RESPONSE SPECTRA ESTIMATIONS INCLUDING FINITE FAULT AND 1D SITE EFFECTS IN FRIULI (NE ITALY) AREA

M. Santulin, L. Moratto, A. Saraò and D. Slejko

OGS - Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, Trieste, Italy

Introduction. The estimation of the ground motion, either by means of empirical relations or by numerical simulations, requires knowledge of earthquake rupture details, of wave-propagation in heterogeneous media and of the effects of local site conditions. The site effects may strongly affect the amplitude, frequency, composition and duration of ground shaking as result of complex interactions between seismic waves and the morphological and stratigraphic characteristics of soil deposits and rock masses. A number of techniques based on empirical approaches, as well as on theoretical ones, are available to estimate the site effects, but the shortage of information about the geological and geotechnical parameters forces very often towards simplified approaches in the majority of cases.

In this study we use a simplified approach, already described in Santulin *et al.* (2012) to estimate response spectra including source and 1D site effects. Usually, we talk about stratigraphic or 1D effects when the seismic motion changes, propagating mainly vertically from the underlying bedrock to the surface and the main amplification of the seismic motion is caused by the impedance contrast between the various layers of the soil, and between them and the bedrock. To generate the response of a soil column, we use a stochastic finite-fault modelling technique (Boore, 2009) together with a code to compute 1D site effects (Sanò and Pugliese, 1991). Both these algorithms are widely tested and allow fast computations of ground shaking for seismic hazard mitigation purposes. The whole methodology has been implemented and validated by Santulin *et al.* (2012), who computed response spectra related to the October18, 1936 Cansiglio (M_s=5.8) and the May 6, 1976 Friuli (M_s=6.5) earthquakes for selected sites placed in the Friuli area (north-eastern Italy) for comparison with macroseismic data and available recorded seismograms.

In this study, the same procedure is applied to compute response spectra generated at two selected sites, Aviano (AVN) and San Pietro al Natisone (SPN), located in the Friuli plain (Fig. 1), by the 1976 Friuli and 1936 Cansiglio-Alpago events. The sites have been selected because of their stratigraphic similarities, so to pinpoint how site effects work on spectra coming from different distances and azimuths. According to the Italian macroseismic database [DBMI11, Locati *et al.* (2011)], the AVN study area experienced an intensity of VII MCS during both the 1936 and 1976 earthquakes; an intensity of VII-VIII MCS was observed at the SPN site for the 1976 event. The Italian seismic hazard map (Stucchi *et al.*, 2011) assigns a peak ground acceleration (PGA) between 0.225 and 0.275 g to either the two municipality areas for the standard return period of 475 years.

For our modelling we fixed a scenario magnitude of M_w=6.7, that is the likely maximum magnitude expected in the region (Meletti and D'Amico, 2011). The influence of the rupture propagation on the ground motion is estimated by computing response spectra for three different positions of the nucleation point in order to represent unilateral rupture propagation from west to east and from east to west and bilateral rupture propagation for both seismic sources.

Methodology. The ground motion at a site is estimated in two separated steps that include finite source and 1D site effects: in the first step the shaking is computed applying the stochastic finite-fault model EXSIM (Boore, 2005, 2009; Motazedian and Atkinson, 2005) which takes into account source and path effects while, in the second step, the PSHAKE (Sanò and Pugliese, 1991) algorithm is used to excite a soil column at specific sites with the ground motion previously calculated.

