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SEISMIC HAZARD AND STRONG GROUND MOTION: AN OPERATIONAL NEO-DETERMINISTIC APPROACH FROM NATIONAL TO LOCAL SCALE

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Contents

Summary

Recent advances in the physical knowledge of seismic waves generation and propagation processes, along with the improving computational tools, make it feasible the realistic modeling of the ground shaking caused by an earthquake, taking into due consideration the complexities of the source and of the propagation path. A neo-deterministic scenario based approach to seismic hazard assessment (NDSHA) has been

developed that naturally supplies realistic time series of ground shaking, including reliable estimates of ground displacement readily applicable to seismic isolation techniques. The NDSHA procedure permits incorporating, as they become available, new geophysical and geological data, as well as the information from the different pattern recognition techniques developed for the space-time identification of strong earthquakes. All this leads to the natural definition of a set of scenarios of expected ground shaking at the bedrock. At the local scale, further investigations can be performed taking into account the local soil conditions, in order to compute the seismic input (realistic synthetic seismograms) for engineering analysis of relevant structures, such as historical and strategic buildings.

The NDSHA approach has been already applied in several regions worldwide, including a number of local scale studies accounting for two-dimensional and three-dimensional lateral heterogeneities in inelastic media. A pilot application of the approach, including the detailed evaluation of the expected ground motion accounting for site effects and seismic engineering analysis, has been carried out at a site located in the Friuli Venezia Giulia Region (NE Italy). Further some applications worldwide of a new, highly efficient analytical methodology, developed for modeling the propagation of the seismic wavefield in three-dimensional inelastic media, are presented. This procedure, based on computer codes developed from a detailed knowledge of the seismic source process and the propagation of seismic waves in heterogeneous media, allows not only the detailed study of instrumental and macroseismic data but also the realistic estimate of the seismic hazard, in those areas for which scarce (or no) historical or instrumental information is available, and the relevant parametric analyses: different source and structural models can be taken into account to create a wide range of possible groundshaking scenarios from which to extract essential information, including uncertainty ranges, for decision making.

1. Introduction

The typical seismic hazard problem lies in the determination of the ground motion characteristics associated with future earthquakes, both at regional and local scale. Seismic hazard assessment can be performed in various ways, e.g. with a description of the groundshaking severity due to an earthquake of a given distance and magnitude (“groundshaking scenario”), or with probabilistic maps of relevant parameters describing the ground motion. The first scientific and technical methods developed for seismic hazard assessment were deterministic and based on the observation that damage distribution is often correlated with the spatial distribution and the physical properties of the underlying soil. The 1970s saw the beginning of the development of probabilistic seismic hazard maps on a national, regional and urban (microzoning) scale. In the 1990s these instruments for the mitigation of seismic hazard came to prevail over deterministic cartography.

The classical PSHA (Cornell, 1968), determines the probability of exceeding, over a specified period of time, various levels of ground motion. The main elements of a PSHA are: 1) the seismic sources (i.e. the seismogenic zones), within which the seismogenic process is frequently assumed to be rather uniform; 2) the characteristics of the earthquakes recurrence within the seismogenic zones, which is assumed to be

Poissonian; 3) the attenuation relations, which provide estimates of ground motion parameters at different distances from the sources. The hazard at a site is given in terms of probability of exceeding different levels of ground motion during a specified period of time. This is achieved through the calculation of the probability of earthquakes with some damaging potential and the calculation of the conditional probability of exceeding of a given ground motion level, for each of these contributing earthquakes (summed over all potentially contributing sources). Thus, PSHA aims at the statistical characterization of ground motion at a site, although, at most of the sites the available data are not sufficient to verify the assumptions nor to adequately constrain the parameters of the statistical model.

Most of the seismic zonations adopted by the current regulations, either on a national or a regional scale, have been defined according to the conventional PSHA approach (Bommer and Abrahamson, 2006, and references therein), and hence they are basically affected by the limitations of such methodology (Panza et al., 2011; Wang, 2011). Specifically, probabilistic seismic hazard maps are: a) strongly dependent on the available observations, unavoidably incomplete due to the long time scales involved in geological processes leading to the occurrence of a strong earthquake; b) do not adequately consider the source and site effects, since they resort to linear convolution techniques, e.g. GMPE (e.g. Boore and Atkinson, 2008), which cannot be applied when dealing with complex geological structures, because the ground motion generated by an earthquake can be formally described as the tensor product of the earthquake source tensor with the Green's function of the medium (Aki and Richards, 2002); c) time-independence, being based on the assumption of random occurrence of earthquakes (Bilham, 2009). Moreover, the conventional PSHA approach describes the hazard in terms of a single parameter, PGA, which is routinely mapped as the values with 10% probability of being exceeded in 50 years. Actually, it is nowadays recognized by the engineering community that seismic PGA alone is not sufficient for the adequate design, particularly for special buildings and infrastructures, since ground shaking amplitude, frequency content and duration can play a decisive role. The design of seismically isolated structures, which is based on displacements (Martelli and Panza, 2010), requires a reliable characterization of the seismic input, since it is necessary to accurately define the maximum displacement at the period relevant for the isolated structure and the energy content at the long periods (above 1 s), which should be expected at the specific site.

In view of the mentioned limits of PSHA estimates, it appears preferable to resort to a scenario-based approach to seismic hazard assessment that may turn out to be necessary/useful to complement and validate the results that will be eventually produced by large scale projects like GEM (http:// www.globalquakemodel.org /). The NDSHA (Peresan et al., 2011 and references therein), permits us to integrate the available information provided by the most updated seismological, geological, geophysical and geotechnical databases for the site(s) of interest, as well as advanced physical modeling techniques, to provide reliable and robust basis for the development of a deterministic design basis for cultural heritage and civil infrastructures in general (Field et al., 2000; Panza et al., 2001a, 2001b) Neo-deterministic means scenario-based methods for seismic hazard analysis, where attenuation relations and other assumptions about local

site responses similarly questionable on mathematical and physical ground, all implying some form of linear convolution, are not allowed in.
Instead realistic synthetic time series are used to construct earthquake scenarios. The NDSHA procedure provides strong ground motion parameters based on the physical modeling of seismic waves propagation at different scales - regional, national and metropolitan – accounting for a wide set of possible seismic sources and for the available information about the mechanical properties of the propagation media. The scenario-based methodology relies on observable data being complemented by physical modeling techniques, which can be submitted to a formalized validation process. The importance to consider different earthquake scenarios to reliably asses the hazard has been recently evidenced by the large earthquakes that stroke Japan, near east coast of Honshu, in 2011. Specifically, the largest event of March 11, 2011 ($M > 9$,where M is the magnitude on Richter Sclae) caused no damage to the Onagawa nuclear power plant, whereas its aftershock of April 7 ($M > 7$) damaged it. When assessing the hazard, such kind of behavior, which can be easily explained by the difference in focal mechanisms between the main shock and the large aftershock, can be dealt with adequately only considering different deterministic scenarios.

Lessons learnt from recent destructive earthquakes, including the L'Aquila (2009), Haiti (2010), Chile (2010) and Japan (2011) earthquakes, provide new opportunities to revise and improve the seismic hazard assessment. There is the need, however, of a formal procedure for the official collection and proper evaluation of seismic hazard assessment results (Peresan et al., 2010; Stein et al., 2011), so that society may benefit from the scientific studies and may not be misled by the incorrect hazard assessment results. In fact, recent studies (Kossobokov and Nekrasova, 2010) showed that the worldwide maps resulting from the Global Seismic Hazard Assessment Program, GSHAP (Giardini et al., 1999), are grossly misleading and fail both in describing past seismicity, as well as in predicting expected ground shaking.

The comparison between the expected PGA values, provided by GSHAP in 1999, and the actual maximum PGA experienced during the period 2000-2009, performed in terms of related intensities, shows major inconsistencies, particularly severe as earthquakes of greater and greater size are considered. This observation is proved by fatal evidence in all the deadliest earthquakes occurred since the year 2000 (Table 1), including the recent Japan earthquake occurred on March, 11 2011. For this earthquake, accelerations observed in land exceeded 1 g at several sites, reaching values as high as 2.93 g, while the maximum expected PGA over the entire Japan was not exceeding 0.6 g in GSHAP maps.

The evidenced limits of PSHA estimates, which are due not only to scarcity of data, but also to the not valid physical model and mathematical formulation employed (Wang, 2011; Paskaleva et al., 2007), become unacceptable when considering the number of casualties and injured people (Wyss et al., 2012). The evolving situation makes it compulsory for any national or international regulation to be open to accommodate the most important new results, as they are produced and validated by the scientific community.

An example is provided by the Ordinance of the Prime Minister (OPCM) n. 3274/2003, plus its amendments and additions, which have enforced the current Seismic Code in Italy: in the Ordinance it is explicitly stated that the rules of the code must be revised as new scientific achievements are consolidated. Destruction and casualties caused by the L'Aquila earthquake (April 6, 2009; M6.3), despite it took place in a well known seismic territory of the Italian peninsula, are just a sad reminder that significant methodological improvements are badly needed toward a reliable assessment of ground shaking and engineering implementation.

Region	**Date**	M	**Fatalities**	**Intensity difference** ΔI_0
Sumatra-Andaman "Indian Ocean Disaster"	26.12.2004	9.0	227898	4.0
Port-au-Prince (Haiti)	12.01.2010	7.3	222570	2.2
Wenchuan (Sichuan, China)	12.05.2008	8.1	87587	3.2
Kashmir (North India and Pakistan border region)	08.10.2005	7.7	~86000	2.3
Bam (Iran)	26.12.2003	6.6	~31000	0.2
Bhuj (Gujarat, India)	26.01.2001	8.0	20085	2.9
Off the Pacific coast of Tōhoku (Japan)	11.03.2011	9.0	15811 (4035 missing)*	3.2
Yogyakarta (Java, Indonesia)	26.05.2006	6.3	5749	0.3
Southern Qinghai (China)	13.04.2010	7.0	2698	2.1
Boumerdes (Algeria)	21.05.2003	6.8	2266	2.1
Nias (Sumatra, Indonesia)	28.03.2005	8.6	1313	3.3
Padang (Southern Sumatra, Indonesia)	30.09.2009	7.5	1117	1.8

Table 1. List of the deadliest earthquakes occurred during the period 2000-2011, and the corresponding intensity differences, $\Delta I_0 = I_0(M) - I_0(mPGA)$, among the observed values and predicted by GSHAP. $I_0(M)$ and $I_0(mPGA)$ are computed from the observed magnitude M and the maximum GSHAP PGA around the observed epicenter, respectively, using existing relationships (modified after Kossobokov and Nekrasova, 2010).

2. The Neo-Deterministic Approach

NDSHA is an innovative, but already well consolidated, procedure that supplies realistic time histories from which it is natural to retrieve peak values for ground displacement, velocity and design acceleration in correspondence of earthquake scenarios (e.g. Parvez et al., 2010; Paskaleva et al., 2010).

The procedure is particularly suitable for the optimum definition of the characteristics of the modern anti-seismic devices, when the accelerometric data available are not representative of the possible scenario earthquakes – as it is often the case – and when non-linear dynamic analysis is necessary. By sensitivity analysis, knowledge gaps related to lack of data can be easily addressed, due to the limited amount of scenarios to be investigated.

NDSHA addresses some issues largely neglected in traditional hazard analysis, namely how crustal properties affect attenuation: ground motion parameters are not derived from overly simplified attenuation relations, but rather from synthetic time histories. Starting from the available information on the Earth's structure (mechanical properties), seismic sources, and the level of seismicity of the investigated area, it is possible to estimate PGA, PGV, and PGD or any other parameter relevant to seismic engineering, which can be extracted from the computed theoretical signals.

Synthetic seismograms can be efficiently constructed with the modal summation technique (e.g. Panza et al., 2001; La Mura et al. 2011) to model ground motion at sites of interest, using knowledge of the physical process of earthquake generation and wave propagation in realistic media and this makes it possible to easily perform detailed parametric analyses that permit to account for the uncertainty in input information.

Where the numerical modeling is successfully compared with records, the synthetic seismograms permit the microzoning, based upon a set of possible scenario earthquakes. Where no recordings are available the synthetic signals can be used to estimate the ground motion without having to wait for a strong earthquake to occur (pre-disaster microzonation). In both cases the use of modeling is necessary since the so-called local site effects can be strongly dependent upon the properties of the seismic source and can be properly defined only by means of envelopes.

In fact, several techniques that have been proposed to empirically estimate the site effects using observations (records) convolved with theoretically computed signals corresponding to simplified models, supply reliable information about the site response to non-interfering seismic phases, but they are not adequate in most of the real cases, when the seismic sequel is formed by several interfering waves.

One of the most difficult tasks in earthquake scenario modeling is the treatment of uncertainties, since each of the key parameters has its own uncertainty and intrinsic variability, which often are not quantified explicitly. A possible way to handle this problem is to vary systematically (within the range of related uncertainties) the modeling parameters associated with seismic sources and structural models, i.e. to perform a parametric study to assess the effects of the parameters describing the mechanical properties of the propagation medium and of the earthquake focal mechanism (i.e. strike, dip, rake, depth etc.).

The parametric studies allow us to generate advanced ground-shaking scenarios for the proper evaluation of the site-specific seismic hazard, with the necessary and complementary check based on both probabilistic and empirical procedures. Once the gross features of the seismic hazard are defined, and the parametric analyses are performed, a more detailed modeling of the ground motion can be carried out for sites of specific interest. Such a detailed analysis duly takes into account the earthquake source characteristics, the mechanical properties of the path and of the local geology, nevertheless it can be easily performed using widely available computational tools, like modern laptops or, for very complex situations, to worldwide grid-and-cloud advanced e-infrastructures (e.g. Prace, EGI, EU-IndiaGRID2, EUMEDGRID-Support and Chain).

2.1. Ground Motion Scenarios at Bedrock

In the NDSHA approach the definition of the space distribution of seismicity accounts essentially for the largest events reported in the earthquake catalogue at different sites. The flexibility of NDSHA permits to incorporate the additional information about the possible location of strong earthquakes provided by the morphostructural analysis, thus filling in gaps in known seismicity. Specifically, the areas prone to strong earthquakes are identified based on the morphostructural nodes, which represent specific structures formed around the intersections of lineaments. Lineaments are identified by the Morphostructural Zonation Method (Alekseevskaya et al., 1977) that, independently from any information about earthquakes, delineates a hierarchical block structure of the study region, using tectonic and geological data, with special care to topography. The boundary zones between blocks are called lineaments and the nodes are formed at the intersections or junctions of two or more lineaments. Among the defined nodes, those prone to strong earthquakes are then identified by pattern recognition on the basis of the parameters characterizing indirectly the amount of neo-tectonic movements and fragmentation of the crust at the nodes (e.g. elevation and its variations in mountain belts and watershed areas; orientation and density of linear topographic features; type and density of drainage pattern). For this purpose, the nodes are defined as circles of radius $R = 25\ \text{km}$ surrounding each point of intersection of lineaments. The morphostructural zonation of Italy and surrounding regions, as well as the identification of the sites where strong events can nucleate, has been performed by Gorshkov et al. (2002), (2004) considering two magnitude thresholds: $M \geq 6.0$ and $M \geq 6.5$.

The identified seismogenic nodes are used, along with the seismogenic zones (Meletti and Valensise, 2004), to characterize the earthquake sources used in the seismic ground motion modeling, as described by (Peresan et al., 2009). The earthquake epicenters reported in the catalogue are grouped into 0.2°x0.2° cells, assigning to each cell the maximum magnitude recorded within it. A smoothing procedure is then applied, to account for spatial uncertainty and for source dimensions. Only the sources located within the seismogenic zones, as well as the sources located within the earthquake prone nodes, are considered; moreover, if the smoothed magnitude M of a source inside a node is lower than the magnitude threshold, M_0, identified for that node, in the computation of the synthetic seismograms M_0 is used.

In the first applications of NDSHA (Costa et al., 1993; Panza et al., 1996, 2000, 2001) a double-couple point source is placed at the centre of each cell, with a focal mechanism consistent with the properties of the corresponding seismogenic zone or node and a depth, which is a function of magnitude (10 km for $M < 7$, 15 km for $M \geq 7$). To define the physical properties of the source-site paths, the territory is divided into an appropriate number of polygons, each characterized by a structural model composed of flat, parallel inelastic layers that represent the average mechanical properties of the lithosphere at regional scale. Synthetic seismograms are then computed by the modal summation technique for sites placed at the nodes of a grid with step 0.2°x0.2° that covers the national territory, considering the average structural model associated to the regional polygon that includes the site. The seismograms are computed for an upper frequency content of 1 Hz, that is consistent with the level of detail of the regional structural models, and the point sources are scaled for their dimensions using the spectral scaling laws proposed by Gusev (1983), as reported in Aki (1987).

