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Report

Review on studies related to spatial variability of ground motion in the near field

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Summary

This report presents a review on the state-of-the-art of studies on spatial variability of seismic ground motion. Spatial variability of seismic ground motion is related to the difference in amplitude and phase of ground motion recorded over extended area. Since variation of ground motion depends on frequency and inter-station distance, the coherence function is mostly used to characterize spatial variability of ground motion. A high number of coherency models were derived over the last four decades. However, these models rely on ground motions recorded at rather few array sites and that they are dependant on sites and seismic events. It thus does not allow capturing the physical mechanism underlying the spatial variation of the seismic ground motions and restricts the actual coherency models to be used at sites where they were developed. Besides, this report shows that there are only very few observational and numerical studies related to ground motion spatial variability and/or ground strains and rotation in the near-field. In the near-field however, all studies outline the importance of source mechanism and site condition on observed or modelled seismic ground motion and strains. We believed that the dense seismological arrays installed during the NERA project (seismic experiment in Argostoli (Greece) from September 2011 to march 2012 and in Italy from march 2012 to july 2012) will provide useful data both in the near and far field for better understanding and modelling ground motion spatial variability.

Introduction

Spatial variability of seismic ground motion is related to the difference in amplitude and phase of ground motion recorded over extended area. Spatial variability results from different contributions: the wave passage effect due to time delays in the arrival times of various seismic phases, the site response effect due to spatial soil heterogeneity, the attenuation along the ray path and the incoherence effects due to scattering of waves by local heterogeneities, the seismic rupture mechanism and especially the source directivity. At few tens of meter scale, such spatial variability may have important effect on the response of extended lifelines such as bridges, pipelines, communication systems, dams because of the spatially variable contributions applied at different supports of the structure. At a more regional scale, development of reliable and well calibrated parametric models that describe the spatial variability of ground motion is also of main importance to improve shake-maps and site-specific ground motion prediction (Harmandar, 2009).

Although the different contributions to spatial variability are recognized for a long time, it is still difficult to clearly understand physical mechanism underlying the spatial variation of the seismic ground motions, to quantify effect of each contribution to the observed spatial variability signal and to derive reliable spatial variability models. Main reasons are the lack of data, different experimental setups, site conditions, source mechanisms and data processing. In this report, we shortly summarize the state-of-the-art of studies related to observation and characterization of ground motion spatial variability since a very detailed and complete review can be found in Zerva (2009). Then we present the very few observational and numerical studies related to spatial variability of ground motion in the near-field.

Spatial variability of ground motion in the far field: observations and characterization

Effects of ground motion spatial variability on lifeline structures (pipelines, tunnels, dams, suspension, bridges) have been extensively studied over the last four decades (e.g. among many others, Bogdanoff et al., 1965; Hindy and Novak, 1980; Abdel-Ghaffar and Stringfellow, 1984; Luco and Wang, 1986; Nadim et al, 1991; Harichandran and Wang, 1990; Harichandran et al., 1996; Zerva, 1990; Zerva, 1994; Hao, 1991; Sextos et al., 2003a & 2003b; Lou and Zerva, 2005; Lupoi et al., 2005; Nuti and Vanzi, 2005). Depending of the type of structures (extended, flexible, multiple foundations), spatial variability may reduce translational responses, increase the rocking and torsional response or increase localized deformation (e.g. Luco and Wong, 1986).

Since variation of ground motion depends on frequency and inter-station distance, the coherence function is mostly used to characterize spatial variability of ground motion. The derived parametric coherency models are then used for simulating spatially variable time histories and their effects on structural response or in random vibration analyses (e.g. Abrahamson, 1992; Zerva and Zhang, 1997). By analysing ground motion recorded at dense arrays, a large number of empirical or semi-empirical coherence functions (generally in lagged coherency form) have been developed since the 1970's: Abrahamson, (1992), Harichandran and Vanmarcke (1986), Harichandran (1991), Loh (1985), Loh and Yeh (1988), Loh (1991), Menke et al., 1991; Novak (1987), Abrahamson et al., 1991; Oliveira et al. (1991), Vernon et al. (1991), Der Kiureghian (1996), and Zerva and Zhang (1997), among many others. Most of these coherency models exhibit an exponential function with values decreasing with inter-station distance and frequency. Although the number of coherency models is large (for a review, see Liao, 2006; Zerva, 2009), they mainly rely on the analysis of ground motion recorded by "few" seismic arrays, and especially the following arrays:

