SPATIAL VARIABILITY OF NEAR-SOURCE SEISMIC GROUND MOTION WITH RESPECT TO DIFFERENT DISTANCE METRICS, WITH SPECIAL EMPHASIS ON MAY 29 2012 PO PLAIN EARTHQUAKE, ITALY

Kiana HASHEMI
PhD researcher, Department of Civil and Environmental Engineering, Politecnico di Milano, Milan, Italy
seyedehkiana.hashemydahaj@polimi.it

Ilario MAZZIERI
Post-doctoral researcher, Department of Mathematics, Politecnico di Milano, Milan, Italy
ilario.mazzieri@polimi.it

Roberto PAOLUCCI
Professor, Department of Civil and Environmental Engineering, Politecnico di Milano, Milan, Italy
roberto.paolucci@polimi.it

Chiara SMERZINI
Post-doctoral researcher, Aristotle University of Thessaloniki, Greece
chiara.smerzini@gmail.com

Keywords: Spatial Variability, Po Plain Earthquake, Distance Metrics, Near-Source Ground Motion.

ABSTRACT

In near-source conditions, earthquake ground motion may illustrate specific features such as long-period velocity pulses and directivity. One of the main features in characterization of ground motion in near-fault conditions is its spatial variability not only as a function of random variations of Fourier amplitude and phase, as it is usually considered in engineering practice, but also depending on physical constrains referring to the seismic source characteristics (fault geometry, kinematics of slip) and the interaction with the site conditions. In order to be able to predict reliably the earthquake ground motion and to simulate the combined effects of the near-source conditions and the site effects induced by complex geological structures, there is a certain need of using large size 3D numerical simulations. Therefore, this paper aims at illustrating the spatial variability of seismic motion predicted by a deterministic physics-based numerical study with emphasis on the sites affected by the Po Plain earthquake of 29 May 2012. Such a study is intended to illustrate the variability of peak ground motion with respect to different distance metrics available in the literature as well as proposing a new metric which can decrease the variability of results and the corresponding inter-event residuals significantly. Finally the results will be compared with the strong ground motions recordings obtained during M_w6.0 29 May 2012 earthquake.

INTRODUCTION

The earthquake ground motion in near-fault condition is known to have different specific characteristics in terms of amplitude, duration and frequency content. One of the main issues corresponding to near-fault earthquake ground response is the spatial variability of seismic ground motion. This denotes the differences in the amplitude and phase of seismic motions over extended area with respect to the distance from the source. Predicting reliably the earthquake ground motion and including the coupled effects of the seismic source, the propagation path through complex geological structures and any localized irregularities such as alluvial basins will not be achieved by using numerical approaches that usually are applied in engineering applications involving vertical plane wave propagation in one-dimensional (1D) soil models. These aforementioned effects impose challenging demands on computational methods and resources. Motivated by these considerations, 3D numerical simulations will be performed by using an open-source code SPEED (Spectral Element in Elastodynamics with Discontinuous Galerkin).

This analysis has been devoted to the numerical simulations of the 29th May 2012 earthquake, because it provides an extensive ground motion dataset, consisting of more than 30 recording stations at less than 30 km epicentral distance, and it has been thoroughly documented as regards the source characterization.

The aim of this article is to evaluate the spatial variability of ground motion predicted by a realistic physics-based numerical simulation of the Po Plain earthquake of 29 May 2012. This study investigates the spatial variability and attenuation of peak ground seismic motion with respect to different distance metrics. Due to existence of large variability of results, a new metric is proposed which provides the best results by decreasing the residuals and the final results is compared with available records.

THE PO PLAIN EARTHQUAKE OF 29 MAY 2012

The 29 May 2012 Emilia earthquake occurred on the southern portion of the Po Plain, surrounded by the Alps to the north and Apennines to the south. Fig. 1 represents a simplified structural map of the Po Plain together with the epicentre of the 29 May 2012 earthquake.