From the set of complete synthetic seismograms, different maps of seismic hazard that describe the maximum ground shaking at the *bedrock can be produced.* The acceleration parameter in NDSHA is usually given by the DGA. This quantity is obtained by computing the response spectrum of each synthetic signal for periods, consistent with the detail of knowledge about earthquake sources and propagation media, of 1 s and longer (the periods considered in the generation of the synthetic seismograms). The spectrum is extended at frequency higher than 1Hz using the shape of the Italian design response spectrum for soil A), which defines the normalized elastic acceleration response spectrum of the ground motion, for 5% critical damping (for details see Panza et al., 1996). In the PSHA the hazard maps are only defined in terms of PGA, which is the horizontal peak ground acceleration. DGA is comparable to the PGA, since an infinitely rigid structure (i.e. a structure having a natural period of 0 s) moves exactly like the ground (i.e. the maximum acceleration of the structure is the same as that of the ground, which is the PGA). This is why PGA has been used over the years to provide a convenient anchor point for the design spectra specified by various regulatory agencies. Moreover, DGA is practically equivalent to EPA, which is defined as the average of the maximum ordinates of elastic acceleration response spectra within the period range from 0.1 to 0.5 seconds, divided by a standard factor of 2.5, for the 5% damping (Panza et al., 2003). Among the parameters representative of earthquake ground motion (maximum displacement, velocity, acceleration), we focus our attention on the maximum displacement estimates, which turn out to be relevant for seismic isolation design (Figure 1).

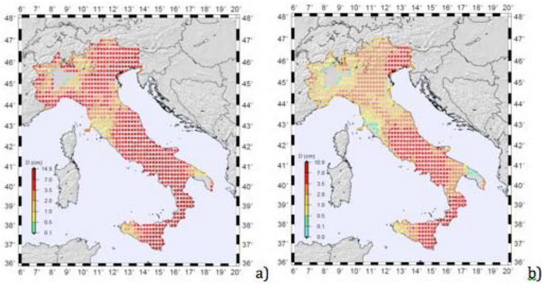


Figure 1. Map of Peak Ground Displacement *D* for the Italian territory. At each node of the grid, the maximum value of a) horizontal displacement and b) vertical displacement, is extracted from the computed synthetic seismograms.

The effect of a change in the properties of the medium traveled by the seismic waves generated at the sources has been tested by replacing the models described in Costa et al. (1993) with a set of cellular structures (1°x1°), obtained through an optimized non-linear inversion of surface wave dispersion curves (Boyadzhiev et al., 2008; Brandmayr et al., 2010). The properties of the uppermost layer are quite different for the two considered structural models; nevertheless, the variation in the computed ground motion, both positive and negative, gives rise to macroseismic intensity variations (Panza et al., 1997) not exceeding one degree in the MCS scale.

NDSHA has been recently extended to frequencies as high as 10 Hz, to account for the source process in some detail (rupture process at the source and the consequent directivity effect). The preliminary results provided by this ongoing research (i.e. the regression relations between the strong motion parameters and the macroseismic intensities), confirm the results obtained with a 1 Hz cut-off frequency in the point-source approximation.

Considering specific faults included within alerted nodes, with this second variant of NDSHA it is possible to perform parametric studies, which permit to single out the relevance of source-related effects, like directivity. In Fig. 2 we provide an example of scenario corresponding to the fault ITIS038 from the database DISS3 (Basili et al., 2008), which falls within the node I26 (Gorshkov et al., 2002).

The rupture process at the source and the consequent directivity effect (i.e. radiation at a site depends on its azimuth with respect to rupture propagation direction) is modeled by means of the algorithm developed by Gusev and Pavlov (2006) and Gusev (2011), that simulates the radiation from a fault of finite dimensions, named PULSYN (PULse-based wide band SYNthesis).

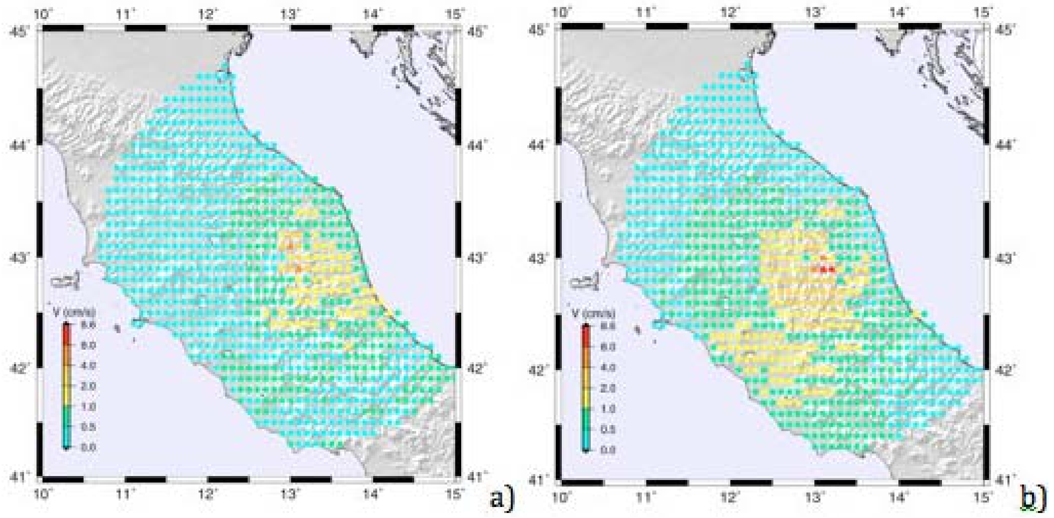


Figure 2. Ground shaking scenarios at bedrock (PGV) a) for source directivity south-east; a) for source directivity north-west. The fault ITIS038 from the database DISS3 (Basili et al., 2008) is considered. Cellular structural models of the lithosphere are considered to model waves propagation.

3. Space-Time Properties of Earthquake Occurrence

Even though temporal property of earthquake recurrence is poorly constrained, it is an important parameter for engineering evaluation and other policy consideration. This can be demonstrated in a case when considering two sites A and B prone to earthquakes with the same magnitude, say $M = 7$, given that all the remaining conditions are the same, the site where the recurrence is lower appears naturally preferable; nevertheless parameters for seismic design (DGA, PGA, PGV, PGD, etc.) should be equal at the two sites, since the expected magnitude is the same ($M = 7$). The evaluation is obviously different from a merely statistical point of view, which may eventually apply to insurances, but still requires an adequate statistical characterization that might not be feasible based on available observations.

As pointed out by Wang (2011), although PSHA has been proclaimed as the best approach for seismic hazard assessment and is used widely for seismic hazard assessment, it is scientifically flawed, since neither the physical model that it is based on nor the mathematical formulation is valid. As a result, the use of PSHA could lead to either unsafe or overly conservative engineering design, with direct negative consequences for society. The practical limits to the use of PSHA analysis for adequate structural design and, in general, for seismic risk mitigation, are clearly outlined by the comparative analysis of PSHA and NDSHA estimates, performed for the Italian territory by Zuccolo et al. (2011). The NDSHA provides values larger than those given by the PSHA in high-seismicity areas and in areas identified as prone to large earthquakes, while lower values are provided in low-seismicity areas. The evidenced tendency of PSHA to overestimate hazard in low seismicity areas seems supported by the results from the studies on precarious unbalanced rocks (e.g. Stirling and Petersen, 2006; Anderson et al., 2010). In addition (Figure 3), the PSHA expected ground shaking estimated with 10% probability of being exceeded in 50 years (grossly associated with a return period of 475 years) appears severely underestimated (by about a factor 2) with respect to NDSHA estimates, particularly for the largest values of PGA (Figure 3a). When a 2% probability of being exceeded in 50 years is considered (i.e. return period of 2475 years) PSHA estimates in high-seismicity areas become comparable with NDSHA (Figure 3b); in this case however, the overall increase related with probabilistic estimates leads to significantly overestimate the hazard in low-seismicity areas.

In view of the above mentioned shortcomings of classical PSHA it appears preferable to resort to a scenario-based approach to reliably assess seismic hazard. From an anthropocentric perspective, buildings and other critical structures should be designed capable to resist future earthquakes. When an earthquake with a given magnitude M occurs, it causes a specific ground shaking that certainly does not take into account whether the event is rare or not; thus ground motion parameters for a seismic design should not be scaled depending on how sporadic an earthquake is but should cope with the seismic history and the earthquake prone areas (seismogenic nodes) identified through a morphostructural analysis, as it is done with the Neodeterministic Seismic Hazard Assessment (NDSHA) with scenario earthquakes (Peresan et al. 2011, and references therein).Therefore, when considering two sites prone to earthquakes with the same magnitude, say $M = 7$, given that all the remaining conditions are the same, the site where the sporadicity is higher appears naturally preferable for new settlements (viceversa for retrofitting); nevertheless the reference parameters for seismic design (Design Ground Acceleration - DGA, Peak Ground Acceleration - PGA, Peak Ground Velocity - PGV, Peak Ground Displacement - PGD, SA - Spectral Acceleration, etc.) must be equal at the two sites, since the magnitude we have to defend against is the same ($M = 7$). The evaluation is obviously different from a merely statistical point of view, which may eventually apply to insurances, but still requires an adequate statistical characterization that often is not feasible based on available observations.

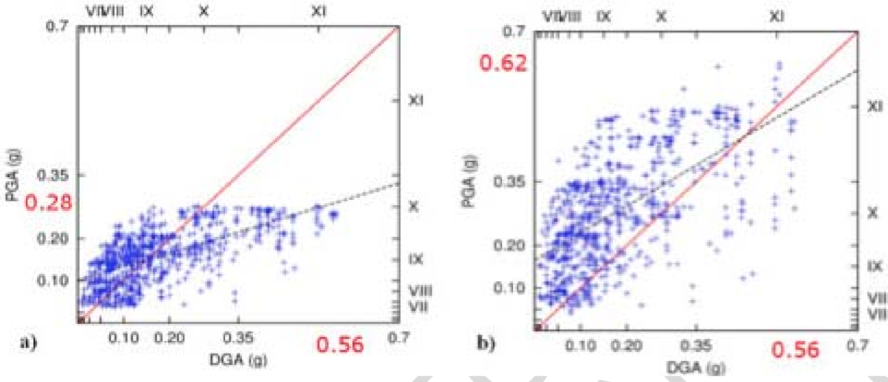


Figure 3. Scatter plots comparing, at given sites, the values of PGA from PSHA analysis and those of DGA from NDSHA (Zuccolo et al., 2011). PGA values correspond to estimates obtained for: a) 10% probability of being exceeded in 50 years; b) 2% probability of being exceeded in 50 years. The red line corresponds to the values for which PGA and DGA estimations coincide. The linear regression line between DGA and PGA (black dashed, line) is shown as well.

3.1. Time-Dependent Scenarios of Ground Motion

Based on the NDSHA an operational integrated procedure for seismic hazard assessment has been developed (Peresan et al. 2009 and 2010; Zuccolo et al., 2004) that allows for the definition of time-dependent scenarios of ground shaking, through the routine updating of earthquake predictions. Accordingly, when an alarm is declared, a set of scenarios of expected ground shaking at bedrock, associated with the alarmed areas identified by means of formally defined algorithms, can be readily computed by means of full waveform modeling, both at regional and local scale, considering all of the possible earthquake sources within the alerted areas.

The intermediate-term medium-range earthquake predictions are performed by means of the algorithms CN and M8S (Keilis-Borok and Rotwain, 1990 and Kossobokov et al., 2002). CN and M8S algorithms belong to a family of fully formalized procedures for intermediate-term medium-range earthquake prediction, which are tested in several regions worldwide since about thirty years. The application of CN and M8S algorithms to the Italian territory is described in detail in Peresan et al. (2005). With the algorithm CN a regionalization composed by three macro-zones, defined strictly based on the seismotectonic zoning and taking into account the main geodynamic features of the Italian area, is considered. For the application of M8S algorithm (i.e. the spatially stabilized variant of M8), seismicity is analyzed within a dense set of overlapping circles, with radius increasing with the magnitude of the target events and covering the monitored area. An experiment is ongoing since 2003, aimed at a real-time testing of M8S and CN predictions for earthquakes with magnitude larger than a given threshold (namely 5.4 and 5.6 for CN algorithm, and 5.5 for M8S algorithm) in the Italian region and its surroundings. Predictions are regularly updated every two months and a complete archive of predictions is made available on-line (http:// www.ictp.trieste.it / www_users /sand /prediction /prediction.htm), thus allowing for a rigorous testing of the predictive capability of the applied algorithms.

According to NDSHA, the expected ground motion is modeled, starting from the available information about seismic sources and regional structural models, at the nodes of a regular grid with step 0.2°x0.2°. Ground shaking scenarios associated with the alerted area are defined considering altogether the set of possible sources included in the region, following the procedure described in (Peresan et al., 2010). In such a way an alarm (which consists of space, time and magnitude information about the impending earthquake) can be associated with maps describing the seismic ground motion caused by the potential sources in the alerted region. The practical example of a time dependent scenario associated with an alarm, declared by M8S algorithm, is illustrated in Figure 4.

Maps of expected intensities can be obtained as well (e.g. Zuccolo et al., 2010) using the available relationships among the computed horizontal ground motion and the observed macroseismic intensities (e.g. Panza et al., 1997). CN and M8S predictions, as well as the related time-dependent ground motion scenarios, are routinely updated every two months and are made available to the Civil Defense of the Friuli Venezia Giulia Region since 2006. The time-dependent ground shaking scenario associated with CN alarmed regions, as defined for the period 1 March 2009 – 1 May 2009, correctly predicted the macroseismic intensities, as large as IX (MCS), observed for the L'Aquila earthquake (April 6, 2009; M6.3), as described by Peresan et al. (2010).

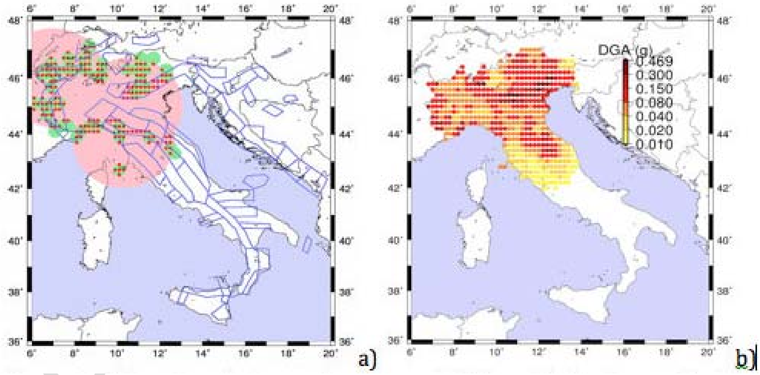


Figure 4. Time-dependent scenario of ground shaking at bedrock associated with an alerted region: a) territory alarmed by M8S algorithm for an earthquake with $6.5 < M < 7.0$, for the time interval 1 July 2008 – 31 December 2008 (pink area: alarmed territory; green full circles: seismogenic nodes (Gorshkov et al. (2002); (2004)); blue polygons: seismogenic zones (Meletti and Valensise (2004)); dots: sources considered for the scenario computation); b) Ground shaking scenario (design ground acceleration, DGA) computed from all the possible sources included in the alerted region.

3.2. Ground Shaking Prediction and Risk Mitigation Actions

The issues and decision-making problems related with seismic hazard assessment have been explored by Stein (2010) and provided matter for significant debate in the last years (Panza et al, Editors, 2011). Surprisingly enough, when discussing about seismic hazard, some authors refers just to PSHA (e.g. ICEF, 2011), completely ignoring other classical, comprehensively described in the literature since the early review by Reiter (1990), and recent deterministic approaches like NDSHA.). The operational relevance of time–dependent seismic hazard assessment is strictly connected with the capability to properly describe the temporal properties of earthquake occurrence, and hence with the development and testing of forecast/prediction. The relevant uncertainties characterizing the space-time identification of impending earthquakes of course limit their operational use oriented to disaster mitigation; there is a number of low-key-actions, however, which can be taken to mitigate the damage from an earthquake, based on formally defined procedures for forecast/prediction of strong earthquakes and related ground shaking scenarios.

In general, the prediction of an earthquake of a certain magnitude may extend, in time, from time-independent seismic zoning (no time information), through the long-term (decades), intermediate-term (months to years) and short-term ones (hours to days), while, in space, it may vary from long-range territories (thousands kilometers) to the exact location of the earthquake source (tens of kilometers). Accordingly, the preparedness measures range from the definition of adequate building codes, to intermediate-term alarm declaration and reinforcement of high-risk facilities, to imminent "red alert". Different time intervals, from decades to seconds, are required to undertake different measures.

A list of possible low-key actions, whose basic concepts were analyzed in detail by Kantorovich and Keilis-Borok (1991), is given by Keilis-Borok and Primakov (1997); the basic concepts were analyzed in detail by Kantorovich and Keilis-Borok (1991). Having different cost, they can be realistically maintained during different time periods and over territories of different size. The key to damage reduction in an area of concern is the timely escalation or de-escalation of preparedness measures, depending on the current state of alert. A list of possible low-key actions is provided below, as reported at the International Framework for Development of Disaster Reduction Technology List on Implementation Strategies ("Disaster Reduction Hyperbase" NIED. Tsukuba, Japan. 27-28 February 2006).

The enlisted safety measures are not independent, but form an obvious hierarchy: they make sense, if activated in a certain set and given order, as a part of a scenario of response to prediction.

a) Permanent safety measures maintained during the decades:

- Restriction of land use, especially for high-risk objects and earthquake-inducing activities.
- Building code, demanding reinforcement of constructions.
- Tightening of general safety regulations.

