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Ground motion modelling including finite fault and 1D site effects in north-eastern Italy

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ABSTRACT The accurate prediction of the ground motion is of utmost importance in the seismic hazard assessment. 3D or 2D modelling is desirable to obtain realistic estimates of ground motion, but often the shortage of information about source and crustal structures compels us to adopt simplified techniques. In this paper we propose and test an expeditious methodology to compute near field ground motion including source and 1D site effects. Our methodology is based on a stochastic finite-fault modelling technique together with a 1D code to generate the soil response. As study area we choose the Friuli region in north-eastern Italy, seen as optimal since it was possible to identify a zone, located in the Friuli plain, and some sites at short distance with different soil conditions where past earthquakes produced severe damage. The 1936 Cansiglio earthquake (M_S=5.8) and the May 6, 1976 (M_S=6.5) Friuli earthquake, together with three aftershocks of the 1976 seismic sequence with M_L ranging between 4.3 and 5.8, were chosen as target events to validate our procedure in a wide frequency contents. We compare peak ground motions or response spectra derived from the synthetic signals with those obtained from the recordings at bedrock or soil stations. When none (1936 Cansiglio earthquake) or few recordings are available (1976 Friuli earthquake), we compare the intensities derived from response spectra with the macroseismic observations. As a final step, we compute the expected ground motion generated by two scenario earthquakes of M=6.7, that is the maximum magnitude expected for the area under investigation.

Key words: strong motion, 1D site effects, stochastic seismograms, Friuli, Italy.

1. Introduction

Modelling ground-motion complexities, either by means of empirical relations or by numerical simulations, requires knowledge of earthquake rupture details, of wave-propagation in heterogeneous media and of the effects of local site conditions. There are several techniques for generating ground motions varying from deterministic solutions of wave equation to stochastic or hybrid models of ground motion (e.g., Olsen *et al.*, 1997; Frankel and Stephenson, 2000; Motazedian and Atkinson, 2005). Current ground-motion simulation approaches are largely based on kinematic source models since they can be efficiently generated by a time-dependent displacement field on a predefined fault plane without considering the forces and stresses that cause these motions on the fault (Mai, 2009).

The site effects may largely affect the amplitude, frequency, composition and duration of ground shaking as result of complex interactions between seismic waves and the morphological and stratigraphic characteristics of soil deposits and rock masses. A number of techniques based on empirical approach, as well as on theoretical approach, are available to estimate the site effects (Kawase, 2003; Pitilakis, 2004). The empirical techniques employ recording of ground motion or seismic noise to estimate the basic characteristics of the expected ground motion. Such approaches include sediment-to-bedrock spectral ratio, sediment-to-bedrock noise ratio, horizontal-to-vertical noise spectral ratio and horizontal-to-vertical spectral ratio (i.e., Nakamura, 1989; Bard, 1999). The theoretical approaches require detailed knowledge of geotechnical parameters of the site and sophisticated computational methods. They are developed to model the seismic source process and the propagation of seismic waves in heterogeneous media through analytical or numerical 1D, 2D or 3D models (i.e., Panza *et al.*, 2001; Igel *et al.*, 2009, and references therein). The choice of the method is usually related to the engineering needs, but it is also related to the availability of detailed information about the seismic source, the geological structure and the geotechnical characteristics of the site. The shortage of information necessarily drives towards simplified approaches in the majority of cases.

In this paper we propose and test a methodology to compute near field ground motion including source and 1D site effects. Usually, we talk about stratigraphic or 1D effects when the seismic motion changes, propagating mainly vertically from the underlying bedrock to the surface. It is mostly attributable to the seismic waves filtering and/or amplification due to the subsoil stratigraphy, to the soil physical-mechanical properties. In such cases, it is possible to consider only one dimension, the depth, assuming the layers infinitely extended in the other two dimensions. For these situations, the main amplification of the seismic motion is caused by the impedance contrast between the various layers of the soil, and between them and the bedrock.

Our methodology is based on commonly used stochastic finite-fault modelling technique [EXSIM: i.e., Boore (2009)] together with a 1D code [PSHAKE: Sanò and Pugliese (1991)] to generate the response of a soil column. Both of these algorithms are widely tested and allow fast computations of ground shaking for seismic hazard mitigation purposes.

As study area we choose the south-western sector of the Friuli region, in north-eastern Italy (Fig. 1). In this area we detect a zone and some sites at short distance each others with different soil conditions where past earthquakes produced severe damage. The test sites, Casarsa della Delizia (Casarsa hereafter), Fontanafredda, Sacile and San Vito al Tagliamento (San Vito hereafter), are located in the Friuli plain (Fig. 1) where the stratigraphic characteristics play a major role and therefore, the modelling of 1D site effects can provide efficient estimate of the effects of local soil conditions on the ground shaking. The Friuli piedmont belt is one of the most tectonically active in the Alpine Chain, where superimposion of several tectonic phases (Castellarin *et al.*, 1992) reflects on present day seismic activity (Slejko *et al.*, 1989; Bressan *et al.*, 2003). Although a single seismogenic zone contributes most to the seismic hazard of the central part of the region, several seismogenic zones affect the peripheral sectors (Slejko *et al.*, 2007, 2008, 2011; Petrini *et al.,* 2012). The present state of stress is a consequence of the Adria microplate progressive motion and its anti-clockwise rotation with respect to the Eurasian plate (Anderson and Jackson, 1987). The seismicity of the area is moderate and mainly concentrated in the piedmont belt in central Friuli, with extension in Veneto to the west and in Slovenia to the east (Slejko *et al.*, 1989). The largest so far recorded event in northern Italy occurred on May 6,

