Seismic hazard estimates for the Vittorio Veneto broader area (NE Italy)

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ABSTRACT. The logic tree approach has been used to compute robust seismic hazard estimates for NE Italy (Friuli - Venezia Giulia and eastern Veneto regions). These hazard estimates were planned to be used for the expected damage assessment at a regional scale. The logic tree approach has been followed, to quantify the epistemic uncertainties. Our logic tree consists of 54 branches for rock and soft soil conditions for which three seismogenic zonations, representing various levels of seismotectonic knowledge, three methods for seismicity rate computation, three approaches for maximum magnitude estimation, and two *PGA* attenuation relations of different spatial relevance (Italian, European) were used. For stiff soil conditions, an additional attenuation relation of regional applicability was considered with an enlargement of the logic tree to 81 branches. The regional hazard assessment was made according to a standard probabilistic approach for several return periods: 189 runs were processed in total. The hazard estimates coming from all branches, contribute to the final aggregate seismic hazard map. Two areas (central Friuli and the area around Vittorio Veneto) show the highest hazard in these maps. All results were stored and elaborated by a GIS system, that allowed us to produce the final soil seismic hazard map. The computed *PGA* with a return period of 475 years in Vittorio Veneto (stiff soil conditions) is 0.38 g, considering the aleatory variability; it becomes 0.51 g when the epistemic uncertainties are added. For damage assessment purposes, an additional hazard map in terms of macroseismic intensity has been obtained transforming the *PGA* estimates into macroseismic intensity by a relation calibrated on the data of the 1976 Friuli earthquake. The intensity hazard map shows similar features as those of the hazard map in terms of *PGA* with the maximum values along the northern Tagliamento River valley.

1. Introduction

The eastern Alps (NE Italy) are one of the most seismic regions of Italy (Slejko *et al*., 1989). In Friuli, in fact, three earthquakes with magnitude (macroseismic magnitude M_m calibrated on the magnitude on surficial waves M_S) 6 and over occurred in the past (Fig. 1): the M_m 6.4 Villach quake in 1348 (Hammerl, 1994; Boschi *et al*., 1995), the M_m 6.2 Gemona - Idrija event in 1511 (Boschi *et al*., 1995), and the M_S 6.5 Gemona earthquake in 1976 (Carulli and Slejko, 2005). The Belluno area, moreover, experienced two events with magnitude larger than 5.5 during the past centuries: the M_m 6.4 Alpago earthquake in 1873 (Boschi *et al*., 1995) and the M_S 5.8 Cansiglio event in 1936 (Peruzza *et al*., 1989; Boschi *et al*., 1995). Lower seismicity interests the western part of the study region, where the major event is the M_m 6.4 Asolo earthquake in 1695 (Boschi *et al*., 1995). Fig. 1 shows the main seismotectonic features for NE Italy. The tectonic structures are taken from Galadini *et al*. (2005) for the Friuli and Slovenia regions (east of 13°) and from Castellarin *et al*. (2003) for the western sector. The main historical (pre-1977) seismicity (events with M_S 4.0 or larger) are taken from the Camassi and Stucchi (1997) catalogue and the recent earthquakes (events with local magnitude M_L 3.0 or larger) refer to the hypocentral locations of the Friuli - Venezia Giulia seismometric network (OGS, 1977-1981, 1982-1990, 1991-2002). Further catalogues (Gruppo di Lavoro CPTI, 1999, 2004) are also used in the elaborations. A general agreement between seismicity and tectonic structures can be seen, and this fact supports the different seismogenic zonations which will be described later. The seismicity remains mainly concentrated along the foothills in Italy while it interests most of the Slovenian territory. Consequently, it is necessary to consider the seismogenesis in the whole region from Lake Garda to Ljubljana and from Venice to the latitude of the northernmost Italian border with Austria for the seismic hazard assessment of Friuli - Venezia Giulia and eastern Veneto.

Recent seismic hazard estimates (Rebez *et al*., 1999) for the eastern Alps showed that the most seismic area is central Friuli with hazard decreasing westwards. The Belluno area, at the border between the Friuli - Venezia Giulia and Veneto regions, represents the limit of the most hazardous area. These results are strongly conditioned by the seismogenic zonation used, especially for the Belluno area, where the major seismicity was associated to a narrow NNE-SSW trending strip (Meletti *et al*., 2000) but it could be linked, alternatively, to the Alpine compressional front (Galadini *et al*., 2002). The influence of the attenuation relation (AR) used is very important, as well. Soil dependent seismic hazard estimates were computed (Carulli *et al*., 2002) in the framework of the compilation of the seismic risk map of the Friuli - Venezia Giulia region (Carulli *et al*., 2003): they pointed out the great influence of the soil typology of the different terrains in the region.

The Vittorio Veneto town, located near Belluno (Fig. 1), was selected as test site by the Italian "Gruppo Nazionale per la Difesa dai Terremoti" (GNDT) to compute the regional seismic risk and some local damage scenarios. The regional expected damage (see Meroni *et al*., 2008) was based on probabilistic seismic hazard estimates, while the damage scenarios for the Vittorio Veneto test site (see Bernardini *et al*., 2008) were mainly based on a complete deterministic ground shaking modelling (see Laurenzano and Priolo, 2008). In the frame of the GNDT project, some preliminary regional hazard estimates were produced (Rebez and Slejko, 2004a) using the logic tree approach, which allowed the quantification of the uncertainties involved in the probabilistic seismic hazard assessment (PSHA). In the present study, all the models and parametrisations used by Rebez and Slejko (2004a) have been revised and updated, substituting some of them with new versions. During that same project, some other local studies were performed: they contributed to a better knowledge about the seismogenesis (Galadini *et al*., 2005) and the ground motion attenuation (Bragato and Slejko, 2005; Slejko and Bragato, 2008) in the eastern Alps. Specific aspects of engineering seismology were studied as well (Slejko and Rebez, 2002, 2004; Rebez and Slejko, 2004b).

Aim of the present study is to estimate the seismic hazard in the Friuli - Venezia Giulia and eastern Veneto regions (the territory of the provinces of Belluno and Treviso in the Veneto region, and Pordenone, Udine, Gorizia, and Trieste in the Friuli - Venezia Giulia region) using the most updated basic data and procedures as branches in the logic tree approach.

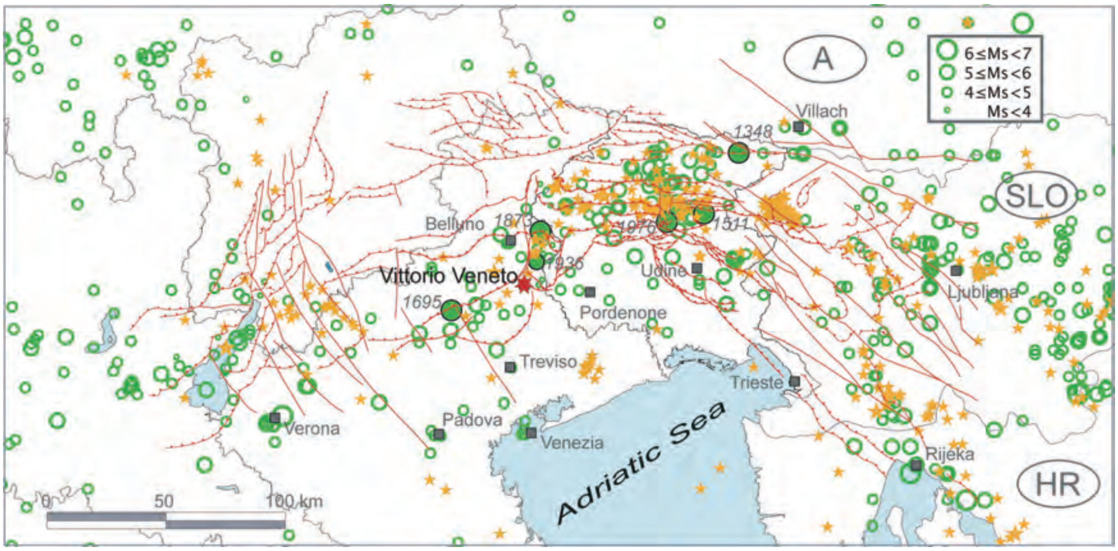


Fig. 1 - Main seismotectonic features of the eastern Alps region: red solid lines represent faults (Castellarin *et al.,* 2003; Galadini *et al.*, 2005), green circles (solid for the major events) indicate the epicenters of earthquakes from 1000 to 1976 with M_S 4.0 and over (from Camassi and Stucchi, 1997), yellow stars represent the epicenters of the earthquakes from 1977 to 2002 with M_L 3.0 and over (from OGS, 1977-1981, 1982-1990, 1991-2002). The red star indicates Vittorio Veneto town.

2. PSHA

The PSHA for the Friuli - Venezia Giulia and eastern Veneto regions has been made according to the standard approach of Cornell (1968) by using the Bender and Perkins (1987) computer formulation. This approach is based on two working hypotheses: the earthquake recurrence times follow a Poisson distribution (made up of independent, non-multiple events, and the process is stationary in time) and the magnitude is exponentially distributed [the Gutenberg - Richter (G-R) relation holds]. In addition, the seismicity is considered uniformly distributed over the seismogenic zone (SZ). The Cornell (1968) method, then, needs the following input data: the SZ geometry definition, the seismicity models (in terms of average number of earthquakes per magnitude interval, and maximum possible magnitude), and the AR of the chosen parameter of ground motion.

