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ON THE MODELLING OF INCOHERENCE OF STRONG-MOTION: A STUDY OF THE MAY 2008 ÖLFUS EARTHQUAKE

Ragnar SIGBJÖRNSSON[1], Rajesh RUPAKHETY[2], Benedikt HALLDORSSON[3], and Jonas Thór SNÆBJÖRNSSON[4]

ABSTRACT

This article recapitulates the main findings of an on-going study on the spatial variability of strong ground motion, highlighting the May 2008 M_w 6.3 Ölfus Earthquake in South Iceland. The focus is on strong-motion accelerometric data recorded by a small-aperture array, ICEARRAY, installed in the Town of Hveragerdi. The spatial dimensions of the array are only ~2 km. The recorded data reveal high variability both in amplitude and frequency content within the dimensions of the array. The preliminary results show that the lagged coherency of a given ground-motion component decreases with increasing frequency and increasing inter-station distance. Orthogonal components of recorded motion are found to have significant correlation indicating need to model of inter-component coherence in earthquake engineering applications.

INTRODUCTION

The objective of this article is to outline some modelling aspects of ground-motion variability for structural engineering purposes (some of which has been discussed by Sigbjörnsson et al., 2013). The motivation is that strong-motion recordings have revealed significant incoherence in earthquake ground motions at different locations within the spatial dimensions of large horizontally expanded structures (see, for further information on theoretical background and applications, Zerva, 2009). Structures of special interest in this connection are dams, e.g. long earth fill dams, pipeline systems, and critical infrastructure life line systems in general. Apparently the routine engineering practice seems to rely on the assumptions that:

(i) Excitations at all support points are the same. This is valid for structures with small horizontal dimensions at the structure-ground interface.

(ii) Excitation at different support points are shifted corresponding to the wave propagation time over the inter-support distance; a procedure implying that the excitations at all support locations are fully correlated. This technique is, however, often considered acceptable for horizontal structures with large dimensions.

These two approaches do not account for the natural incoherence of the surface ground motion, which may lead to incorrect or inaccurate results. These problems were addressed by Newmark and

[1] Professor, Earthquake Engineering Research Center, 800 Selfoss, Iceland, ragnar.sigbjornsson@hi.is
[2] Associate Professor, Earthquake Engineering Research Center, 800 Selfoss, Iceland, rajesh@hi.is
[3] Research Professor, Earthquake Engineering Research Center, 800 Selfoss, Iceland, skykkur@hi.is
[4] Professor, Reykjavik University, Menntavegur 1, Reykjavik, Iceland, jonasthor@ru.is

Rosenblueth (1971), Hindy and Novak (1980) presenting a pioneering engineering model accounting for the incoherence; Harichandran and Vanmarcke (1986), Der Kiureghian (1996), Zerva (2009), and the references therein contain a more detailed discussion on the engineering implications of spatially varying ground motions. The estimation procedures adopted are in most cases based on Fourier type methods (see, for instance, Zerva, 2009). A new estimation technique based on parametric systems approach has been presented by Rupakhety and Sigbjörnsson (2012) improving the resolution of estimates obtained from short duration strong-motion acceleration signals.

THE STUDY CASE

The event studied in the article is the so-called Ölfus Earthquake, on 29 May 2008 at 15:45 UTC (Sigbjörnsson et al. 2009; Halldórsson and Sigbjörnsson, 2009). The epicentre was in the Ölfus District between the towns of Selfoss and Hveragerdi (see Fig. 1). The moment magnitude of the earthquake was 6.3 according to the Global Centroid Moment Tensor (CMT) database and the Instituto Nazionale di Geofisica e Vulcanologia (INGV). The earthquake can be characterised as a shallow crustal earthquake on a north-south trending right-lateral strike-slip faults. The basic properties of this event are found to be similar to the characteristics of the South Iceland earthquakes in June 2000 (Ambraseys et al. 2004; Sigbjörnsson and Ólafsson 2004; Sigbjörnsson et al. 2007). A noteworthy feature of this earthquake is the fact that it originated on two parallel faults rupturing almost simultaneously (see Fig. 1). This is characteristic for the South Iceland Seismic Zone and can be explained with a simplified kinematic model known as the 'bookshelf' mechanism (see, for instance, Rupakhety and Sigbjörnsson, 2014).