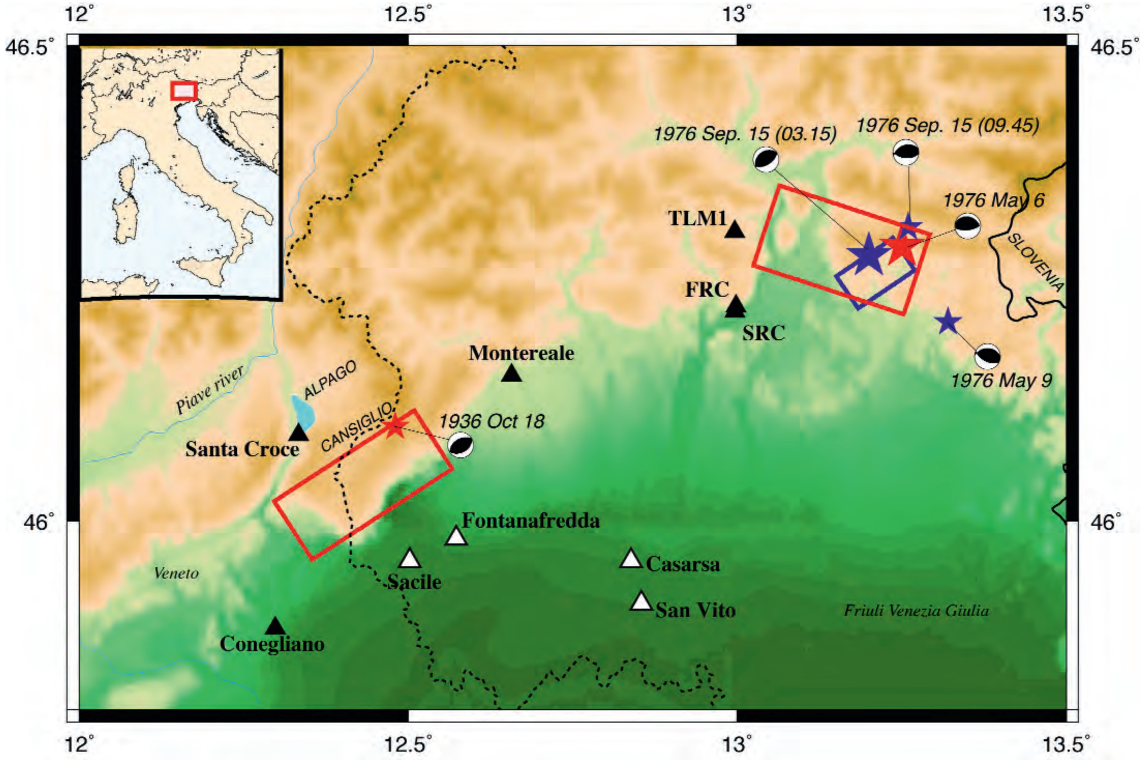

Fig. 1 - Map of the studied region with locations of the seismic sources and the focal mechanisms of the investigated earthquakes. The stations (black triangles) and the test sites (white triangles) at which we computed the ground motion are also plotted.

1976 (M_S=6.5), followed by a strong aftershock sequence (Slejko *et al.*, 1999; Aoudia *et al.*, 2000), and caused about 1,000 casualties and a widespread damage in Friuli (Carulli and Slejko, 2005). The Friuli area suffered in the past also because of earthquakes generated in the near Veneto zone. Indeed, two severe earthquakes occurred in the Belluno source: the 1873 event which caused 80 casualties and widespread damage (I_0 = IX-X MCS) in the Alpago area (Boschi *et al.*, 1995), and the 1936 event that produced 19 victims and many total or partial collapses of buildings (I_0 = IX MCS) in the Cansiglio area (Boschi *et al.*, 1995). According to the Italian macroseismic database [DBMI11 hereinafter: Locati *et al.* (2011)] the study area with the four test sites experienced an intensity respectively from V to VIII MCS during the 1873 earthquake, from VI to VIII in the case of the 1936 quake, and from VI to VII because of the 1976 event. The national seismic hazard map (Stucchi *et al.*, 2011) assigns a peak ground acceleration (*PGA*) between 0.125 and 0.200 g to the area for the standard return period of 475 years.

In the following sections, after a brief description of the methodology, we validate the here presented approach on the 1976 Friuli earthquake and on three its aftershocks, using instrumental data downloaded from that Italian strong motion database [ITACA from hereafter: ITACA Working Group (2010)], and on the 1936 Cansiglio earthquake, using observed macroseismic data. Finally, we compute the expected ground motion generated in the studied south-western sector of Friuli by two scenario earthquakes of *M*=6.7, that is the likely maximum magnitude expected in the region (Meletti and D'Amico, 2011).

2. Methodology

To simulate the expected ground shaking at a site, including source and 1D site effects we 1) first compute ground motion including source and path effects using the stochastic finite-fault model EXSIM (Boore, 2005, 2009; Motazedian and Atkinson, 2005) and 2) then we use the computed ground motion to excite a soil column at specific sites and we compute the 1D response using the PSHAKE (Sanò and Pugliese, 1991) algorithm.

2.1. Ground motion from source to bedrock

The stochastic finite fault algorithm named EXSIM (Boore, 1983, 2009; Motazedian and Atkinson, 2005) works in the assumption that motions to be simulated are S waves, that are the most important motions for seismic hazard. It combines parametric or functional descriptions of the ground motion amplitude spectrum with a random phase spectrum modified such that the motion is distributed over a duration related to the earthquake magnitude and to the distance from the source. The path effects are modeled through geometrical spreading, anelastic attenuation and ground motion duration effects (Boore, 2009). For large earthquakes the finite-fault approach is adopted in order to account for finite-fault effects such as rupture geometry, slip inhomogeneity and source directivity, which can strongly affect the duration, frequency content and amplitude of simulated ground motions. The rectangular fault plane is divided into small subfaults, and each subfault is considered to be a point source. The rupture starts at the hypocentre and propagates kinematically until each subfault is triggered. The regional dependence of duration and amplitude on distance are employed in the simulations to model the propagation effects. Finally, the ground motion at a receiver from the entire fault is obtained by summing up the contribution from each subfault, computed by the stochastic point-source model, with a proper time delay (Boore, 2005). To overcome the problems related to the discretization of the fault (i.e., the dependence of the total radiated energy on the subfault size), Motazedian and Atkinson (2005) introduced the dynamic corner frequency approach to scale the high-frequency spectral level of the subfault. Therefore, the corner frequency of the subfaults decreases with time and then radiated energy at high frequencies also decreases. The high-frequency spectral amplitudes are controlled by stress drop, whereas the percentage of pulsing area defines the level of spectra at low frequencies. Stress drop and percentage of pulsing area are considered "free parameters" and have to be properly calibrated for each study area.

The effectiveness of the method has been widely demonstrated by fitting observations in different environments by a number of authors (i.e., Ugurhan and Askan, 2010; Moratto and Saraò, 2012, and references therein). To be effective the method needs to be calibrated for the study region. Calibrations of the method involve finding the parameters so as to be able to fit empirically-derived equations for predicting ground motions. After the calibration, a validation of the method, which consist of checking predictions against data, needs to be performed.