The quantification of the uncertainties (McGuire, 1977) is a crucial point in modern PSHA. Two kinds of uncertainties characterise the results in PSHA: the aleatory variability and the epistemic uncertainty (McGuire and Shedlock, 1981; Toro *et al*., 1997). Aleatory variability is the natural randomness in a process. It is considered in PSHA taking into account the standard deviation of the relation describing the process. Epistemic uncertainty is the scientific uncertainty in the model of the process and it is due to limited data and knowledge. It is considered in PSHA using alternative models. The logic tree approach for PSHA (Kulkarni *et al*., 1984; Coppersmith and Youngs, 1986) has been introduced to quantify the epistemic uncertainties. Each node of the logic tree collects a series of choices, represented by each branch of the logic tree. The final aggregate result is obtained by adequately weighting the individual results coming from the different branches [see more discussion in Rebez and Slejko (2004a)].

In the present study, a logic tree (Fig. 2) with 54 branches has been constructed for the rock and soft soil hazard maps, and with 81 branches for the stiff soil hazard map: it consists of three zonations, three approaches for the seismicity rate definition, three methods for maximum magnitude (M_{max}) assessment, and two ARs for peak ground acceleration (*PGA*). In the case of the stiff soil hazard map (dominating soil type at Vittorio Veneto, test site of the GNDT project), a further third AR (Bragato and Slejko, 2005; Slejko and Bragato, 2008), ad hoc developed for the study region, has been considered. The results of the present study in terms of *PGA*, transformed into macroseismic intensity values, were used as ground motion input for the damage estimates in the broader Vittorio Veneto area (see Meroni *et al.*, 2008).

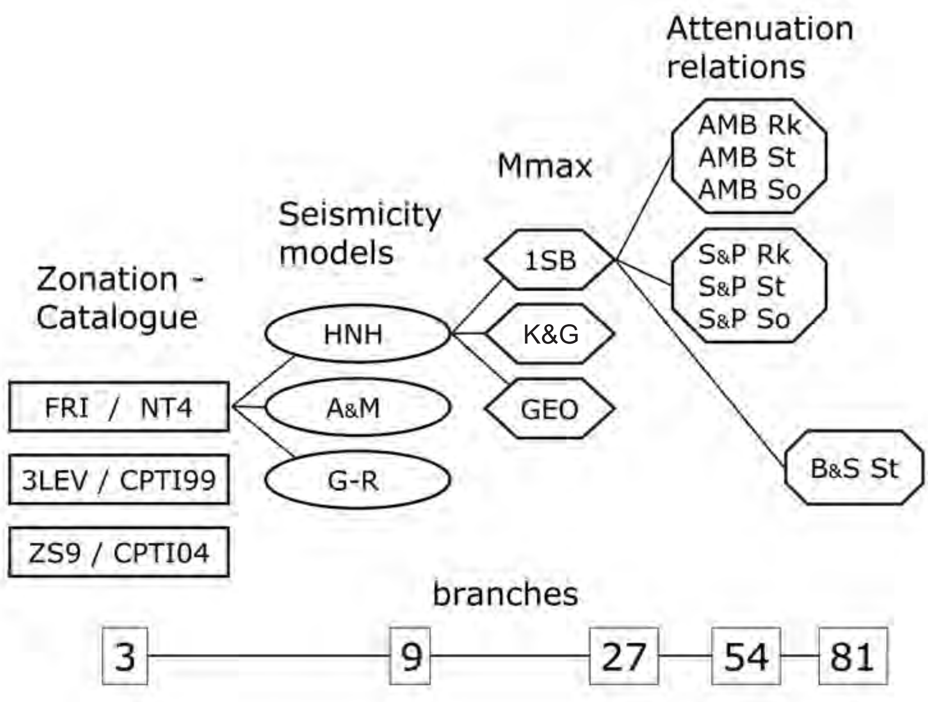


Fig. 2 - The logic tree used for PSHA of the Vittorio Veneto broader area. It consists of 3 seismogenic zonations and related catalogues: SZ9 [geometry modified from Gruppo di Lavoro (2004), catalogue CPTI04 (Gruppo di Lavoro CPTI, 2004)]; FRI [geometry modified from Slejko and Rebez (2002), catalogue NT4 (Camassi and Stucchi, 1997)]; 3LEV [geometry modified from Poli and Galadini (written personal communication), catalogue CPTI99 (Gruppo di Lavoro CPTI, 1999)]; 3 methods to compute the seismicity rates: HNH (Slejko *et al.*, 1998); A&M (Albarello and Mucciarelli, 2002); G-R (Gutenberg - Richter fit of the mean values of the two previous rates); 3 methods for M_{max} assessment: 1SB (Slejko *et al.*, 1998); K&G (Kijko and Graham, 1998); GEO (Wells and Coppersmith, 1994); and 2 *PGA* ARs: AMB (Ambraseys *et al.*, 1996); S&P (Sabetta and Pugliese, 1987). The additional B&S (Bragato and Slejko, 2005) AR was used for stiff soil. Consequently, the number of branches is 54 for rock (Rk) and soft soil (So), and 81 for stiff soil (St). All branches were evenly weighted (see the text for details).

3. SZ geometry

In the standard PSHA, seismic sources are modelled as SZs, where the earthquakes can randomly occur. Three seismogenic zonations have been used for the present PSHA (Fig. 3): they represent different levels of seismotectonic knowledge. Two of the models used derive from the Meletti *et al*. (2000) zonation, hereafter referred to as GNDT zonation, which was used for the Italian seismic hazard maps of Slejko *et al*. (1998) and Albarello *et al*. (2000), and is composed of 80 SZs for the whole of Italy. The first model (Fig. 3a), hereafter referred to as the ZS9 zonation (Gruppo di Lavoro, 2004), is a simplification of the GNDT zonation and was used for the latest version of the Italian seismic hazard map (Gruppo di Lavoro, 2004). The second zonation (Fig. 3b), hereafter referred to as FRI (Friuli) zonation, is a regional improvement (Slejko and Rebez, 2002) of the GNDT zonation mainly based on the distribution of the recent seismicity in NE Italy. The third zonation (Fig. 3c), hereafter referred to as the 3LEV (3 levels) zonation, is based on a different concept: strong earthquakes are linked to regional faults while the lower seismicity is associated to wider areas characterised by a general tectonic deformation (Stucchi *et al*., 2002). More precisely, in this zonation, seismicity refers to three zones: high seismicity (M>6) at the presently active front, intermediate seismicity (M>5) at the wider foothill strip, and the low seismicity at the less active belt.

Entering into detail, five SZs (SZs with labels starting with 9 in Fig. 3a) of the ZS09 zonation (Gruppo di Lavoro, 2004) were used for the present PSHA. The SZ 904 represents the Dinaric transpressive front, while SZ 222 collects the low to medium seismicity of central Slovenia. The SZ 905 is characterised by the high seismicity of the most active Alpine thrusts in Veneto and Friuli and by the mixed (Alpine and Dinaric) seismicity of the border area between Italy and Slovenia. The SZ 906 experienced earthquakes of medium magnitude related to the thrusts of the Southalpine belt from central Veneto to Lake Garda. The SZ 907 collects the low magnitude seismicity in Lombardy, and the SZ 903 represents the system of seismogenic faults in Engadin. In addition, two background zones, not present in the original ZS09 zonation, were introduced in the present elaboration to account for the active Dinaric front (SZ 111), and all the remaining earthquakes of the catalogue (SZ 200).

The FRI zonation (Fig. 3b) consists of 15 SZs as three SZs were added westwards to the Slejko and Rebez (2002) zonation simply taking the SZs of Meletti *et al*. (2000) as they are far away from the study area and, consequently, less important. In addition, the general background SZ 920 collects all the remaining earthquakes.

The 3LEV zonation (Galadini and Poli, written personal communication) consists of 9 SZs (Fig. 3c): two of those with strong earthquakes are in Slovenia (SZs 103 and 104), one in Friuli (SZ 101) and one in Veneto (SZ 102). The high seismicity SZs are contained in three wider medium seismicity SZs (SZs 201 in Friuli, 202 in Veneto, and 203 in Slovenia), and these last in two larger low seismicity SZs, one in Slovenia (SZ 303) and the second covers, mostly, the Friuli and Veneto plains (SZ 301). In addition, SZ 302 accounts for the low seismicity of the Alps while the background ZS 910, not present in the original version of the map, collects all the remaining earthquakes.