EXSIM is a stochastic finite fault algorithm (Boore, 2005, 2009; Motazedian and Atkinson, 2005) assuming that motions to be simulated are S waves that are the most important motions for seismic hazard. The software is based on a combination of parametric or functional descriptions of the ground motion amplitude spectrum with a random phase spectrum modified such that the motion is distributed over a duration related to the earthquake magnitude and to the distance from the source. The path effects are modeled through geometrical spreading, anelastic attenuation, and ground motion duration effects (Boore, 2009). The regional dependence of duration and amplitude

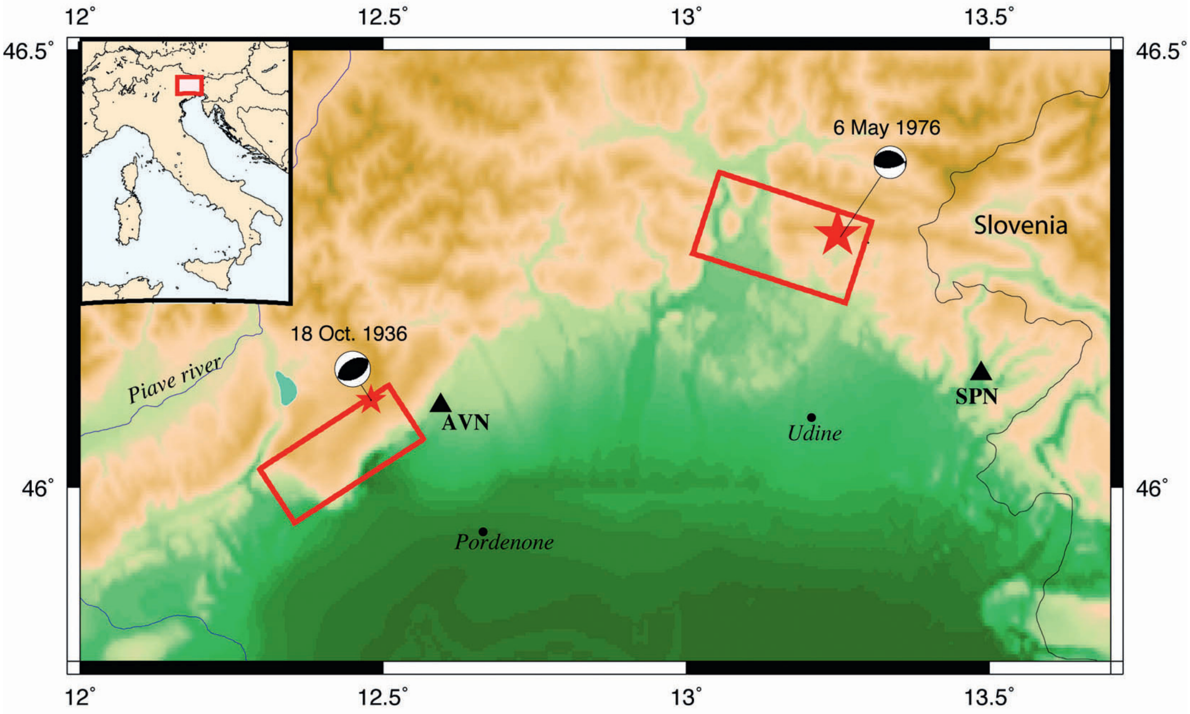

Fig. 1 - Map of the study area with locations of the seismic sources and the focal mechanisms of the investigated earthquakes. The two sites (black triangles) where we computed the ground motion are also plotted.

on distance are employed in the simulations to model the propagation effects. For large earthquakes, the finite-fault effects as rupture geometry, slip inhomogeneity, and source directivity influence strongly the shaking jointly with the related duration, frequency content and amplitude of simulated ground motions. EXSIM takes into account the finite-fault effects dividing the rectangular fault plane into small subfaults, and each subfault is considered to be a point source: the rupture starts at the hypocentre and propagates kinematically until each subfault is triggered. Finally, the total ground motion from the entire fault at a receiver is obtained by summing up the contribution from each subfault, computed by the stochastic point-source model, with a proper time delay (Boore, 2005). Motazedian and Atkinson (2005) introduced the dynamic corner frequency approach to scale the high-frequency spectral level of the subfault to overcome the problems related to the discretization of the fault (i.e., the dependence of the total radiated energy on the subfault size). Therefore, the corner frequency of the subfaults decreases with time and then the radiated energy at high frequencies also decreases. It is worth noting that the high-frequency spectral amplitudes are controlled by stress drop, whereas the percentage of pulsing area defines the level of spectra at low frequencies; stress drop and percentage of pulsing area are considered "free parameters" and have to be properly calibrated for each study area selecting the parameters able to fit empirically-derived equations for predicting ground motions. After the calibration, a validation of the method, which consists of checking predictions against data, needs to be performed. The effectiveness of the stochastic seismograms including finite fault effects has been widely demonstrated by fitting observations in different environments by a number of authors (i.e., Ugurhan and Askan, 2010; Moratto and Saraò, 2012, and references therein).