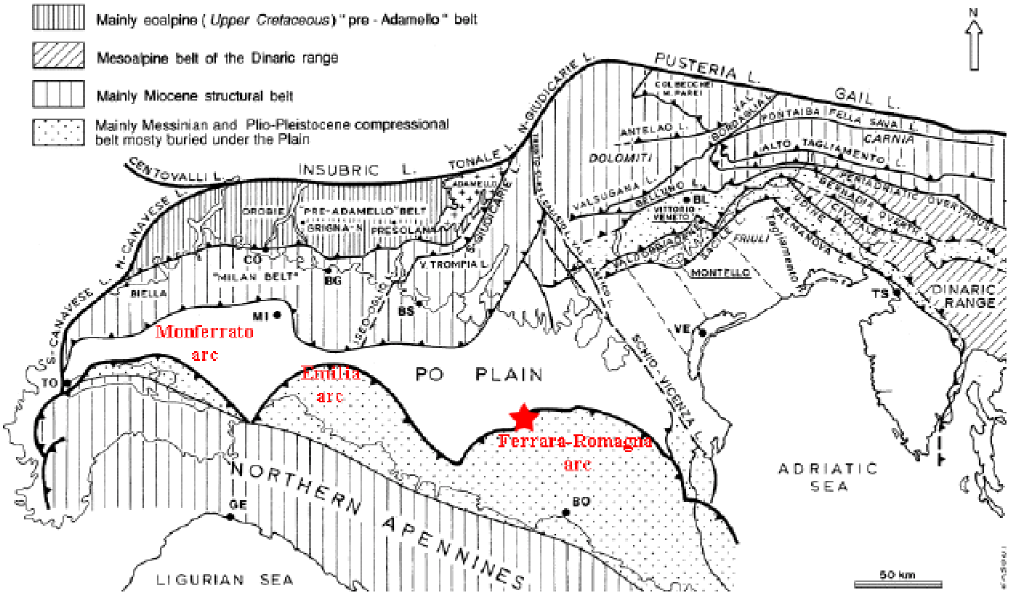


Figure 1. Geologic and seismo-tectonic setting of the Po Plain (adapted from Castellarin et al, 2006) with superimposed star denotes the approximate location of the epicenter of the 29 May 2012 M_L5.8 earthquake.

The 2012 Emilia seismic sequence was generated by the central portion of the Ferrara-Romagna arc. It showed pure reverse faulting and focal depths in the range between 1 and 12 km (Burrato et al., 2012). The 29 May earthquake with local magnitude of 5.8 occurred at 07:00:03 (UTC) after an event of M_L5.9 in 9 days earlier and followed by three relevant aftershocks with $M_L \geq 5.0$ (Mirandola Earthquake Working Group, 2012a and 2012b). The co-seismic slip distribution of both earthquakes is illustrated in Fig. 2.

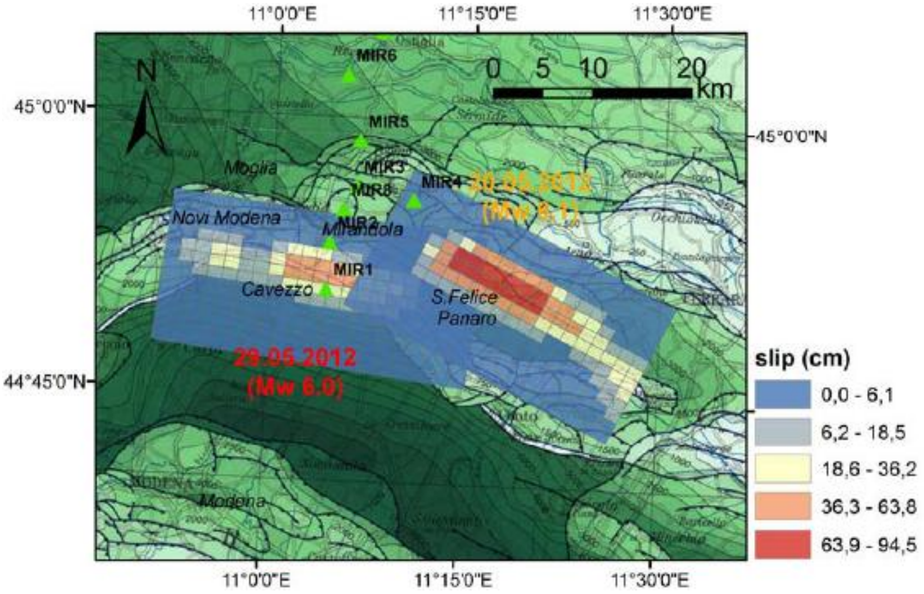


Figure 2. Kinematic seismic source models for the 20 May (Ferrara fault) and 29 May (Mandorla fault) earthquakes (Atzori et al., 2012).The main parameter of this earthquake are summarized in Table 1.