- Enforced public safety services.
- Insurance and special taxation.
- Observations and data-analyses to estimate seismic risk and to monitor earthquake precursors.
- Preparation of the response to time-prediction, and of post-disaster activities: planning; establishment of legal background; accumulation of the stand-by resources; simulation of alarms; training of population etc.

b) Temporary safety measures activated in response to time-prediction:

- Enhancement of permanent measures (see list with permanent safety measures)
- Emergency legislation (up to martial one), to facilitate the rational response to prediction
- Mandatory regulation of economy
- Neutralization of the sources of high risk: life-lines; nuclear power plants; chemical plants; unsafe buildings, up to suspension of operation partial disassembling, demolition, etc.
- Evacuation of population and highly vulnerable objects (e.g., schools and hospitals)
- Mobilization of post-disaster emergency services
- Preparation of measures for long-term post disaster relief (restoration of dwellings, jobs, production, credit etc.)
- Monitoring of socio-economic changes, and prevention of prediction induced hazards

Some additional low-key action could be:

- Develop a retrofitting plan for strategic buildings in the alerted area.
- Control that the rescue plan is ready to start with minimal delay
- Control the maintenance state of temporary housing, stored in the civil defense centers, and guarantee their timely mobilization
- Intensify preparedness practice, increasing the frequency of actions involving students and civil defense.
- Diffuse in a systematic way by media simple instructions like establishing small restoration corners in the strongest parts of the building with basic supplies (water, emergency foods, basic tools, etc).

The listed measures are in different forms applicable to international, national, regional, provincial and local levels.

4. Earthquake Ground Motion in Laterally Heterogeneous Inelastic Media

To assess the hazard for engineering design applications and due to the limited availability of strong ground motion records, it has become increasingly common to compute broad-band synthetic seismograms that allow us to perform realistic waveform modeling for different seismotectonic environments, by mean of modeling tools. The modeling has to take simultaneously into account the properties (e.g. dimensions, directivity and near field effects) of the radiating source, lateral heterogeneities along the path and local site effects.

The joint use of reliable synthetic signals and of observations can be fruitfully used for design purposes. In fact, even if recently some strong-motion records in near-fault, soft soils, or basin conditions have been obtained, their number is still very limited to be statistically significant and representative of possible seismic ground motion scenarios for dependable seismic engineering applications.

The lack of a representative set of observations is due to the low frequency of large earthquakes, to the difficulty of providing a proper instrumental coverage of all the areas prone to strong shaking and to the inadequacy of using empirical Green functions (Panza and Kouteva, 2003; Yagi and Fukahata, 2011). The variability of ground motion, due to different causes, e.g. spatial variability, source parameter variability, azimuthal variability (Strasser and Bommer, 2009), shows how the currently available strong motion data still represent only a small sample of the main categories of physically possible ground motion.

The mathematical modeling, with different degrees of complexity, is a fundamental step to resort to broadband synthetic seismograms: where no records are available, synthetic signals can be used to estimate the ground motion without having to wait for a strong earthquake to occur.

The realistic modeling of ground motion requires the simultaneous knowledge of the mechanical parameters and topography of the medium, on one side, and tectonic, historical, palaeoseismological, seismotectonic models, on the other. The initial stage for the realistic ground motion modeling is thus devoted to the collection of all available data concerning the shallow geology, and the construction of a three-dimensional structural model to be used as input for the computation of the synthetic seismograms. The typical seismic hazard problem lies in the determination of the ground motion characteristics associated with future earthquakes. An adequate definition of the seismic hazard can be given by NDSHA, which addresses some issues largely neglected in probabilistic hazard analysis. Synthetic seismograms are computed, using the knowledge of the physical process of earthquake generation and wave propagation in realistic media, in short time and at a very low cost/benefit ratio.

The proposed methodology for seismic microzoning has been successfully applied to several urban areas worldwide in the framework of the UNESCO/IUGS/IGCP projects “Realistic Modeling of Seismic Input for Megacities and Large Urban Areas” (e.g. Panza et al. , 2001a, 2001b, 2002), as well as in the framework of various scientific networks like “Seismic Hazard and Risk Assessment in North Africa”, "Seismic microzoning of Latin America cities" and “Seismic Hazard in Asia”. The methodology has been applied to assess the importance of non-synchronous seismic excitation of long structures as well.

To take into account the local variability of the ground motion, due to source effects, local lateral heterogeneities and attenuation properties, can be crucial for the realistic definition of the asynchronous motion at the base of bridge piers (e.g. Romanelli et al., 2004). Several examples of application of NDSHA, both at regional and local scales, can be found in “Advanced seismic hazard assessment” (Panza, Irikura, Kouteva, Peresan, Wang and Saragoni, Editors, 2011).

4.1. Modeling of Strong Ground Motion along profiles

A pilot application of NDSHA at local scale, including a detailed evaluation of the expected ground motion accounting for site effects, has been carried out, among others (Panza et al., 2002), for the municipality of Nimis (NE Italy), aimed at the design of residential dwellings seismically isolated (Zuccolo et al., 2008).

Nimis is located in the Friuli Venezia Giulia region (Italy), in a seismically very active area at the Alps–Dinarides junction. It is located at the centre of a sedimentary valley (Figure 5); therefore the site response is expected to play a relevant role in the ground shaking of the area. The analysis has been carried on with the aim to compute synthetic signals to be used as seismic input in subsequent engineering analysis for the design of a residence seismically isolated, located in the municipality of Nimis. The town and all the surrounding area were strongly hit by the 1976 Friuli earthquake.

For an efficient seismic hazard assessment, it is not sufficient to consider only the observed data in fact, for each site, a representative set of observations is not available due to the low frequency of large earthquakes and to the difficulty of providing an adequate instrumental coverage. Further, the variability of ground motion due to several causes, e.g. source parameter variability, spatial variability, source parameter variability (Strasser and Bommer, 2009) suggest a large amount of physically possible ground motion. The mathematical modeling based on probabilistic concepts is inaccurate and introduces systematic errors in the calculation process that leads to results that could represent only a gross approximation of the reality (Panza et al., 2004, Klügel, 2007). The neo-deterministic approach permits a realistic description of the seismic ground motion due to an earthquake of given distance and magnitude (e.g. Panza et al., 2001) without having to wait for an earthquake to occurr for estimating its destructive potential.

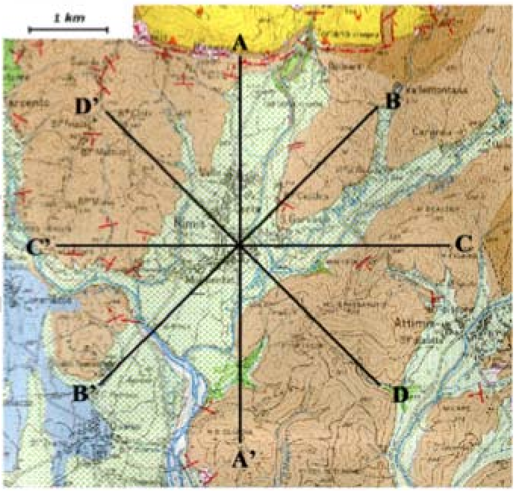
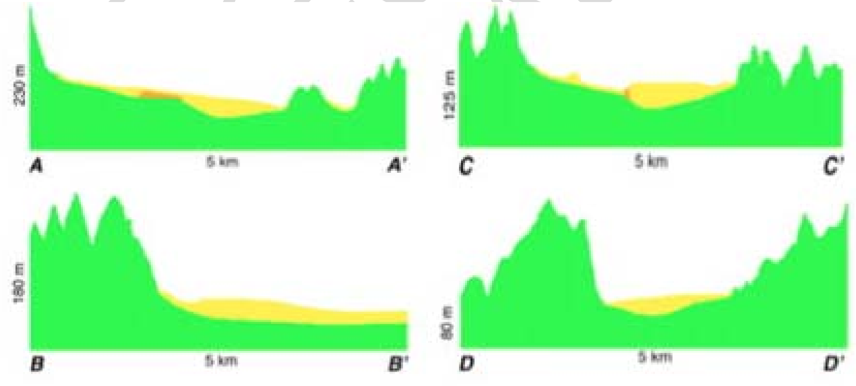


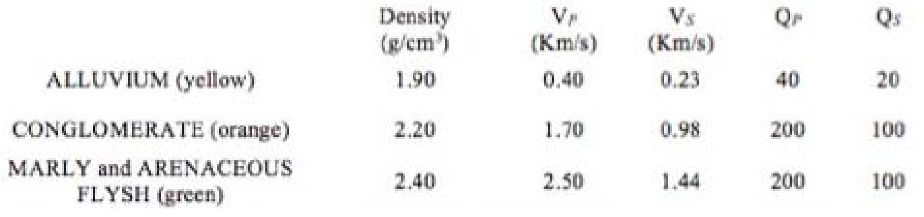
Figure 5. Geology of Nimis area (Martinis, 1977) and profiles considered for the detailed modeling of seismic ground motion and the assessment of site effects. Each profile is 5 km long.

The seismic input has been defined considering different levels of detail for the earthquake source, including extended source models, both for a bedrock model and taking into account the specific site conditions (Figure 6).

At a first stage, synthetic seismograms are calculated at national scale by the MS technique (Panza et al., 2001) to obtain scenarios at the bedrock, i.e. not accounting for the local site conditions. Specifically, seismograms are computed at the nodes of a grid with step 0.2°, that covers the whole Italian territory, for an upper frequency content of 1Hz, that is consistent with the detail level of the regional structural models, and the point-sources are scaled for their dimensions using the spectral scaling laws by Gusev (1983). This regional-scale result is used as the starting point for the detailed analysis of earthquake ground motion in Nimis (Zuccolo et al., 2008).

As can be seen in Figure 5, Nimis is located at the centre of a sedimentary valley with the bottom and the sides occupied by flysch, so the site response is expected to play a relevant role in the ground shaking response. Thus, in a second approximation, a seismic microzoning has been performed, including local geological conditions and considering time series with a frequency content up to 5 Hz. Site effects are then evaluated as spectral amplifications, described by the ratios (2D/1D) of the acceleration response spectra, with 5% damping, computed along the bedrock model (1D) profile and along the one containing the local model (2D). As shown in Figure 5, four profiles have been selected for the detailed modeling of earthquake ground motion. The profiles, each 5 km long, are representative of the most populated areas of the municipality and intersect at their middle point (Figure 5) in correspondence of the mechanical drilling located in the vicinity of the central square of Nimis.





	Density (g/cm^3)	V_P (Km/s)	V_S (Km/s)	Q_P	Q_S
ALLUVIUM (yellow)	1.90	0.40	0.23	40	20
CONGLOMERATE (orange)	2.20	1.70	0.98	200	100
MARLY and ARENACEOUS FLYSH (green)	2.40	2.50	1.44	200	100

Figure 6. Cross-sections used for the detailed modeling of ground motion along the profiles shown in Figure 5. In the table the mechanical properties of the lithotypes are listed.

All the details concerning the topography and the parameters necessary to reconstruct the ground characteristics are obtained by the pertinent documentation available about the area (for details, see Zuccolo et al., 2008) The cross-sections along the profiles with the mechanical properties associated with the lithotypes used for the modeling of seismic ground motion are given in Figure 6.

Along the profiles, the ground motion is modeled with broadband synthetic seismograms computed by the hybrid technique (Panza et al., 2001). The details about the bedrock model to compute the synthetic seismograms from the source to the beginning of the local profile of interest and for the computation of the reference signals at the bedrock, necessary for the definition of the site effects, are given in Vaccari et al. (2005) and Zuccolo et al. (2008). Four seismic sources (Figure 7), aligned with the direction of the selected profiles, have been defined on the basis of the morphostructural model of the zone (Gorshkov et al., 2009). For all sources the assumed magnitude is 6.5 as indicated by historical seismicity and seismic potential of the area DISS3 (Basili et al. 2008).

The source S1 models the 1976 Friuli earthquake, whose focal mechanism parameters, according to Aoudia et al. (2000) are: strike=288°, dip=29°, rake=112°, depth=5 km. The same parameters have been assigned to the source S2, which has the same South-Alpine geological characteristics of the S1 source. For the sources S3 and S4, which belong to the Dinaric system, we use strike=315°, dip=82°, rake=189°, depth=7.6 km (Bajc et al. 2001), i.e. the parameters of the 1998 Bovec earthquake, the main event occurred in this area, for which instrumental recordings are available.

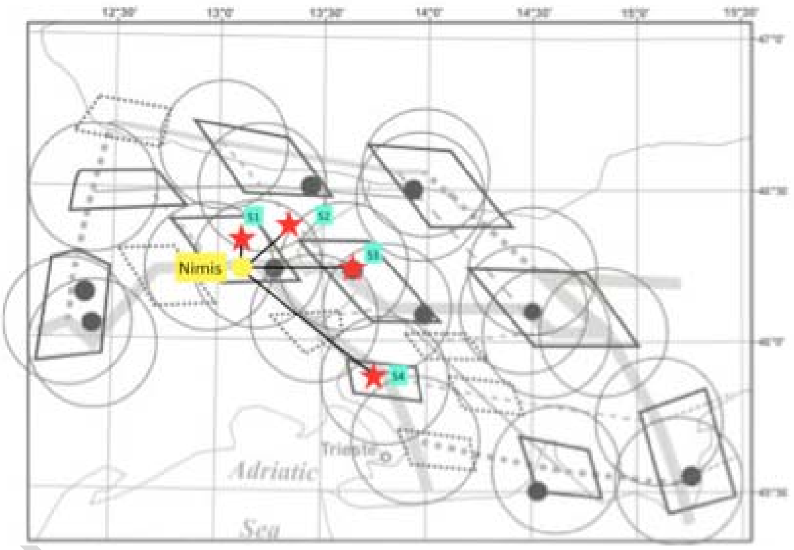


Figure 7. Sources (S1, S2, S3 and S4) used for the computations of the ground shaking scenarios in Nimis. Seismogenic nodes (circles and solid line polygons), epicenters of earthquakes, with $M \geq 6$, occurred in the last millennium (full dots) after Gorshkov et al., (2004, 2009). Thick, medium and thin lines are the lineaments of the first, second and third rank respectively after Gorshkov et al., (2009). Source S2 has been deliberately located in between two nodes.

In order to perform, as realistically as possible, the modeling of the rupture process at the source and the related directivity effect (i.e. the dependence of the radiation at a site on its azimuth with respect to the rupture propagation direction), extended sources have been considered. Use is made of the algorithm for the simulation of the source radiation from a fault of finite dimensions, named PULSYN (PULse-based wideband SYNthesis), developed by Gusev and Pavlov (2006). The code PULSYN generates a source (phase and amplitude) spectrum, which is close in amplitude to the Gusev's (1983) empirical curves and reproduces the directivity effects as in the theoretical Haskell model. Synthetic signals are then computed for each source-profile pair, considering an azimuth of 90° with respect to a bilateral rupture direction.

Among the four considered earthquake sources, the most dangerous one for Nimis is with no doubt the source S1, because of its large magnitude ($M = 6.5$) and small epicentral distance (7.5 km from the beginning of the profile AA′). The computed accelerograms, shown in Figure 8, give in the centre of Nimis a value of about 1.2 g, a value significantly greater than the corresponding value obtained at the bedrock, that is, 0.5 g. Therefore the local soil conditions cannot be captured by the average values typical of bedrock modeling, but they must be the object of further detailed analysis for those sites where an impending earthquake is expected since they do amplify the DGA by a factor of about 2. The amplification pattern, obtained as 2D/1D response spectra ratio, along the profile is shown in Figure 9.

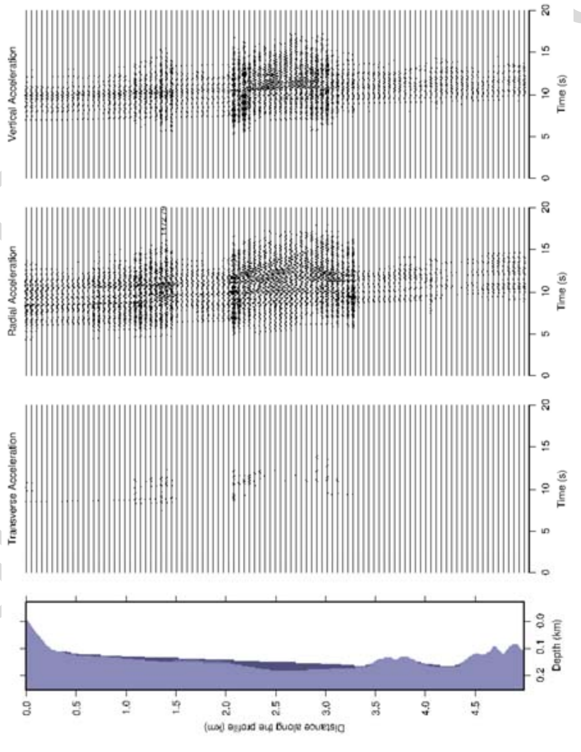


Figure 8. Modeled accelerations along the profile AA′. From top to bottom: vertical, radial and transverse component of motion. The profile at the very bottom is show to facilitate the recognition of the effect of the sediments. (Zuccolo et al., 2008).