The program PSHAKE (Sanò and Pugliese, 1991) is an improvement of the program SHAKE (Schnabel *et al.*, 1972) and was used in our approach to estimate 1D site effects. It calculates the response of a layered half-space traversed by shear waves travelling in the vertical direction. The input for the program is the bedrock shaking (time history or response spectrum) at the study site and the mechanical properties of each layer forming the sedimentary cover, expressed in terms of thickness, density, shear wave velocity, and damping. For weak motions, the algorithm works with the linear analysis assuming that the characteristics of the materials are independent from the deformation. Conversely, for strong earthquakes, soil degradation curves for each material of the stratigraphic model take into account the dependence of the shear modulus and of the damping from the shear deformation and the linear equivalent analysis is applied.

In this study we have used as input the response spectrum at 5% damping obtained from the finite fault stochastic modelling (Boore, 2009) and the linear-equivalent analysis for ground motion modelling. The dependence of the shear modulus and the damping on the shear deformation are applied for each material (lithological layer) by introducing specific mean dynamic property curves taken from the literature (Seed and Idriss, 1969; Seed *et al.*, 1986) as laboratory test values for the studied soil are not available.

Response spectra generated by the largest earthquake expected in Friuli area. Two scenarios related to an M_w=6.7 earthquake are generated for the selected sites AVN and SPN (Fig. 1), assuming the source parameters of the 1936 Cansiglio and 1976 Friuli earthquakes as proposed, by Sirovich and Pettenati (2004) and Aoudia *et al.* (2000), respectively. Being the magnitude of 6.7 larger than the values estimated for the 1936 Cansiglio and 1976 Friuli earthquakes, we resized accordingly the fault dimensions using the Wells and Coppersmith (1994) relationships with a random seismic moment distribution because not predictable a priori. To analyze the directivity effects we considered three models for both seismic sources: a rupture propagating from west to east (model W-E), a rupture propagating from east to west (model E-W) and a rupture with bilateral propagation (model BLT).

The stratigraphy of AVN and SPN (Fig. 1 and Tab. 1) is similar and based on geological, geophysical, and geotechnical data, achieved from water-wells, multichannel analysis surface waves (MASW), and seismic profiles. The bedrock is quite shallow, located at a depth of 7 and 9 m respectively. Two differently consolidated gravel layers constitute the sedimentary cover, and the site natural period, obtained from the stratigraphy (Kim and Yoon, 2006), *Tg* is equal to 0.06 s for both the places.

In Fig. 2 we plot the response spectra computed at AVN (Figs. 2a and 2b) and SPN (Figs. 2c and 2d). The amplitude of the response spectra reflects the source-receiver distance and the rupture propagation, as clearly visible by the bedrock response spectra (dashed lines in Fig. 2). The Cansiglio-Alpago seismogenic source is distant about 6 km from AVN and 71 km from SPN; on the other side the Friuli source is about 33 km away from AVN and 20 km from SPN. Moreover, AVN is placed north-eastwards and very close to the Cansiglio fault and a strong directivity effect is visible on the spectrum when the W-E propagation model is applied (Fig. 2a, blue lines); SPN is placed at SE of the Friuli fault, with an azimuth of 25-30º, and minor amplification is observed for the W-E model (Fig. 2c, blue lines). The larger source-receiver distance attenuates the finite fault effects and the signal spectra is weak in the high frequency range, as visible when modelling the shaking at AVN related to the Friuli source (Fig. 2b) and at SPN related to the Cansiglio fault (Fig.