Moreover, a rough soil characterisation has been defined for the study territory to compute a soil seismic hazard map [see Rebez *et al*. (2001) for Friuli - Venezia Giulia]. In agreement with the seismic Eurocode 8 (EC8: CEN, 2002), the terrains have been classified in rock, stiff, and soft

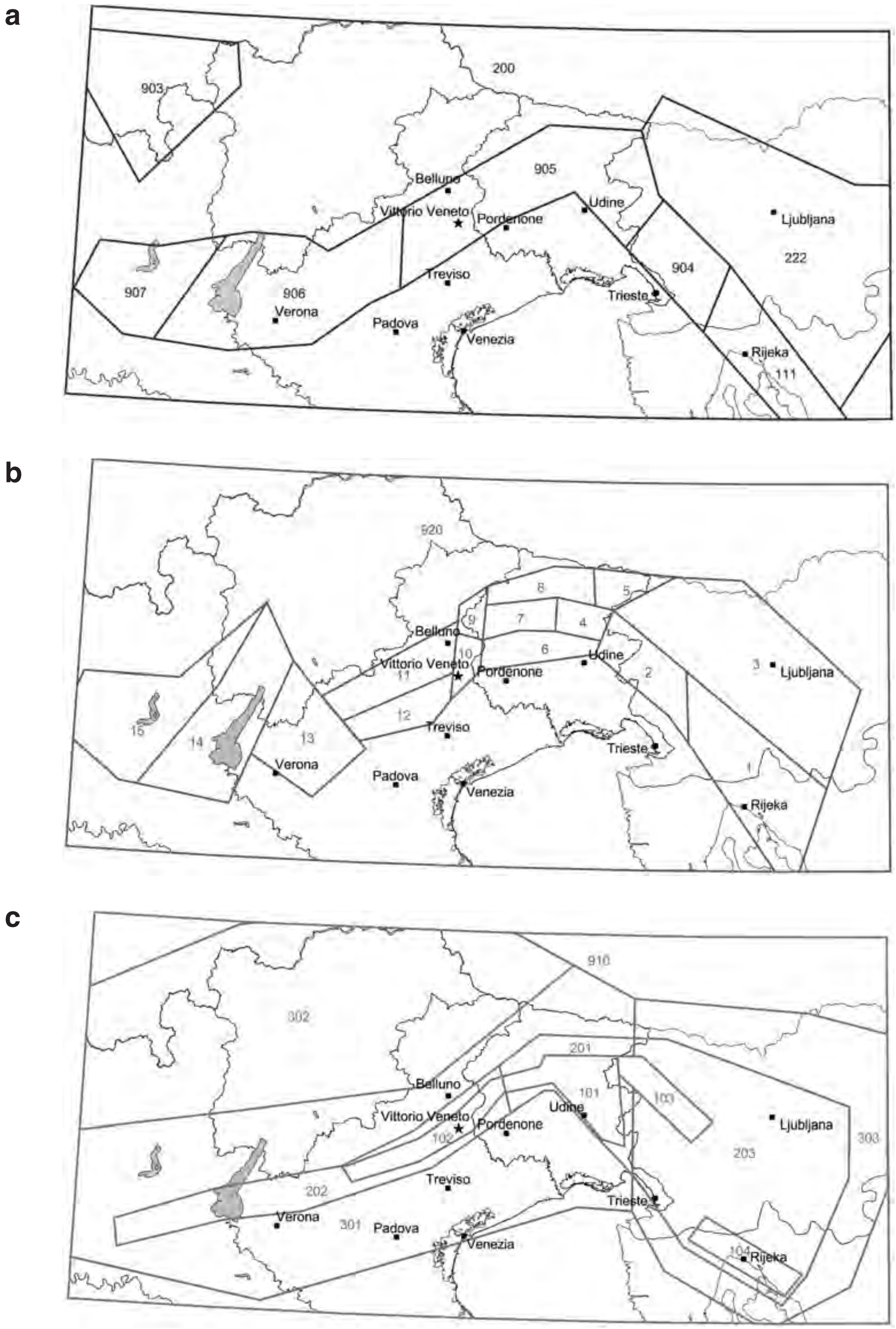


Fig. 3 - The 3 seismogenic zonations used: a) the ZS9 zonation [modified from Gruppo di Lavoro (2004)]; b) the FRI zonation [modified from Slejko and Rebez (2002)]; c) the 3LEV zonation [modified from Poli and Galadini (personal written communication)].

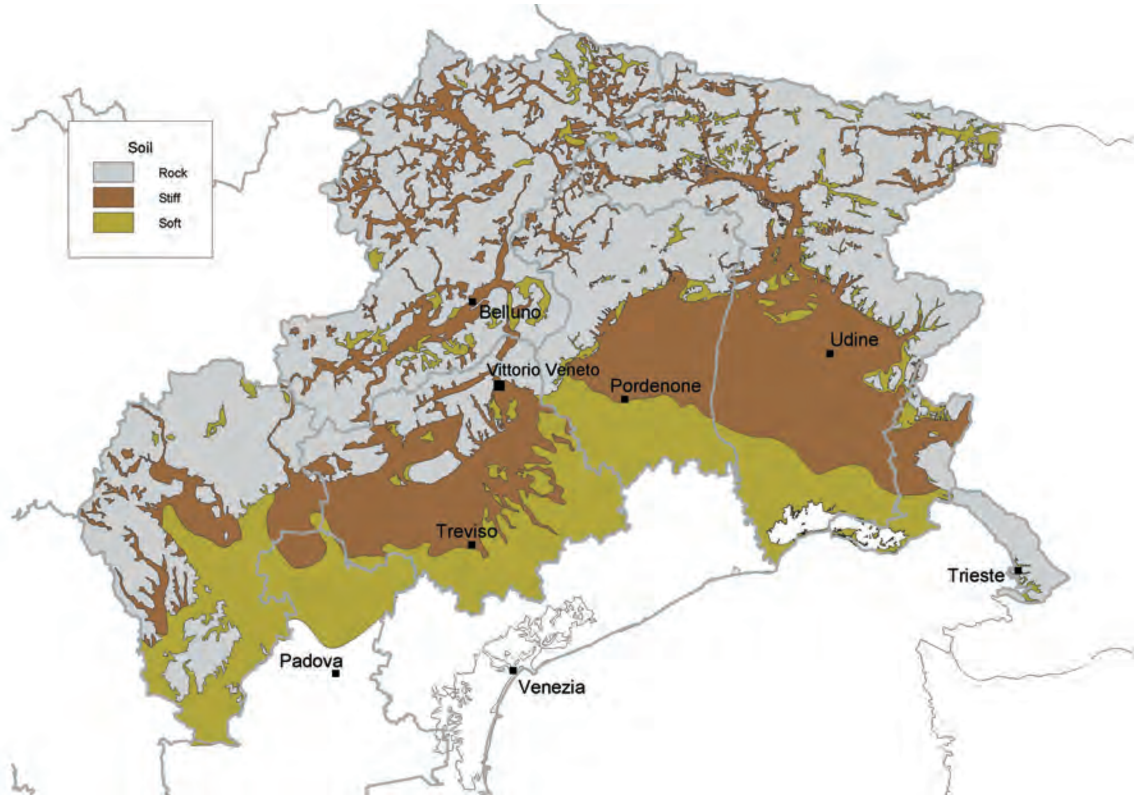


Fig. 4 - Soil characterisation [see Carulli *et al.* (2002) for Friuli and Zanferrari and Poli (personal written communication) for Veneto] according to EC8 (CEN, 2002) for the territory of NE Italy based on the geological and geophysical information available at the scale 1:50,000: rock (grey), stiff (brown), and soft soil (yellow).

soils according to the geological and geophysical information available at the scale 1:50,000 [see Carulli *et al*. (2002) for Friuli - Venezia Giulia and Zanferrari and Poli (written personal communication) for Veneto]. Fig. 4 shows the soil zonation, where rock dominates in the whole northern part of the study region and soft soil refers to the Veneto and Friuli plains. Stiff and soft soils, distributed everywhere in the mountain domain, indicate the Alpine valleys.

4. Seismicity rates

Different earthquake catalogues were associated with the three zonations because the zonations themselves were drawn considering different catalogues, according to the basic data used in the SZ construction. More precisely, the Camassi and Stucchi (1997) catalogue, hereafter NT4 catalogue, was used for the FRI zonation, the parametric catalogue prepared by the Gruppo di Lavoro CPTI (1999), hereafter CPTI99 catalogue, for the 3LEV zonation, and the latest version of the CPTI catalogue (Gruppo di Lavoro CPTI, 2004), hereafter CPTI04 catalogue, for the ZS9 zonation. All the catalogues were implemented with additional data taken from the bulletins of the Friuli - Venezia Giulia seismometric network (OGS, 1977-1981, 1982-1990, 1991-2002). Specific researches were used to integrate the historical (Camassi, personal communication) and instrumental (Renner, personal communication) parts of the catalogue: these integrations regarded a very limited number of events. As the reference magnitude in the Italian catalogues is M_S, the M_L reported in the OGS bulletins was converted into M_S (Margottini *et al.*, 1993). This relation was chosen instead of that by Camassi and Stucchi (1997) because the first was calibrated specifically on earthquakes which occurred in NE Italy. All events with M_S larger than, or equal to, 2.3 were considered for the period 1977 to 2002. In the case of double entries (from the national catalogues and from the OGS bulletins), preference was given to the national data (NT4, CPTI99, CPTI04 catalogues). The aftershock removal was done considering a time-space window (Gardner and Knopoff, 1974) calibrated on the data of the 1976 seismic sequence in Friuli (Slejko and Rebez, 2002).