Table 1. Source parameters for 29 May 2012 earthquakes. Moment magnitude estimates come from http://autorcmt.bo.ingv.it/quicks.html

Moment Magnitude M_w	Lat, Lon (°N, °E)	Focal Depth (km)	Length L (km)	Width W (km)	Strike φ (°)	Dip δ (°)	Rake λ (°)
5.96	44.851, 11.086	10.2	32	20	95	40	90

3D NUMERICAL SIMULATION OF 29 MAY 2012 EARTHQUAKE IN PO PLAIN

This study has made use a high-performance computer code, SPEED - *Spectral Elements in Elastodynamics with Discontinuous Galerkin*: http://mox.polimi.it/it/progetti/speed/SPEED/Home.html which is developed at Politecnico di Milano. The code, based on the Discontinuous Galerkin Spectral Elements Method (Mazzieri et al., 2013; Paolucci et al., 2014a), allows to deal with non-conforming meshes and, thus, turns out to be particularly useful in tackling multi-scale seismic wave propagation problems in highly heterogeneous media.

The numerical model of the Po Plain (Fig. 3) extends to over a volume of about $74 \times 51 \times 20\ \text{km}^3$ and is discretized using an unstructured hexahedra mesh. The characteristic size of elements is ranging from ~ 150 m at the surface to ~ 1400 m at the bottom of the model. Because of small variation of the topography in the area, a flat free surface was taken into consideration. The mesh was generated using the software CUBIT (http://cubit.sandia.gov/). The mesh also includes the kinematic source model (Mirandola fault). For the subsoil model, a homogenous average soil profile was defined for the Po Plain sediments (see Table 2), and for the rock formations, a horizontally layered model was considered (see Table 3).

The model consists of 1.852.651 spectral elements, yielding 50.850.136 Legendre- Gauss-Lobatto (LGL) nodes, for spectral degree equal to 3. The model can propagate frequencies up to about 1.5 Hz. The numerical simulations were carried out on the supercomputer FERMI at CINECA (http://www.cineca.it/en/content/fermi-bgq). The total computer time using 512 cores and 16 threads (exploiting a hybrid MPI-OpenMPI programming) for a duration of synthetics equal to 50 s and time step Δt = 0.001 s (<16% of the well-known Courant-Friedrichs-Levy, CFL, stability limit for 1D wave propagation) is about 4.55 hours. Details on the construction of the numerical model and analysis of numerical results is provided in Paolucci et al. (2015).

Table 2. Mechanical properties within the Po Plain sediments.
Q_s is the quality factor at a representative frequency of 0.67 Hz.

Depth (m)	V_s(m/s	V_p(m/s	$\rho\ (kg/m^3)$	$Q_s(-)$
0 - 120	300	1500	1800	30
120 - 500	800	1800	2000	80
> 500	$800+15\sqrt{z-500}$	$1800+20\sqrt{z-500}$	2000+0.0725.(z-500)	800+0.03.(z-500)

Table 3. Mechanical properties of the rock Miocene formations.

Depth (m)	V_s(m/s	V_p(m/s	$\rho\ (kg/m^3)$	$Q_s(-)$
< 1000	1200	2300	2100	150
1000 - 3000	2100	3500	2200	200
3000 - 6000	2750	4750	2400	250
> 6000	3670	6340	2800	350