Tab. 1 - Stratigraphic profiles for AVN and SPN sites.

Site	Depth (m)	Thickness (m)	Lithology	Density (g/cm3)	Vs (m/s)
Aviano	0-3	3	Gravel	2.05	469
	3-7	4	Gravel	2.03	434
	>7		Rock	2.18	800
San Pietro al Natisone	0-4	4	Gravel	2.16	730
	4-9	5	Gravel	2.11	580
	>9		Rock	2.23	800

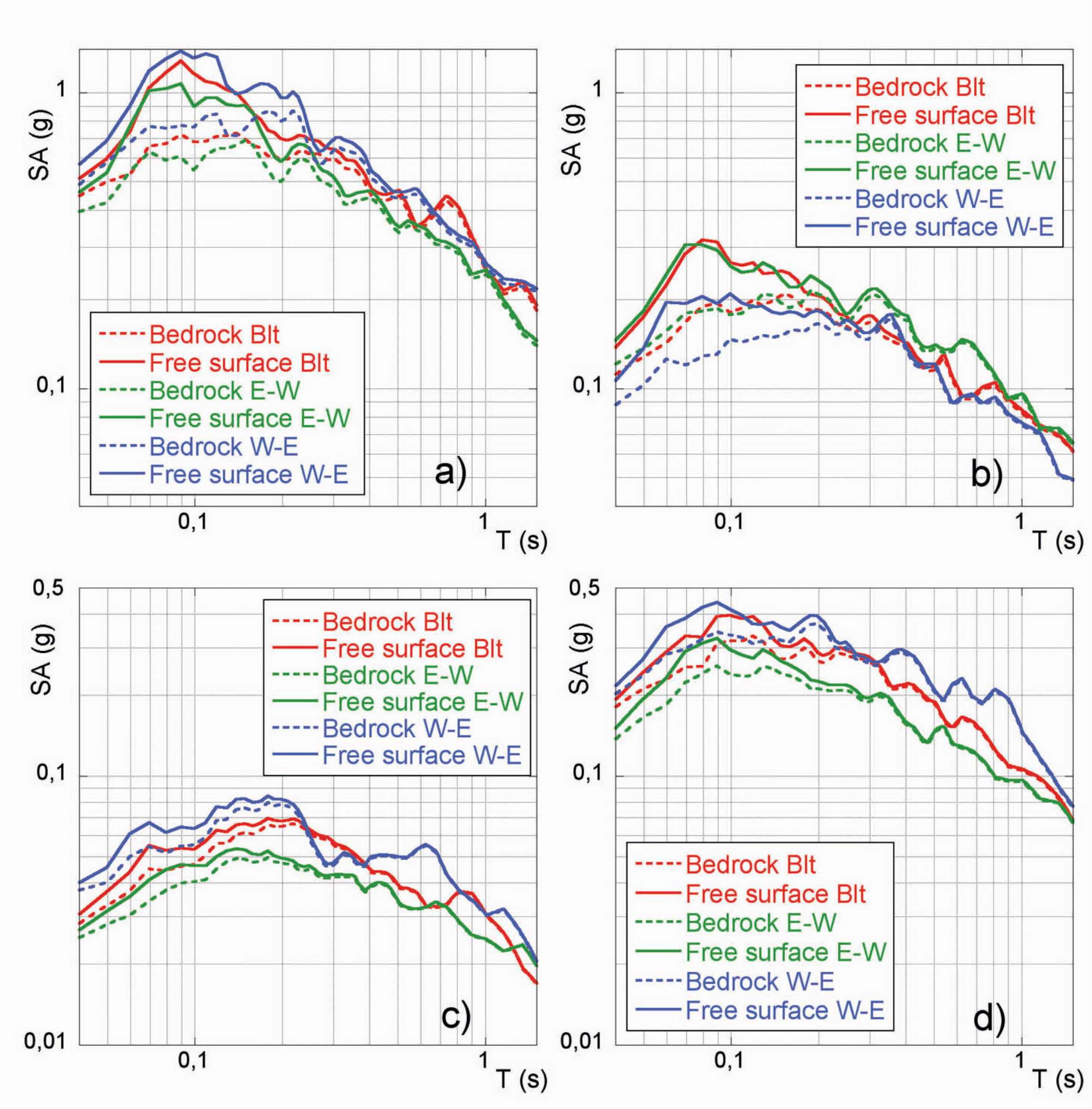

Fig. 2 – Rock (dotted line) and soil (solid line) response spectra for an *Mw*=6.7 scenario earthquake computed at AVN using the Cansiglio-Alpago seismogenic source model (a) and the Friuli seismogenic source model (b), and at SPN using the Cansiglio-Alpago seismogenic source model (c) and the Friuli seismogenic source model (d). Blue lines (marked W-E) show the response spectra computed by the W-E rupture propagation model, red lines (marked BLT) indicate a bilateral rupture, and green lines (marked E-W) display a westward propagation.

2c). At the AVN site, the shaking is strong for the Cansiglio-Alpago W-E model while the E-W model produces lower spectra for frequency content larger than 1 Hz (Fig. 2a); the BLT model amplifies the shaking similarly to the unilateral W-E model because, in both cases, the rupture propagates from the nucleation toward the receiver along whole (W-E) or middle (BLT) fault length. In the E-W model the rupture moves away from the receiver westwards (Veneto region), producing back-directivity attenuation. The estimated bedrock PGA is 0.40 g for the W-E, 0.30 g for the BLT and 0.24 g for the E-W models, meaning that directivity effects generate a PGA of the W-E model that is about 1.5 larger than that of the E-W model. The bedrock response spectra at AVN related to the Friuli source (Fig. 2b) with the BLT and E-W models evidence stronger shaking while the W-E rupture propagates away from the site producing a signals with weak high frequency content. In this case the estimated bedrock PGA is 0.07 g for W-E, 0.08 g for BLT and 0.09 g for E-W models.