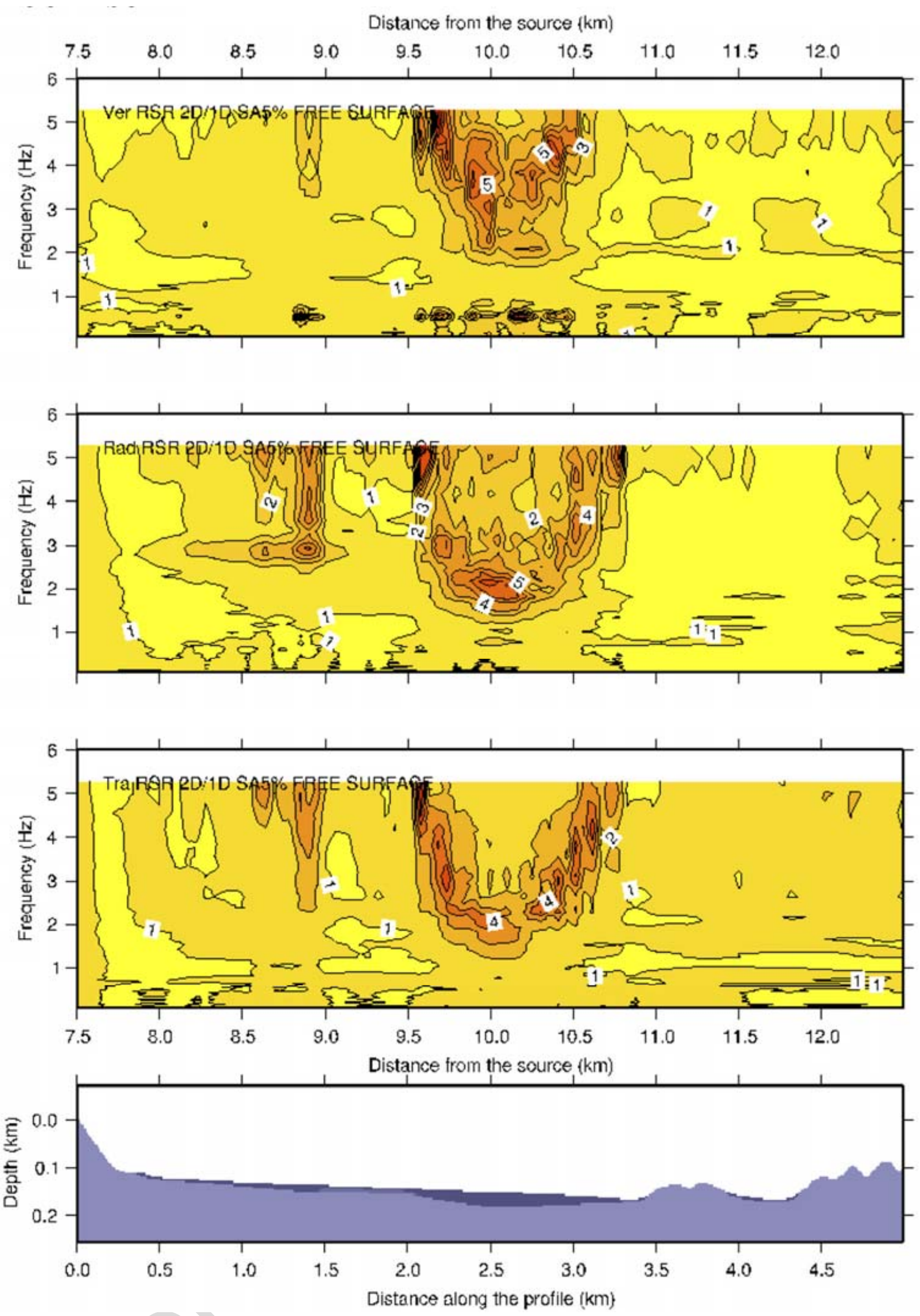


Figure 9. Modeled spectral amplification, obtained as 2D/1D response spectra ratio, along the profile AA′. From top to bottom: vertical, radial and transverse component of motion. (Zuccolo et al., 2008).

The effects due to the sedimentary basin are evident along the profile BB′.

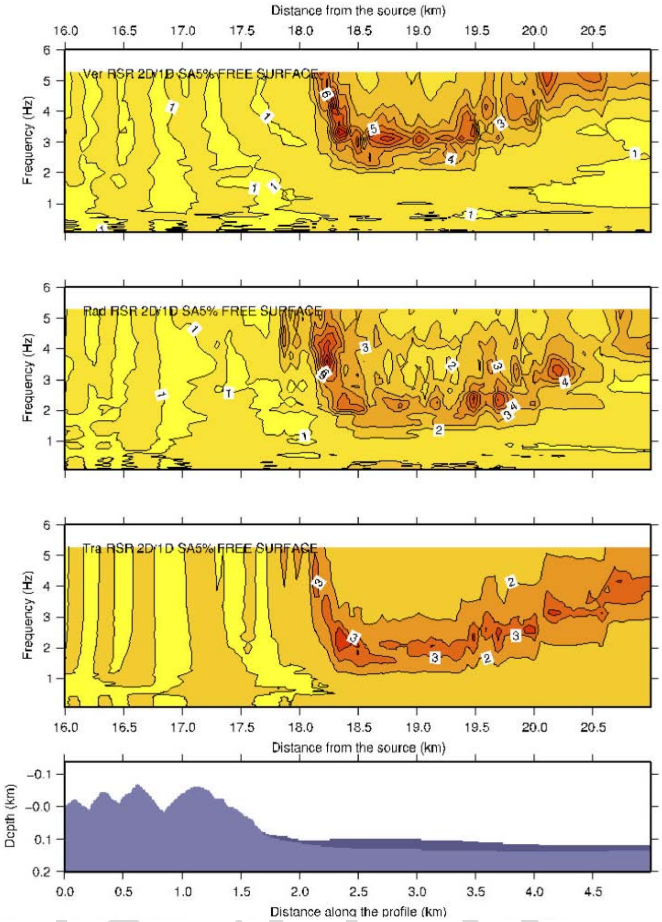


Figure 10. Modeled spectral amplification, obtained as 2D/1D response spectra ratio, along the profile BB′. From top to bottom: vertical, radial and transverse component of motion (Zuccolo et al., 2008).

In Figure 10 it is seen that the sedimentary cover is predominant with respect to the effect associated with topography, and a great amplification can be seen in correspondence of it.

4.2. 3D Modeling of Strong Ground Motion

To deal with 3D models it means to take into account the lateral heterogeneities in both the horizontal directions together with the vertical one. The computation of synthetic seismograms underwent an impressive progress in the last decades due to the increasing efficiency of computers' performances. A description of both analytical and numerical methods can be found, e.g., in Anderson (2003), Bolt and Abrahamson (2003), Bielak et al. (2003). Several hybrid techniques, obtained combining analytical and numerical methods, as already mentioned in section 4.1, have been developed and a review of these methods is available in Moczo et al. (1997). Several numerical methods are available for modeling inelastic wave propagation, that take into account propagation path, local site effects and the earthquake source. Simulations based on FD scheme (see e.g. Sato et al., 1998) or, more recently, FEM (see e.g. Bielak et al., 2003) and SEM (see e.g. Komatitsch and Tromp, 2002a; Komatitsch and Tromp, 2002b; Komatitsch et al.,

2004) have been largely used in order to compute synthetic seismograms in three-dimensional structures. A very recent development (La Mura et al., 2011) extended the very efficient analytical modal summation (Panza et al., 2001) to three-dimensional inelastic media, combining it with the ray theory in the framework of the WKBJ approximation. In this section, the methodology is illustrated, discussing its limits and possibilities by means of some applications.

4.2.1. 3D Modeling Theory

Exact formulas describing the seismic wavefield for a structure with both vertical and lateral variations have been not derived so far: an arbitrary lateral heterogeneity can be handled only by numerical methods. Nevertheless, under the WKBJ approximation, it is possible to construct an analytical solution of the wavefield. The main assumption of WKBJ method, widely used in seismology (Woodhouse, 1974), is that the lateral variations of the elastic parameters characterizing each layer of the stratified structure are small within a wavelength. In this way, the lateral heterogeneity can be viewed as a perturbation of an initial lateral homogeneous model. Once this hypothesis is satisfied (i.e. this perturbation is small within a wavelength), it can be assumed that the energy carried by each mode in a given structure is neither reflected nor transmitted to other modes. In other words, modes are not coupled; each mode propagates with a wavenumber driven by the local structure. This allows us to use a procedure based on the ray method to construct an approximate solution corresponding to the wavefield (see e.g. Woodhouse, 1974, Levshin et al., 1985). The principal quantities that ray methods uses are travel time and geometrical spreading, which are characteristics of rays.

Therefore, if the lateral heterogeneous model is made up of two, or more, vertically heterogeneous juxtaposed structures, the procedure for the calculation of synthetic seismograms consists of four steps:

- Application of the smoothness condition to the considered media;
- Construction of the 3D model (i.e. definition of the grid) that satisfies the smoothness condition;
- Calculation of the integrals along the ray path (travel time and geometrical spreading);
- Calculation of synthetic seismograms by 3D modal summation technique.

The WKBJ approximation requires that the minimum wavelength involved in the problem excedes the lateral gradient in the mechanical properties of the medium. If the lateral heterogeneous model is made up of juxtaposed vertically heterogeneous inelastic structures, this means that two adjacent structures have to be sufficiently close in the parameter’s space to allow the application of the WKBJ approximation. When, in the parameter’s space, the distance between two structures (laterally homogenous) does not satisfy WKBJ requirements, the problem is solved expanding, at the expenses of the lateral extension of the two initial models, the sharp boundary between them into a smoothing zone formed by a sequel of substructures, with equal lateral extent. This procedure has the goal to generate a “smooth” gradient in the new laterally varying model where smooth is meant in the sense of the wavelength. Thus we need to determine the length of the smoothing zone, i.e. the amount by which the lateral extent of each of the two structures, in contact in the initial model, has to be reduced in order to accommodate the substructures, all with the same lateral extent, and the number of substructures that have to be used to define the mechanical properties of the smoothing zone. The WKBJ approximation implies that:

$$\left|\nabla_{\perp} p\right| \ll \frac{\omega}{c} p \tag{1}$$

where p is any structural parameter, describing the mechanical properties of the medium, and the gradient is computed along the direction of propagation.

With respect to the development by La Mura et al. (2011), where condition (1) is applied when p is in turn density, P-wave velocity and S-wave velocity, here, taking advantage of the fact that MS technique is defined in the (ω, c) space, we consider $p = c$, i.e. the phase velocity.

Let us assume a reference system with a downward *z*-axis and the *x*–axis (direction of propagation) positive from left to right. Using $p = c$, (1) can be written as:

$$\left|\nabla_{\perp} p\right| = \frac{\partial c}{\partial x} = \frac{\left|c_1 - c_2\right|}{L^*} \ll \omega \tag{2}$$

where c_1 and c_2 are the phase velocities of the two initially juxtaposed structures. L^*, the quantity we seek for, is the length of the zone needed to smooth the lateral heterogeneity, represented by the sharp boundary in the initial model.

Since $\omega = 2\pi f$, and indicating the mode with m, (2) becomes:

$$\frac{\left|c_{1m}(f) - c_{2m}(f)\right|}{L^*} \ll 2\pi f \tag{3}$$

where the phase velocity difference in (3) is computed between the homologous modes and frequencies. Taking the maximum over m and f, we have:

$$L^* \gg \max_m \left(\max_f \left(\frac{\left|c_{1m}(f) - c_{2m}(f)\right|}{2\pi f} \right) \right) \tag{4}$$

Looking at (4), it can be seen that the leading term in the expression of L^* is the maximum difference between phase velocities, i.e. the greater the difference, the larger the length of the zone within which the sharp boundary has to be expanded to smooth the heterogeneity, consistently with WKBJ requirement. Canonical values used in numerical computations to satisfy the double inequality in (4) are around 10; numerical tests show that a satisfactory lower boundary value that can be used without affecting significantly the accuracy of the computed seismograms, is 5. For more details see La Mura (2009).

The sharp boundary between the two initial structures is replaced by a set of 1D structures obtained interpolating linearly between the elastic parameters of the initial structures in contact. In other words, L^* is filled with a set of contiguous laterally homogeneous structures, all with equal lateral extent, obtained by means of linear interpolation of the mechanical parameters characterizing the two structures initially juxtaposed. To express the subregion density, i.e. the number of substructures, required to model accurately any given lateral heterogeneity, the parameter $\lambda_{\min}/(\delta h)_{\max}$ is considered. $\lambda_{\min}$ is the minimum wavelength involved in the model and $(\delta h)_{\max}$ is the maximum step size in the staircase modeling with subregions (Gurung at al. 2011). On a qualitative level we asked how large the parameter $\lambda_{\min}/(\delta h)_{\max}$ must be before the wave motion is effectively unable to sense the difference between the true structure and the approximation. Comparing time series computed for successively higher densities of subregions, it is found that a subregion division with:

$$\frac{\lambda_{\min}}{(\delta h)_{\max}} > 10 \qquad (5)$$

is a satisfactory choice for ensuring the smoothness required by the WKBJ – approximation validity. To be consistent with the formulation in terms of phase velocity, c , (5), formulated for the thickness of the layers, is modified. Hence, since $\lambda = c/f$, and substituting h with c, (5) becomes:

$$\frac{\frac{c_{\min}}{f_{\max}}}{\max_m\left(\max_f\left|c_{1m}(f)-c_{2m}(f)\right|\right)} f_{\max} > 10 \qquad (6)$$

that is:

$$\frac{c_{\min}}{\max_m\left(\max_f\left|c_{1m}(f)-c_{2m}(f)\right|\right)} > 10 \qquad (7)$$

Finally, the number, n , of substructures necessary to expand the sharp boundary so that the entire medium satisfies WKBJ approximation is given by:

$$n > 10.\frac{\max_m\left(\max_f\left|c_{1m}(f)-c_{2m}(f)\right|\right)}{c_{\min}} \qquad (8)$$

and the length of each substructure is given by L^*/n. So, once the procedure is applied to all the structures in contact that model the study area, the 3D model is simply constructed by distributing all the resulting vertically heterogeneous structures on a regular grid, associated with a Cartesian reference system (x-axis is longitude and y-axis is the latitude). The grid can be rectangular or squared and the grid steps (Δx and Δy) are determined by the minimum substructure length, $L^*/n_{\max}$, along x and y, respectively. This choice assures the validity of the WKBJ approximation.

Obviously if L^* turns out to be larger than half of the length of the two structures juxtaposed in the initial model, the procedure cannot be applied and to resort to purely numerical method (e.g. Bielak et al. 2003) or to different analytical procedures (see e.g. Vaccari et al. 1989, Panza et al. 2001, 2012) becomes mandatory.

An example of discretization of the medium, with square cells, is shown in Figure 11.

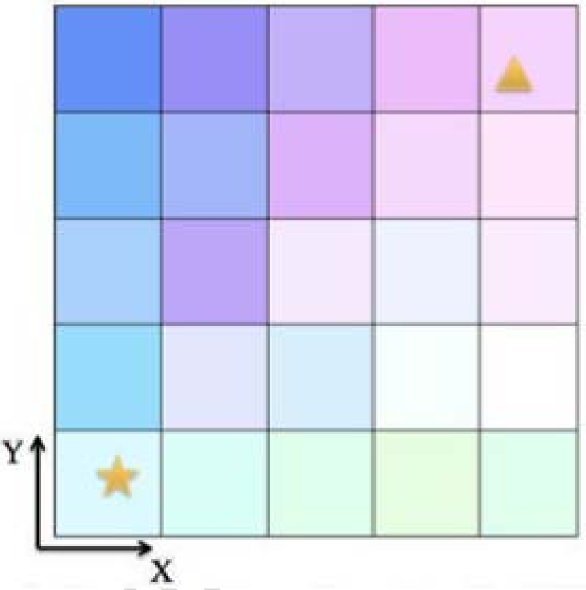


Figure 11. Discretization of a medium with regular cells. Different colors mean different cellular models, which satisfy the WKBJ-approximation and Eqs. (4) and (8). The star stands for the source, the triangle stands for the receiver; the arrows show the Cartesian axes *x* and *y*.

With MS, for each cell, occupied by a 1D structure, both the phase velocity, c , and the phase attenuation, η, can be easily computed in the required portion of the (ω, c) space; using the bilinear interpolation, c and η, are computed, where necessary along the path source-receiver, as a weighted average of the values at the knots of the grid. The source and the receiver are located inside the grid with respect to a Cartesian reference system, properly introduced in the grid itself. In this way a vertically heterogeneous structure, hence one-dimensional structure, is associated to the source and another to the receiver. The eigenfunctions of these two structures do contribute to the seismogram (Levshin, 1985).

4.2.2. Ray Tracing

The ray method uses the concepts of travel time and geometrical spreading, which are characteristics of rays. The algorithm presented in this work is based on the *two-point ray tracing* performed by the shooting method (Cerveny, 2001).

Since we compute modes (i.e. we solve simultaneously eigenvalues and eigenvectors problem) the use of 2D ray-tracing is fully sufficient to treat 3D models, with obvious consequences as far as stability and speed of computation is concerned.

Once the ray-tracing theory derived for seismic body waves is used in surface-wave ray-tracing, it must be remembered that the phase velocity and the components of the slowness vector depend on frequency. It has to be stressed that along the whole ray the frequency remains fixed, and the rays computed for different frequencies are different. The basic idea of the method we developed for the computation of signals propagating in 3D media is therefore to determine the ray that connects two given points on a horizontal (2D) plane. These points are the source and the receiver, identified by their own Cartesian coordinates given within the grid: $(X_\mathrm{S}, Y_\mathrm{S})$ and $(X_\mathrm{R}, Y_\mathrm{R})$, respectively. In the method, the two-point ray tracing performed by the shooting method is used to determine the parameters of the ray, i.e. the angle, in the horizontal plane, under which the ray leaves the source (take-off angle).