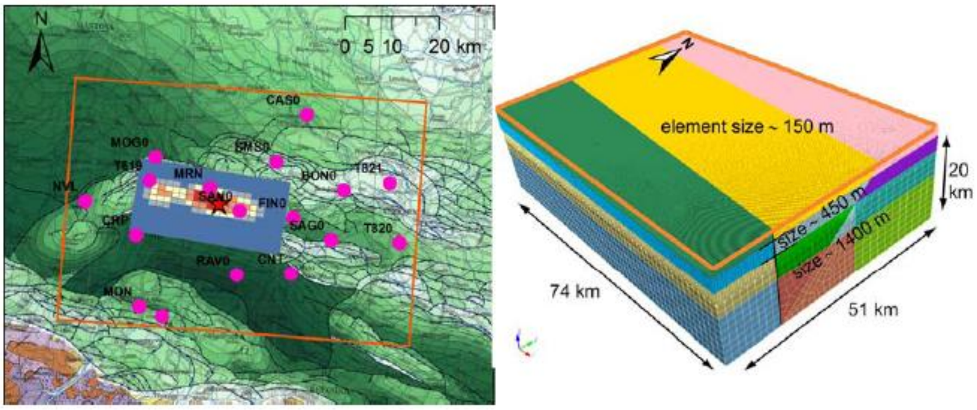


Figure 3 . Left: kinematic rupture model of the 29 May 2012 Emilia earthquake plotted on the structural map of Italy (Bigi et al., 1992). The dots denote the location of the strong motion stations operated by the RAN and the RAIS, while the superimposed rectangle indicates the extension of the numerical model. Right: numerical model pointing out the variable element size adopted to correctly sample the shear wave velocity (300 m/s) of the shallowest layers of the Po Plain up to frequencies of about 1.5 Hz. From Paolucci et al. (2014b).

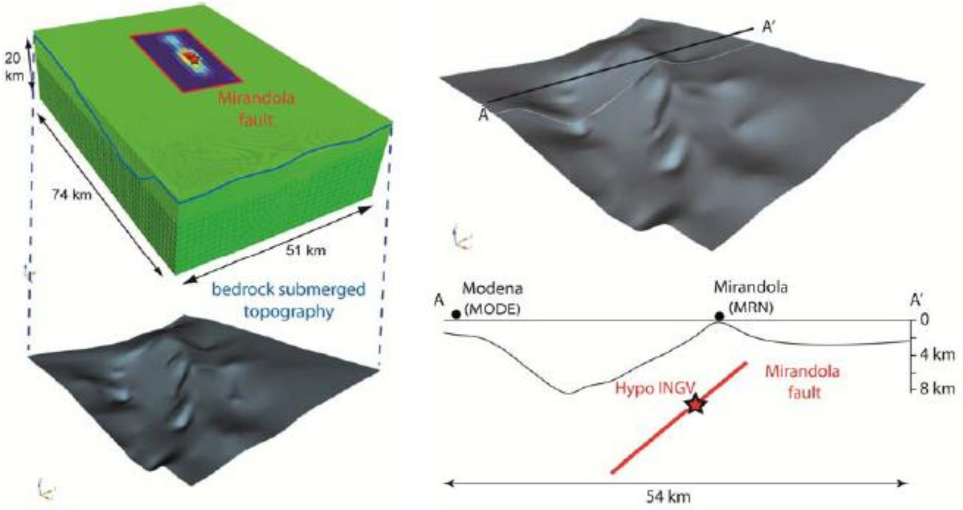


Figure 4. Left panel: sketch of the numerical model including the kinematic seismic source model for the Mirandola fault and the 3D shape of the bedrock-sediment interface. Right panel: representative ~NS cross-section passing through the Mirandola site, as adopted in the numerical model. From Paolucci et al. (2014b).

SPATIAL VARIABILITY OF GROUND MOTION

Spatial variability of ground motion is presented in Fig. 5 containing the map of understudy region superimposed with the fault normal PGV map of 29 May 2012 Emilia earthquake. In the map, also shown the Mirandola (MRN) recording station which is the closest station to the area of maximum ground motion. The maximum value of peak ground velocity in normal direction of fault is $\sim 100\ cm/s$.