Also the bedrock response spectra estimated at SPN for the Friuli source (Fig. 2d) are influenced by directivity effects and the W-E model amplifies the signal in the high frequency range while the E-W model attenuates the signal due to back-directivity effects; the PGA is 0.129 g for the W-E, 0.126 g for the BLT and 0.092 g for the E-W models. Notably, the W-E model produces again a maximum acceleration that is about 1.5 larger than that obtained by the E-W model. The Cansiglio-Alpago seismogenic source generates weaker shaking at SPN (Fig. 2c) with the E-W model generating bedrock spectra larger than the other rupture propagations (BLT and W-E); the PGA is 0.031 g for the W-E, 0.024 g for the BLT and 0.018 g for the E-W models.

The soil spectra for the Cansiglio-Alpago (Figs. 2a and 2c) and Friuli (Figs. 2b and 2d) earthquakes keep the same trend of the bedrock spectra at both considered sites (AVN and SPN), without clear indications of a non-linear behaviour. The soil spectra are amplified mostly in the periods lower than 0.3 s, and the highest amplification of the soil spectra is found at very short periods (less than 0.1 s), in good agreement with the site natural period (Tg = 0.06 s for both sites), with the maximum acceleration values about 1.5 times larger than the bedrock ones. Looking at the same event, it is notable a little shift of the highest amplification peaks with respect to the bedrock spectra to shorter periods (from 0.09 s to 0.07 s for both the sites) moving from the nearest site to the farthest one.