- The El Centro differential array (Bycroft, 1980)
- The Chusal differential array (King, 1981)
- The Chiba array (Yamazaki and Turker, 1992)
- The SMART-1 (Strong Motion Array in Taiwan-Phase 1) and LSST arrays located in the north-east of Taiwan (Iwan, 1979; Bolt and al., 1982; Loh et al., 1982; Abrahamson et al., 1987) (Figure 1)
- The EPRI Parkfield, USGS Parkfield, Hollister, Stanford, Coalinga, UCSC ZAYA and Pinyon Flat arrays (Abrahamson et al., 1991; Schneider et al., 1992)
- The Parkway array in New-Zealand (Stephenson, 2007; Liao, 2006)
- The Istanbul Earthquake Rapid Response System (IERRS) (Erdik et al., 2003; Harmandar, 2009)

Besides, Liao (2006) compiled a complete list of available seismic ground motion dense arrays that were already used or could be used for assessing spatial variability of ground motion.

As reviewed in Zerva (2009), lagged-coherency models derived for the same type of site conditions (soil or rock sites) and from different arrays differ significantly (Figure 2), especially for the rock sites. Such variability of models at rock site may come from scattering from heterogeneities within the shallow crust (Toksoz et al., 1991; Menke et al., 1990) or near-surface rock weathering (Steidl *et al.*, 1996). While Liao (2006) did not observed any directional dependence of the coherencies computed for various station pairs at the SMART-1 array, station-pair coherencies derived from the Parkway array data exhibit very clear directional dependence (Figure 3) that was attributed to the complex wave propagation pattern of the narrow basin of Parkway valley. Besides, Harichandran and Vanmarke (1986) observed that coherencies observed for the same array and from different earthquakes can also differ significantly (Figure 4).

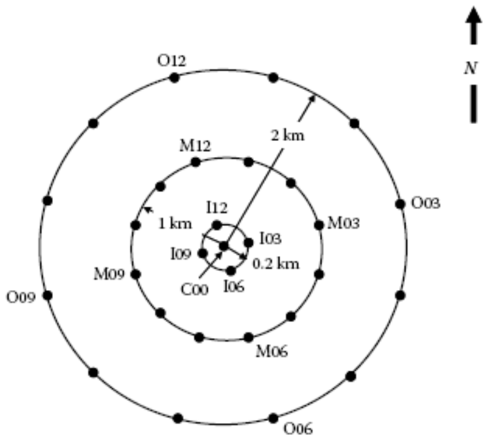

Figure 1: Configuration of the SMART-1 array. Reproduced from Zerva (2009).