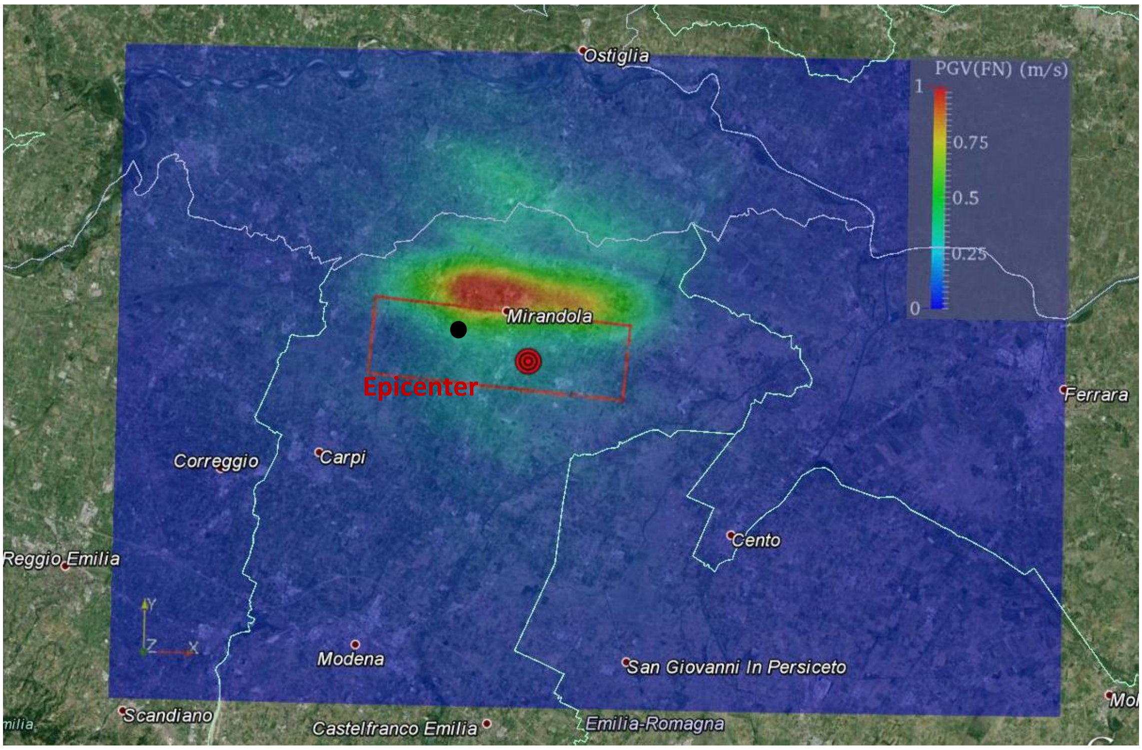


Figure 5. Peak Ground Velocity map of the Po Plain in fault normal direction with superposition of the surface projections of the fault and epicenter.

DEFINING NEW DISTANCE METRIC

Shown in Fig. 7 are the PGV values in normal and parallel fault directions obtained through the numerical simulation of Emilia earthquake. PGV attenuation is computed for different distance metrics from point-source metrics (hypocentral distance, R_{hyp}) to extended-source metrics (such as R_{JB} and R_{rup}) for $R_* \leq 50km$. It can be observed from these curves that by considering these distance metrics, there is a large variability of the results which may reach even an order of magnitude. On one hand, the PGV maps presented in Fig. 5 showed that the regions of large slip do not coincide with the surface projection of the fault and therefore an area-distance metric such as R_{JB} may not yield the best results. On the other hand, by moving to larger magnitude events, the rupture size will achieve significance and just a point-source metrics cannot be used. Considering the PGV map of the normal component of motion (higher values comparing to fault parallel component), it is apparent that the region of larger ground motion is located near the line obtained by the intersection of the fault plane with the ground surface as it is presented in Fig. 6. Therefore, this can reasonably be introduced as an element for the new distance metric. To define the length of this line, we decided to use the scaling laws proposed by Wells and Coppersmith (1994), considering, as the mid-point of the line, the surface projection of the hypocenter along the fault plane.