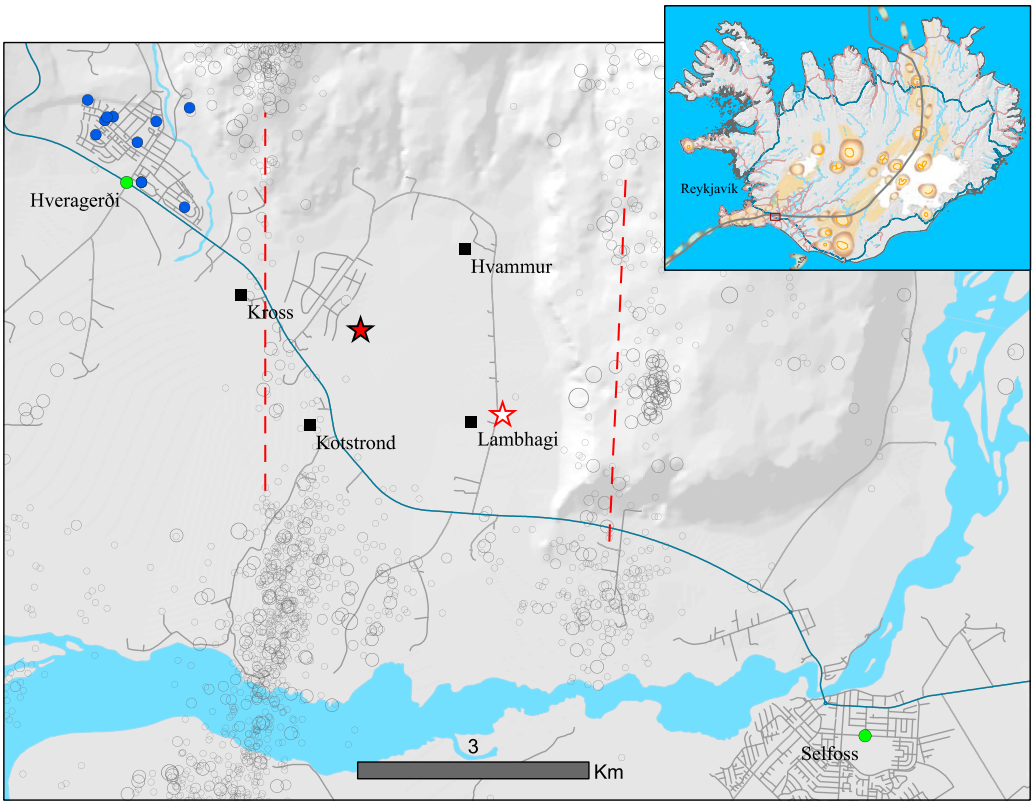

Figure 1. The main picture displays the seismicity distribution for the period of 23 May to 31 June, 2008, (open circles denote earthquake epicentres) indicating the location of the two causative faults (approximated by the red dashed lines) of the 15:45 UTC 29 May 2008 Ölfus earthquake. The top right inset picture shows Iceland with the mid-Atlantic ridge (grey curve). The solid red rectangle on the inset map indicates the area shown in the main picture. The solid star indicates the macroseismic epicentre and the hollow start indicates the epicentre estimated from strong-motion data of the Ölfus Earthquake (see, Sigbjörnsson et al., 2009). The blue circles in Hveragerdi indicate the locations of the recording stations of the ICEARRAY.

The recorded acceleration in the epicentral area was high (Halldórsson and Sigbjörnsson, 2009) and the instantaneous earthquake action on buildings exceeded the codified design loading. The damage was widespread and significant, even though the majority of buildings withstood the high accelerations without visible damage. There were several cases of totally damaged buildings, i.e. buildings that were not judged economically feasible to repair. The structural damage to buildings has been assessed to 5% of the renewal value, while the damage to pipeline systems was significantly higher, i.e. up to or above 20% of the renewal cost (Rupakhety and Sigbjörnsson, 2014).