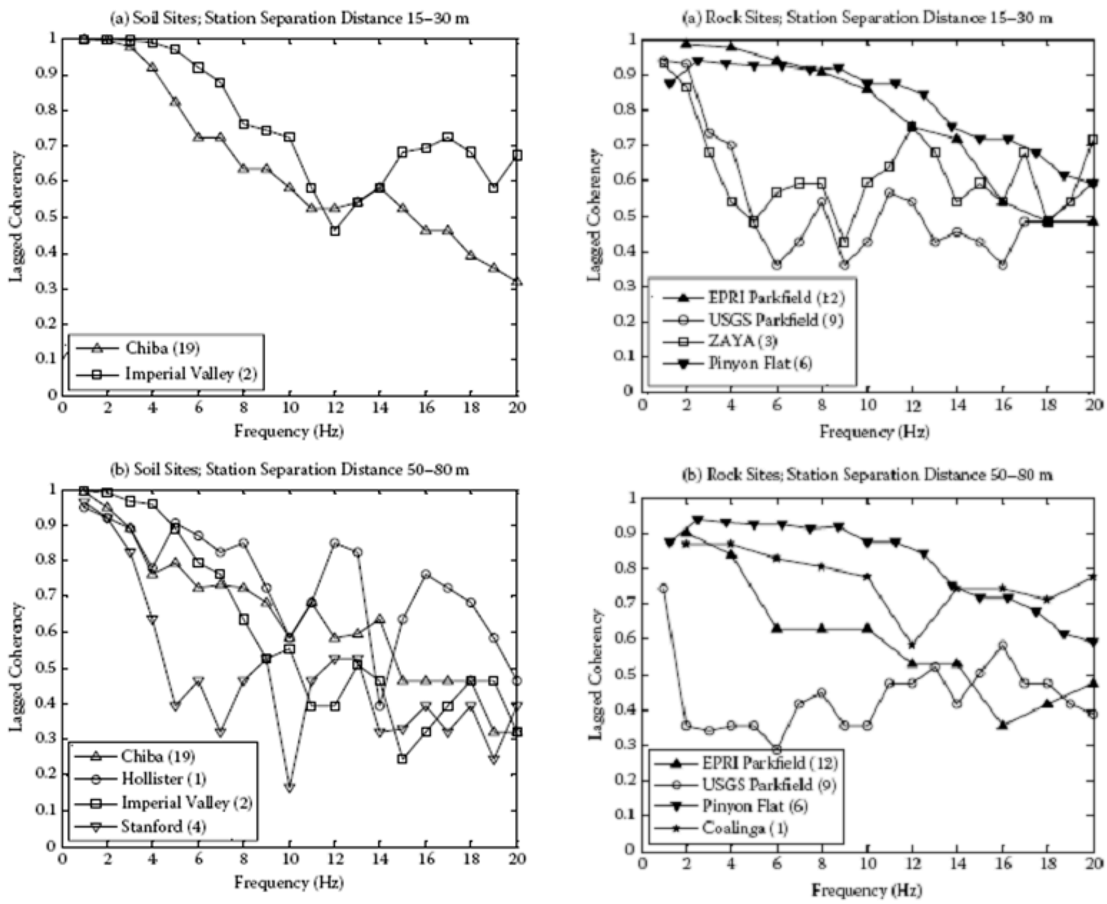

Figure 2. Lagged coherencies estimated at soil (left) and rock sites (right) by Schneider et al., 1992. The average coherency was estimated for inter-station distance ranging from 15 to 30 m and from 50 to 80 m. Used arrays as well as the number of seismic events considered for the evaluation of the average coherence are indicated in the legend. Reproduced after Zerva (2009).

