Ridge (KR).

The SISZ is an approximately 10–20 km wide and 70–80 km long, EW striking sinistral shear zone. Faulting takes place on subparallel, NS striking dextral faults [27,57], as demonstrated by the shape of the damage zones of historical earthquakes [1,22,62,63], their mapped surface traces [16,24], the subsurface fault mapping through high-precision earthquake relocations [30], and the static-slip distributions on finite fault planes [20,31]. The RP is a highly oblique spreading segment of the Mid-Atlantic Ridge, oriented about 30° from the direction of absolute plate motion [15]. There are four distinct volcanic fissure swarms on the peninsula [34], with an average strike of 40°N. Similar to the SISZ, strong earthquakes on Reykjanes peninsula occur on NS striking faults that intersect the volcanic fissure swarms [16,2,3,32].

The oldest rocks at the surface of the study area (Fig. 1b) are Pliocene period lavas and hyaloclastites (formed in sub-glacial eruptions), along with interglacial basaltic lava flows. In the axial rift zone [15] the products of early post-glacial shield eruptions and episodic fissure eruptions are mostly covered by basaltic lavas of Holocene age. Quaternary sediments of fluvial, glacial and glaciofluvial origin are outcropping near the South coast and along the river with variable thickness up to 100 m ([4] and references therein).

3. Estimation of seismic site effects

3.1. Earthquake and noise spectral ratios

We studied 22 seismic events with moment magnitudes (M_w) in the range of 3.0–5.0, (Table 1) at 15 seismic stations of the Icelandic seismic network named SIL (Fig. 1b, [7]). Each station is instrumented with a RD3 or Guralp DM24 data acquisition system and a three component Lennartz 1 s or Lennartz 5 s seismometer, recording at a sampling rate of 100 Hz. The location and magnitude of recorded events are based on the SIL catalogue. The recording quality of each event was tested using a signal-to-noise ratio criterion, with a 10 s time window of the shear wave and coda and pre-event noise, respectively. Thus only good quality recordings were used, having a signal to noise ratio greater than 3 units in the frequency band 0.5–10.0 Hz (Fig. 2). The selected earthquake waveforms were baseline corrected and band-pass filtered in the range 0.08–20.0 Hz using a fourth order causal Butterworth filter prior to obtaining a Fourier spectrum of each