The damage to household articles and building contents was extensive in the near-fault region. Only 28 people suffered physical injury due to the earthquake effects, and luckily there were no fatalities out of roughly ten thousand people living in the epicentral area. Landslides and rock-falls were significant. Geothermal areas were affected and new hot springs were formed. Some damage to roads and bridges in the area was observed after the earthquake. Furthermore, the water supply systems in the area were affected by the event, which resulted in leakages and cloudy drinking water, at least temporarily. No interruption occurred in the supply of electricity during the earthquakes. The seismic activity in the wake of this earthquake produced numerous events that may have augmented the structural damage and the post-earthquake stress of the people living in the affected area.

The event was recorded by the Icelandic Strong-motion Network (IceSMN, see, for retrieval of the recorded data from the ISESD, Ambraseys et al., 2002; and 2004) and the newly installed ICEARRAY network (Halldórsson et al. 2008), which is a small-aperture array located in the extreme near-fault area (see Fig. 1). The peak ground acceleration (PGA) recorded close to the epicentre was high (Halldórsson and Sigbjörnsson, 2009). In the village of Selfoss, towards the southeast of the epicentre, the horizontal acceleration reached 50% g. In the village of Hveragerdi, northwest of the epicentre, the horizontal and the corresponding vertical acceleration reached 85% g at some locations. Near the epicentre there was an indication that the vertical acceleration had exceeded 1 g. In the Reykjavik area, roughly 40 km from the epicentre, the horizontal PGA was less than 4% g.

Figure 1 gives a geographical overview of the location of the strong-motion stations, as well as assessed causative faults of the current event. Furthermore, the fault-normal component of the recorded acceleration is plotted in Fig. 2 below. The range of PGA recorded by the array expressed as a percentage of g is 38-86, 44-88, and 30-82, in the fault-normal, fault-parallel, and vertical directions, respectively. The velocity time series (see Fig. 3) contained dominant long-period pulses characteristic of forward-directivity related focussing of seismic energy in the fault-normal direction (see Rupakhety et al., 2011). The PGA of the resultant acceleration vector within the array varied from 50% g to 101% g; indicating a large variability in the small area covered by the array. The frequency-content of ground-motion across the array also varied significantly according to spectral representation by Halldórsson and Sigbjörnsson (2009).

STOCHASTIC MODELLING

By assuming that the strong-motion phase of ground motion is locally homogeneous and stationary stochastic process (see, for instance, Vanmarcke, 1983; Zerva, 2009), the spectral representation of the process is achieved through the spectral density matrix $\boldsymbol{S}_{\boldsymbol{a}_r\boldsymbol{a}_s}$, with $\boldsymbol{a}_r$ and $\boldsymbol{a}_s$ referring to the temporal acceleration in two different points, r and s, in space, respectively. It is noted that the spectral density matrix $\boldsymbol{S}_{\boldsymbol{a}_r\boldsymbol{a}_s}$ is a complex matrix which is Hermitian symmetric by definition. The spatial-temporal incoherence is represented by the coherence spectrum derived from the spectral density matrix as:

$$C_{kl}(\boldsymbol{\kappa},\omega) = |S_{kl}(\boldsymbol{\kappa},\omega)|^2 / S_k(\omega) S_l(\omega) \tag{1}$$

Here, the auto-spectral densities of the k- and l-component are denoted as S_k and S_l, respectively; $S_{kl}(\boldsymbol{\kappa},\omega)$ denotes the cross-spectral density as a function of wavenumber vector $\boldsymbol{\kappa}$ and frequency ω. In strong-motion engineering seismology, the so-called lagged coherency, defined below, provides a simplified representation of incoherence (Zerva, 2009):