2.2. 1D site effects

The program PSHAKE (Sanò and Pugliese, 1991) is an improvement of the program SHAKE

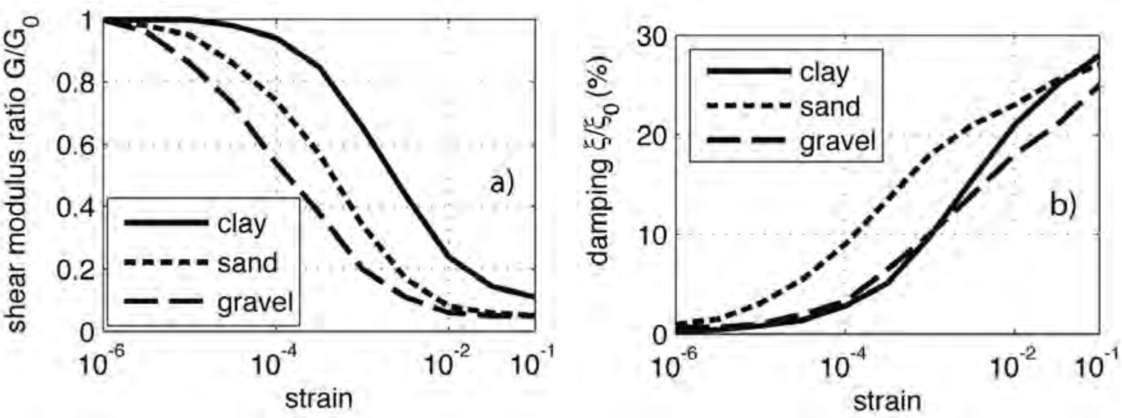

Fig. 2 - Curves of the dynamic properties of the materials: a) shear modulus attenuation and b) damping growth.

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

In this study we use as input the response spectrum at 5% damping obtained from the fine-fault stochastic modelling (Boore, 2009) and the linear-equivalent analysis for ground motion modelling. The dependence of the shear modulus and the damping on the shear deformation are applied for each material (lithological layer) by introducing specific mean dynamic property curves (Fig. 2) taken from the literature (Seed and Idriss, 1969; Seed *et al.*, 1986) as laboratory test values for the studied soil are not available.

3. Validation

To validate the here proposed approach, we have selected some events among the most energetic ones that occurred in the study area. Therefore, we chose the October 18, 1936 Cansiglio earthquake (M_S=5.8), the May 6, 1976 (M_S=6.5) Friuli earthquake, and, in addition, three aftershocks of the 1976 seismic sequence (Table 1) with magnitude values ranging between 4.6 and 6.0 (ITACA Working Group, 2010; Moratto *et al.*, 2012) to check the procedure in a wide frequency content.

In the validation process, we have compared peak ground motions and complete response spectra derived from the synthetic signals with those actually recorded on rock and soil. When few (1976 Friuli earthquake) or none (1936 Cansiglio earthquake) recording is available, we have compared the macroseismic intensities derived from synthetic response spectra by applying the

Table 1 - Model parameters used by EXSIM (Boore, 2009) for simulation of ground motion.

Event	October 18, 1936 **Cansiglio**	May 06, 1976 **Friuli**	September 15, 1976 **Friuli**	May 09, 1976 **Friuli**	September 15, 1976 **Friuli**
Origin Time	03:10	20:00	03:15	00:53	09:45
M_w	6.3	6.4	6.0	5.1	4.6
M_S	5.8	6.5	6.0*	4.5**	3.8**
Epicentre latitude	46.10°	46.29°	46.27°	46.21°	46.31°
Epicentre longitude	12.48°	13.25°	13.20°	13.32°	13.26°
Strike	238°	288°	236°	272°	252°
Dip	47°	29°	34°	36°	40°
Fault type	Reverse	Reverse	Reverse	Reverse	Reverse
Fault length	19.6 km	18.5 km	8.0 km	3.6 km	2.0 km
Fault width	12.0 km	11.2 km	5.5 km	3.1 km	1.9 km
Nucleation position	15% fault length	1% fault length	50% fault length	random	random
Nucleation depth	15.3 km	7.0 km	7.0 km	13.3 km	11.8 km
Seismic moment distribution	random	3 asperities	k^2	random	random
* M_S value retrieved from NEIC catalogue [further details in ITACA Working Group (2010)].					
** M_S value retrieved from Ekström and Dziewonski (1988).					

Faenza and Michelini (2011) relationship with the macroseismic observations reported in the DBMI11, that links MCS intensity to spectral acceleration at 0.3, 1.0 and 2.0 s. Still, it is worth evidencing that the macroseismic intensity is a discrete integer value and, being related to feelings and damages, it is not directly connected to the actual ground motion; further, the intensity value in a selected place is often the average estimate of all punctual observations in the neighbourhood.

The estimate of the wave field propagation from source to a rock site needs some parameters describing the attenuation due to the propagation from the source to the receivers through the structural model. To account for the geometrical spreading, the anelastic attenuation, and the distance-dependent duration, we employ the values proposed by Malagnini *et al.* (2002) for north-eastern Italy and the duration function by Herrmann (1985). The stress drop was chosen after testing values between 40 and 140 bars and the pulsing percentage value was tuned to adjust the lower frequency amplitudes. A stress drop of 60 bars, proposed by Malagnini *et al.* (2002) for the study area, with a pulsing percentage of 50%, was found to give the best fit between synthetic and recorded Fourier amplitude spectra (*FAS*), *PGA* and peak ground velocity (*PGV*) values, respectively. These values will be, therefore, adopted for all the simulations described in this paper. The parameters required for describing the finite source model as the hypocentre, the magnitude, the focal mechanism, the fault dimensions, the rupture propagation and the seismic moment distribution have been settled for each earthquake (Table 1) in accordance with the most recent literature.

For each earthquake the choice of sites for the ground shaking simulation was restricted by the scarcity of records or the absence of detailed soil information. In fact, despite the availability of a number of strong motion records for the 1976 earthquakes in ITACA only few of them were eligible for the validation of our approach, due to large epicentral distances (the EXSIM approach is operatively best suited for a distance less than 100 km, using a finite fault model) or unknown soil conditions. Only Tolmezzo (TLM1 in Fig. 1), which is classified as rocky site, was suitable for the validation of the 1976 Friuli mainshock, whereas for the 1976 aftershocks two close stations (San Rocco and Forgaria, SRC and FRC, respectively, in Fig. 1) classified as rock and soil sites, respectively, have been considered.

The stratigraphy of Forgaria (Table 2, obtained from ITACA) is based on geological (borehole), geophysical (cross-hole), and geotechnical (laboratory tests) data. The bedrock is located at a depth around 35 m, where the glacial deposits become cemented and the V_S is around 800 m/s. The sedimentary cover consists in a shallow layer of silt (5 m) underlaid by gravels, sands and silts locally cemented.

The stratigraphy of the four test sites, Sacile, Fontanafredda, Casarsa, and San Vito (Fig. 1 and Table 2) is based on a large amount of geological, geophysical, and geotechnical data, mainly obtained from water-wells, multichannel analysis of surface waves (MASW), and seismic profiles. The bedrock is located at a quite different depth in the four sites, ranging between 10 and 36 m. The sedimentary cover is quite similar in three of the sites (Fontanafredda, Casarsa, and San Vito) with differently consolidated gravel alternated sometimes by thin lenses of sand. The Sacile site, conversely, is characterized by clay with a lens of sand [see some data in Slejko *et al.* (2011)].