Since the phase velocity and its spatial derivatives and can be calculated at any given point of the investigated area, the ray may be calculated by numerical integration of the ray-tracing system, which is formalized as a Cauchy problem of ordinary non-linear differential equations:

$$\begin{cases} \dfrac{dx}{dt} = c(x,y)\cos\alpha \\ \dfrac{dy}{dt} = c(x,y)\sin\alpha \\ \dfrac{d\alpha}{dt} = c_x \sin\alpha - c_y \cos\alpha \end{cases} \tag{9}$$

with the initial conditions $x(0) = X_\mathrm{S}$, $y(0) = Y_\mathrm{S}$, $\alpha(0) = \alpha_\mathrm{S}^{(0)}$, where:

$$\alpha_\mathrm{S}^{(0)} = \arctan\frac{Y_\mathrm{R} - Y_\mathrm{S}}{X_\mathrm{R} - X_\mathrm{S}} \tag{10}$$

is the azimuth of the straight line connecting the source and the receiver. With these initial conditions (starting point and trial propagation direction), the shooting method is used to reach the receiver point R. This is done iteratively adjusting $\alpha_\mathrm{S}^{(0)}$ until the target end point R is reached, within a pre-assigned tolerance. The integration of the system (10) is performed by means of the Runge–Kutta algorithm and the value of

corresponding to the ray that effectively reaches the receiver point is determined. Further details can be found in La Mura et al. (2011).
Once the ray is calculated the travel time τ is computed:

$$\tau = \int_{S}^{R} c^{-1}\left(x, y\right) ds \qquad (11)$$

The attenuation, Γ, along the ray is obtained by adding a fourth equation to the ray-tracing system (10)

$$\frac{d\Gamma}{dt} = C_2\left(x, y\right) c\left(x, y\right) \qquad (12)$$

and integrating numerically the system of 4 ordinary non-linear differential equations by the Runge-Kutta algorithm. In this case, the initial condition for α is fixed as $\alpha\left(0\right) = \alpha_{\mathrm{f}}$.

The geometrical spreading is determined calculating two auxiliary rays computed by the ray-tracing system with the initial conditions for α given by $\alpha_1 = \alpha_{\mathrm{f}} + \Delta\alpha$ and $\alpha_2 = \alpha_{\mathrm{f}} + \Delta\alpha$, respectively, where $\Delta\alpha$ is a conveniently small parameter, which can be defined by trial and error (routine values can vary from 10^{-3} to 10^{-4} . These two rays (Figure 12) are calculated, solving again the ray-tracing system (10) with initial conditions $\alpha\left(0\right) = \alpha_1$ and $\alpha\left(0\right) = \alpha_2$, until they reach the wavefront that hits the receiver. In this way the two points (1 and 2) are determined. The geometrical spreading is then computed as:

$$J = \frac{D}{2\Delta\alpha} \qquad (13)$$

where D is the distance between points 1 and 2.

Figure 12. Schematic representation of the procedure used for the computation of the geometrical spreading (the rays follow piecewise linear paths); violet rays are the two auxiliary rays leaving the epicenter with $\alpha_1 = \alpha_{\mathrm{f}} - \Delta\alpha$ and $\alpha_2 = \alpha_{\mathrm{f}} + \Delta\alpha$, respectively.

The quantities τ, J and Γ are computed for each mode and frequency to be used in the calculation of synthetic seismograms in 3D media.

The spectrum of the wave field represented by a sum of normal modes in a half-space with weak lateral heterogeneity in the WKBJ approximation can be written as (e.g. Levshin et al. (1989)):

$$\mathbf{U}(x,y,z,\omega)=\sum_k \frac{\exp(-i\pi/4)}{\sqrt{8\pi}}\frac{\exp(-i\omega\tau_k-\omega\Gamma)}{\sqrt{J_k\omega}}$$
$$\frac{\mathbf{V}_k(z,\omega)}{\sqrt{u_k I_{0k}}}\bigg|_{\mathrm{R}}\frac{W_k(h,\omega)}{\sqrt{c_k u_k I_{0k}}}\bigg|_{\mathrm{S}} \tag{14}$$

where k is the index identifying the mode, c_k is the phase velocity, u_k the group velocity, J_k the geometrical spreading, τ_k the phase travel time given by

$$\tau_k=\int_{\mathrm{S}}^{\mathrm{R}} c^{-1}(x,y)\,ds\,,$$

I_{0k} is the energy integral, Γ_k the attenuation factor given by

$$\Gamma_k=\int_{\mathrm{S}}^{\mathrm{R}} \eta(x,y)\,ds\,,$$

$\mathbf{V}_k$ is the eigenfunction of the wave (Rayleigh or Love), W_k is the source function depending on the source mechanism and source spectrum, R and S indicate receiver and source sites, respectively, h is the source depth and z is the receiver depth.

4.2.3. Simulations

Following La Mura et al. (2011), we show the simulation of the seismic wavefield propagation, across the Kanto basin in Japan, due to the 1990 Odawara earthquake. A comparison of synthetic seismograms with records at the station Fuchinobe (FCN) is shown together with the synthetic signal computed by Sato et al. (1999) who used a full FD scheme (Figure 13). All the details concerning the computations and the construction of the 3D model are given in La Mura et al. (2011).

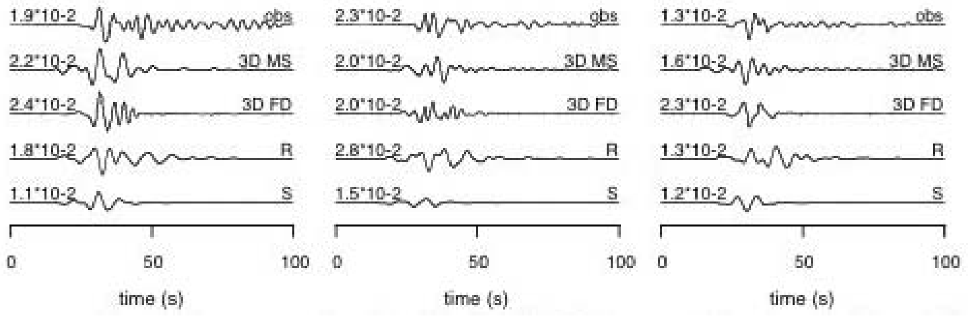


Figure 13. Comparison at station Fuchinobe (FCN) between band-pass filtered (0.1 – 0.3 Hz) displacement record (obs) and analytical synthetics (3D MS), numerical synthetics (3D FD), and 1D synthetics calculated using, along the entire path, the mechanical properties at the receiver (R) and at the source (S). On the left of each trace absolute peak amplitudes are given in centimeters.

A further validation of the 3D MS has been performed by comparing the synthetic seismograms with the records available at three accelerometric stations, in the Romanian territory, triggered by the 30 May 1990 Vrancea intermediate-depth earthquake (see Table 2). The modeled area is shown in Figure 14.

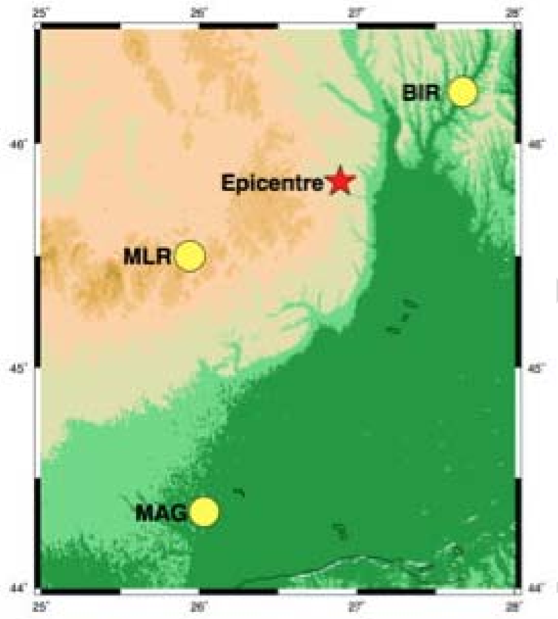


Figure 14. Map showing the epicenter (red star) and the locations of the accelerometric stations (yellow full circles) used in the simulation of Vrancea 1990 main event.

The 3D model has been constructed using the regional polygons, each defining a one-dimensional average layered structure, defined by Radulian et al. (2000). These models have been revised in the depth range from 50 km up to 350 km considering the tomographic results obtained by Raykova and Panza (2006). Acceleration signals have been computed for the scaled point-source (Gusev et al., 2002), whose focal mechanism is given in Table 2:

Quake	**Hypocenter**			**Focal Mechanism Solution**			
M/D/Y	**Lat. (°)**	**Long. (°)**	**Depth (km)**	**Strike (°)**	**Dip (°)**	**Rake (°)**	**Mw**
05/30/1990	45.83	26.89	74	236	63	101	6.9

Table 2. Seismic source parameters used for the 3D simulations (www.globalcmt.org/CMTsearch.html, Ocenscu et al., 1999)

Synthetic signals have been computed at the locations of the three stations shown in Figure 14, Bucharest – Magurele (MAG), Muntele Rosu (MLR), Birlad (BRL) at epicentral distances of 185 km, 82 km and 75 km, respectively. The records have been downloaded from the Internet Site for European Strong Motion Data (Ambraseys at al., 2002). Consistently with the available information (epistemic uncertainty) the cut off frequency for the modeling is 1Hz, and the records have been low-pass filtered with the same cutoff frequency.

In Figure 15 the comparison between the records of the North-South and East-West components of acceleration at the three stations with the corresponding synthetic signals is shown.

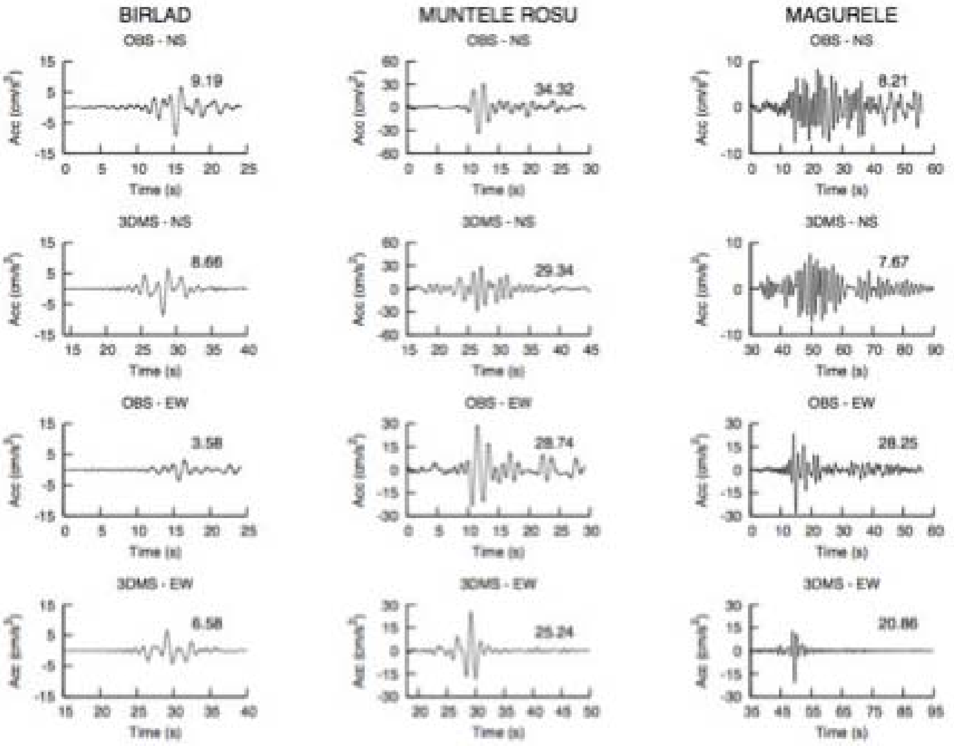


Figure 15. Comparison of North-South (NS) and East-West (EW) acceleration's time histories. The station name is shown on the top of each column; OBS is meant for records and 3D MS is meant for synthetic accelerations. The absolute peak values are given on the right side of each trace. The origin time is not the same for the synthetic and the recorded signals, since the time of the first sample of the records is not known.

It can be seen that the direct modeling, which is a blind prediction of ground motion once source and medium are assumed to be known, reproduces the main features of the records, both in the waveforms and in the peak values and, to some extent, in the effective duration.

For the Vrancea earthquakes a further test has been performed, of very practical engineering use. The derivation of relations between ground motion accelerations and macroseismic intensity has been performed. In Enescu (1997) the analysis of the accelerograms recorded at 38 stations distributed on the Romanian territory led to the following regression relation:

$$Log\left(acc\right) = 0.2714 * I + 0.2085 \qquad V < I < IX\left(MSK\right)$$

a is the recorded PGA at the 38 recording sites and I is the macroseismic intensity, in the MSK scale, at the same sites. By mean of the three-dimensional computation of synthetic seismograms (3D MS) in the scaled point-source approximation (Gusev at al., 2002) with a cut-off frequency of 1 Hz (La Mura et al., 2011), the accelerations at the same sites of the 38 stations used by Enescu (1997) have been computed and the subsequent processing of synthetic PGA gives: with the errors estimation on the values of the constants

$$Log(acc) = 0.27 \pm 0.03 * I + 0.24 \pm 0.20 \qquad V < I < IX(MSK)$$

3D computations have been performed for the in the framework of point source approximation.

As last example we describe the simulation carried out for some accelerometric records of the Bam earthquake of December the 26th, 2003, in Iran. For this simulation, the 3D model has been constructed using Rahimi et al. (2010) and Jeddi and Tatar (2011) structural models.

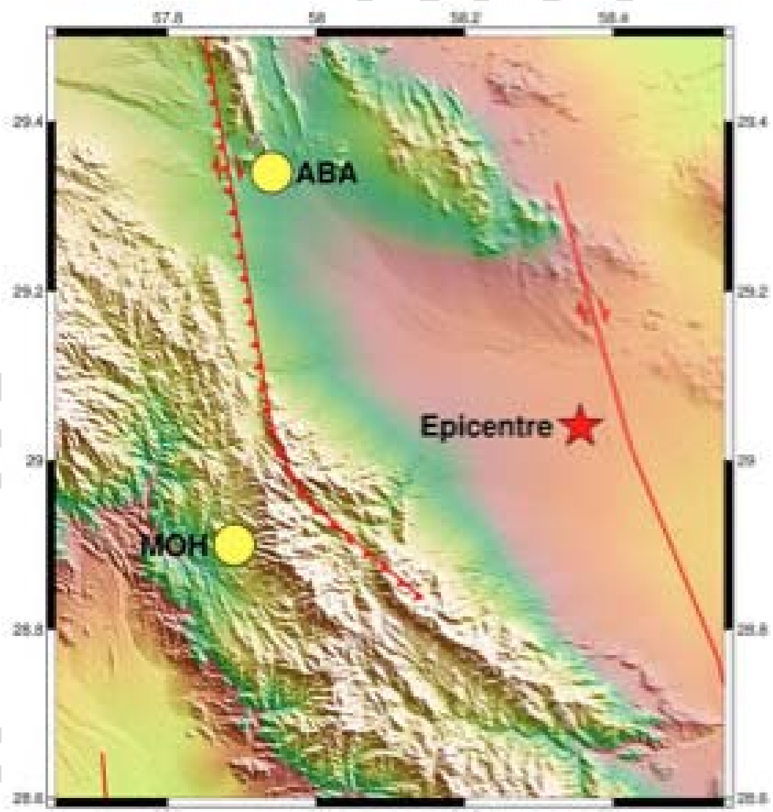


Figure 16. Map showing the epicenter (red star) and the locations of stations (yellow circles) used in the simulation of Bam event.

Acceleration signals have been computed for the scaled point-source, whose parameters are given in Table 3, by 3D MS:

Quake	**Hypocenter**			**Focal Mechanism Solution**			
M/D/Y	**Lat. (°)**	**Long. (°)**	**Depth (km)**	**Strike (°)**	**Dip (°)**	**Rake (°)**	**Mw**
12/26/2003	29.04	58.22	8	354	85	178	6.6

Table 3. Seismic source focal mechanism parameters used for the 3D simulations of Bam earthquake.

The records have been provided by the International Institute of Earthquake Engineering and Seismology (IIEES) in Teheran. For this simulation two cut off frequencies have been chosen: 1Hz and 6Hz, and the records have been low-pass filtered with the same cutoff (La Mura et al., 2011b, Gholami et al., 2012). Synthetic signals have been computed at the locations of the two stations shown in Figure 16, Abaraq (ABA) and Mohamad Abad (MOH) at epicentral distances of 75 km and 82 km, respectively. The records have been provided by the International Institute of Earthquake Engineering and Seismology (IIEES) in Teheran. For this simulation two cut off frequencies have been chosen: 1Hz and 6Hz, and the records have been low-pass filtered with the same cutoff.