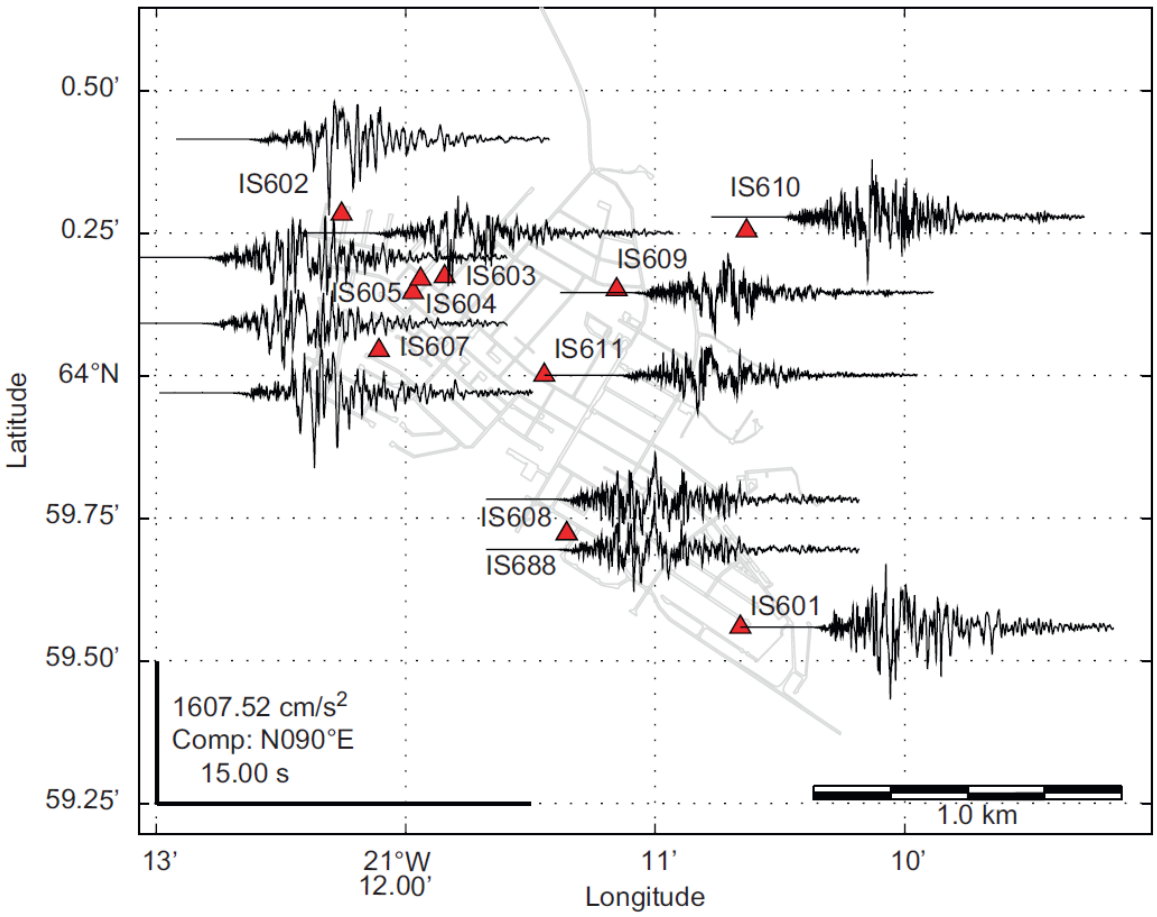

Figure 2. Strong-motion acceleration time series recorded by ICEARRAY during the Ölfus Earthquake of 29 May 2008, 15:45 UTC (after Halldorsson and Sigbjörnsson, 2009). Only fault-normal (east-west) components are presented here; other orthogonal components can be found in Halldorsson and Sigbjörnsson (2009).

$$|Coh_{kl}(\boldsymbol{\kappa},\omega)| = |S_{kl}(\boldsymbol{\kappa},\omega)|/\sqrt{S_k(\omega)S_l(\omega)} \tag{2}$$

The coherence spectrum defined in Eq. 1 is the square of lagged coherency defined in Eq. 3.2. Furthermore, the value of lagged coherency lies between 0 and 1, representing fully incoherent and fully coherent motion, respectively. If the motion is assumed to be isotropic, spatial properties of lagged coherency can be modelled as a function of inter-station distance only, i.e.:

$$|Coh_{kl}(\xi,\omega)| = |S_{kl}(\xi,\omega)|/\sqrt{S_k(\omega)S_l(\omega)} \tag{3}$$

with ξ representing the spatial distance between the k and l components of motion. It is worth noting that the coherency as defined above (see Eq. 1 to Eq. 3) in terms of strong-motion acceleration equals the coherency for the strong-motion velocity and displacement. This is advantageous in the estimation procedure as coherency estimates derived using the velocity are in general more stable in the high frequency range than estimates derived directly from the recorded acceleration (see, Rupakhety and Sigbjörnsson, 2012).