3.1. The May 6, 1976 Friuli earthquake

The May 6, 1976 earthquake [M_S=6.5 and M_W=6.4: Aoudia *et al.* (2000)] had epicentre in central Friuli and is the largest instrumentally recorded event in northern Italy; the mainshock was preceded by a foreshock (M_S=4.5) and followed by a long seismic sequence that included four strong aftershocks in September with magnitude larger than 5.0 (Slejko *et al.*, 1999; Moratto *et al.*, 2012). Aoudia *et al.* (2000) revisited the seismic sequence of 1976 by combining relocation of hypocentres, inversion of long-period waves, and field geology; they modelled the source of the mainshock and, on the basis of the spatial distribution of the aftershocks, suggested that the rupture was unilateral and westward propagating. The source parameters as proposed by Aoudia *et al.* (2000) together with the values previously tuned to model the propagation effects (Table 1) were settled to compute the synthetic seismograms at the selected sites.

Among the accelerometric stations that recorded the earthquake, only four stations, placed within 100 km from the epicentre, are available in ITACA; among them, two (Codroipo, Conegliano) are classified as EuroCode 8 soil B (CEN, 2002), although no information about their stratigraphy is given. Two others (Barcis and Tolmezzo), despite their classification as EuroCode8 A sites, are affected by local effects. Particularly, Castro *et al.* (1996) estimated an average near-surface attenuation parameter for the site of the Barcis station about 5 times smaller than the average value of that of the sites where the stations of the Friuli Venezia Giulia Seismographic Network are located. This parameter is specific for the recordings at the site and

Table 2 - Stratigraphic profiles for Forgaria and the 4 study sites.

Site	Depth (m)	Thickness (m)	Lithology	Density (g/cm^3)	V_S (m/s)
Forgaria nel Friuli	0-5	5	Clay	1.90	233
	5-35	30	Gravel	2.15	350-670
	>35		Rock	2.20	800
Casarsa della Delizia	0-5	5	Gravel	2.04	346
	5-10	5	Gravel	2.14	600
	>10		Rock	2.20	924
Fontanafredda	0-3	3	Gravel	2.00	350
	3-6	3	Gravel	2.05	450
	6-16	10	Gravel	2.10	500
	16-19	3	Sand	2.10	550
	19-25	6	Gravel	2.15	600
	>25		Rock	2.20	800
Sacile	0-7	7	Clay	1.12	290
	7-13	6	Sand	1.84	350
	13-18	5	Clay	1.63	400
	18-36	18	Clay	1.94	650
	>36		Rock	2.04	800
San Vito al Tagliamento	0-5	5	Sand	1.54	330
	5-15	10	Gravel	2.03	600
	>15		Rock	2.17	800

mostly depends on the local conditions. Barnaba *et al.* (2007) demonstrated that the high-acceleration peaks recorded at Tolmezzo (TLM1) were strongly affected by the presence of the dam-reservoir system located near the station as well as by the surrounding hills. Barnaba *et al.* (2007) estimated the amplification correction on the peak values recorded at TLM1, hence this signal could be used for our validation. After the correction, the peak values are reduced by a factor of about 1.6-1.8, and the *PGA* value of 350.0 cm/s^2 becomes 188.8 cm/s^2 (Barnaba *et al.*, 2007). Therefore, the peak values (*PGA*=189.8 cm/s^2 and *PGV*=22.5 cm/s) computed at TLM1 site by EXSIM are in good agreement with the corrected records. Also the comparison of synthetic time histories and *FAS* (Fig. 3) with the corrected data of TLM1 is satisfactory on the complete accelerometric frequency range (0.1-25 Hz).

We have next computed the rock and soil response spectra at the four test sites (Fig. 1) for comparison with the macroseismic observed intensities (DBMI11). At all the four sites, the peak

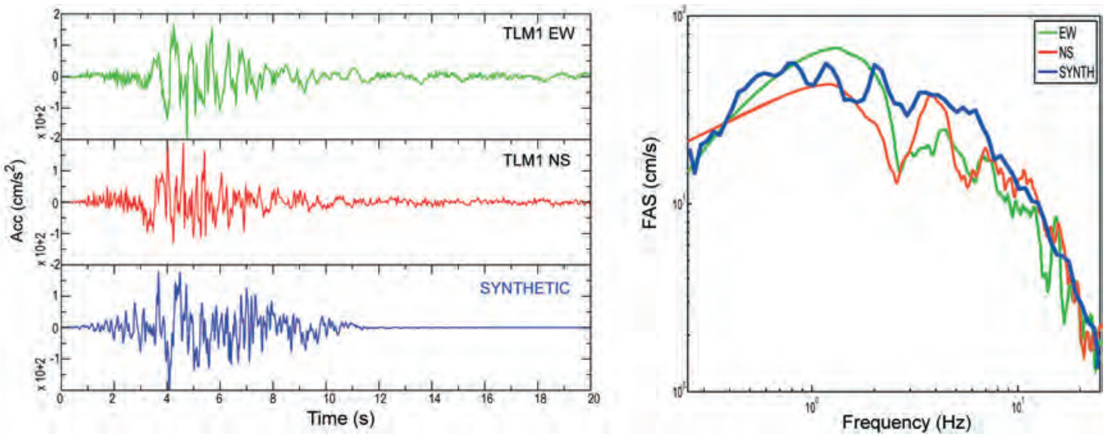

Fig. 3 - Comparison of time histories and *FAS* of synthetic (blue line) with real data (green lines = E-W component, red lines = N-S component) for the May 6, 1976 Friuli earthquake at the TLM1 station. The records of TLM1 were corrected for local effects by Barnaba *et al.* (2007).

value of the soil spectrum is almost 2 times larger than that of the rock one, being the highest site amplification at Casarsa (Fig. 4a) and Sacile (Fig. 4c) and the lowest at Fontanafredda (Fig. 4b). The soil spectra are amplified mostly in the periods lower than 0.2 s at Casarsa and San Vito (Figs. 4a and 4d), whilst at the other sites the amplification involves the whole considered period

Table 3 - Comparison of computed and observed (DBMI11) MCS intensities; the computed intensities are estimated by Faenza and Michelini (2011) from the spectral acceleration at 0.3 and 1.0 s (respectively FM0.3s and FM1.0s in the table).