Individual seismicity rates [the Bender and Perkins (1987) formulation of the Cornell (1968) approach does not need an exponential distribution for magnitude] have been computed following two different approaches: the “higher not highest” (HNH) method developed for the GNDT seismic hazard map of the Italian territory (Slejko *et al.*, 1998), and the Albarello and Mucciarelli (2002: A&M) method already applied to the seismic hazard map of the Italian territory prepared jointly by the Servizio Sismico Nazionale and the GNDT (Albarello *et al.*, 2000). Moreover, an additional branch was added smoothing (Aki, 1965; Utsu, 1965, 1966) the average value of the rates computed with the two cited methods by the G-R relation. The computed number of events in 100 years is reported in Table 1 and it can be seen that in some cases the difference between the results obtained by the HNH and the A&M approaches differ notably. This can be explained by the fact that, when the historical catalogue is particularly poor (case of SZs with a small area and not very seismic), the A&M method fixes the seismicity rate on the basis of the well documented seismicity in the last years.

The scaling law between magnitude M_S and moment M_0 is not linear from low to high values and two linear branches have been proposed, with changing point around 6.4 (Reiter, 1990). This fact affects the *b*-value estimates when M_S is considered instead of the moment magnitude M_W. We performed a preliminary check with the seismicity rates computed with both approaches for the whole study area and no slope variation was identified in the frequency – magnitude relation around M_S 6.4, while some doubts remain around M_S 6.7, which is represented by very few events. Anyway, the shift should be very limited (Ambraseys, 2003) and can be, then, not taken into account in the *b*-value estimation.

Different methodologies for assessing the *b*-value of the G-R relation are available in literature. The least-squares method (LSM) is often used, although not formally suitable since magnitude is not error free, cumulative event counts are not independent, and the error distribution of the number of earthquake occurrences does not follow a Gaussian distribution. The maximum likelihood method (MLM) has been widely applied (Aki, 1965; Utsu, 1965): Weichert (1980) proposed a general routine suitable also for different completeness periods of the earthquake catalogue. For our purposes, the MLM has been applied together with the LSM, which better fits the high-magnitude data when all data points are weighted equally. As the *b*-values obtained with the MLM range quite largely, only those between 0.7 and 1.3 have been considered acceptable: *b*-values outside this range have been obtained for a few SZs where the scarce historical data perhaps show a different trend from that of the few instrumental ones too.

The hypothesis of merging some poor SZs together has been discarded because the geometry of the SZs was defined on the basis of the seismicity characteristics. The *b*-values coming from the LSM have resulted acceptable in all these peculiar cases, consequently they have then been taken. The final *b*-values are reported in Table 2: the flag identifies the very few cases where the estimates come from the LSM. The seismicity rates computed sampling the G-R curve constructed with the calculated *b*-values are reported in Table 1, together with the rate (not used in the hazard calculations) obtained averaging the HNH and A&M rates. It can be seen that the G-R rates do not differ much from the average rates: they simply smooth the fluctuations.

5. M_{max}

A detailed analysis of the seismicity in the SZs has been carried out to identify M_{max} for each SZ, to be introduced in the PSHA. This analysis is restricted to the only four SZs (out of the 10 SZs used for the hazard assessment) of the 3LEV zonation where earthquakes larger than 6 can occur. M_{max} was estimated in three different ways: the first two are statistical while the third is based on geological information.

The first way is the “one step beyond” (1SB) approach used for the Italian GNDT seismic hazard map (Slejko *et al*., 1998). It extrapolates the observed seismicity rates by one step (in the present study 0.3 magnitude units) according to the G-R *b*-value of the SZ when the corresponding return period exceeds the time length of the earthquake catalogue [1000 years; see more detailed description in Slejko *et al*. (1998)]. For several SZs, especially of the ZS9 zonation, it was not possible to define M_{max} according to the 1SB method because the M_{max} computed for them refers to a return period shorter than 1000 years and the events should, then, be contained in the catalogue.

The second way uses a statistical approach [Kjiko and Graham (1998): K&G]. This approach computes M_{max} for a source on a statistical basis using as input data: the maximum observed magnitude, the threshold magnitude considered complete in the catalogue, the average error in the magnitude estimates (fixed in our case arbitrarily at 0.2), the *b*-value of the G-R relation and its standard deviation, the annual rate (i.e.: the number of earthquakes with magnitude greater than, or equal to, the threshold magnitude) and the catalogue time span which is considered complete. This last parameter was set at 500 years as both methodologies used for the seismicity rate computation scan the whole catalogue and either choose the period which is the most seismic in agreement with the return period of each magnitude class, a priori estimated (HNH method), or average the weighted seismicity rates computed on different periods (A&M method). The K&G approach considers four formulations for M_{max} computation: the most robust Bayesian Kijko-Sellevol formula has been applied here. It was possible to compute an M_{max} different from the maximum observed one only for some SZs (Table 2) and also in these cases the increment is limited (in general 0.1), this depending on the long completeness period (500 years) considered. Larger differences between the maximum observed magnitude and M_{max} have been obtained in the case of the most detailed FRI zonation, where the SZ catalogues contain few events.

The third way is a geological (GEO) approach and it is based on the tectonic characteristics of each SZ. More precisely, the main tectonic feature was identified in each SZ and its length was estimated. No univocal definition is available for the fault rupture length: the general use is to

Table 1 - Seismicity rates (number of earthquakes in 100 years) of the SZs. The asterisk after the G-R rate indicates that the LSM was used.

Zone	Ms	A&M	HNH	G-R
ZS9				
903	2,8	14,4	95,24	47,89
	3,1	13,66	42,86	27,93
	3,4	1,09	7,69	16,29
	3,7	2,87	14,29	9,5
	4	5,51	14,29	5,54
	4,3	6,83	9,52	3,23
	4,6	0,7	0,66	1,89
	4,9	0,99	1,48	1,1
	5,2	0,16	0,2	0,64
	5,5	0	0	0,37
	5,8	0,13	0,13	0,52
904	2,5	139,49	261,9	278,02
	2,8	109,02	214,29	119,27
	3,1	36,04	80,95	51,16
	3,4	13,41	34,62	21,95
	3,7	1,66	3,77	9,42
	4	2,89	4,85	4,04
	4,3	1,16	1,94	1,73
	4,6	0,42	0,65	0,74
	4,9	0	0	0,32
	5,2	0	0	0,14
	5,5	0,54	0,4	0,1
905	2,5	618,18	2419,05	2355,9
	2,8	569,39	2204,76	1170,39
	3,1	599,57	1042,86	581,44
	3,4	292,52	390,48	288,85
	3,7	49,83	104,76	143,5
	4	52,16	54,72	71,29
	4,3	31,81	37,74	35,42
	4,6	8,8	11,76	17,59
	4,9	7,48	9,43	8,74
	5,2	1,54	1,96	4,34
	5,5	2,51	1,98	2,16
	5,8	1,32	1,32	1,07
	6,1	0	0	0,53
	6,4	0,87	0,66	0,26
	6,7	0,24	0,27	0,26
906	2,8	107,56	285,71	213,98
	3,1	66,49	161,9	103,99
	3,4	22,01	109,52	50,54
	3,7	6,2	28,57	24,56
	4	3,13	3,92	11,94
	4,3	5,63	5,88	5,8
	4,6	4,24	5,23	2,82
	4,9	2,01	3,27	1,37
	5,2	0,32	0,27	0,67
	5,5	0,74	0,5	0,32
	5,8	0	0	0,16
	6,1	0,12	0,11	0,08
	6,4	0,11	0,11	0,07

Zone	Ms	A&M	HNH	G-R
907	2,8	12,18	61,9	22,8
	3,1	1,85	19,05	13,36
	3,4	0,98	9,52	7,83
	3,7	0,47	1,89	4,59
	4	0,14	0,13	2,69
	4,3	3,74	7,69	1,58
	4,6	1,84	2,61	0,92
	4,9	0,18	0,25	0,54
	5,2	0	0	0,32
	5,5	0,23	0,13	0,45
111	2,8	142,04	376,92	349,17
	3,1	117,27	226,92	165,89
	3,4	82,03	204,76	78,82
	3,7	5,04	23,81	37,45
	4	4,4	15,38	17,79
	4,3	11,84	19,05	8,45
	4,6	1,46	1,94	4,02
	4,9	0,91	0,99	1,91
	5,2	0,57	0,66	0,91
	5,5	0,6	0,5	0,43
	5,8	0	0	0,2
	6,1	0,23	0,27	0,19
222	2,8	426,57	1019,05	704,48
	3,1	167,57	633,33	335
	3,4	55,13	257,14	159,3
	3,7	7,43	52,38	75,75
	4	14,45	19,05	36,02
	4,3	23,02	33,98	17,13
	4,6	11,85	14,29	8,14
	4,9	5,7	9,15	3,87
	5,2	1,88	2,91	1,84
	5,5	1,1	1,74	0,88
	5,8	0	0	0,42
	6,1	0,36	0,5	0,2
	6,4	0,29	0,11	0,18
200	2,8	534,87	1076,19	820,06
	3,1	197,12	457,14	364,53
	3,4	172,02	300	162,04
	3,7	15,24	47,62	72,03
	4	24,9	38,46	32,02
	4,3	15,65	18,3	14,23
	4,6	8,62	14,29	6,33
	4,9	1,99	2,61	2,81
	5,2	0,49	0,25	1,25
	5,5	0	0	0,56
	5,8	0	0	0,25
	6,1	0	0	0,11
	6,4	0	0	0,05
	6,7	0,17	0,11	0,04