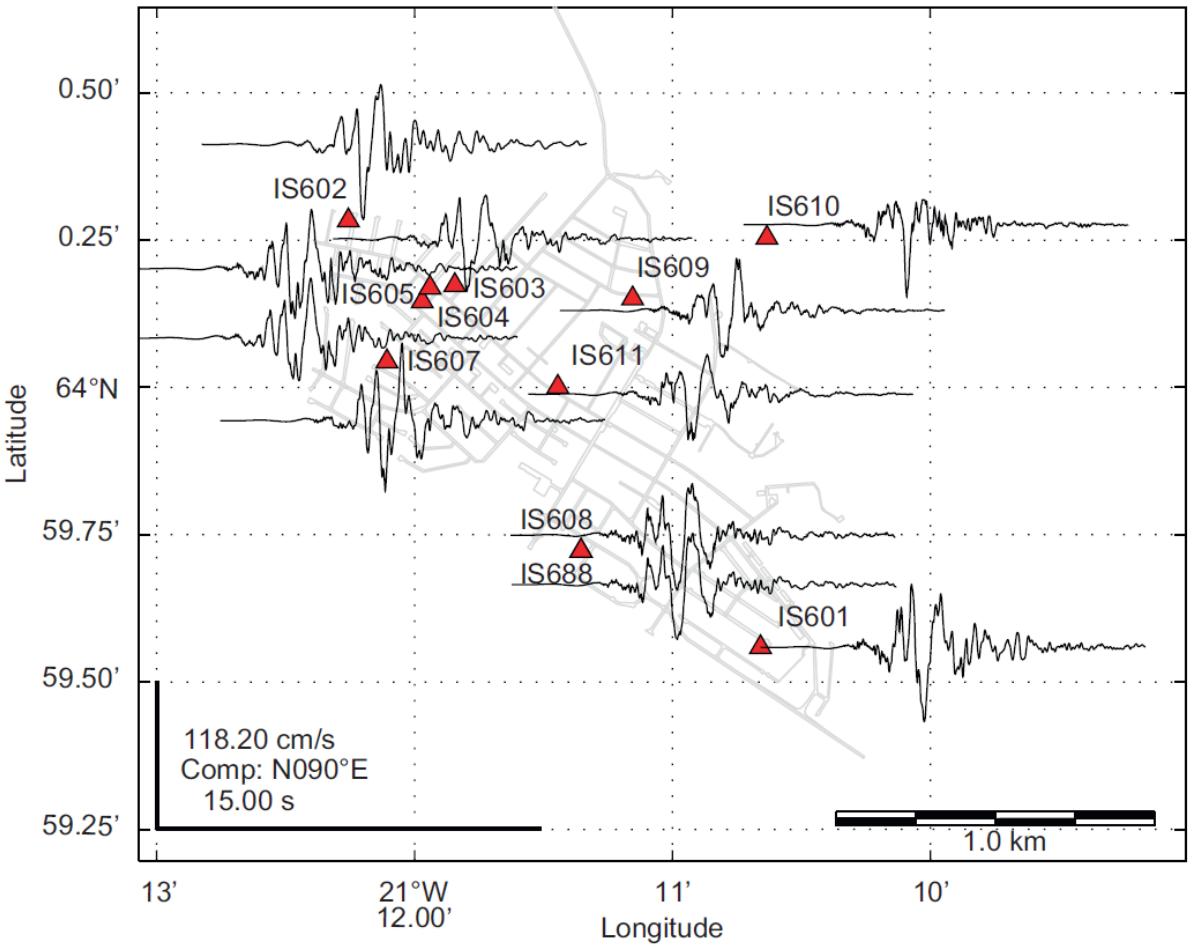

Figure 3. Strong-motion velocity time series recorded by ICEARRAY during the Ölfus Earthquake of 29 May 2008, 15:45 UTC (after Halldorsson and Sigbjörnsson, 2009). Only fault-normal (east-west) components are presented here; other orthogonal components can be found in Halldorsson and Sigbjörnsson (2009).