Main Friuli 1976			
Sites	**FM0.3s**	**FM1.0s**	**DBMI11**
Fontanafredda	VI	VI	VI
Casarsa	VI	VII	VI-VII
Sacile	VI	VII	VI-VII
San Vito	VI	VI	VI
Cansiglio 1936			
Sites	**FM0.3s**	**FM1.0s**	**DBMI11**
Fontanafredda	VII	VII	VII
Casarsa	VI	VI	VI*
Sacile	VII	VII	VII-VIII
San Vito	VI	VI	VI-VII
Montereale	VI	VI	VI
Alpago	VII	VII	VII
Conegliano	VII	VII	VII
* Data not observed at Casarsa but close this site			

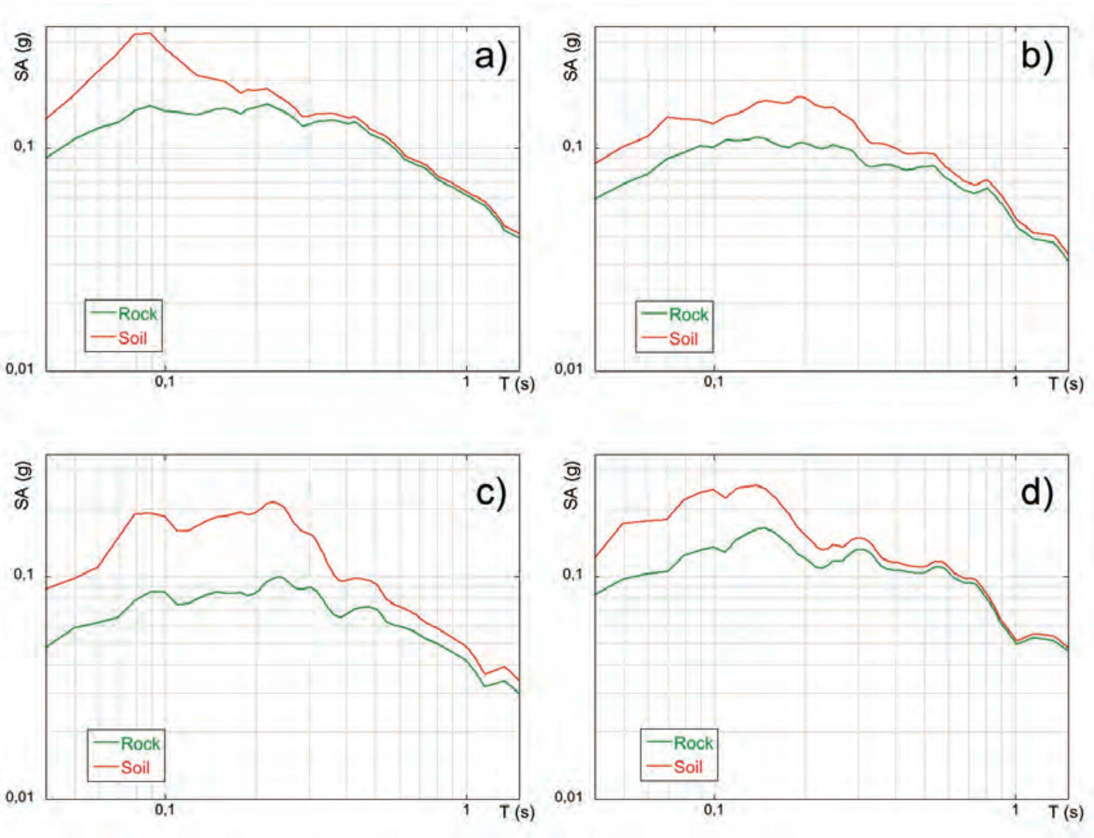

Fig. 4 - Rock (green line) and soil (red line) response spectra computed for the May 6, 1976 Friuli earthquake at Casarsa (a), Fontanafredda (b), Sacile (c) and San Vito (d).

range. This effect may be related to the bedrock depth: the deeper is the bedrock, the larger is the period range interested by the amplification. From the computed response spectra we retrieved macroseismic intensity values at each site (Table 3) through the Faenza and Michelini (2011) relationship and the agreement with the observed intensity data (DBMI11) is quite satisfactory.

3.2. Three 1976 Friuli aftershocks

On the basis of the available records, we selected three events with M_W ranging between 4.6 and 6.0 (Table 1) among the aftershocks that followed the 1976 Friuli mainshock. The hypocentral locations for the May 9, 1976 at 00:53 (M_L=5.3, M_W=5.1) and for the September 15, 1976 at 09:46 (M_L=4.3, M_W=4.6) events were obtained by Slejko *et al.* (1999). For both events we derived the size of the finite sources modelled using the Wells and Coppersmith (1994) relationships with a random moment distribution, although moderate earthquakes are not very sensitive to finite fault effects, since small rupture areas produce negligible finite-fault effects on the recorded data (Moratto *et al.*, 2012). Instead, the finite source of the September 15, 1976 at 03:15 (M_L=5.8, M_W=6.0) was taken from Moratto *et al.* (2012), who validated their model by comparing synthetic and real *PGA* values.