Zone	Ms	A&M	HNH	G-R
3LEV				
101	2,5	323,74	1133,33	
	2,8	370,9	1057,14	301.79*
	3,1	193,31	400	156.95*
	3,4	73,14	138,46	81.63*
	3,7	18,12	26,92	42.45*
	4	11,49	15,38	22.08*
	4,3	7,81	11,54	11.48*
	4,6	2,31	2,91	5.97*
	4,9	2,67	2,91	3.11*
	5,2	1,85	2,91	1.62*
	5,5	0,55	0,13	0.84*
	5,8	0,77	0,5	0.44*
	6,1	0	0	0.23*
	6,4	0,57	0,27	0.25*
102	2,8	34,13	104,76	78,93
	3,1	22,97	71,43	41,44
	3,4	18,9	57,69	21,76
	3,7	0,43	1,89	11,42
	4	1,24	1,89	6
	4,3	2,71	3,77	3,15
	4,6	1,18	1,96	1,65
	4,9	1,66	2,61	0,87
	5,2	0,26	0,25	0,46
	5,5	0	0	0,24
	5,8	0,37	0,13	0,13
	6,1	0	0	0,07
	6,4	0,44	0,5	0,07
103	2,8	112,44	285,71	91.48*
	3,1	57,7	152,38	45.34*
	3,4	7,89	42,86	22.47*
	3,7	2,77	19,05	11.13*
	4	2,66	3,77	5.52*
	4,3	2,12	2,91	2.73*
	4,6	0,76	0,99	1.36*
	4,9	0	0	0.67*
	5,2	0	0	0.33*
	5,5	0,69	0,13	0.16*
	5,8	0	0	0.08*
	6,1	0,2	0,13	91,48
104	2,8	46,58	165,38	
	3,1	49,77	96,15	21.49*
	3,4	26,49	90,48	12.2*
	3,7	0	0	6.93*
	4	0	0	3.94*
	4,3	1,8	2,91	2.24*
	4,6	0,55	0,66	1.27*
	4,9	0,38	0,25	0.72*
	5,2	0,24	0,25	0.41*
	5,5	0,62	0,66	0.23*
	5,8	0	0	0.13*
	6,1	0,23	0,27	0.17*

Zone	Ms	A&M	HNH	G-R
201	2,5	170,48	657,14	635,48
	2,8	155,71	619,05	315,06
	3,1	156,83	266,67	156,2
	3,4	65,72	95,24	77,44
	3,7	17,93	30,77	38,39
	4	11,82	16,98	19,03
	4,3	11,23	16,98	9,44
	4,6	0,92	1,31	4,68
	4,9	3,17	3,92	2,32
	5,2	0	0	1,15
	5,5	0	0	0,57
	5,8	0,43	0,5	0,56
202	3,1	65,75	190,48	101,43
	3,4	20,25	52,38	46,09
	3,7	7,19	28,57	20,94
	4	6,56	9,43	9,51
	4,3	2,36	5,66	4,32
	4,6	2,61	3,27	1,96
	4,9	0,66	0,99	0,89
	5,2	0,33	0,4	0,41
	5,5	0,59	0,5	0,18
	5,8	0,33	0,22	0,15
203	2,8	805,54	1171,43	950,14
	3,1	272,83	585,71	415,82
	3,4	111,81	314,29	181,98
	3,7	15,02	61,9	79,64
	4	13,92	19,05	34,85
	4,3	17,47	19,42	15,25
	4,6	10,66	13,07	6,68
	4,9	3,65	5,88	2,92
	5,2	2,55	3,88	1,28
	5,5	1,77	1,99	0,56
	5,8	0,25	0,13	0,44
301	2,8	339,24	947,62	612,1
	3,1	150,79	371,43	293,78
	3,4	107,97	238,1	141
	3,7	17,82	76,19	67,67
	4	21,29	38,46	32,48
	4,3	15,46	16,99	15,59
	4,6	11,44	19,05	7,48
	4,9	3,07	4,58	6,9
302	2,5	234,95	471,43	447,25
	2,8	181,17	352,38	221,74
	3,1	66,42	133,33	109,94
	3,4	56,23	104,76	54,51
	3,7	8,57	23,81	27,02
	4	10,29	15,38	13,4
	4,3	6,71	9,15	6,64
	4,6	1,77	2,91	3,29
	4,9	1,5	1,96	3,24

Table 1 - Cont.

Zone	Ms	A&M	HNH	G-R
303	2,8	177,68	300	336,26
	3,1	172,62	290,48	166,94
	3,4	67,11	133,33	82,88
	3,7	9,96	28,57	41,15
	4	9,19	15,38	20,43
	4,3	17,73	23,3	10,14
	4,6	3,86	4,85	5,04
	4,9	2,78	3,92	4,97
910	2,8	103,4	184,62	128,94
	3,1	33,53	107,69	62,21
	3,4	13,4	46,15	30,02
	3,7	0,46	1,89	14,48
	4	2,63	7,55	6,99
	4,3	6,55	9,43	3,37
	4,6	0,81	0,99	1,63
	4,9	1,48	1,94	0,78
	5,2	0,44	0,4	0,38
	5,5	0	0	0,18
	5,8	0,12	0,13	0,09
	6,1	0,18	0,13	0,04
	6,4	0	0	0,02
	6,7	0,15	0,11	0,02
FRI				
1	2,8	251,91	496,15	439,32
	3,1	142,16	285,71	202,78
	3,4	67,26	233,33	93,6
	3,7	4,67	33,33	43,2
	4	2,34	14,29	19,94
	4,3	12,17	14,56	9,2
	4,6	3,21	5,66	4,25
	4,9	0,91	0,99	1,96
	5,2	1,06	1,31	0,91
	5,5	1	1,48	0,42
	5,8	0	0	0,19
	6,1	0,23	0,27	0,17
2	2,5	93,72	471,43	
	2,8	109,76	319,05	139.27*
	3,1	27,51	114,29	60.19*
	3,4	21,43	85,71	26.01*
	3,7	2,75	11,54	11.24*
	4	0,36	0,97	4.86*
	4,3	0,43	0,97	2.1*
	4,6	0,32	0,65	0.91*
	4,9	1,2	1,32	0.39*
	5,2	0,14	0,13	0.17*
	5,5	0,13	0,13	0.13*
3	2,8	379,47	933,33	635,56
	3,1	139,91	538,1	290,69
	3,4	45,8	214,29	132,95
	3,7	5,62	52,38	60,81
	4	8,22	19,05	27,81
	4,3	15,01	17,65	12,72
	4,6	7,35	9,15	5,82

Zone	Ms	A&M	HNH	G-R
	4,9	5,55	9,15	2,66
	5,2	1,43	1,94	1,22
	5,5	1,41	0,74	0,56
	5,8	0,29	0,13	0,25
	6,1	0,18	0,13	0,21
4	2,5	368,98	900	416.83*
	2,8	319,72	819,05	219.72*
	3,1	138,48	304,76	115.82*
	3,4	49,15	84,62	61.05*
	3,7	4,39	15,38	32.18*
	4	7,14	11,54	16.96*
	4,3	9,21	11,54	8.94*
	4,6	0,64	0,66	4.71*
	4,9	1,02	0,99	2.48*
	5,2	1,87	1,96	1.31*
	5,5	0,47	0,13	0.69*
	5,8	0,64	0,13	0.36*
	6,1	0,18	0,13	0.19*
	6,4	0,64	0,11	0.21*
5	2,5	85,51	200	62.71*
	2,8	59,6	152,38	33.82*
	3,1	14,63	71,43	18.24*
	3,4	1,4	9,52	9.84*
	3,7	0,54	1,89	5.31*
	4	1,37	3,77	2.86*
	4,3	3,36	3,92	1.54*
	4,6	0	0	0.83*
	4,9	0	0	0.45*
	5,2	0	0	0.24*
	5,5	0	0	0.13*
	5,8	0,21	0,13	0.07*
	6,1	0	0	0.04*
	6,4	0,15	0,11	0.04*
6	2,5	31,94	66,67	66,57
	2,8	19,65	47,62	30,85
	3,1	14,42	38,46	14,3
	3,4	0,68	3,85	6,62
	3,7	1,56	3,77	3,07
	4	0	0	1,42
	4,3	0,54	0,97	0,66
	4,6	0,49	0,65	0,31
	4,9	0	0	0,14
	5,2	0,32	0,27	0,12
	5,2	0	0,121	0
7	2,5	252,78	471,43	
	2,8	205,65	509,52	371,82
	3,1	160,56	247,62	175,1
	3,4	53,06	76,19	82,46
	3,7	18,46	42,86	38,83
	4	28,54	30,77	18,29
	4,3	6,23	7,69	8,61