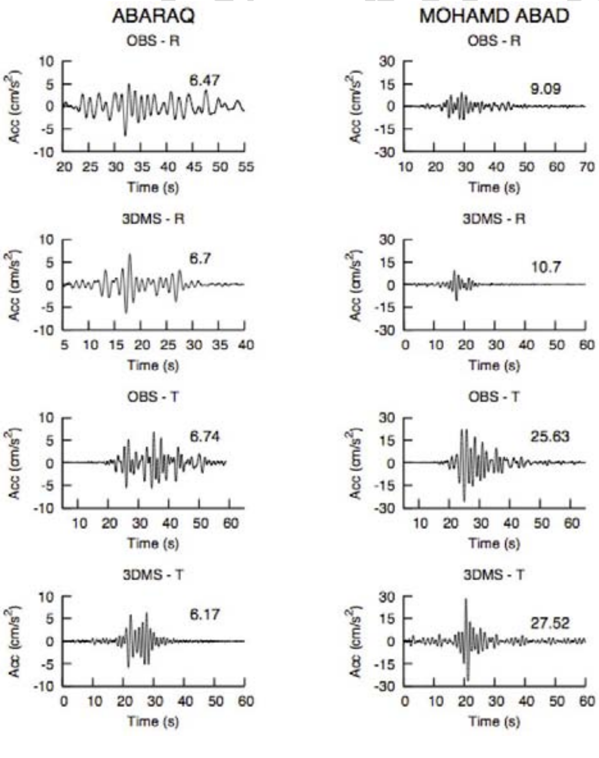


Figure 17. Comparison of Radial (R) and Transversal (T) components of accelerations. The station name is shown on the top of each column; OBS is meant for records and 3D MS is meant for synthetic accelerations. The absolute peak values are given on the right side of each trace. The origin time is not the same for the synthetic and the recorded signals, since the time of the first sample of the records is not known. Cut off frequency 1Hz.

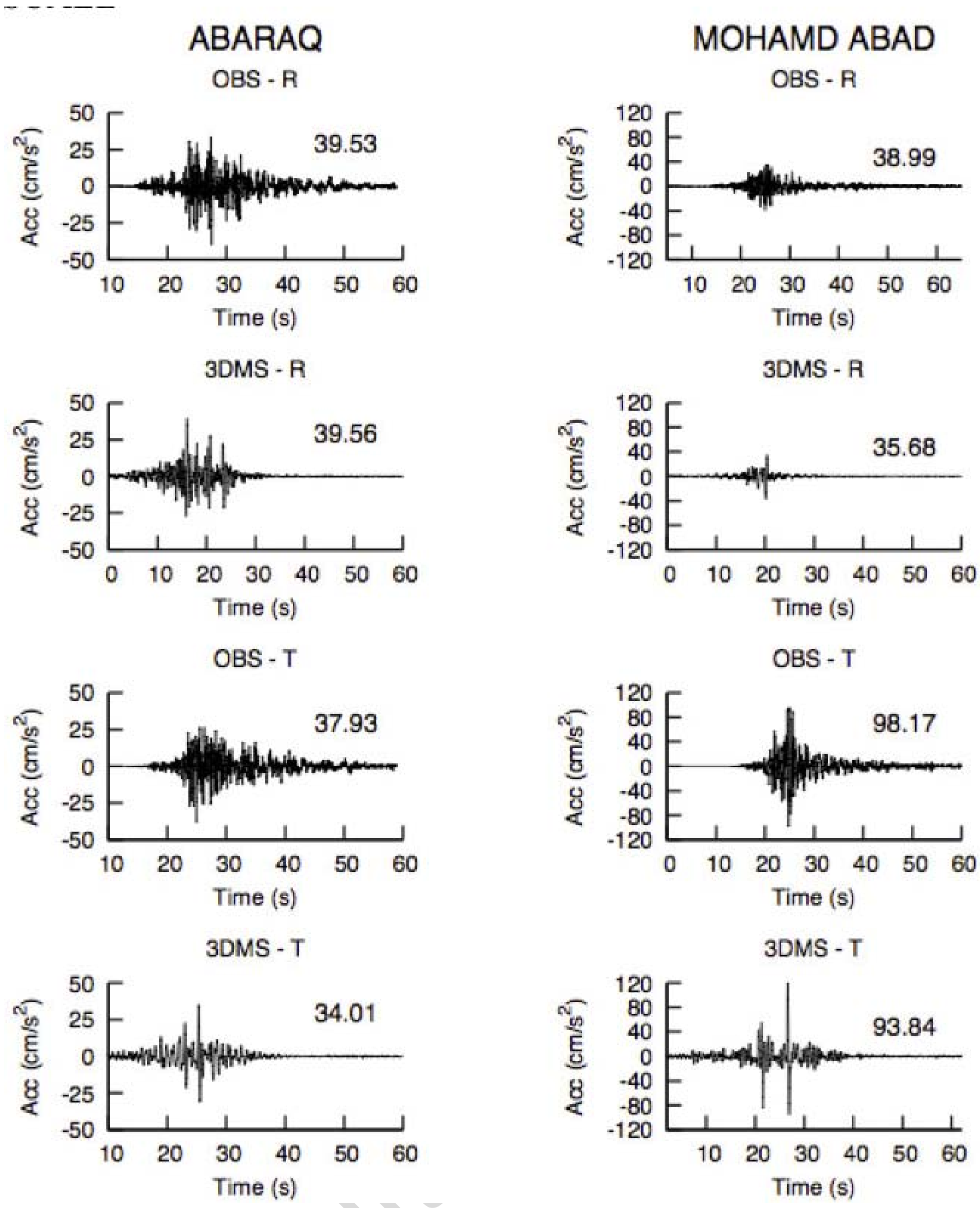


Figure 18. Comparison of Radial (R) and Transversal (T) time histories of accelerations. The station name is shown on the top of each column; OBS is meant for records and 3DMS is meant for synthetic accelerations. The absolute peak values are given on the right side of each trace. The origin time is not the same for the synthetic and the recorded signals, since the time of the first sample of the records is not known. Cut off frequency 6Hz.

As it can be seen comparing the duration and the amplitudes of the signals, there is a good agreement between the records and the synthetic accelerograms. The computations of synthetic accelerations compared with the recoded signals at the stations Abaraq (ABA) and Mohamd Abad (MOH) performed with a cut off frequency of 6Hz are shown in Figure 18.

The agreement is even more satisfactory for practical engineering purposes acceleration response spectra at both stations are compared. The discrepancies at the higher frequencies can be easily explained by some local soil properties not parameterized, due to lack of information (epistemic uncertainty), in the models used for the construction of the 3D model.

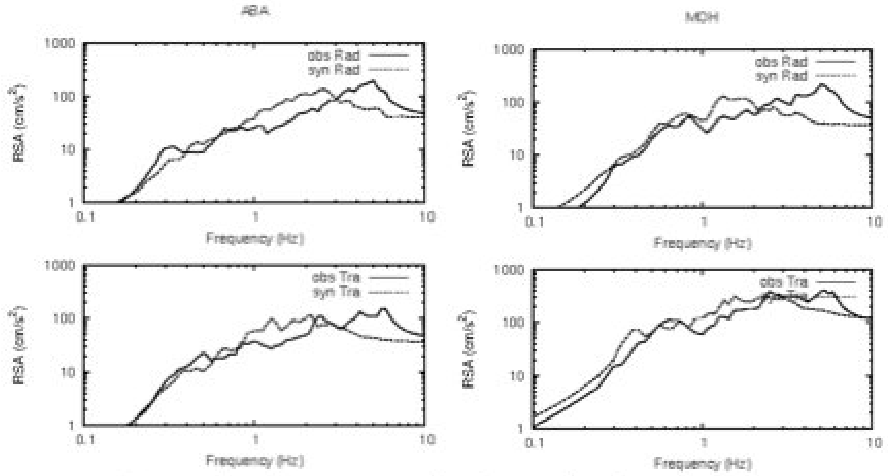


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Figure 19. Comparison between synthetic acceleration response spectra with 5% damping at ABA station (left column) and MOH station (right column) for both radial (top line) and transversal (bottom line) components; cut off frequency 6Hz.

5. Discussion and Conclusions

Lessons learnt from the largest earthquakes, occurred worldwide during the last decade, show that the performances of the standard probabilistic approach to seismic hazard assessment (PSHA) as implemented by GSHAP are very unsatisfactory (e.g. Kossobokov and Nekrasova, 2010). This is due not only to scarcity of data (epistemic uncertainty) but also to the not valid physical model and mathematical formulation employed (Wang, 2011; Paskaleva et al., 2007). Moreover, it is nowadays recognized by the engineering community that peak ground acceleration (PGA) estimates alone are not sufficient for the adequate design, in particular for special buildings and infrastructures, since not only velocities but also displacements may play a critical role and the dynamical analysis of the construction response requires complete time series of ground motion. Therefore the need for an appropriate estimate of the seismic hazard, aimed not only at the seismic classification of the national territory, but also capable of properly accounting for the local amplifications of ground shaking (with respect to bedrock), as well as for the fault properties (e.g. directivity) and the near-fault effects, is a pressing concern for seismic engineers.

On a global scale, the existing practices of widely-advertised (ICEF, 2011) “long-term time-independent earthquake forecasting models” (e.g., GSHAP PGA map) and “routine use of operational earthquake forecasting” (i.e., STEP) in California, when compared against actual seismic activity, are proved to be grossly misleading and unacceptable for responsible seismic risk evaluation and knowledgeable disaster prevention (Kossobokov and Nekrasova, 2010; 2011; Kossobokov, 2005; 2008; 2009), even if it keeps being advocated as promising (e.g. Lee et al., 2011). On the other side, the established routine practice of the intermediate-term middle-range earthquake predictions by M8 and CN algorithms are statistically significant (Healy et al., 1992; Peresan et al., 2011), as confirmed by ICEF Report (2011).

The existing operational practice of definition of time-dependent scenarios for the territory of Italy has been developed and carried on routinely in the framework of the Agreement between Friuli Venezia Giulia Civil Defence and the Abdus Salam International Centre for Theoretical Physics ("Convenzione PCFVG-ICTP: aggiornamento delle previsioni CN ed M8S e scenari di moto del suolo" (DGR 2226 dd. 14.9.2005 and DGR 1459 dd. 24.6.2009; http:// www.regione.fvg.it /asp / delibereinternet /reposit/DGR2226_9_20_05_12_53_12_PM.zip). In particular, every two months since 2005, the intermediate-term middle-range predictions and the related estimates of ground motion from the expected earthquakes are routinely updated, following an integrated neo-deterministic approach (Panza et al., 2001, Peresan et al., 2002; Peresan et al., 2011) and reported to Civil Defence. Algorithm CN failed to predict L'Aquila (M=6.3, 2009) event, since its epicenter has been located about 10 km outside from the alarmed area, nevertheless the ground motion scenarios computed accordingly with the rules of the Agreement PCFVG-ICTP did quite well and predicted the maximum intensities observed in L'Aquila (Panza et al., 2009; Peresan et al., 2011). Moreover, in the framework of the SISMA project (Crippa et al., 2008; Panza et al., 2011) of the Agenzia Spaziale Italiana, an integrated prototype system for real-time joint processing of seismic and geodetic data streams is made available to the Civil Defence of the Friuli Venezia Giulia Region for independent testing. The SISMA prototype is fully formalized and highly automated (including version control for software and products), and provides a reliable tool for the systematic real-time monitoring of deformations and seismicity patterns. The mentioned examples of the existing operational practice in predicting seismic ground shaking are perfectly in line, or even anticipating, the guidelines and recommendations given in the Report of the International Commission on Earthquake Forecasting (ICEF, 2011).

A reliable characterization of the seismic input for the design of seismically isolated structures requires to accurately define the maximum displacement at the periods relevant to the isolated structure and the energy content at the low frequencies, which should be expected at the specific site (Martelli, 2010; Martelli and Forni 2010, 2011).

Since the safety of the isolated structures fully relies on the deformation capability of the isolators to withstand the earthquake and, in several countries, the design forces acting on the superstructure and foundations are somewhat lowered to account for the isolators effects, the design displacement must not be underestimated. At the same time the overestimation of the expected displacement must be avoided. In fact, it may lead to design an isolated structure with an overly rigid behavior at low excitations. Such a design is inadequate in case of relatively smaller and more frequent earthquakes, which are likely to affect the structure during its lifetime. In addition, since seismic isolation requires the design of a structural gap compatible with the design displacement, an overestimation of the expected displacement might lead to the unjustified rejection of this technique, especially when dealing with the retrofit of existing buildings, where usually there are strict space constraints.

Last but not least, PSHA is totally unsafe for structures of considerable linear dimensions (e.g. bridges and also some buildings), where it is necessary to account for the possible asynchronous ground motion along the base of structure, independently on whether the structure is seismically isolated or conventionally designed (Romanelli et al., 2004).

A viable alternative capable of minimizing the drawbacks of traditional PSHA is represented by the use of scenario earthquakes (NDSHA) characterized at least in terms of magnitude, distance, faulting style and complexity of the source processes. The relevance of the realistic modeling, which permits the generalization of empirical observations by means of mathematically and physically sound theoretical considerations, is evident, as it allows for the optimization of the structural design with respect to the site of interest.

NDSHA naturally supplies realistic time series of ground motion, which represent reliable estimates of ground displacement readily applicable to seismic isolation techniques, useful to preserve historical heritage and relevant man made structures. It is evident, in fact, that deriving displacements by double integration of the estimated accelerations by simply dividing PGA by ω^2 (as it is often if not routinely done in PSHA) may introduce serious thus not acceptable errors (e.g. the period at which PGA is attained is, as a rule, quite different - usually larger - than that of peak displacement).

Current computational resources and recent advances in seismic hazard assessment, along with the acquired knowledge on the response of different structural typologies (including seismic isolators and dissipation systems) supply effective tools for seismic risk mitigation. The proposed time-dependent approach complements the traditional approach to seismic hazard estimates, since it supplies routinely updated information about the expected seismic input. The time information associated to the scenarios of ground motion, given by the intermediate-term middle-range earthquake predictions, can be useful to public authorities in assigning priorities for timely mitigation actions, such as the seismic safety appraisal of strategic buildings and structures.

Urban planners and Civil Defense may also highly benefit from the proposed advanced method for seismic hazard assessment, in order to properly evaluate the vulnerability of urban settlements and to develop prevention plans, paying special attention to the structures that must be efficiently operating after the earthquake (i.e. hospitals, fire stations, pipelines and other distribution networks, etc.).

The aforesaid remarks and proposals are part of two resolutions concerning recommended modifications of the Italian and European design rules for the isolated structures that have been approved in February 2011 by the Commission for the Environment, Territory and Public Works of the Italian Chamber of Deputies (Benamati et al., 2011). Seismic isolation is very likely one of the most promising preventive ways to protect humanity from seismic hazard in that it can be successfully applied (Panza et al., 2011; Indirli et al., 2010; Romanelli et al., 2010; Vaccari et al., 2009) to new manufacts and to the effective antiseismic retrofit of existing ones, including cultural heritage, with very limited marginal additional costs.

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Glossary

DGA	: Design Ground Acceleration
EPA	: Effective Peak Acceleration
FEM	: Finite Element Method
FD	: Finite Difference
GEM	: Global Earthquake Model
GMPE	: Ground motion prediction equations
GSHAP	: Global Seismic Hazard Assessment Program
ICTP	: International Centre for Theoretical Physics
M	: Moment Magnitude, it is indicated by M_w, also
MCS	: Mercalli-Cancani-Sieberg
MS	: Modal Summation
MSK	: Medveded - Sponheuer - Karnik
NDSHA	: Neo-deterministic Seismic Hazard Analysis
PCFVG	: Protezione Civile Friuli Venezia Giulia
PGA	: Peak Ground Acceleration
PGD	: Peak Ground Displacement
PGV	: Peak Ground Velocity
PSHA	: Probabilistic Seismic Hazard Analysis
SEM	: Spectral Element Method
SISMA	: Seismic Information System for Monitoring and Alert

WKBJ : G. Wentzel, H. Kramers, L. Brillouin, and H. Jeffreys

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Gorshkov A.I., Panza G.F., Soloviev A.A., Aoudia A. (2004). Identification of seismogenic nodes in the Alps and Dinarides, *Bollettino Della Società Geologica Italiana* 123, 3-18. [In this paper seismogenic nodes - specific structures formed at the intersections of fault zones - have been identified in the Alps and Dinarides. The nodes have been delineated by the morphostructural zoning (MZ) method and their seismic potential has been evaluated by the pattern-recognition method.]

Gorshkov A.I., Panza G.F., Soloviev A.A., Aoudia A., Peresan A., (2009). Delineation of the geometry of nodes in the Alps-Dinarides hinge zone and recognition of seismogenic nodes ($M \geq 6$), *Terra Nova* 21 (4), 257-264. [A procedure, based on the morphostructural lineaments, is applied to allow for a detailed definition of the geometry of seismogenic nodes. The study permitted to better constrain the areas prone to large events at the Alps-Dinarides junction zone].

Gusev A.A. (1983). Descriptive statistical model of earthquake source radiation and its application to an estimation of short period strong motion, *Geophysical Journal of the Royal Astronomical Society* 74, 787-800. [A wide-band spectrum scaling law is derived from various data sources; the spectrum scaling law is used to determine near-field accelerations and applied to calculate the average relation between maximum acceleration and intensity, and distance and magnitude.]

Gusev A.A., Radulian M., Rizescu M., Panza G.F. (2002). Source scaling of intermediate-depth Vrancea eartquakes, *Geophysical Journal International* 151, 879-889. [In this paper source scaling properties are studied for the intermediate-depth seismic nest in the Vrancea region, Romania.]

Gusev A.A., Pavlov V. (2006). Wideband simulation of earthquake ground motion by a spectrum-matching, multiple-pulse technique. First European Conference on Earthquake Engineering and Seismology, Geneva, Switzerland, 3-8 September 2006. Abstract Book, 408. 2006. [In this paper to simulate earthquake ground motion, a multiple-point stochastic earthquake fault model and a suite of Green functions computed with discrete wavenumber method are combined. The simulation package can generate example motions, as a test, realistic analogues of recorded motions in the epicentral zone of the 1994 Northridge, California earthquake were synthesized, and related uncertainties were estimated.]