NUMERICAL FINDINGS

The above outlined stochastic model has been applied to the ICEARRAY data. The recorded data is expressed in a rectangular coordinate system with horizontal axes in fault-normal and fault-parallel direction along with a vertical axis. The strong-motion phase of the record is extracted for further analysis. This must be done for each record implying that there is a fixed starting point in time for all three components (see Rupakhety and Sigbjörnsson, 2014) and a fixed ending time. The starting and ending time considered here correspond to 5 and 95 percent accumulation of time dependent Arias Intensity (see, for instance strong-motion duration by Trifunac and Brady, 1975). To ensure that the time window applied for each component at a recording station represents the same absolute time, a scalar measure of the time dependent Arias Intensity tensor, furnished by the trace of the tensor, is utilized. This is equivalent to the time dependent Arias Intensity of the resultant acceleration vector at the recording station (Rupakhety and Sigbjörnsson, 2013). Before evaluating the incoherence, the wave passage effects are removed from the data (see Rupakhety and Sigbjörnsson, 2012; Rupakhety and Sigbjörnsson, 2013; Zerva, 2009). This is difficult to achieve for a multi-channel three-component signals. In general it is "[…] presumed that the signals [are] temporally-aligned, phase-aligned, frequency-aligned, and scale-aligned in order to compute a single coherence value." (for further discussion, see, Marple and Marino, 2004). In practical terms it is recommended that one of the records of two is temporally shifted based on one preselected component only. This leaves the remaining components non-aligned which may lead to coherency less than one for those. The selection

of the component used in the temporal-alignment procedure is, on the other hand, not a simple task and is the subject of on-going study. Candidates may be (i) the larger horizontal principal component and (ii) the fault-normal component. Other measures should also be considered (Rupakhety and Sigbjörnsson, 2012). Furthermore, in this context it may be needed to take into consideration the fact that the wave front is not planar, strictly speaking, but is curved as a result of the extreme near fault properties resulting from the short source to site distances in the current case. The complexity is augmented further by the two causative faults in the current case (Halldorsson and Sigbjörnsson, 2009).

The time-aligned time series are then used to estimate the cross spectral densities. They are computed for all inter-station distances available in the applied data set. The inter-station distances should ideally be uniformly distributed on the interval covered by the array. In the case of ICEARRAY, the distribution is not far away from a uniform one, with the exception of one station. From a statistical point of view the inter-station distribution of the ICEARRAY is found acceptable. In the current study the spectral densities are obtained using the Welsh spectral estimation methods (see, e.g., Proakis and Manolakis, 1996) for each inter-station distance. The coherency is then computed using Eq. 3.1 above. No smoothing is performed at this stage other than the averaging included in the Welsh procedure. Finally, the coherency spectral estimates are smoothed over the inter-station distances. This is performed in two steps: (i) re-sampling of the coherency estimates in the spatial domain; (ii) smoothing the re-sampled coherency estimates using a moving average window. The spatial resolution obtained by this procedure is about 50 m. The resulting lagged coherency is displayed in Fig. 4 using the fault-normal case as an example.