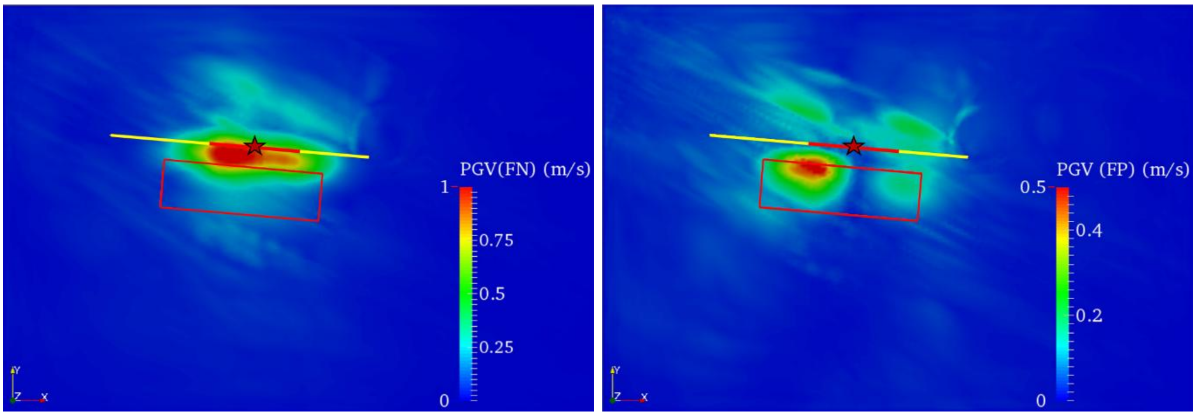
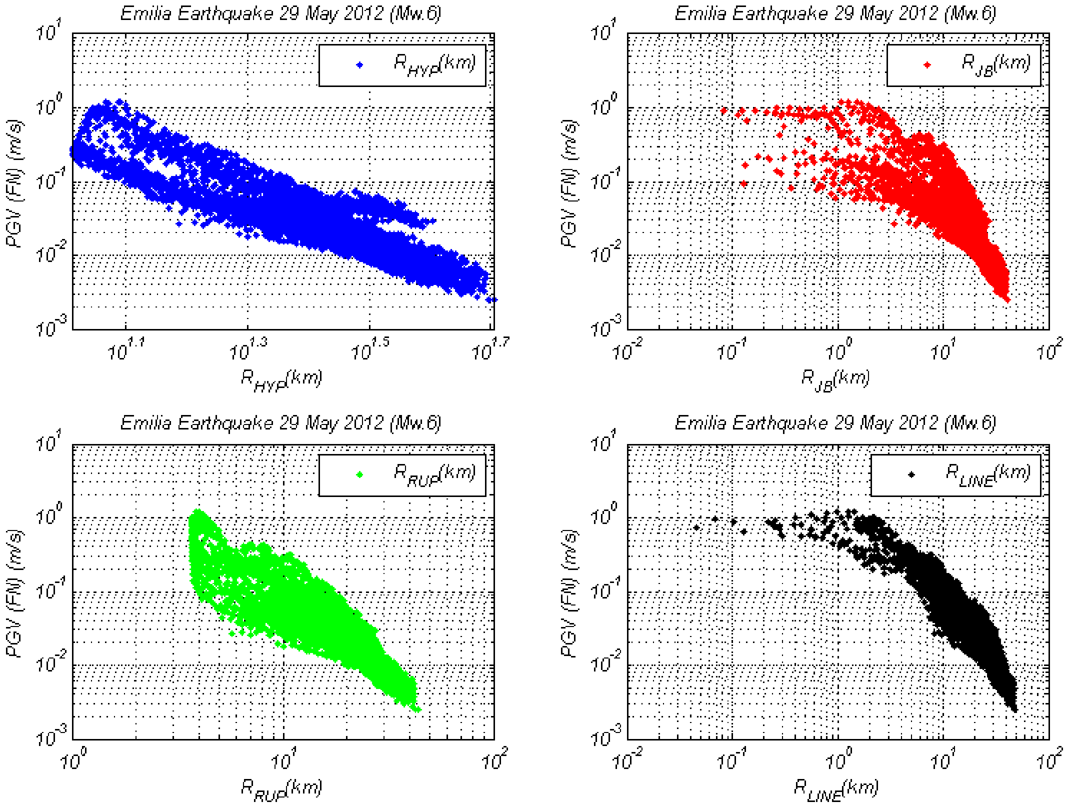


Figure 6. Left panel: Peak Ground Velocity map of fault normal component of motion with superposition of the surface projections of the fault (red rectangle), intersection of the fault plane with the ground surface (yellow line), the new distance metric (red line), and the projection of hypocenter in direction of fault plane (red star). Right panel: Peak Ground Velocity map of fault parallel component of motion.

Comparing the attenuation of PGV values with this new distance metrics, shown as R_{Line} in Fig. 7, with the previous metrics, illustrate the considerable decrease of variability of results. It should be mentioned that, although it is clear that the FP component is not as well described as the FN one by such new metric, we are mostly interested in the maximum values.