Gusev A.A. (2011). Broadband Kinematic Stochastic Simulation of an Earthquake Source: a Refined Procedure for Application in Seismic Hazard Studies, Pure and Applied Geophysics 168 (1), 155-200. [The approach in this paper to model to specify earthquake source is well adapted to the study of deterministic seismic hazard: it may be used for simulation of individual scenario events, or suites of such events, as well as for analysis of uncertainty for expected ground motion parameters from a particular class of events.]

Healy J. H., Kossobokov V.G., Dewey J.W. (1992). A test to evaluate the earthquake prediction algorithm, M8, *U.S. Geol. Surv. Open-File Report* 92-401, 23 p. with 6 Appendices. [The document provides essential information and reference about the real-time testing procedure of the intermediate-term middle-age earthquake prediction algorithm M8. This prediction experiment, ongoing since more than twenty years now, already permitted to assess the significance of the issued predictions.]

Indirli M., Nunziata C., Romanelli F., Vaccari F., Panza, G.F. (2009). Design and placing of an innovative 3D-Isolation system under the Herculaneum Roman ship. In: Protection of Historical Buildings PROHITECH, vol. 1, Ed: F.M. Mazzolani, CRC Press, Taylor and Francis Group, London, 681-687. [An innovative 3D-Isolation system has been designed and installed to protect the Herculaneum Roman ship. In the design process, the expected ground motion has been estimated also taking into account the Design Ground Acceleration obtained with the neo-deterministic approach, based on the computation of synthetic seismograms.]

Indirli M., Puglisi C., Screpanti A., Romanelli F. (2010). Multi-hazard maps for the Valparaiso area (Chile). CRC Press, Taylor and Francis Group, London: pp.999-1004, 9780415606851 : In: Proceedings of the final COST Action C26 Conference. [In the framework of the MAR VASTO Project the impact of main hazards have been evaluated in the Valparaìso urban area.]

Indirli M., Razafindrakoto H., Romanelli F., Puglisi C., Lanzoni L., Milani E., Munari M. and S. Apablaza S. (2010). Hazard Evaluation in Valparaíso: the MAR VASTO Project, *Pure and Applied Geophysics*, DOI: 10.1007/s00024-010-0164-3. [In this paper realistic modeling of ground motion in the Valparaìso urban area is carried out and a successful comparison with records did permit the generation of ground-shaking maps for the area.]

Kantorovich L.V., Keilis-Borok V.I. (1991). “Earthquake prediction and decision-making: social, economic and civil protection aspects” (Proc. International Conference on Earthquake Prediction: State-of-the-Art, pp. 586-593, Scientific-Technical Contributions, CSEM-EMSC, Strasbourg, France, 1991). Based on "Economics of earthquake prediction" (Proc. UNESCO Conference on Seismic Risk, Paris, 1977). [The paper discusses the possible use of formally defined earthquake predictions in decision making processes. It provides a hierarchical list of mitigation actions that, having different costs, can be reasonably implemented over different space-time scales and can be increased or decreased depending on the specific state of alert].

Keilis-Borok V.I., Rotwain I.M. (1990). Diagnosis of time of increased probability of strong earthquakes in different regions of the world: algorithm CN, *Physics of Earth Planet Interior* 61, 57-72. [The paper provides a definition of the algorithm CN, where pattern recognition procedures for infrequent events are used to identify patterns of clustering of small- and intermediate-scale seismicity before large earthquakes. Identification procedures derived from analysis of large California and Nevada earthquakes are successfully tested in several regions of the world].

Keilis-BorokV.I., Primakov I. (1997). "Earthquake Prediction and Earthquake Preparedness: The Possibilities to Reduce the Damage from Earthquakes". Fourth Workshop on Non-Linear Dynamics and Earthquake Prediction, 6 - 24 October 1997, Trieste: ICTP, H4.SMR/1011-11, 30 pp. [The document provides a hierarchical list of the wide set of possible mitigation actions that can be taken in response to an earthquake prediction].

Kossobokov V.G., Romashkova L.L., Panza G.F., Peresan A. (2002). Stabilizing intermediate-term medium-range earthquake predictions, *Journal of Seismology and Earthquake Engeneering* 8, 11-19. [A new stabilized scheme for M8 algorithm application is proposed, where the precursory seismicity patterns are analyzed within a dense set of circles covering the study area].

Kossobokov V. (2005). Regional Earthquake Likelihood Models: A realm on shaky grounds? Eos Trans. AGU, 86(52), Fall Meet. Suppl., Abstract S41D-08. [The abstract provides a brief critical re-appraisal of Regional Earthquake Likelihood Models, RELM, pointing to the low significance of their results.]

Kossobokov V. (2008). "Testing earthquake forecast/prediction methods: "Real-time forecasts of tomorrow's earthquakes in California". Geophysical Research Abstracts, Volume 10, Abstracts of the Contributions of the EGU General Assembly 2008, Vienna, Austria, 13-18 April 2008 (CD-ROM), EGU2008-A-07826. [The abstract briefly discusses the results from real-time forecasting of California earthquakes, coming to the conclusion of low significance of the obtained results.]

Kossobokov V. (2009). Testing earthquake forecast/prediction methods: "Real-time forecasts of tomorrow's earthquakes in California". In *Some Problems of Geodynamics*, Moscow, KRASAND, p. 321-337 (*Comput. Seismol*., 39). (in Russian) [The paper discusses in some detail the results from real-time forecasting of California earthquakes, providing a critical re-appraisal of the obtained results and evidencing the low significance of the issued forecasts.]

Kossobokov V. G., Nekrasova A.K. (2010). Global Seismic Hazard Assessment Program Maps Are Misleading. Eos Trans. AGU, 91(52), Fall Meet. Suppl., Abstract U13A-0020. [The abstract summarizes the results from a systematic analysis, comparing intensities from recent M>6 earthquakes with those predicted according to GSHAP global map. It concludes that the global hazard map underestimated actual ground shaking, particularly for the larges earthquakes]

Kossobokov V.G., Nekrasova A. K. (2011). Global seismic hazard assessment program (GSHAP) maps are misleading*, Problems of Engineering Seismology* 38 (1), 65-76 (in Russian). [The capability of Global Seismic Hazard Assessment Program in anticipating ground shaking from future earthquakes has been evaluated against the earthquakes which occurred since the publication of its results. This systematic analysis shows that the results of GSHAP maps, published in 1999, are in poor agreement the actual occurrence of recent strong earthquakes. Specifically, all of the sixty earthquakes with magnitude larger than 7.5 occurred since 2000, exceeded the ground shaking values predicted by the GSHAP maps.]

La Mura C., Yanovskaya T.B., Romanelli F., Panza G.F. (2011). Three-Dimensional Seismic Wave Propagation by Modal Summation: Method and Validation, *Pure and Applied Geophysics*, 168, 201-216. [This paper contains the development and the validation of a new analytic methodology for computing synthetic seismograms in 3D inelastic media.]

La Mura C., Gholami V., Panza G.F. (2011). Three-dimensional synthetic seismograms computation by Modal Summation: method and applications, 30 GNGTS, 14-17 November, 2011. Trieste, Italy. [This abstract contains the computation of synthetic seismograms in 3D inelastic media with the new analytic methodology and their comparison with available records both at low and high frequencies.]

Lee Y., Turcotte D.L., Holliday J.R., Sachs M.K., Rundle J.B., Chen C., Tiampo K.F. (2011). Results of the Regional Earthquake Likelihood Models (RELM) test of earthquake forecasts in California. PNAS, 108 (40): 16533-16538. doi: 10.1073/pnas.1113481108. [The paper presents results from The Regional Earthquake Likelihood Models (RELM) test of earthquake forecasts in California, a competitive evaluation of forecasts of future earthquake occurrence. In this paper, the authors compare the forecasts to evaluate which forecast is the most "successful" in terms of the locations of future earthquakes].

Levshin A. L. (1985). Effects of lateral inhomogeneities on surface waves amplitudes measurements, Annals of Geophysics 3, 511-518. [This paper is the main reference in the study of the influence of lateral inhomogeneities on surface wave amplitude spectra]

Martelli A. (2010). On the need for a reliable seismic input assessment for optimized design and retrofit of seismically isolated civil and industrial structures, equipment and cultural heritage, *Pure and Applied Geophysics*, DOI 10.1007/s00024 -010-0120-2. [The paper discusses the limit of traditional approaches to seismic hazard assessment from the point of view of engineering design. The paper pays special attention to the design of seismically isolated structures, which requires an accurate definition of the maximum value of displacement and a reliable evaluation of the earthquake energy content at low frequencies, for the site and ground of interest. It is concluded that to overcome the limits of PSHA, this method shall be complemented by the development and application of deterministic approaches].

Martelli A., Forni M. (2010). Seismic isolation and other anti-seismic systems: recent applications in Italy and worldwide, Seismic Isolation And Protection Systems (SIAPS), DOI 10.2140/siaps.2010.1.75, Mathematical Sciences Publishers (MSP), Berkeley, Vol. 1, N. 1, pp. 75-123. [A number of applications of seismic isolation systems are illustrated, pointing to the need for an appropriate definition of the seismic input to be used for seismic design].

Martelli A., Panza G.F. (2010). Note sull'International Advance Conference on Seismic Risk Mitigation and Sustainable Development svoltasi a Miramare (TS) dal 10 al 14 maggio 2010 – Valutazione della pericolosità sismica – È importante affiancare l'utilizzo dell'approccio deterministico a quello del consueto approccio probabilistico e non ignorare le previsioni a medio termine, *Rivista degli Ingegneri del Veneto*, FOIV 29, 35-39. [The paper evidences the need and practical relevance of integrating the traditional approaches for seismic hazard assessment with the newly available information provided by ground motion modeling and validated earthquake predictions.]

Martelli A., Forni M. (2011). Recent worldwide application of seismic isolation and Energy dissipation and conditions for their correct use, SEWC, Cernobbio (Como), April 2011. [The paper mentions the increasing number of structures that have been protected by anti-seismic systems, including bridges and viaducts, civil and industrial buildings, cultural heritage. It provides a short overview on the dissemination of such applications worldwide, paying particular attention to applications in Italy. Some important conditions for the correct use of the antiseismic systems and devices are mentioned in the conclusions].

Meletti C., Valensise G. (2004). Zonazione sismogenetica ZS9 – App.2 al Rapporto Conclusivo. In: Gruppo di Lavoro MPS, 2004. Redazione della mappa di pericolosità sismica prevista dall'Ordinanza PCM 3274 del 20 marzo 2003, Rapporto Conclusivo per il Dipartimento della Protezione Civile. In Italian. [The report provides the basic reference for the seismogenic zonation ZS9, which is used to define the probabilistic seismic hazard map of the Italian territory, including an overview of the considered input data].

Panza G.F., Vaccari F., Costa G., Suhadolc P., Fah D. (1996). Seismic input modeling for zoning and microzoning, *Earthquake Spectra* 12 (3), 529-566. [Ground shaking scenarios have been computed both at the regional (Italy, Ethiopia, Bulgaria) and at the local scale (Mexico City, Rome, Naples, Benevento), based on the computation of synthetic seismograms.]

Panza G.F., Cazzaro R., Vaccari F. (1997). Correlation between macroseismic intensities and seismic ground motion parameters, *Annali di Geofisica* 40, 1371-1382. [The authors propose correlation relations between the macroseismic intensity felt in Italy and displacement, velocity, acceleration, design ground acceleration obtained from synthetic seismograms modeling the ground motion generated by past seismicity.]

Panza, G. F., Radulian, M. e Trifu, C. (2000) - Editors "Seismic Hazard in the Circum Pannonian Region", PAGEOPH Topical Volume, Birkhauser Verlag, 280. [The special volume collects several contribution concerning the topics related to the seismic hazard assessment with special attention to the region affected by the intermediate depth Vrancea earthquakes.]

Panza G.F., Romanelli F., Vaccari F. (2001). Seismic wave propagation in laterally heterogeneous inelastic media: theory and applications to the seismic zonation, *Advances in Geophysics 43*, 1-95. [This paper contains a detailed presentation of the Modal Summation method and its application for the modeling of seismic wave propagation in laterally heterogeneous structures in connection with the seismic hazard assessment.]

Panza G.F., Romanelli F., Vaccari F. (2001). Realistic modeling of seismic input in urban areas: a UNESCO-IUGS-IGCP project, *Pure and Applied Geophysics* 158(12), 2389-2406. [This paper represents a contribution to seismic disasters preparedness that requires producing results using the knowledge available now, improving scenarios as new data become available. Ongoing activities, at the times the paper was published, within the UNESCO-IUGS-IGCP project 414 are described.]

Panza G. F., Alvarez L., Aoudia A., Ayadi A., Benhallou H., Benouar D., Chen Yun-Tai, Cioflan C., Ding Zhifeng, El-Sayed A., Garcia J., Garofalo B., Gorshkov A., Gribovszki K., Harbi A., Hatzidimitriou P., Herak M., Kouteva, M., Kuznetzov I., Lokmer I., Maouche S., Marmureanu G., Matova M., Natale M., Nunziata C., Parvez I., Paskaleva I., Pico R., Radulian M., Romanelli, F., Soloviev A., Suhadolc P., Triantafyllidis P., Vaccari F. (2002). Realistic modeling of seismic input for megacities and large urban areas (the UNESCO/IUGS/IGCP project 414), *Episodes* 25 (3),160-184. [Considerations are made on pre-disaster activities (hazard prediction, risk assessment, and hazard mapping) in connection with seismic activity and man-induced vibrations. The definition of realistic seismic input has been obtained from the computation of a wide set of time histories and spectral information, corresponding to possible seismotectonic scenarios for different source and structural models. In the framework of the UNESCO/IUGS/IGCP project 414, ground shaking scenarios have been computed for the following cities: Algiers, Beijing, Bucharest, Cairo, Debrecen, Delhi, Naples, Rome, Russe, Santiago de Cuba, Sofia, Thessaloniki, Zagreb.]

Panza G.F., Romanelli F., Vaccari F., Decanini L., Mollaioli F. (2003). Seismic ground motion modeling and damage earthquake scenarios, a bridge between seismologists and seismic engineers. OECD Workshop on the Relations between Seismological DATA and Seismic Engineering, Istanbul, 16-18 October 2002, NEA/CSNI/R (2003) 18, 241-266. [Advanced seismic hazard indicators, like the earthquake damaging potential, are considered in order to better describe the outcome of simulated ground shaking scenarios, with an approach that can better suit the needs of the seismic engineers in the design of seismo-resistant structures]

Panza G.F., Kouteva, M., (2003). Earth Sciences Contribution to the Sustainable Development of Ground Transportation Systems: Relevant Case Studies in Central Europe. Geodynamics of Central Europe and Transportation. Ed: T. Beer and A. Ismail-Zadeh, Risk Science and Sustainability, pp. 127-148. [The article deals with the general problem of seismic safety of lifelines and transportation systems, paying attention to safety during road design, construction and maintenance and urban safety management schemes.]

Panza G.F., Irikura K., Kouteva M., Peresan A., Wang Z., Saragoni R. (2011). Introduction to the Special Issue on Advanced seismic hazard assessments, *Pure and Applied Geophysics*, 168 (1-2). [Introduction to the special issue on advanced seismic hazard assessment.]

Panza, G.F., Irikura I., Kouteva M., Peresan A., Wang Z., Saragoni R. Eds., (2011) - Topical Volume on “Advanced seismic hazard assessments”. Pure and App. Geophys., Vol. 168. ISBN 978-3- 0348-0039-6 & ISBN: 978-3-0348-0091-4., 752 pp. [The aim of this special issue is to supply multifaceted information on the modern tools for seismic hazard assessment.]

Panza G.F., A. Peresan, A. Magrin, F. Vaccari, R. Sabadini, B. Crippa, A.M. Marotta, R. Splendore, R Barzaghi, A. Borghi, L. Cannizzaro, A. Amodio, S. Zoffoli (2011). "The SISMA prototype system: integrating Geophysical Modeling and Earth Observation for time-dependent seismic hazard assessment". *Natural Hazards*. DOI 10.1007/s11069-011-9981-7. [The paper illustrates an innovative approach to seismic hazard assessment that, based on Earth observation data and geophysical forward modeling, allows for a time-dependent definition of the seismic input. In the proposed system the modeled deformation maps at the national scale complements the space- and time-dependent information provided by real-time monitoring of seismic flow and permits the identification and routine updating of alerted areas. At the local scale, EO data and geophysical modeling permit to indicate whether a specific fault is in a critical state. In this way, a set of neo-deterministic scenarios of ground motion, which refer to the time interval when a strong event is likely to occur within the alerted area, is defined both at national and at local scale.]

Panza G.F., Peresan A., Vaccari F., Romanelli F. e Martelli A. (2011). “Scenario-based time-dependent definition of seismic input: an effective tool for engineering analysis and seismic isolation design” Proceedings del congresso “SEWC2011 - Structural Engineers World Congress (Como, 4-6 April 2011). [The paper discusses the method and advantages of the time-dependent neo-deterministic approach to seismic hazard assessment, where the seismic input is defined by realistic modeling of seismic wave propagation. It presents examples of regional scale scenarios of ground motion at bedrock, including the analysis of source directivity effects. The local scale scenarios, accounting for site effects, are also introduced, considering a selected site in the city of Trieste (North-Eastern Italy)].