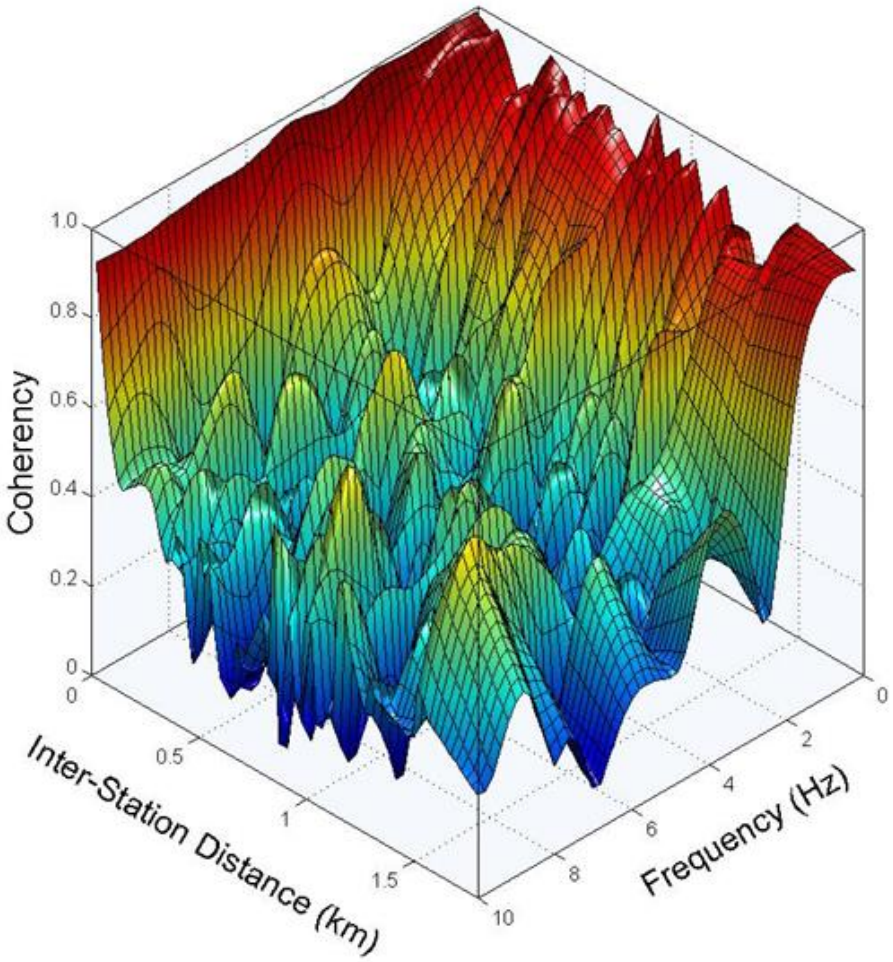

Figure 4. Lagged coherency derived from the ICEARRAY data set recorded during the Ölfus Earthquake of 29 May 2008, 15:45 UTC: the fault normal component (Sigbjörnsson et al. 2009).

This three dimensional plot reveals the basic behaviour that seem characteristic for the structure of the lagged coherency. Over all, the coherency decreases with increasing frequency and inter-station distances. Furthermore, the figure reveals quite coherent motion for inter-station less than 100 m or so. Within the spatial-frequency range considered the same is the case for frequencies less than 2 Hz or thereabout.

The lagged coherency matrix is shown in Fig. 5. Broadly speaking, the behaviour of the single component coherency revealed in these figures is comparable with what is seen in Fig. 4. By comparing the coherency of the individual components, i.e. fault normal, fault parallel and fault vertical, it can be seen that the coherence is apparently greatest in the case of the fault normal component and smallest for the vertical component (see Fig. 5). This applies especially to the greatest inter-station distances. It is also worth noting that the inter-component coherencies (see Fig. 4) are significant, typically with lagged coherency in the range 0.3 to 0.5, which implies that these cross-components may contribute significantly to earthquake-induced structural response.

A preliminary study including the effects of the spatial variability on the earthquake-induced structural response of multi-support pipeline systems reveals that the response depends on the orientation of the pipeline, i.e. fault normal or fault parallel; furthermore, the effects of observed coherency are greater on stiff structures than on flexible ones; and finally, the inter-component coherency should not be neglected in response analyses. It is also found that the local 'site' effects (see Fig. 2, revealing great variability throughout the recording array) result in great variability of structural response