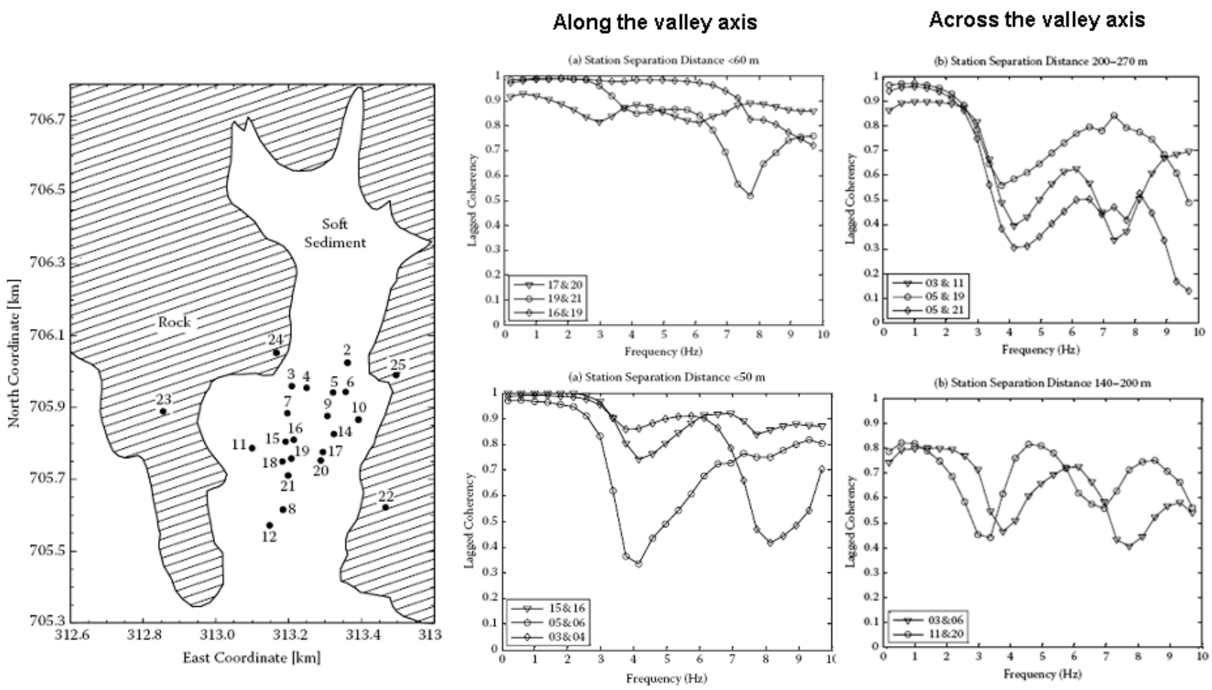

Figure 3: (Left) configuration of the Parkway array (Stephenson, 2007); (Right) Lagged coherency models computed for the EW component for different station pairs lying across or along the valley axis (Liao, 2006) . Reproduced after Zerva (2009)

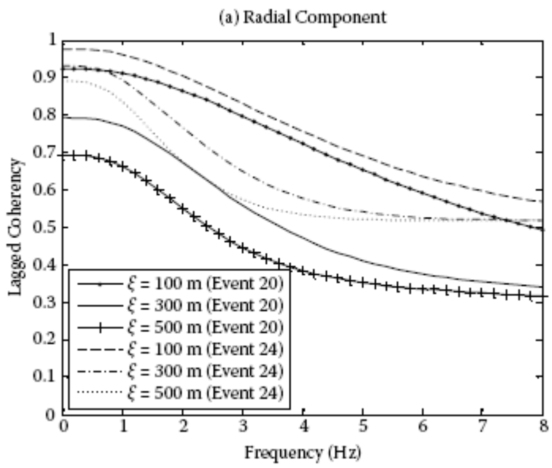

Figure 4: Parametric coherency model derived by Harichandran and Vanmarcke (1986) for different inter-station distances and two different earthquakes (events 20 and 24) recorded at the SMART 1 array. Reproduced after Zerva (2009).

Spatial variability of ground motion in the near-field: observations and modelling

Densification of permanent and temporary seismic networks over the last two decades has allowed increasing the number of ground motion recordings close to the active faults. The observed near-field recordings is highly variable as a consequence of seismic rupture properties: directivity effects and slip distribution (e.g. Shakal et al., 2006; Figure 5), path effects as focusing or scattering of the seismic waves, non-linearity in the fault zone (e.g. Karabulut and Bouchon, 2007; Figure 6), local site effects close to seismic stations (non-linearity, amplification, liquefaction, etc.).

Despite the increase of near-field ground motion recordings, the main study regarding the spatial variability in the near-field remains the one performed by Abrahamson et al. (1991) by using 15 events recorded by the LSST array with magnitude ranging from 3 to 7.8 and epicentral distance from 5 km to 113 km. Abrahamson et al. (1991) did not observe any dependence of coherency with magnitude and distance, that Spudich (1994) explains for unilateral rupture as the radiation (that propagated with the wave front) at any time of only a very small portion of the total rupture radiation.