Zone	Ms	A&M	HNH	G-R
	4,6	4,6	3,92	4,06
	4,9	1,71	1,31	1,91
	5,2	0,34	0,25	0,9
	5,5	0,83	0,13	0,42
	5,8	0,64	0,5	0,38
8	2,5	142,9	490,48	463,84
	2,8	129,56	447,62	229,22
	3,1	107,01	184,62	113,27
	3,4	44,56	71,43	55,98
	3,7	9,97	19,23	27,66
	4	5,82	9,43	13,67
	4,3	11,01	13,21	6,76
	4,6	2,07	2,91	3,34
	4,9	2,03	2,91	1,65
	5,2	0	0	0,82
	5,5	0,15	0,13	0,4
	5,8	0,22	0,13	0,39
9	2,8	42,97	57,14	
	3,1	39,69	71,43	15.96*
	3,4	4,21	9,52	7.69*
	3,7	0	0	3.7*
	4	0	0	1.78*
	4,3	2,34	3,77	1.66*
10	2,8	43,84	76,19	79,34
	3,1	32,87	47,62	39,15
	3,4	28,45	47,62	19,32
	3,7	3,15	3,77	9,53
	4	3,14	3,92	4,7
	4,3	1,4	1,31	2,32
	4,6	0,67	0,65	1,15
	4,9	0	0	0,57
	5,2	0	0	0,28
	5,5	0	0	0,14
	5,8	0,88	0,13	0,07
	6,1	0	0	0,03
	6,4	0,62	0,11	0,03
11	2,8	41,34	95,24	84,6
	3,1	25,93	85,71	40,87
	3,4	5,9	28,57	19,74
	3,7	3,33	14,29	9,54
	4	1,21	1,96	4,61
	4,3	3,63	4,85	2,23
	4,6	1,65	1,96	1,08
	4,9	0,46	0,25	1
12	2,8	10,11	30,77	
	3,1	5,93	23,81	
	3,4	9,49	50	14,13
	3,7	0	0	7,53
	4	1,04	3,77	4,01
	4,3	1,26	1,96	2,14
	4,6	0,6	1,31	1,14
	4,9	1,67	2,61	0,61
	5,2	0,28	0,25	0,32

Zone	Ms	A&M	HNH	G-R
	5,5	0	0	0,17
	5,8	0	0	0,09
	6,1	0	0	0,05
	6,4	0,21	0,11	0,06
13	2,5	31,53	157,14	
	2,8	38,3	152,38	96,89
	3,1	10,82	61,9	45,82
	3,4	11,67	61,9	21,67
	3,7	1,34	14,29	10,25
	4	0,45	1,89	4,85
	4,3	1,57	1,97	2,29
	4,6	1,01	1,94	1,08
	4,9	0,62	0,99	0,51
	5,2	0,22	0,27	0,24
	5,5	0,31	0,13	0,11
	5,8	0	0	0,05
	6,1	0	0	0,03
	6,4	0,11	0,11	0,02
14	2,8	27,37	142,86	
	3,1	28,77	71,43	41,51
	3,4	4,84	33,33	22,29
	3,7	2,43	14,29	11,96
	4	2,32	5,66	6,42
	4,3	5,97	7,19	3,45
	4,6	3,6	3,92	1,85
	4,9	0,42	0,5	0,99
	5,2	0,28	0,25	0,53
	5,5	0,3	0,13	0,29
	5,8	0,11	0,11	0,33
15	2,8	7,99	47,62	26,09
	3,1	2,32	11,54	15,05
	3,4	5,07	33,33	8,68
	3,7	0,62	1,89	5,01
	4	0	0	2,89
	4,3	2,35	3,77	1,67
	4,6	1,89	2,61	0,96
	4,9	0,42	0,27	0,55
	5,2	0,2	0,25	0,32
	5,5	0,28	0,13	0,44
920	2,8	565,07	1000	778,4
	3,1	230,52	509,52	374,45
	3,4	136,78	276,19	180,13
	3,7	32,33	61,9	86,65
	4	32,22	42,31	41,68
	4,3	35,54	48,54	20,05
	4,6	7,69	10,68	9,65
	4,9	4,8	7,55	4,64
	5,2	0,51	0,4	2,23
	5,5	0	0	1,07
	5,8	0,13	0,13	0,52
	6,1	0	0	0,25
	6,4	0	0	0,12
	6,7	0,17	0,11	0,11

take the half of the total length (Mark, 1977) but also the lower value of one third was often used. We took the one third of the total fault length as rupture length when not explicitly declared (Galadini *et al*., 2005). It was, then, possible to compute M_{max} according to the relations calibrated by Wells and Coppersmith (1994).

The seismicity rate related to M_{max} was computed extrapolating the G-R interpolation of the seismicity rates, whatever the method used to compute them. The M_{max} was considered in different ways in the PSHA: adding the rate of the 1SB M_{max}, when possible; adding all the rates (calculated through the G-R relation) from the maximum observed magnitude to the K&G M_{max}; adding only the rate of the GEO M_{max}.

6. Attenuation

A specific AR of *PGA* for NE Italy was recently proposed (Bragato and Slejko, 2005: B&S): it refers to a rigid soil. In addition, the most popular Italian and European relations were considered in the present study. More precisely, the Ambraseys *et al*. (1996: AMB) relation, calibrated on European strong-motion data according to the S-wave velocity in the upper 30 m (V_{30}) for three soil types [rock (V_{30} >750 m/s), stiff (750 ≥ V_{30} ≥360 m/s), and soft soil (V_{30} <360 m/s)] and the Sabetta and Pugliese (1987: S&P), calibrated on Italian data for two soil types [EC8 classification: stiff (V_{30} >800 m/s, almost equivalent to rock in the AMB relation) and soil (800 ≥ V_{30} ≥400 m/s, almost equivalent to the stiff soil of the AMB relation)], were used. The soil category is further subdivided into two classes according to the thickness of the soil layer (H): shallow soil (5≤H≤20 m) and deep soil (H >20 m). Terrains with H<5 m are considered stiff. For horizontal *PGA* computation, the S&P relation for deep soil is equal to that for stiff soil. Considering that in the study region almost all terrains with a V_{30} between 400 and 800 m/s (see Fig. 4) are characterized by an H greater than 20 m (Carulli, personal communication), the S&P stiff soil relation was applied to rock and stiff soil of Fig. 4, while the S&P shallow soil relation was applied to soft soil of Fig. 4 (Sabetta, personal communication). Since the S&P relation refers to two different kinds of magnitude according to the size of the earthquake, the M_S magnitudes from the catalogue were converted into M_L using the GNDT relation (Camassi and Stucchi, 1997), when necessary. The B&S relation refers to M_L and the proper transformation has been applied as well.

The AMB relation is defined for distance from the fault, although only for large magnitudes was it possible to assess such distances, which were otherwise substituted by the epicentral distance. The Cornell (1968) approach, in the Bender and Perkins (1987) formulation, computes the hazard at each site of the study region by discrete summation of the individual contributions from the centre of the mass of the small circular elements into which the SZ is subdivided. This distance is rigorously neither the epicentral distance nor that of the causative fault, but in practice can be assumed to be equal to the epicentral one. The consequent correction (Montaldo *et al*., 2005) has been, then, introduced into the AMB relation.

The S&P and AMB ARs were defined for similar magnitude ranges and, consequently, their standard deviation (σ_a) does not differ very much (0.19 and 0.25, respectively). On the contrary, the B&S AR was calibrated also for low magnitudes and, consequently, its σ_a is remarkably higher (0.399). For the sake of homogeneity, a reduced standard deviation has been computed for

Table 2 - Statistical parameters for the SZs. M_x = maximum observed magnitude; M_0 = minimum magnitude considered in the elaboration; a, b = coefficients of the G-R relation; σ_b = standard deviation on the b-value; M_{max} = computed maximum magnitude; σ_{Mmax} = standard deviation of M_{max}; λ_{max} = 100-year rate of M_{max}. The asterisk after the λ_{max} value indicates that the LSM was used.