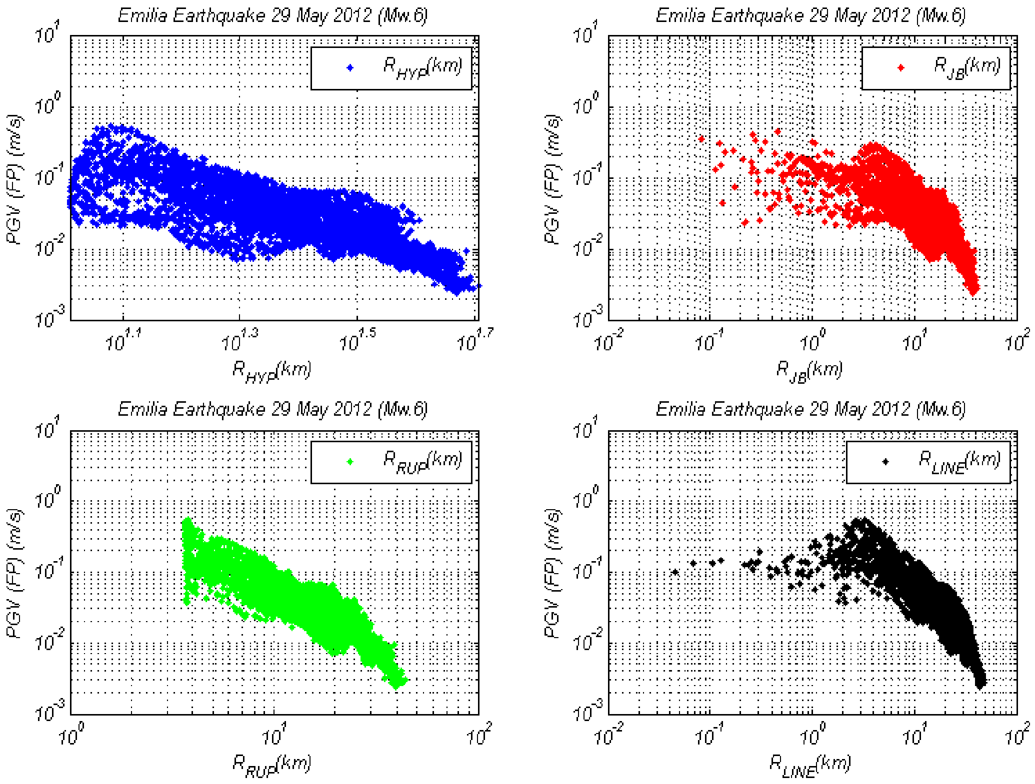


Figure 7. Top panel: Comparing the PGV (m/s) attenuation with different distance metrics, R_{hyp}, R_{JB}, R_{rup} and the proposed new distance metric R_{Line} for fault normal component of motion. Bottom panel: Comparing the PGV (m/s) attenuation with different distance metrics, R_{hyp}, R_{JB}, R_{rup} and the proposed new distance metric R_{Line} for fault parallel component of motion

COMPARING THE RESULTS WITH AVAILABLE RECORDS

The seismic ground motion due to M_w6.0 earthquake of 29 May 2012 in Po Plain was recorded by the Italian strong motion network (RAN) including some temporary stations (Mirandola Earthquake Working Group, 2012a), operated by the Department of Civil Protection (DPC), and by the regional accelerometric network (RAIS), operated by the INGV Milano-Pavia, from which 20 of them are installed in the Po Plain. There is numerous recordings available for the 29 May shock because many temporary arrays managed by the DPC and the INGV were installed soon after the 20 May event.

Fig. 8 shows the comparison between the synthetics results and the recordings (magnet dots) in terms of fault normal component of peak ground velocity at 34 representative strong ground motion stations. On the whole, it turns out that the agreement between synthetics and recordings is satisfactory.

Here, just shown the fault normal component of motion since in the epicentral region of this earthquakes, maximum peak ground motion values are obtained on the normal component owing to source directivity effects.