Panza, G.F., La Mura, C., Peresan, A., Romanelli, F., & Vaccari, F. (2012). Seismic Hazard Scenarios as Preventive Tools for a Disaster Resilient Society. In R. Dmowska (Ed.), Advances in Geophysics. Elsevier, London, 93–165. [This paper contains the recent advances in seismic wave modeling by mean of the Modal Summation method and presents the use of a scenario-based approach, that permits to integrate the available information provided by the most updated seismological, geological, geophysical, and geotechnical databases for the site of interest to provide reliable and robust background for the development of a deterministic design basis for cultural heritage and civil infrastructures in general. This paper is the newest milestone in Neo-Deterministic Seismic Hazard assessment.]

Parvez I.A., Vaccari F. and Panza G. F. (2003). A deterministic seismic hazard map of India and adjacent areas, *Geophysical Journal International* 155(2), 489-508. [A seismic hazard map of the territory of India and adjacent areas has been prepared using a deterministic approach based on the computation of synthetic seismograms complete with all main phases.]

Parvez I.A., Romanelli F., Panza G. F. (2010) Long period ground motion at bedrock level in Delhi city from Himalayan earthquake scenarios, *Pure and Applied Geophysics* doi: 10.1007/s00024-010-0162-5 [In this paper a sound description of the seismic ground motion due to an earthquake in the range of distances of 250–300 km, is given simulating the ground motion, at bedrock level, in Delhi city, for an earthquake scenario corresponding to a source of Mw = 8.0 located in the central seismic gap of Himalayas, using modeling techniques developed from physics of the seismic source generation and propagation processes].

Paskaleva I., Dimova S., Panza G. F., Vaccari F. (2007). An Earthquake scenario for the microzonation of Sofia and the vulnerability of structures designed by use of the Eurocodes, *Soil Dynamics and Earthquake Engineering*, 27, 1028-1041. [The study of the site effects and the microzonation of a part of the metropolitan Sofia, based on the modeling of seismic ground motion along three cross-sections are performed, for M=7 scenario earthquakes.]

Paskaleva I., Kouteva M., Vaccari F., Panza G.F. (2010). Some Contributions of the Neo-Deterministic Seismic Hazard Assessment Aproach to the Earthquake Risk Assessment for the City of Sofia, *Pure and Applied Geophysics* doi: 10.1007/s00024-010-0127-8. [This paper describes the outcome of seismic hazard and seismic risk estimates performed for the city of Sofia, Romania]

Peresan A., Kossobokov V.I., Romashkova L.L., Panza G.F. (2005). Intermediate-term middle-range earthquake predictions in Italy: a review, *Earth Science Reviews* 69 (1-2), 97-132. [The paper includes a comprehensive overview of formally defined methods for intermediate-term middle-range earthquake predictions for the Italian territory. Specifically, it provides detailed information about CN and M8 algorithms, ranging from their theoretical basis to the considered input data. The paper provides the basis for the real-time earthquake prediction experiment ongoing for the Italian territory since July 2003.]

Peresan A., Zuccolo E., Vaccari F. and Panza G.F. (2009). Neo-Deterministic Seismic Hazard Scenarios For North-Eastern Italy, *Bollettino Della Società Geologica Italiana* 128 (1), 229-238. [This paper describes the neo-deterministic scenarios of ground motion defined for North-Eastern Italy, based on the information provided by CN and M8S algorithms, as well as by the pattern recognition of earthquake prone areas. An example of local scale scenario, including site effects, is provided for the city of Trieste.]

Peresan A., Zuccolo E., Vaccari F., Gorshkov A., Panza G.F. (2010). Neo-deterministic seismic hazard and pattern recognition techniques: time dependent scenarios for North-Eastern Italy, *Pure and Applied Geophysics*, 168 (3-4). DOI 10.1007/s00024-010-0166-1. [The paper illustrates how different pattern recognition techniques can contribute reducing the space and time uncertainty of impending strong earthquakes. These techniques allow for a formalized, systematic and testable analysis of seismicity changes and of morphostructural features. The paper describes the procedure which allows us to compute the time-dependent ground shaking scenarios at regional and local scale, accounting for the information provided by pattern-recognition].

Peresan A., Kouteva M., Dmowska R., Roubhan B. (2010). Towards validation of SHA: lessons learnt from recent earthquakes. Panel Discussion. Panelists: A. Lerner-Lam, V. Kossobokov, Z. Wang, Z. Wu. In: Advanced Conference on "Seismic risk mitigation and sustainable development", ICTP. Trieste, Italy. http://cdsagenda5.ictp.trieste.it/askArchive.php?base=agenda&categ=a09145&id=a09145s3t12/Panel_dis

cussion. [Summary report of the Panel Discussion, evidencing the need for formal testing and validation of seismic hazard estimates].

Romanelli F., Panza G.F., Vaccari F. (2004). Realistic Modeling of the Effects of Asynchronous motion at the Base of Bridge Piers, *Journal of Seismology and Earthquake Engineering* 6(2), 19-28. [In this paper a complete synthetic accelerogram dataset is computed by using as input a set of parameters that describes the geological structure and seismotectonic setting of the area near Vienna (Austria) where the Warth bridge is placed. The results show that lateral heterogeneities can produce strong spatial variations in the ground motion even at small incremental distances. In absolute terms, the differential motion amplitude is comparable with the input motion amplitude when displacement, velocity and acceleration domains are considered.]

Romanelli F., Peresan A., Vaccari F., Panza G.F., (2010). Scenario based earthquake hazard assessment. Proceedings: Urban Habitat Constructions under Catastrophic Events. Mazzolani (Ed). © 2010 Taylor & Francis Group, London, p.p. 105-110. [The paper discusses the advantages of the neo-deterministic, NDSHA, approach to seismic hazard assessment, which is based on the possibility to compute synthetic seismograms by the modal summation technique, particularly when dealing with historical and strategic buildings, when it is necessary to consider very long return period. The realistic modeling of the seismic input, taking in account the source and site effects, combined with the evaluation of the seismic response of buildings provides an effective approach to the assessment of seismic risk].

Stein S. (2010) Disaster Deferred: How New Science Is Changing our View of Earthquake Hazards in the Midwest. Columbia University Press. The book revisits the 1811-12 series of large earthquakes in the New Madrid seismic zone. The author clearly explains the techniques seismologists use to study Midwestern quakes and shows how limited scientific knowledge has exaggerated these hazards. Stein shows how new geological ideas and data, including those from the Global Positioning System, provide a much less frightening hazard estimate].

Stein S., Geller R., Liu M. (2011). Bad assumptions or bad luck: why earthquake hazard maps need objective testing, Seismological Research Letters 82, 5. [This opinion paper evidences the need for a systematic and objective validation of developed hazard maps. The motivation for a formal testing of existing seismic hazard maps is provided by the several fatal failures of PSHA maps, particularly in occasion of the Tohoku 2011 and Haiti 2010 earthquakes. Only by understanding whether such failures are due methodological limits it is possible to improve the future hazard assessments.]

Stirling M., Petersen M. (2006). Comparison of the historical record of earthquake hazard with seismic-hazard models for New Zealand and the continental United States, *Bulletin of the Seimological Society of America* 96, 1978–1994. [The paper includes examples evidencing inconsistencies between historical records of seismic hazards and PSHA estimates].

Vaccari F., Romanelli F., Panza, G.F. (2005). Detailed modeling of strong ground motion in Trieste, *Geologia Tecnica and Ambientale* 2, 7–40. [Using the specific knowledge about geology and geotechnical properties described in the cartographic material available for the Trieste area, ground motion scenarios have been computed along three profiles in the city, varying the source position and magnitude. The three-component synthetic seismograms, computed, with a broad band content and in laterally inelastic models in the domains of displacement, velocity and accelerations, have been processed to estimate the site effects and to extract some parameters significant from the engineering point of view.]

Vaccari F., Peresan A., Zuccolo E., Romanelli F., Panza G.F., Marson C., Fiorotto V. (2009). Neo-deterministic seismic hazard scenarios: Application to the engineering analysis of historical buildings. In: Protection of Historical Buildings PROHITECH, vol 2, Ed: F.M. Mazzolani, CRC Press, Taylor and Francis Group, London, 1559-1564. [The paper illustrates the integrated neo-deterministic approach to seismic hazard assessment and its application to the engineering analysis of an historical building located in the city of Trieste (Italy).]

Wang, Z. (2011). Seismic Hazard Assessment: Issues and Alternatives. *Pure and Applied* Geophysics 168, 11-25. [The article analyzes the main shortcomings of traditional PSHA and DSHA approaches to seismic hazard assessment, starting from the basic concepts and focusing on practical application to the New Madrid (USA) zone. It favors using DSHA particularly when available information is not sufficient to reliably estimate earthquake recurrence.].

Wyss M., Nekrasova A., Kossobokov V. (2012). Errors in expected human losses due to incorrect seimic hazard estimates, *Natural Hazards*, DOI 10.1007/s11069-012-0125-5. [The paper shows that the numbers of fatalities in recent disastrous earthquakes were underestimated by the global seismic hazard maps, developed in the framework of GSHAP, by approximately two to three orders of magnitude. This observation suggests that the maps based on the standard PSHA method do not allow a reliable estimate of the risk to which the population is exposed due to large earthquakes.]

Zuccolo E., Vaccari F., Peresan A., Dusi A., Martelli A., Panza, G.F. (2008). Neo-deterministic definition of seismic input for residential seismically isolated buildings, *Engineering Geology*, doi:10.1016/j.enggeo.2008.04.006. [This paper deals with the neo-deterministic definition of the seismic input in the municipality of Nimis (Italy), aimed at the design of residential seismically isolated buildings. The seismic input is defined by the computation of realistic synthetic seismograms considering different levels of detail for the earthquake source.]

Zuccolo E., Vaccari F., Peresan A., Panza G.F. (2010). Neo-deterministic (NDSHA) and probabilistic seismic hazard (PSHA) assessments: a comparison over the Italian territory, *Pure and Applied Geophysics* 168 (1-2). DOI 10.1007/s00024-010-0151-8. [Estimates of seismic hazard obtained using the neo-deterministic approach (NDSHA) and the probabilistic approach (PSHA) are compared for the Italian territory. The differences suggest the adoption of the flexible, robust and physically sound NDSHA approach to overcome the proven shortcomings of PSHA.]

Biographical Sketches

Giuliano Francesco Panza is Full Professor of Seismology at the University of Trieste, Italy. The scientific activity of Giuliano F. Panza is marked by the broad multidisciplinary nature of the problems considered: integrated analysis of structure and dynamics of the lithosphere-asthenosphere system; integrated approach to modeling of the seismic waves in the near-field and far-field; earthquake-prone lineaments and premonitory seismicity patterns. A wide range of sophisticated theoretical methods and models was developed in these studies: the advanced methodology for seismogram synthesis; inversion; pattern recognition. He received, in 2000, the Beno Gutenberg medal by the European Union of Geosciences for outstanding contributions to Seismology, is dedicated and successful leader of several international projects. He has been coordinating, for the CEI University network, Seminars and stages on “Earth and Environmental Physics: Geodynamical Model of Central Europe for Safe Development of Ground Transportation Systems”, at the Department of Earth Sciences of the University of Trieste and at The Abdus Salam International Center for Theoretical Physics. With the Seismology Group of Dipartimento di Matematica e Geoscienze dell'Universita' di Trieste and with the SAND group of the Abdus Salam International Centre for Theoretical Physics (ICTP), he supervises, has developed a very powerful, essentially analytical tool for the computation of realistic synthetic seismograms in three-dimensional inelastic media, that is at the base of his methodology for the neodeterministic assessment of seismic hazard, currently applied in several large urban settlements and megacities. Recently, in cooperation with ASI, the Italian space agency, the simultaneous use of the neodeterministic approach for the ground motion estimation, of the monitoring of the space-time variation of hazard, and of the Earth observation data, lead to the construction of time-dependent hazard models based on strong geophysical ground, that have generated particular interest at Civil Defense level.

ACADEMIC EXPERIENCE Laurea in Fisica University of Bologna (Italy) 1967 Post Doc University of Bologna (Italy) 1968-1970 Visiting post Doc University of Uppsala (Sweden) 1969 Assistant Professor University of Bari (Italy) 1970-1980 Post Doc Fellow University of California Los Angeles (USA) 1971/1974 Associate Professor University of Bari (Italy) 1973-1980 Associate Professor University della Calabria Cosenza (Italy) 1975-1977 Visiting Professor Polytechnic of Zurich (Switzerland) 1977 Prof. Geophysical Prospecting University of Trieste (Italy) 1980- 1988 Professor of Seismology University of Trieste (Italy) 1988- Lecturer Diploma Course in Earth System Physics at ICTP, 2006-
HONORS (before 2003) Prize Ettore Cardani, Università di Torino 1968; Fulbright Fellow 1970; Premio Linceo Accademia Nazionale dei Lincei Roma 1990; Beno Gutenberg medal from the European Geophysical Society, for outstanding contributions to Seismology, 2000; Doctor Honoris Causa in Physics from University of Bucharest - Romania, 2002. SERVICES (before 2003) Council member: European Geophysical Society 1982-1986; European Union of Geosciences 1983-1994; Vice President European Union of Geosciences 1991-1994 Chairman UNESCO-IUGS-IGCP project “Realistic modeling of seismic input for Megacities and large urban areas” 1997-2001. Project leader NATO SfP project “Impact of Vrancea earthquakes on the security of Bucharest and other adjacent urban areas” 2000-2004

PUBLICATIONS Author and coauthor of more than 480 scientific papers in refereed journals; Co-Author, Editor and Co-editor of 12 books. h-index (2011) 26.
FIELDS OF EXPERTISE Elastic wave propagation, interior structure of the earth, plate tectonics, earthquake prediction, active tectonics, seismic microzonation of urban settlements and seismic hazard, volcano seismology.
REFERENCE LISTINGS Who's Who in the World; Who's Who in Italy; Who's Who in Science and Engineering; Dictionary of International Biography

Antonella Peresan is a researcher at ICTP-SAND Group and Department of Mathematics and Geosciences, University of Trieste (Italy) since 1997. She earned her academic degrees at University of Trieste, Italy: MSc Physics, 1996; PhD in Geophysics of the Lithosphere and Geodynamics, University of Trieste, 2001.
Guest Editor of the PAGEOPH Topical Volume on “Advanced seismic hazard assessments” and Director of the Advanced Conference on “Seismic risk mitigation and sustainable development”, ICTP, Trieste (May 2010). Organized and participated in several seismological courses and workshops. Further she has been:

- Lecturer of the “Environmental Data Analysis” Course, within the framework of the ICTP pre-PhD Diploma in Earth System Physics, since 2006.
- Lecturer in the framework of various courses in Seismology and Seismic and Volcanic Hazard at the University of Trieste, since 1998.

Other Appointments:

- Research fellow. Department of Earth Sciences, University of Trieste (1997).
- Visiting scientist at the Department of Astronomy and Meteorology - Geophysics University of Barcelona, Spain (2000)
- Visiting scientist at the Institute of Geophysics, Vietnam National Centre for Natural Science and Technology. Hanoi, Vietnam (2002)
- Visiting scientist at the Institut de Ciènces de la Terra “Jaume Almera”, Barcelona, Spain (2002 and 2003)
- Member of the IASPEI Commission on "Earthquake Sources - Modeling and Monitoring for Prediction"
- Convenor at AGU, ESC and AES; invited lecturer in several international Conferences, Workshops and Schools.

Main fields of Research and Scientific contribution: Seismic hazard and risk; non-linear dynamics and earthquake prediction:

- Development of an integrated procedure for the time dependent neo-deterministic seismic hazard assessment. Application of seismic input for engineering analysis, based on the application of pattern-recognition methodologies and ground shaking modeling
- Analysis, integration and updating of earthquake catalogs for seismic hazard assessment and analysis of seismicity patterns in several regions of the world.
- Analysis of seismicity and its evolution and correlation at various space and time scales, including studies of temporal variations of volcano seismicity. Application and evaluation of intermediate-term earthquake prediction algorithms, using data on past and present seismicity, as well as synthetic catalogs.
- Application and validation of intermediate-term earthquake prediction algorithms.
- Analysis of the possible correlations existing between seismic energy release and secular and seasonal climatic variations
- Numerical simulation of seismicity in the block structure model of lithosphere dynamics.

Cristina La Mura is a Post-Doc researcher in Seismology at the Department of Mathematics and Geosciences, University of Trieste, Italy, since 2009. She earned the Master Degree in Physics at University of Napoli FEDERICO II on 2003 and the Ph.D. in Geophysics of Lithosphere and Geodynamics at University of Trieste, under the supervision of Prof. Giuliano F. Panza. She attended the Master Program in Mechanical Engineering at the Department of Engineering Science and Mechanics at Virginia Polytechnic Institute and SU, VA, US, on 2001/2004 with a good standing grade (3.8/4.0). Her

research activity, since 2006, is devoted to the modeling of seismic wavefield in three-dimensional inelastic media. Since 2004 she is member of the Gruppo Nazionale di Fisica Matematica (Italian National Group of Mathematical Physics). She earned several grants issued by Department of Engineering Science and Mechanics, Virginia Polytechnic Institute and SU, VA, US; INOGS - Istituto Nazionale di Oceanografia e Geofisica Sperimentale, Trieste, Italy; CISM – International Centre of Mechanical Science, Udine, Italy; The Abdus Salam International Centre for Theoretical Physics, Trieste, Italy.
REFERENCE LISTINGS Who's Who in the World 2011; Great Minds of 21st Century.

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