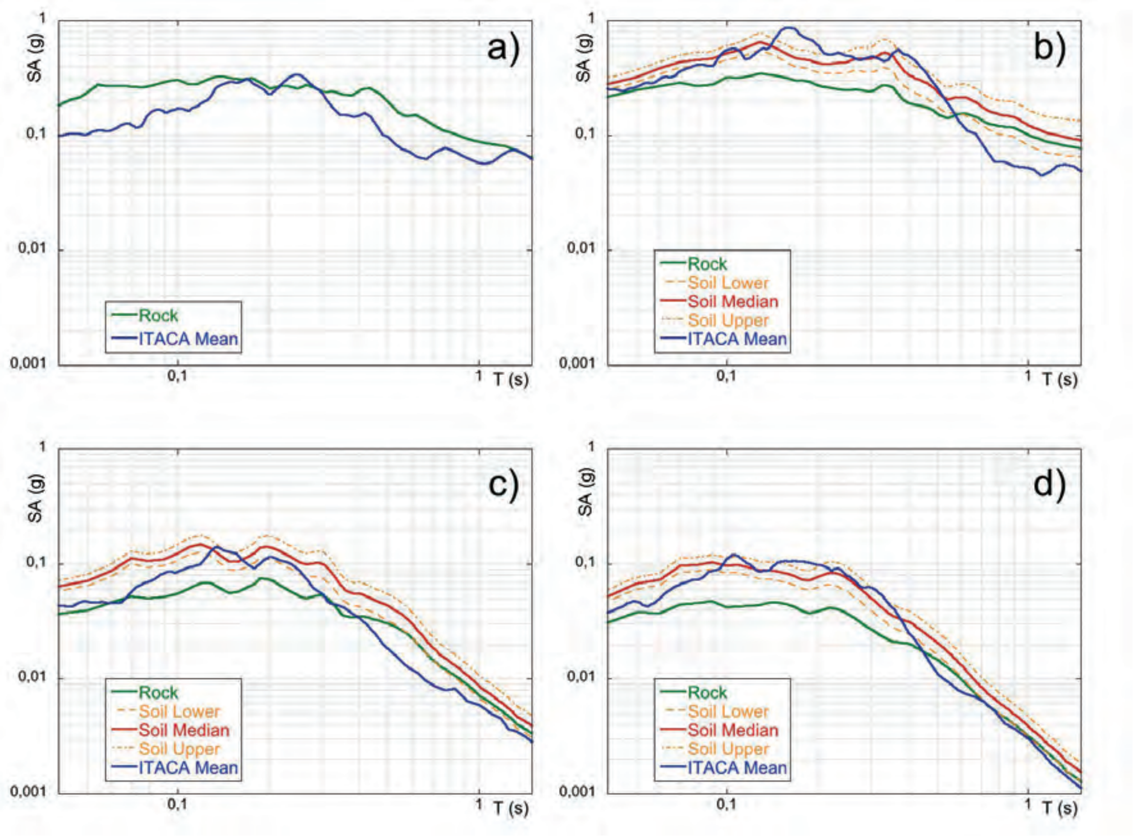

Fig. 5 - Recorded and modelled response spectra comparison for the September 15, 1976 (M_W=6.0) earthquake at SRC (a) and FRC (b); the 1976 May 9, 1976 (M_W=5.1) event at FRC (c), and the 1976 September 15, 1976 (M_W=4.6) at FRC (d). The green solid lines (marked as Rock) show the simulated ground motion at the bedrock. The red solid curves (marked as Soil Median) represent the median values of the modelled response spectra, while the yellow dashed curves (marked as Soil Lower and Soil Upper) represent, respectively, the 16th and the 84th percentiles related to the uncertainty on the estimation of the modelled spectral values. The blue solid lines (marked as ITACA Mean) show the average value of the two horizontal recordings.

The station Forgaria Cornino (FRC), classified as EuroCode8 B soil (in ITACA), for which detailed soil information is available (Table 2), recorded all the three events. The strongest event (M_W=6.0) was also recorded at a rocky site (SRC), less than 2 km from FRC. Therefore, only for this event, we will include SRC in the computation to validate the ground shaking at bedrock. The same data from FRC and SRC were used by Sanò *et al.* (1993) to validate the PSHAKE algorithm, but in their exercise they used the records of SRC as input to compute the response spectra at FRC site getting a good agreement with recorded data. In our validation test, we also compute the data at the SRC rocky site and we compare them with real data. The values of *PGA* (132 cm/s^2) and *PGV* (7 cm/s) recorded at SRC are satisfactorily reproduced by our computation, which estimates values of *PGA*=125 cm/s^2 and *PGV*=9 cm/s, and the response spectrum (Fig. 5a) calculated from synthetic data fits appreciably the average of spectra related to two recorded horizontal components for the whole considered period range. The fit is particularly good between 0.1 and 0.3 s with the reproduction of the pick at 0.15 s while the stochastic seismograms overestimate the spectra for periods ranging between 0.4-0.7 s and at very short period (T<0.1 s). The comparison of response spectrum computed for the same earthquake at FRC (Fig. 5b) highlights the presence of soil effects and the discrepancy is reduced when the 1D soil response is modelled. The soil median spectrum fits appreciably the average spectrum of the two recorded horizontal components for the whole considered period range. In particular, the two picks of the recorded data are well reproduced by the modelled spectrum. For periods longer than 0.7 s we overestimate the recorded one even when just considering rock conditions (Fig. 5b). The green solid lines (marked as Rock) in Figs. 5b, 5c, and 5d show the simulated ground motion at the bedrock. The red solid curves (marked as Soil Median) represent the median values of the modelled response spectra, while the yellow dashed curves (marked as Soil Lower and Soil Upper) represent, respectively, the 16th and the 84th percentiles related to the uncertainty on the estimation of the modelled spectral values. Finally, the blue solid lines (marked as ITACA Mean) show the average value of the two horizontal recordings (data from ITACA).

We have then compared the response spectra derived from recorded data and those calculated at FRC for the May 9, 1976 (M_L=5.3; M_W=5.1) event (Fig. 5c), and for the smaller one (Fig. 5d) occurred on September 15, 1976 at 09:46 (M_L=4.3; M_W=4.6). For both events, the soil median spectra fit appreciably well the average of spectra related to two recorded horizontal components for the whole considered period range, although for one of them (Fig. 5c) we slightly overestimate the spectrum values for periods longer than 0.4 s, probably caused by the fit discrepancie obtained by the simulation on rock as in the case of the event of September 15 with an M_L of 6.0 (Figs. 5a and 5b).

3.3. The October 18, 1936 Cansiglio earthquake

The Cansiglio earthquake occurred on October 18, 1936 in the Cansiglio Plateau near the piedmont zone between the Friuli plain and the Southern Alps. The area is located at the border between the Veneto and the Friuli Venezia Giulia regions (north-eastern Italy). This piedmont zone is characterised by compressive stresses, the most relevant tectonic features being the two principal adjacent tectonic lines: the Bassano-Valdobbiadene fault and the Polcenigo-Maniago fault [for major details see Burrato *et al.* (2008)]. Several authors (e.g., Slejko *et al.*, 1989; Sirovich and Pettenati, 2004; Laurenzano and Priolo, 2008) suggested consistent source models based on different analyses. Sirovich and Pettenati (2004), using macroseismic data inversion, estimated a moment magnitude value equal to 6.3 and proposed a fault model NNE-SSW oriented, in agreement with the maximum horizontal geodynamical compressive stress, and a rupture propagating from NE to SW. In this study we adopt their results (Table 1) to set the fault geometry and we use a random moment distribution on the fault.