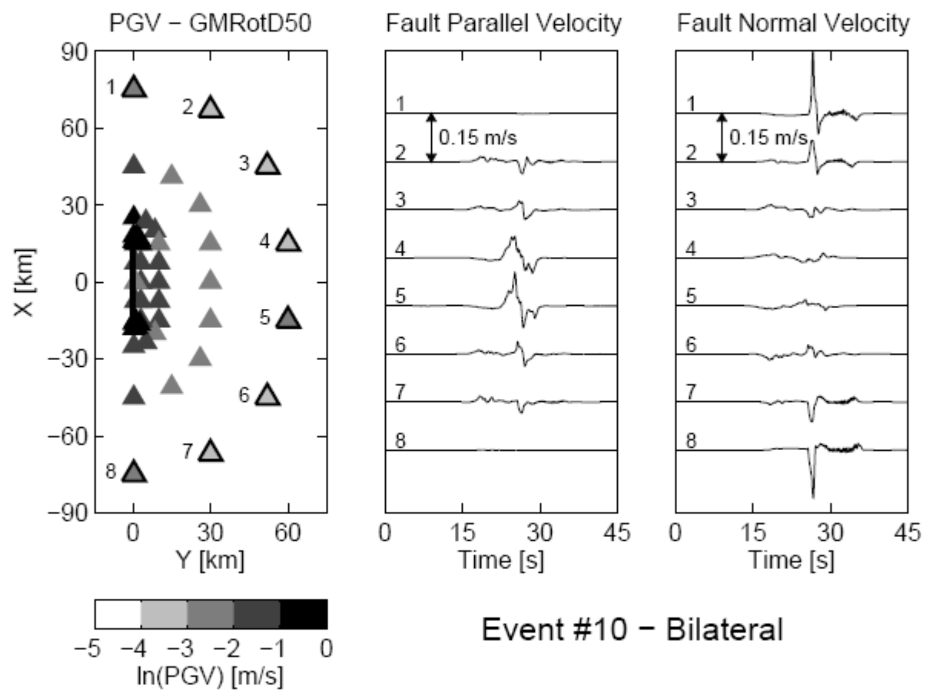

Figure 5. Map of horizontal PGV values and time histories computed at different receivers (1 to 8 labels) around the fault. The rupture mechanism is a single bilateral event. Reproduced from Ripperberg et al. (2008)

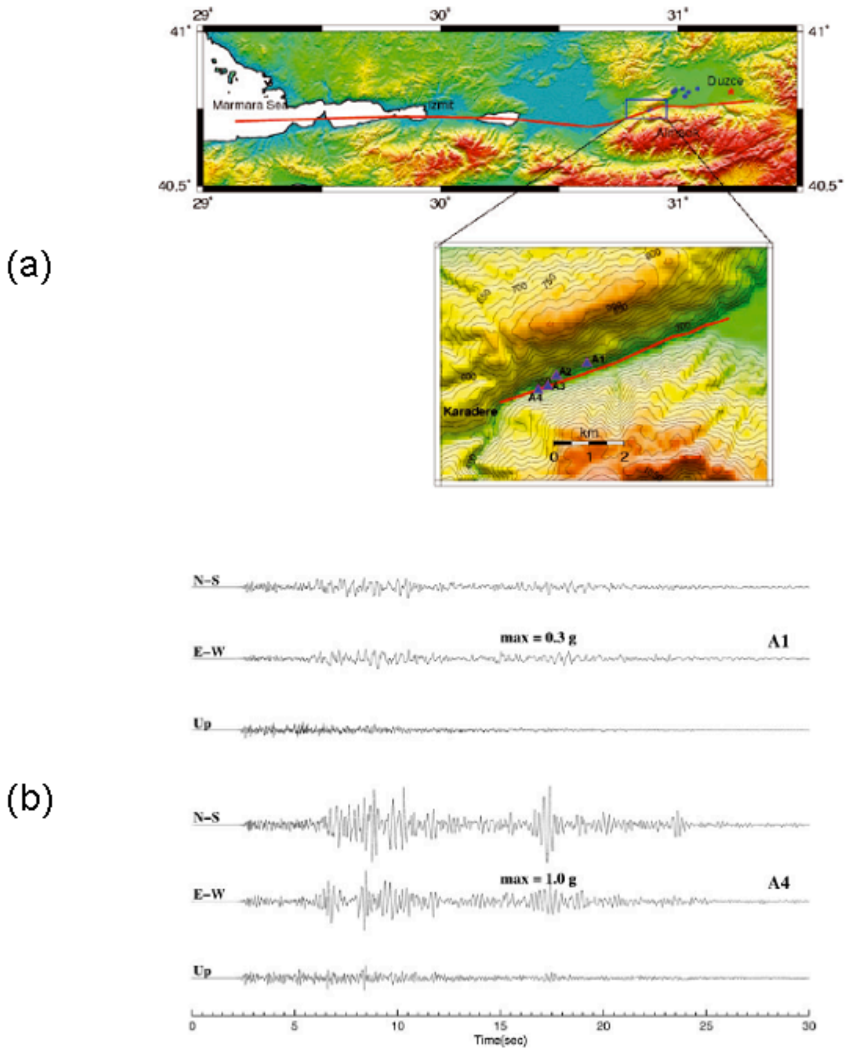

Figure 6: (a) Location of the array close to the North Anatolian Fault segment which ruptured during the Izmit and Duzce earthquakes (solid line). The triangles show the location of the four stations. The epicentre of the Duzce earthquake is indicated by a star and the aftershocks by blue circles. (b) Acceleration time histories recorded recorded during the main schok at two stations 1.5 km apart. After Karabulut and Bouchon (2007)