Conclusions. We calculated the response spectra considering the finite-fault and 1D site effects for two sites (Aviano and San Pietro al Natisone) placed in the Friuli area (NE Italy); the ground motion was calculated for the Cansiglio-Alpago and Friuli seismogenic sources, both capable to generate earthquakes with a maximum magnitude value of 6.7 (Meletti and D'Amico, 2011). The bedrock response spectra are strongly influenced by the source-receiver distance and by the different rupture propagations considered; the forward directivity model produces signals with high frequency content larger than those generated by the back-directivity models. Further, in case of forward directivity, the PGA value is estimated to be about 1.5 larger if compared with the maximum acceleration retrieved from back-directivity models. It is worthwhile evidencing that the stochastic models are able to reproduce the signal in the high frequency range (f > 1 Hz) while a deterministic procedure should be applied for the longer period content (f < 1 Hz); so, a hybrid deterministic-stochastic approach could be the best way to generate synthetic seismograms in both low and high frequency ranges. Furthermore, the directivity of the rupture and the seismic moment distribution are not predictable a priori, so parametric studies have to be performed by selecting different input values in order to evaluate their related weight on shaking estimations (Moratto *et al.*, 2009). The soil spectra for the Cansiglio-Alpago and Friuli earthquakes keep the same trend of the bedrock spectra at both considered sites. The soil spectra are amplified mostly in the periods lower than 0.3 s, and the highest amplification of the soil spectra is almost at very short periods (less than 0.1 s, 1.5 times larger than the bedrock ones), in good agreement with the site natural period (Tg = 0.06 s for both sites). Looking at the same event, it is notable a little shift of the highest amplification peaks to shorter periods (from 0.09 s to 0.07 s for both the sites) moving from the closest to the farthest one.

The approach applied in this paper, compounded by EXSIM (to compute the bedrock stochastic seismograms applying finite-fault model) and PSHAKE (to consider the 1D site effect) software, proved to be effective in prediction of 1D site effects (Santulin *et al.*, 2012) in the same study area. Surely, it cannot replace a sophisticated modelling, but it can offer an easy and fast picture of several extreme scenarios and, being based on open software, it can be easily implemented for seismic hazard purposes.

Acknowledgements. The GMT software (Wessel and Smith, 1991) was used to draw Fig. 1.

References

Aoudia A., Saraò A., Bukchin B. and Suhadolc P.; 2000: The 1976 Friuli (NE Italy) thrust faulting earthquake: a reappraisal 23 years later. Geophys. Res. Lett., 27, 573-576.

Boore D.M.; 2005: SMSIM - Fortran programs for simulating ground motions from earthquakes: version 2.3 – A Revision of OFR 96-80- A. Open-File Report 00-509, U.S. Geol. Surv., 55 pp., available from the online publications link on https://profile.usgs.gov/professional/mypage.php?name=boore.

Boore D.M.; 2009: Comparing stochastic point-source and finite-source ground motion simulations: SMSIM and EXSIM. Bull. Seismol. Soc. Am., 99, 3202-3216.

Kim D., Yoon J.; 2006: Development of new site classification system for the regions of shallow bedrock in Korea. Journal of Earthquake Engineering, Vol. 10, No. 3, 331–358.

Locati M., Camassi R. and Stucchi M.; 2011: Database Macrosismico Italiano versione DBMI11. http://emidius.mi.ingv.it/DBMI11, last access March 2012.

Meletti C. and D'Amico V.; 2011: Determining maximum magnitude for seismic hazard assessment in Europe (SHARE Project). In: Slejko D. and Rebez A. (a cura di), 30° Convegno Nazionale G.N.G.T.S. - Riassunti estesi delle comunicazioni, Mosetti, Trieste,pp. 382-385.

Moratto L., Costa G. and Suhadolc P.; 2009: Ground motion estimation using ShakeMaps and scenarios. International Conference on Earthquake Engineering, Banja Luka, 26-28 October 2009, p. 311-329.

Moratto L. and Saraò A.: 2012: Improving ShakeMap performance by integrating real with synthetic data: tests on the 2009 Mw=6.3 L'Aquila earthquake (Italy). J. Seismology, 16, 131-145.

Motazedian D. and Atkinson G.M.; 2005: Stochastic finite-fault modeling based on a dynamic corner frequency. Bull. Seismol. Soc Am., 95, 995-1010.