The stochastic seismograms modelled for a rocky site were used to compute the soil response spectra at the four test sites placed at SE from the fault in the test area (Fig. 1) but also to some other nearby sites to check the effect of propagation in different directions as Montereale (NE from the source), Santa Croce (NW from the source) and Conegliano (SW from the fault). The macroseismic intensities obtained applying the Faenza and Michelini (2011) relationship are compared with the DBMI11 observations in Table 3. The fit is appreciable for all considered sites regardless of the site position with respect to the fault. In Fig. 6 we show the resulting soil spectra for the four test sites. The peak value of the soil spectrum is almost 2 times larger than that of the rock one in all four test

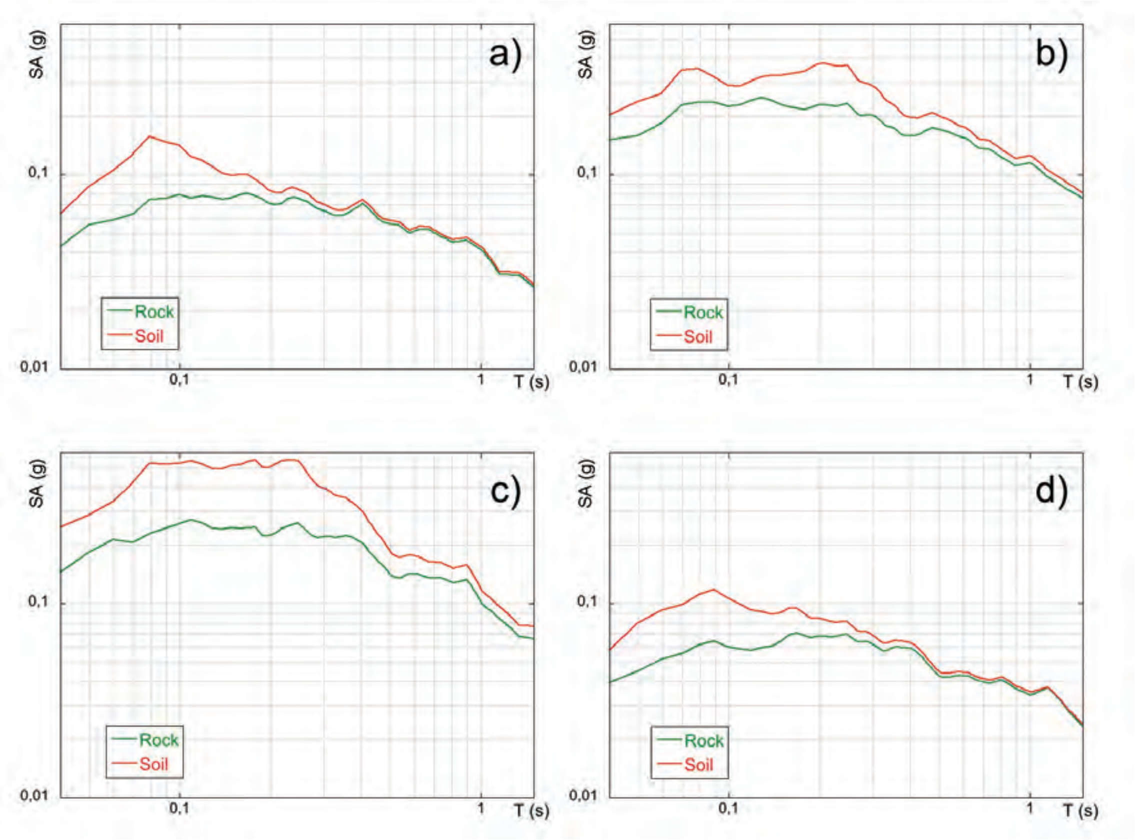

Fig. 6 – Rock (green line) and soil (red line) response spectra computed for the October 18, 1936 Cansiglio earthquake at Casarsa (a), Fontanafredda (b), Sacile (c) and San Vito (d).

sites. At Casarsa and San Vito (Figs. 6a and 6d) the soil spectra are amplified mostly in the periods lower than 0.3 s while for the other two stations the amplification involves the whole period range. The site amplification is moderately high at Fontanafredda (Fig. 6b) and maximum at Sacile (Fig. 6c), confirming the high contribution of the local lithology in the expected ground motion. Furthermore, the receivers of Fontanfredda and Sacile are placed close to the rupture area (Joyner-Boore fault distance about 7 km) where the shaking is relevant and it can be strongly influenced by source effects while Casarsa and San Vito are placed at a fault distance of about 25 km.

4. Ground motion scenario for a small area

Within a recent project aimed at providing an updated community-based seismic hazard model for the Euro-Mediterranean region (SHARE, FP7 EU 2009-2012), Meletti and D'Amico (2011) suggested a value of 6.7 as the most likely maximum magnitude for both the seismogenic sources (Friuli and Cansiglio-Alpago) considered in the present study. We therefore computed two scenarios, each one generated by an M_w=6.7 earthquake, for the four test sites (Fig. 1), assuming the model parametres of the 1936 Cansiglio and 1976 Friuli earthquakes (Table 1) with

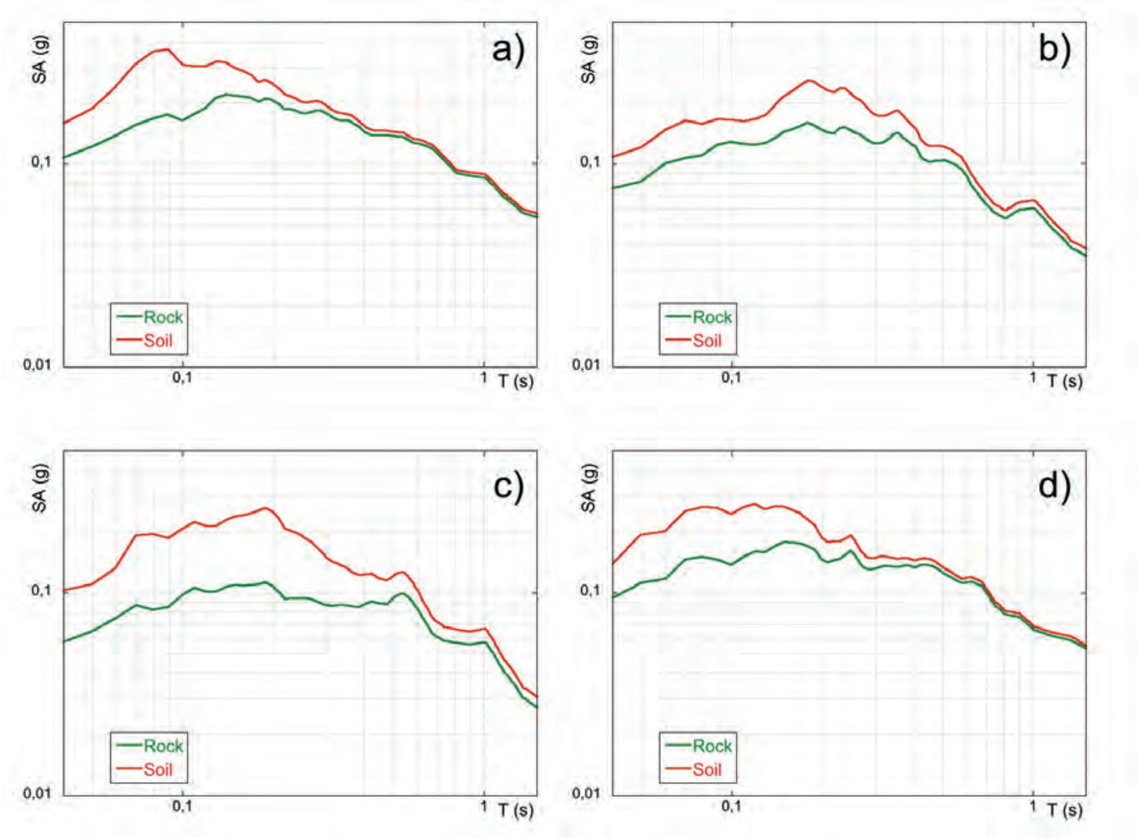

Fig. 7 - Rock (green line) and soil (red line) response spectra computed for the M_w=6.7 scenario earthquake using the 1976 Friuli source model at Casarsa (a), Fontanafredda (b), Sacile (c) and San Vito (d).