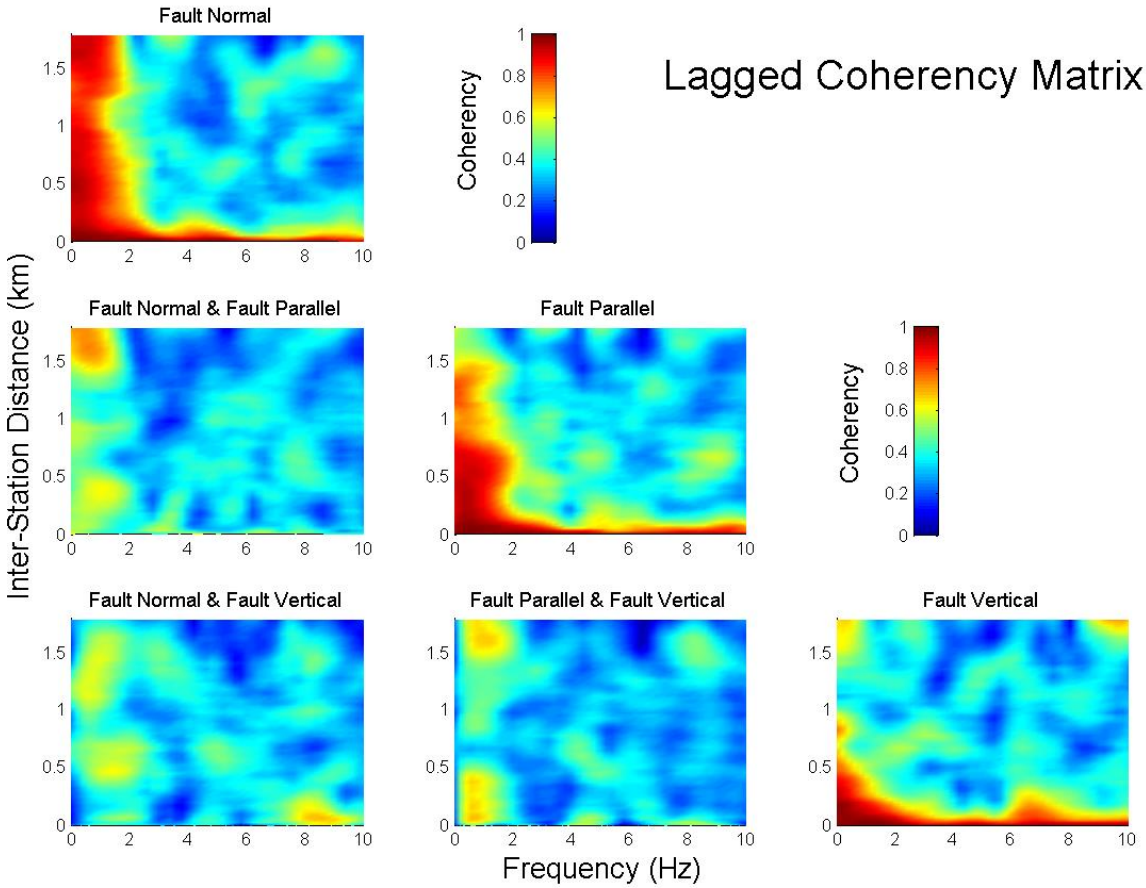

Figure 5. The lagged coherency derived from the ICEARRAY data set recorded during the Ölfus Earthquake of 29 May 2008, 15:45 UTC (Sigbjörnsson et al., 2009).

CONCLUDING REMARKS

This paper outlines the main results obtained in a study of the spatial variability of strong-ground motion in the near-fault zone. The study is based on data from a single 6.3 M_w event, with short epicentral distance, originating from two causative faults rupturing almost simultaneously. The main findings of this study can be summarised as follows:

- ✓ The coherency of a given strong ground-motion component decreases with increasing frequency and increasing inter-station distance
- ✓ The fault normal component is the most coherent ground-motion component
- ✓ The inter-component coherency is significant, i.e. coherency of fault normal and fault parallel component etc.

It should be emphasised that these results should be treated with caution as they are based on limited data. However, it seems clear that they reveal more complicated picture than obtained using far- fault data. Hence, further research is needed into the properties of incoherence of strong ground motion in the near-fault zone.

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