Sanò T. and Pugliese A.; 1991: PSHAKE, Analisi probabilistica della propagazione delle onde sismiche. RT/DISP/91/03, ENEA, Roma

Santulin M., Moratto L., Saraò A. and Slejko D.; 2012: Ground motion modelling including finite fault and 1D site effects in north-eastern Italy. Boll. Geof. Teor. Appl., in press, doi: 10.4430/bgta0071.

Schnabel P.B., Lysmer J. and Seed H.B.; 1972: SHAKE: a computer program for earthquake response analysis of horizontally layered sites. Report N. UCB/EERC-72-12, Earthquake Engineering Research Center, University of California, Berkley, 102 pp.

Seed H.B. and Idriss I.M.; 1969: The influence of soil conditions on ground motions during earthquakes. Journal of the Soil Mechanics and Foundation Engineering Division, ASCE, 94, 93-137.

Seed H.B., Wong R.T., Idriss I.M. and Tokimatsu K.; 1986: Moduli and damping factors for dynamic analyses of cohesionless soils J. Geotech. Eng., ASCE, 112(1), 1016-1032.

Sirovich L. and Pettenati F.; 2004: Source inversion of intensity patterns of earthquakes: a destructive shock in 1936 in northeast Italy. J. Geophys. Res., 109, B10309, doi:10.1029/2003JB002919.

Stucchi M., Meletti C., Montaldo V., Crowley H., Calvi G.M. and Boschi E.; 2011: Seismic hazard assessment

(2003–2009) for the Italian building code. Bull. Seism. Soc. Am., 101, 1885-1911, doi: 10.1785/0120100130.

Ugurhan B. and Askan A.; 2010: Stochastic strong ground motion simulation of the 12 November 1999 Du?zce (Turkey) earthquake using a dynamic corner frequency approach. Bull. Seismol. Soc. Am., 100, 1498-1512.

Wells D.L. and Coppersmith K.J.; 1994: New empirical relationships among magnitude, rupture length, rupture width, rupture areaand surface displacement. Bull. Seism. Soc. Am., 84, 974-1002.

Wessel P. and Smith W.H.F.; 1991: Free software helps map and display data. Eos Trans., AGU, 72, 441.

THE PRE-EARTHQUAKES EU-FP7 PROJECT: PRELIMINARY RESULTS OF THE PRIME EXPERIMENT FOR A DYNAMIC ASSESSMENT OF SEISMIC RISK (DASR) BY MULTI-PARAMETRIC OBSERVATIONS.

V. Tramutoli[1], S. Inan[2], N. Jakowski[3], S. Pulinets[4], Alexey Romanov[5], C. Filizzola[6], I. Shagimuratov[7], N. Pergola[8], D. Ouzounov[9], G. Papadopulos[10], N. Genzano[1], M. Lisi[1], R. Corrado[1], E. Alparslan[2], V. Wilken[3], K. Tsybulia[4], Alexander Romanov[5], R. Paciello[6], I. Coviello[6], I. Zakharenkova[7], Y. Cherniak[7] and G. Romano[8]

1 University of Basilicata, Potenza, Italy
2 TUBITAK Marmara Research Center, Gebze - Kocaeli, Turkey
3 Deutsches Zentrum Fuer Luft - Und Raumfahrt EV,Linder Hoehe, Koeln, Germany
4 Fiodorov Institute of Applied Geophysics, Moscow, Russia,
5 JSC Russian Space Systems, Moscow, Russian Federation
6 Geospazio Italia srl., Potenza, Italy
7 West Department of N.V. Pushkov IZMIRAN RAS, Kaliningrad, Russia,
8 Institute of Methodologies for Environmental Analysis of the National Research Council, Tito Scalo (Potenza), Italy
9 Chapman University, Orange (CA), United States of America
10 Institute of Geodynamics, National Observatory of Athens, Athens, Greece,

Introduction. The appearance of anomalous space-time patterns of geophysical parameters measured from days to week before earthquakes occurrence have been reported by several authors in the past years. However, even in presence of physical models able to justify the observations