On the contrary, the last two decades has witnessed an increase of strain components (rotation, strain, tilt) studies in the near-field from both experimental and numerical viewpoints. Indeed, the evaluation of induced transient ground strains and rotations – which are closely related to the spatial variability of seismic motions - is of critical importance for the seismic response and design of lifeline structures and buildings (e.g. Newmark, 1969;Trifunac, 1982, 2009). In addition, measurement of ground strain may enable measurement of seismic phase velocity (Mikumo and Aki, 1964; Igel et al., 2005) or provide useful constraints on seismic rupture mechanisms (Takeo and Ito, 1997)

Direct observation of ground strains and rotation is possible using solid-state instruments (Nigbor, 1994), ring lasers (Stedman et al., 1997; Suryanto et al., 2006), and rotation meters (Lin et al., 2009). Most frequently however, the strain components of motion are derived from spatially recorded array data (e.g. Niazi, 1986; Oliveira and

Bolt, 1989; Spudich et al., 1995; Bodin et al., 1997; Huang, 2003; Suryanto et al., 2006; Spudich and Fletcher, 2008; Paolucci and smerzioni, 2008; Liu et al., 2009).

In the near field, Takeo (1998) observed by using a gyros in the Inzu peninsula in Japan a larger rotational rate than expected in the source vicinity (at 3 km distance) of a magnitude 5.7 earthquake, which he attributed to the spatial variation of rupture slip velocity and, hereafter, to the excitation of rotational motion. Spudich and Fletcher (2009) derived ground strains and rotations for the mainshock and aftershocks of the Mw 6.0 2004 Parkfield earthquake recorded by the USGS Parkfield array. However, they do not estimate rotations as large as the ones observed by Takeo (1998) that they attributed either to local spatial heterogeneities in soil structure or to a douple-couple source mechanism that radiates less rotations that non-double-couple mechanisms like the event studied by Takeo (1998). Huang (2003), by measuring large rotational motions after the 1999 Chi-Chi earthquake, also outlines the relation between the slip distribution and the observed rotation. Rotations measured by Niazi (1986) at the El Centro differential array during the 1979 Imperial Valley earthquake and by Oliveira and Bolt (1989) at the SMART-1 array (Ms 5.7 to 7.8 magnitude events, epicentral distance ranging from 6 to 84 km) were used to calibrate the analytical estimates of the surface strain field (e.g. Hao, 1996).

From a numerical point of view, Bouchon and Aki (1982a) simulated in a layered media rotations, strains and tilts in the near-field of strike-slip and dip-slip faults. While Bouchon and Aki (1982) concluded that computed strains and tilt were small compared to the amplitude of ground motion, Bouchon et al. (1982b) observed that additional lateral heterogeneity in the ground structure may significantly amplify the differential motions. Recent simulations of Stupazzini et al. (2009) and Wang et al. (2009) for more complex structures and source mechanisms outlined that rotation rates depends mostly on hypocenter location and source directivity and the local site conditions (non-linear behaviour, topography, lateral heterogeneity). Besides, both studies also show that the Peak Ground Accelerations or Peak Ground Velocities were linearly correlated to the peak rotation rates (Figures 7 and 8)