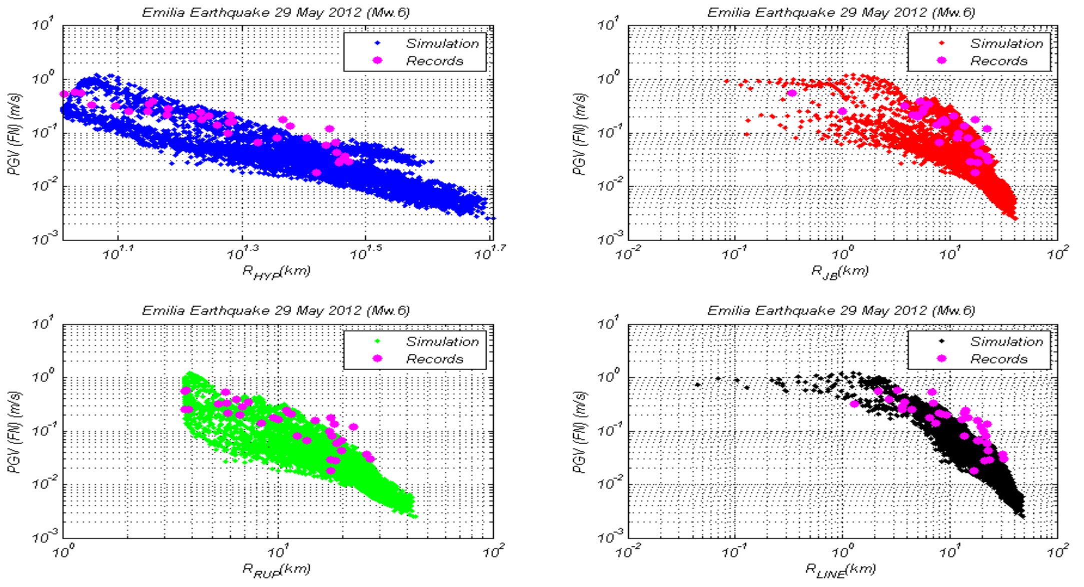


Figure 8. Comparing the PGV (m/s) attenuation with different distance metrics, R_{hyp}, R_{JB}, R_{rup} R_{Line} with the available strong ground motion recordings for fault normal component of motion.

CONCLUSION

In this analysis, the spatial variability of the peak ground motion from the earthquake occurred on 29 May 2012 in Emilia-Romagna region with moment magnitude of M_W 6.0 simulated numerically by SPEED has been investigated. The computed values of **P**eak **G**round **V**elocity (**PGV)** have been plotted with respect to different distance metrics such as R_{hyp}, R_{jb}, R_{rup} as well as a new distance metric which is defined as the distance of site to a line of intersection of the fault plane with ground surface with length defined by the correlation proposed by Wells & Coopersmith1994. The comparison of peak ground motion with respect to different distance metrics has illustrated that the variability of results decreased significantly in the case of using the proposed line distance metric. Further studies are in progress to check the performance of this novel distance metric against results of other numerical case studies on different fault mechanisms.

REFERENCES

Mazzieri I, Stupazzini M, Guidotti R and Smerzini C (2013) SPEED: SPectral Elements in Elastodynamics with Discontinuous Galerkin: a non-conforming approach for 3D multi-scale problems, *International Journal for Numerical Methods in Engineering* 2013; 95:991–1010.

Paolucci R, Mazzieri I, Smerzini C and Stupazzini M (2014a) Physics-Based Earthquake Ground Shaking Scenarios in Large Urban Areas. In A. Ansal (ed.), Perspectives on European Earthquake Engineering and Seismology, Geotechnical, *Geological and Earthquake Engineering* 34, Chapter 10, 331-359

Paolucci R, Faccioli E, Smerzini C and Vanini M (2014b) Approaches to account for site effects in the PSHA of selected sites in the Po Plain area. Deliverable D3-96 of Project SIGMA (http://projet-sigma.com/organisation.html)

Paolucci R, Mazzieri I and Smerzini C (2015) Anatomy of an earthquake: strong motion records and 3D physics-based numerical simulations of the Mw6.0 May 29 2012 Po Plain earthquake, Italy. Submitted for publication to *Geohysical Journal International*

Stupazzini M, Paolucci R and Igel H (2009) Near-fault earthquake ground-motion simulation in the Grenoble Valley by a high-performance spectral element code, Bulletin of the Seismological Society of America, 99: 286–301

Wells DL and Coppersmith KJ (1994) New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement, *Bulletin of the Seismological Society of America*, 84: 974–1002