	Zone	M_x	M_0	a	b	σ_b	M_{max}	σ_{Mmax}	λ_{max}
	ZS9								
HNH	903	5,5	2,7	2,63	0,85	0,04	5,5	0,2	
	904	5,6	2,4	3,88	1,23	0,04	5,8	0,3	0,056
	905	6,7	2,4	4,58	1,1	0,01	6,8	0,2	0,126
	906	6,5	2,7	3,87	1,1	0,03	6,9	0,4	0,019
	907	5,5	2,7	3,2	1,1	0,11	5,7	0,2	0.085*
	111	6	2,7	4,04	1,1	0,03	6	0,2	
	222	6,3	2,7	4,48	1,13	0,02	6,4	0,2	0,177
	200	6,6	2,7	4,68	1,21	0,02	7	0,4	0,016
A&M	903	5,5	2,7	2,55	0,93	0,08	5,6	0,2	0.22*
	904	5,6	2,4	2,78	1	0,07	5,8	0,2	0.095*
	905	6,7	2,4	3,57	0,87	0,01	6,7	0,2	
	906	6,5	2,7	2,9	0,92	0,05	6,8	0,4	0,044
	907	5,5	2,7	1,51	0,74	0,1	5,7	0,2	0.196*
	111	6	2,7	3,49	1,03	0,04	6,1	0,2	0,161
	222	6,3	2,7	3,46	0,95	0,03	6,3	0,2	
	200	6,6	2,7	4,11	1,11	0,03	6,9	0,4	0,028
G-R	903	5,5	2,7	2,25	0,78	0,05	5,5	0,2	
	904	5,6	2,4	3,75	1,23	0,04	5,9	0,3	0,031
	905	6,7	2,4	4,2	1,01	0,01	6,7	0,2	
	906	6,5	2,7	3,54	1,04	0,04	6,9	0,4	0,023
	907	5,5	2,7	1,91	0,77	0,07	5,5	0,2	
	111	6	2,7	3,84	1,08	0,03	6,1	0,2	0,179
	222	6,3	2,7	4,14	1,08	0,02	6,4	0,2	0,169
	200	6,6	2,7	4,46	1,17	0,02	7	0,4	0,019
	3LEV								
HNH	101	6,5	2,4	4,47	1,19	0,02	6,9	0,4	0,018
	102	6,3	2,7	3,23	1,01	0,05	6,6	0,4	0,037
	103	6	2,7	3,76	1,17	0,08	6,4	0,4	0.019*
	104	6	2,7	2,8	0,92	0,1	6,1	0,2	0.154*
	201	5,8	2,4	3,99	1,09	0,02	5,8	0,2	
	202	5,8	3,1	4,25	1,23	0,06	5,9	0,2	0,098
	203	5,8	2,7	4,7	1,2	0,02	5,8	0,2	
	301	4,9	2,7	4,33	1,11	0,02	4,9	0,2	
	302	4,9	2,4	3,65	1,03	0,02	4,9	0,2	
	303	4,8	2,7	3,81	1,03	0,03	4,8	0,2	
	910	6,6	2,7	3,63	1,1	0,04	7,3	0,7	0,004
A&M	101	6,5	2,7	2,97	0,85	0,03	6,6	0,2	0.229*
	102	6,3	2,7	2,09	0,78	0,06	6,5	0,3	0,105
	103	6	2,7	2,31	0,85	0,06	6,2	0,3	0.11*
	104	6	3,1	3,48	1,17	0,11	6,6	0,6	0,006
	201	5,8	2,4	3,03	0,88	0,02	5,8	0,2	
	202	5,8	3,1	3,01	0,97	0,07	5,9	0,2	0,194
	203	5,8	2,7	4,41	1,19	0,03	5,8	0,2	
	301	4,9	2,7	3,54	0,97	0,03	4,9	0,2	
	302	4,9	2,4	3,25	0,99	0,03	4,9	0,2	
	303	4,8	2,7	3,46	0,99	0,03	4,8	0,2	
	910	6,6	2,7	2,86	0,97	0,06	7,3	0,7	0,006
G-R	101	6,5	2,7	3,45	0,95	0,04	6,6	0,2	0.151*
	102	6,3	2,7	2,83	0,93	0,05	6,6	0,3	0,043
	103	6	2,7	3,1	1,02	0,07	6,3	0,3	0.047*
	104	6	3	2,24	0,82	0,1	6,1	0,2	0.173*

	Zone	M_x	M_0	a	b	σ_b	M_{max}	σ_{Mmax}	λ_{max}
	201	5,8	2,4	3,64	1,02	0,02	5,8	0,2	
	202	5,8	3,1	3,81	1,14	0,06	5,9	0,2	0,121
	203	5,8	2,7	4,58	1,2	0,02	5,8	0,2	
	301	4,9	2,7	4,05	1,06	0,02	4,9	0,2	
	302	4,9	2,4	3,49	1,02	0,03	4,9	0,2	
	303	4,8	2,7	3,66	1,01	0,03	4,8	0,2	
	910	6,6	2,7	3,35	1,06	0,05	7,3	0,7	0,004
	FRI								
HNH	1	6,2	2,7	4,2	1,12	0,02	6,3	0,2	0,139
	2	5,5	2,4	4,11	1,23	0,03	5,6	0,2	0,167
	3	6,2	2,7	4,57	1,18	0,02	6,3	0,2	0,137
	4	6,5	2,4	4,47	1,24	0,02	7,1	0,6	0,005
	5	6,4	2,4	2,78	0,98	0,09	7,1	0,7	0.007*
	6	5,2	2,4	3,07	1,13	0,07	5,3	0,2	0,121
	7	5,9	2,7	4,25	1,17	0,03	6	0,2	0,17
	8	5,9	2,4	3,85	1,09	0,02	5,9	0,2	
	9	4,4	3	2,97	1,08	0,36	4,4	0,2	*
	10	6,4	2,7	3,51	1,15	0,06	7,2	0,8	0,002
	11	4,8	2,7	3,48	1,1	0,05	4,8	0,2	
	12	6,4	3,3	3,31	1,06	0,11	7	0,6	0,008
	13	6,4	2,4	3,18	0,99	0,03	6,7	0,4	0,035
	14	5,9	2,7	3,29	1,02	0,04	6	0,2	0,148
	15	5,5	2,7	2,54	0,9	0,06	5,5	0,2	
	920	6,7	2,7	4,35	1,09	0,02	6,9	0,3	0,067
A&M	1	6,2	2,7	3,8	1,11	0,04	6,5	0,3	0,038
	2	5,5	2,7	2,93	1,05	0,09	5,7	0,3	0.088*
	3	6,2	2,7	3,55	1,01	0,03	6,3	0,2	0,154
	4	6,5	2,4	2,7	0,8	0,04	6,5	0,2	*
	5	6,4	2,4	1,75	0,77	0,07	6,9	0,5	0.027*
	6	5,2	2,4	2,55	1,08	0,1	5,5	0,3	0,041
	7	5,9	2,4	3,12	0,89	0,02	5,9	0,2	
	8	5,9	2,4	2,93	0,89	0,03	5,9	0,2	
	9	4,4	2,7	3,06	1,17	0,25	4,4	0,2	*
	10	6,4	2,7	2,54	0,88	0,06	6,8	0,4	0,036
	11	4,8	2,7	2,51	0,93	0,08	4,8	0,2	
	12	6,4	2,7	1,38	0,67	0,05	6,8	0,4	0.067*
	13	6,4	2,7	2,3	0,9	0,08	7,1	0,7	0,008
	14	5,9	3	2,69	0,93	0,08	6,1	0,3	0.104*
	15	5,5	2,7	1,31	0,67	0,06	5,6	0,2	0.361*
	920	6,7	2,7	3,83	1,01	0,02	6,9	0,3	0,073
G-R	1	6,2	2,7	4,05	1,12	0,03	6,4	0,3	0,076
	2	5,5	2,7	3,79	1,21	0,09	5,6	0,2	0.103*
	3	6,2	2,7	4,24	1,13	0,03	6,3	0,2	0,132
	4	6,5	2,4	3,26	0,93	0,04	6,6	0,2	0.132*
	5	6,4	2,4	2,37	0,89	0,08	6,9	0,6	0.017*
	6	5,2	2,4	2,88	1,11	0,08	5,4	0,3	0,077
	7	5,9	2,7	3,9	1,09	0,03	5,9	0,2	
	8	5,9	2,4	3,51	1,02	0,02	5,9	0,2	
	9	4,4	3	2,77	1,06	0,36	4,4	0,2	*
	10	6,4	2,7	3,06	1,02	0,06	7	0,6	0,008
	11	4,8	2,7	3,16	1,05	0,06	4,8	0,2	
	12	6,4	3,3	2,58	0,91	0,12	6,9	0,6	0,02
	13	6,4	2,7	3,3	1,08	0,06	7,1	0,7	0,004
	14	5,9	3	2,74	0,9	0,07	6	0,2	0,219
	15	5,5	2,7	2,02	0,8	0,07	5,5	0,2	
	920	6,7	2,7	4,14	1,06	0,02	6,9	0,3	0,067

the B&S AR considering only events with M_s 4.0 and larger and the smaller σ_a obtained (0.324) was used in the PSHA (see also Slejko and Bragato, 2008). All the three ARs were extrapolated outside their range (Ambraseys, 1995) as seismicity rates of magnitude classes below 4.5 were also used in the hazard computation.

7. Results for the Friuli - Venezia Giulia and eastern Veneto regions

Fifty-four branches constitute the logic tree (Fig. 2) for rock and soft soil PSHA: 3 zonations, 3 methods to compute seismicity rates, 3 M_{max} estimates, and 2 ARs. The B&S AR was considered for stiff soil as well bringing the number of branches in this case to 81. The aleatory uncertainties of the ARs have been taken into account by introducing their σ_a into the computation.