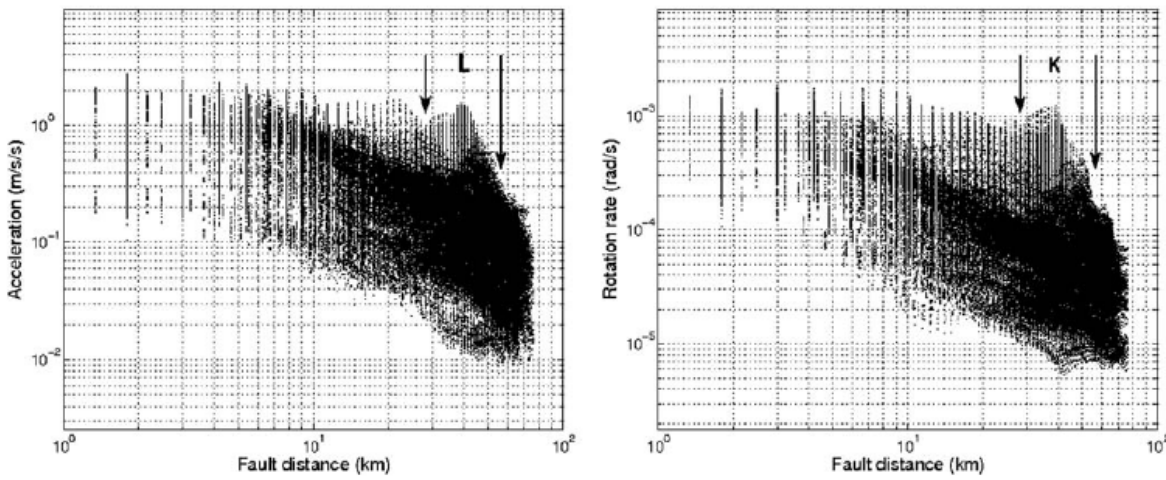

Figure 7. Comparison of peak ground accelerations and rotation rate as a function of distance to the fault when varying hypocenter location. Left-hand panel: y component of acceleration. Right-hand panel: z component of rotation rate. Reproduced from Wang et al. (2009)

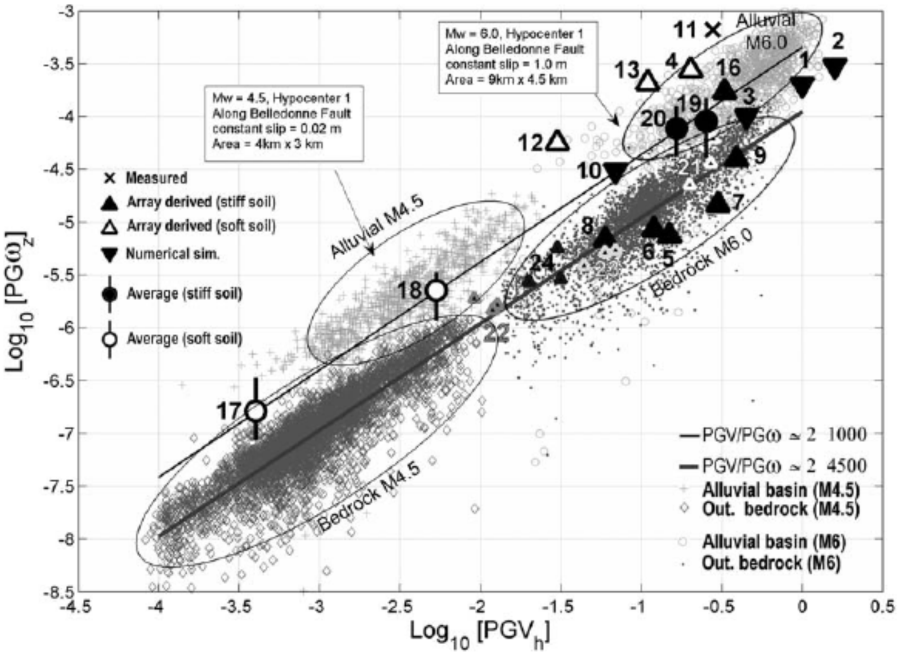

Figure 8. Simulated peak ground horizontal velocity (PGVh) versus peak ground rotation (PGωz) in logarithmic scale obtained with Mw 6.0 and Mw 4.5, neutral directivity, and elastic soil behavior. Superimposed are the individual data retrieved from literature. Reproduced from Stupazzini et al. (2009)

Conclusion

A very large number of coherency models were derived over the last four decades. However, one has to recognize that these models rely on ground motions recorded at rather few array sites, and that they are dependant on sites and seismic events. It thus does not allow capturing the physical mechanism underlying the spatial variation of the seismic ground motions and restricts the actual coherency models to be used at sites where they were developed.

Besides, despite the recent increase of near-fault ground motion observations, there are still only very few studies related to spatial variability of ground motion or/and strains and rotations in the near-field, which all outline the dependence of strains and rotations on source mechanism (hypocenter location, source directivity) and local site conditions.

In 1982, Bouchon and Aki (1982) stated *"The deployment over the past 50 yr of strong motion accelerographs in many seismic areas has provided an invaluable set of data on the motion of the ground during earthquakes. These data yield the absolute ground motion at discrete locations but, because the spacing between neighboring accelerograph sites is usually much larger than the wavelengths of the disturbances, little is known about differential motions in the near-field of earthquakes. To date, indeed, no records of strain, tilt, or rotation have been obtained in the vicinity of an earthquake source. Recent successful deployment of a dense, small array of strong motion seismographs in Taiwan (Tsai et al., 1981) is however encouraging because the data from such an array can be used to synthesize strain, tilt, or rotation (Saito, 1968)."*

Almost three decades later, one has to recognize that this statement is still almost valid and that dedicated and specific array measurements spanning different wavelength ranges and site conditions especially close to the active faults are clearly required to improve our understanding and modelling of ground motion spatial variability.