the exception of the fault dimensions that have been resized using the Wells and Coppersmith (1994) relationship. The seismic moment distribution and the rupture propagation are supposed to be random because not predictable a priori.

The scenario soil spectra for the Friuli (Fig. 7) and Cansiglio (Fig. 8) earthquakes respectively keep the same trend of the previously computed spectra. The peak value of the soil spectrum is almost twice larger than that of the rock one in all four test sites. Also in these cases, the higher amplification is at Sacile, (Figs. 7c and 8c) and it is moderately high at Fontanafredda (Figs. 7b and 8b). For these two sites the amplification involves the whole considered period range, while at Casarsa and San Vito (Figs. 7a, 8a, 7d and 8d) the soil spectra are amplified mostly in the periods lower than 0.3 s. This is related to the bedrock depth: the deeper is the bedrock, the larger is the period range interested by the amplification.

5. Conclusions

The computation of the expected ground motion for extreme earthquakes is of paramount importance. In this paper we suggest a simplified approach to compute ground motion including

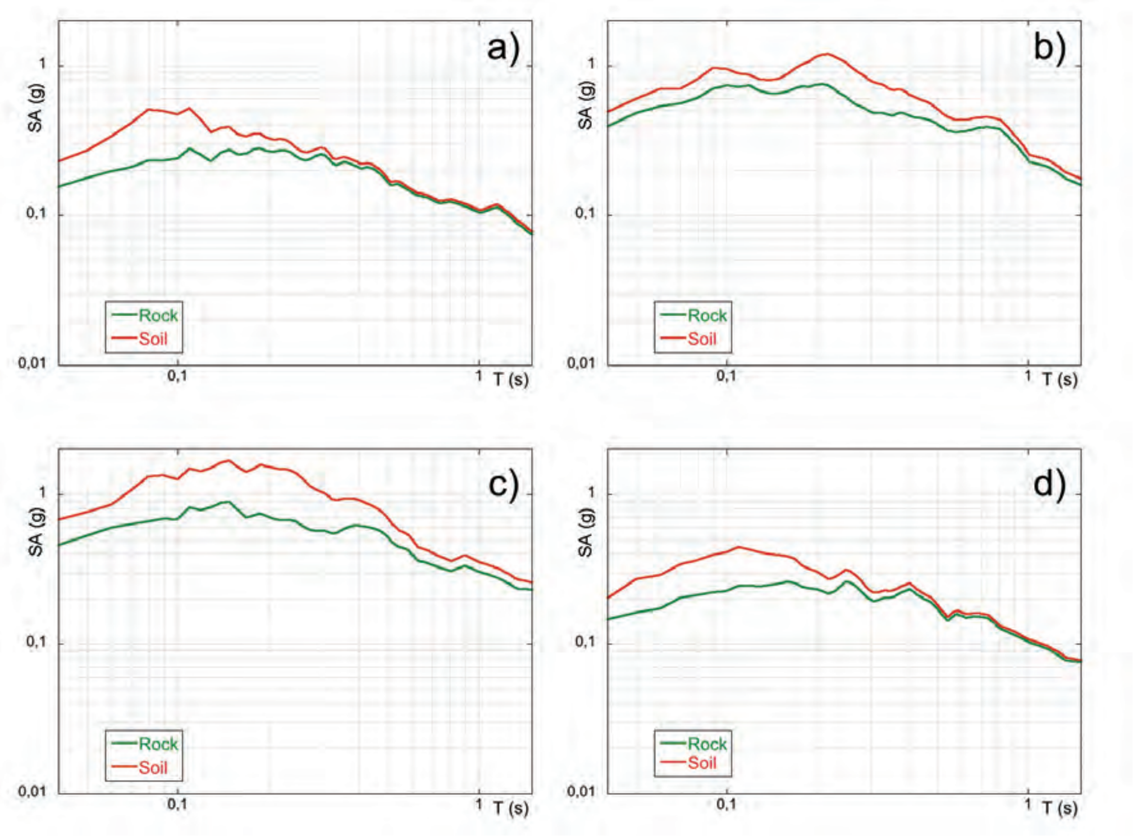

Fig. 8 - Rock (green line) and soil (red line) response spectra computed for the M_W=6.7 scenario earthquake using the 1936 Cansiglio source model at Casarsa (a), Fontanafredda (b), Sacile (c) and San Vito (d).

1D site effects. We validate the proposed procedure in the seismic region of north-eastern Italy, where two major seismogenic sources contribute to the seismic hazard. After modelling the 1936 Cansiglio earthquake (M_S=5.8) and the 1976 May 6 (M_S=6.5) Friuli earthquake, together with three of its aftershocks for comparison with recorded data and macroseismic observations, we computed the ground motion produced by two scenario earthquakes at four sites located in NE Italy, characterized by well documented different soil conditions. The extreme events for the two sources have been defined on the basis of the strongest earthquakes occurred in the past and on the expected maximum magnitude for the region (6.7 magnitude earthquake in the Cansiglio and Friuli sources). Comparing the soil spectra of the scenario earthquakes, it is evident that the four sites behave in a similar way, both in terms of amplitude and frequency, regardless the considered source. In particular, in the two sites where the bedrock is located at a greater depth (Fontanafredda and Sacile) the high amplification is shifted to higher periods, around 0.2 to 0.25 s, while the other two sites, the peak of amplification is found around to 0.1 s or less.

The approach that we applied in this paper proved to be effective in prediction of 1D site effects and it is based on well trained and freely available software that can be easily implemented for seismic hazard purposes. Surely, it cannot replace a sophisticated modelling, where robust results are guaranteed only in presence of very detailed information about the source and the crustal structure. Conversely, it can offer an easy and fast picture of several extreme scenarios.

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