We also believed that the dense seismological arrays installed during the NERA project (seismic experiment in Argostoli (Greece) from September 2011 to march 2012 (Figure 9) and in Italy from march 2012 to july 2012) will provide useful data both in the near and far field for better understanding and modelling ground motion spatial variability.

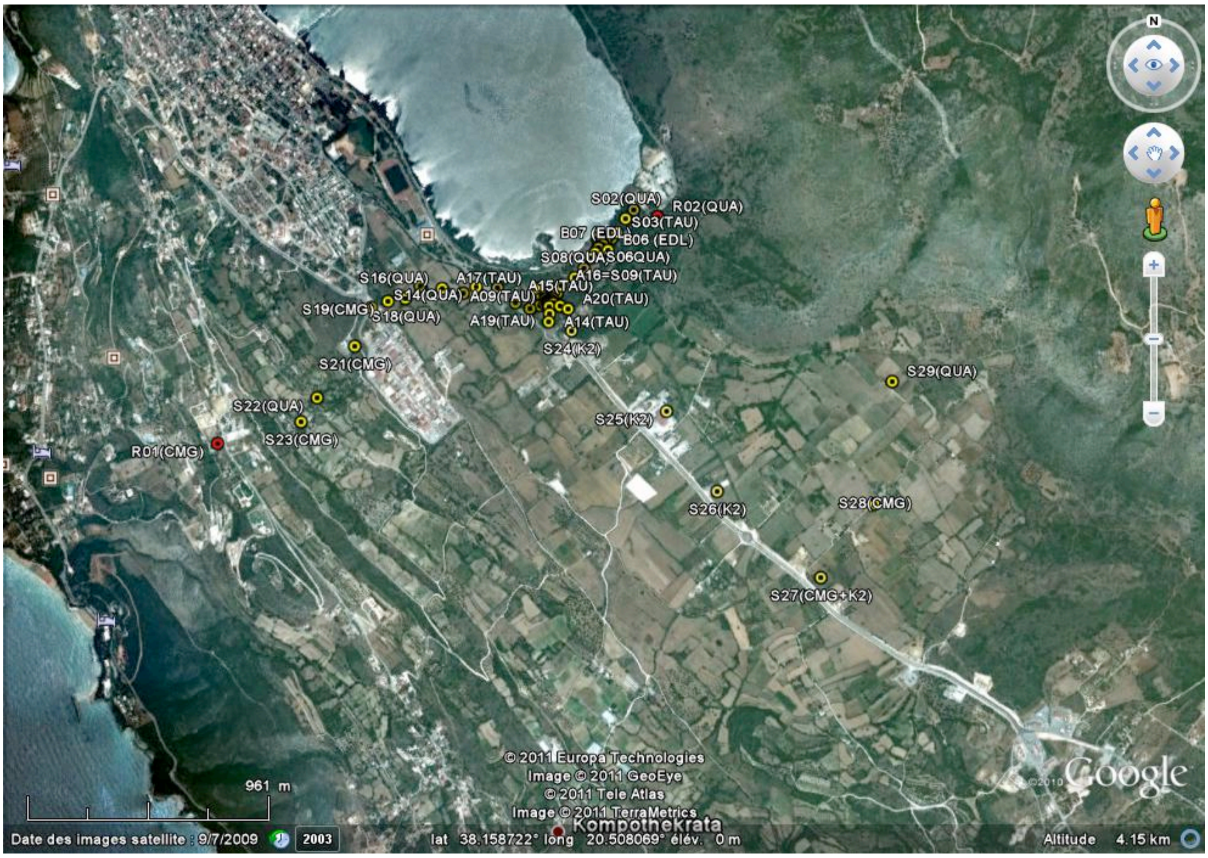

Figure 9: Configuration of the array layout installed in Argostoli (Greece) within the NERA project. The array consists of 64 sensors (54 Broad-band, 10 Short-Periods, 5 Accelerometers) installed along and across the valley among which 21 stations composed the central array with interstation distance ranging from 10 m to 160 m and 10 stations composed the eastern array with interstation distance ranging from 5 m to 65 m.

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