A total of 189 runs of the Seisrisk III code (Bender and Perkins, 1987) have been processed in order to compute the hazard results of all the branches of the logic tree for each of the 3 soil types. Some results of individual branches related to different ARs can be found in Slejko and Bragato (2008). The median values without considering the AR σ_a are not considered in the present study because they do not represent the result of the application of a fully probabilistic approach. Some of those maps can be found in Slejko and Bragato (2008), where the influence of the AR in hazard results is investigated. Hazard for rock and stiff and soft soil has been computed for 20 return periods ranging from 20 to 50,000 years. In each run, the median value of *PGA* has been estimated as well as the value which accounts for the σ_a of the AR used. In such a way, the complete hazard curve (with and without the AR σ_a) related to each branch was obtained. According to the Senior Seismic Hazard Analysis Committee (1997), the mean hazard curve [see discussion about mean and median hazard curves in Abrahamson and Bommer (2005), McGuire (2005) and Musson (2005)], with its standard deviation (σ_e which represents the epistemic uncertainty), was calculated by weighted interpolation of the branch probabilities. To do this, we wrote a simple routine which runs Seisrisk III several times and aggregates the individual results according to their weights. At the end, two hazard estimates have been obtained for each soil typology [see also Rebez and Slejko (2004a)]: the first estimate quantifies the median *PGA*, calculated considering the AR σ_a (aleatory uncertainty), and the second takes into account also the epistemic uncertainty (scatter of the individual hazard curves, each calculated considering the aleatory variability) as one σ_e was added to the median *PGA*. Both estimates, by the way, consider the epistemic uncertainties because they represent average values of the hazard curves coming from the several branches.

Fig. 5 shows the seismic hazard maps obtained considering the aleatory variability (AR σ_a): *PGA* is the mean value of the branch hazard curves (the dispersion of the hazard curves is not added in these maps) for rock (Fig. 5a), stiff soil (Fig. 5b), and soft soil (Fig. 5c) respectively. These maps are similar to the usual hazard maps that were computed before the introduction of the logic tree approach and refer to a return period of 475 years: this is now a standard practice in seismic design [see discussion in Rebez and Slejko (2004a)]. All the branches of the logic tree were evenly weighted (see the details in Fig. 2). It can be quite surprising to see that the stiff soil map displays very similar values to the soft soil map. This is due to the introduction of the stiff soil B&S AR, that is characterised by a larger σ_a than the other two relations, also considering its

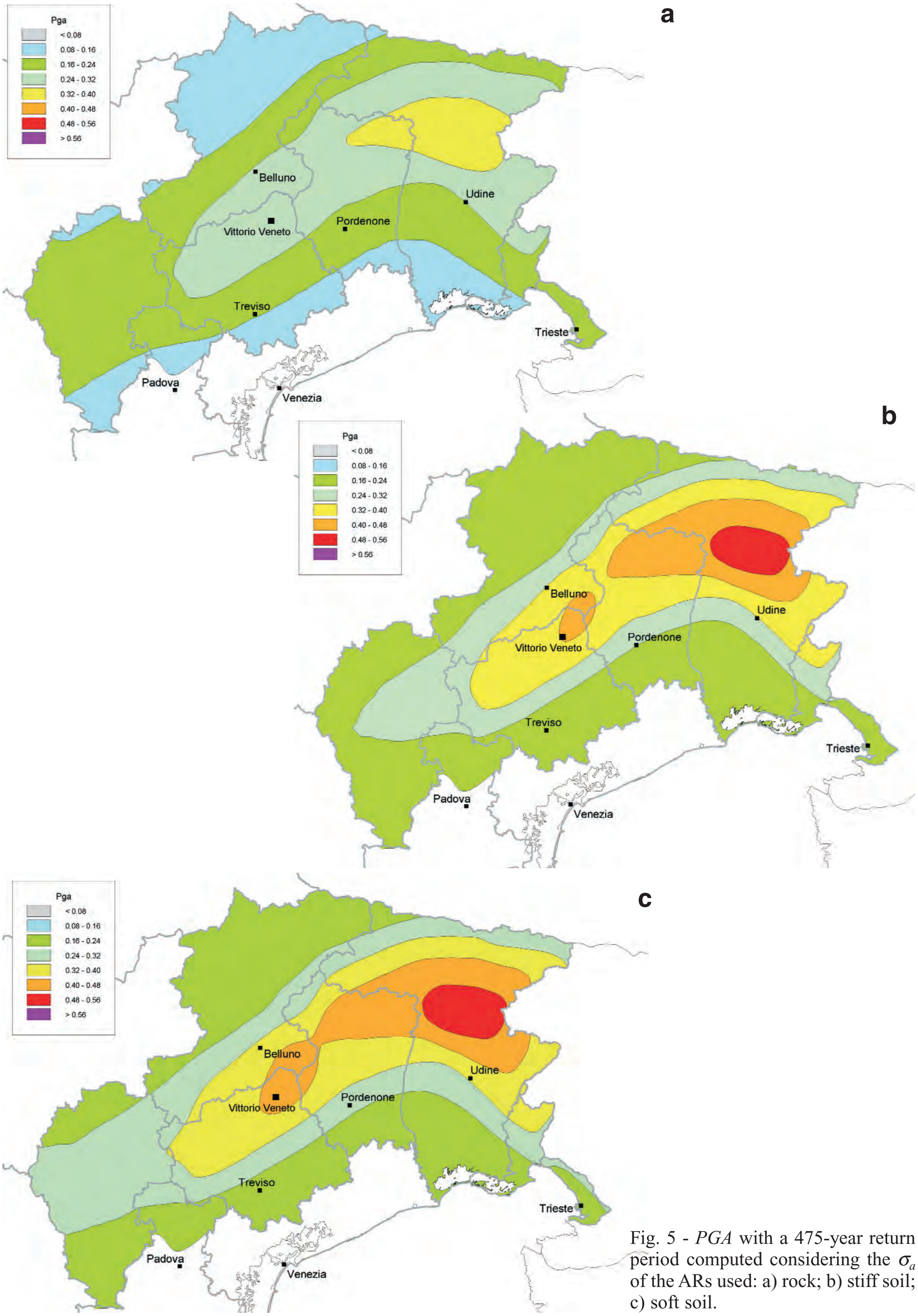


Fig. 5 - *PGA* with a 475-year return period computed considering the σ_a of the ARs used: a) rock; b) stiff soil; c) soft soil.

reduced value. The influence of the individual input parameters in the final hazard results is smoothed by the use of several different hypotheses (branches). The hazard map for rock (Fig. 5a) shows the maximum *PGA* (values between 0.32 and 0.40 g) in central Friuli while the Vittorio Veneto area is characterised by a *PGA* between 0.24 and 0.32 g. Again the maximum *PGA* refers to central Friuli in the map for stiff soil (Fig. 5b) with values between 0.48 and 0.56 g, while Vittorio Veneto remains located in a secondary island of high values (between 0.40 and 0.48 g). A very similar pattern and a slightly higher *PGA* can be seen in the map related to soft soil (Fig. 5c). It is very satisfactory to point out that the rock hazard map (Fig. 5a) is in a very good agreement with the results of Rebez and Slejko (2004a), although these authors used a simplified logic tree.

Taking into account the soil typologies identified in the study region (Fig. 4), the adequate 475-year return period *PGA* value has been associated to the different area units using the potentialities of a GIS and the final soil hazard maps have been constructed (Fig. 6). The map in Fig. 6a refers to the median *PGA* values, where the aleatory variability was considered, introducing the AR $\sigma_a s$ in the computation, while also one σ_e (epistemic uncertainty) of the mean hazard curve was added in the map of Fig. 6b.

The importance of the pertinent soil type is pointed out in all the maps. In fact, the hazard is notably higher in the plain and along the Alpine valleys than in the mountain sectors. The *PGA* increase is larger when the aleatory uncertainty is considered than when the epistemic one is taken into account (the difference between Figs. 6a and 6b is much smaller than that between results obtained with and without considering the σ_a): this fact testifies that the variability in attenuation is more important in PSHA than the uncertainty we have about some seismicity models. In all maps, the largest *PGA* is expected along some Alpine valleys, especially in Friuli. A *PGA* between 0.48 and 0.56 g is reached along the northern Tagliamento River valley and a few other close valleys (Fig. 6a). Vittorio Veneto remains located in a peculiar situation with expected values exceeding 0.40 g, while all around the town much lower values are forecasted. The expected *PGA* exceeds 0.56 g when also one σ_e (epistemic standard deviation) is added (Fig. 6b), with a few small spots even exceeding 0.64 g. Again these high values refer to the northern Tagliamento River valley but values larger than 0.48 g can be seen also east of Belluno and around Vittorio Veneto. The results presented by Rebez and Slejko (2004a) refer only to rock and, consequently, a direct comparison with the present maps cannot be done. Considering the rocky mountain sector, they obtained a *PGA* between 0.32 and 0.36 g almost along all the foothills, when the σ_a is considered in the elaboration and one σ_e is added. The map in Fig. 6b shows a median *PGA* between 0.40 and 0.48 g in the mountain sector when the σ_a is considered in the elaboration and one σ_e is added. The comparison is again quite satisfactory: our new estimates for rock are slightly higher than those of Rebez and Slejko (2004a) probably because of some new branches of the logic tree.

A direct comparison with the recent Italian seismic hazard map (Gruppo di Lavoro, 2004) for NE Italy can be made considering Fig. 5a because the national estimates refer to rock. The hazard level computed by the present study, and shown in Fig. 5a, is slightly higher than that displayed by the national map, where a lower *PGA*, between 0.250 and 0.275 g was estimated for a large strip covering central Friuli from east to west. On the other side, Fig. 5a shows an area in central Friuli where a *PGA*, between 0.32 and 0.40 g, is expected, surrounded by an E-W oriented strip,

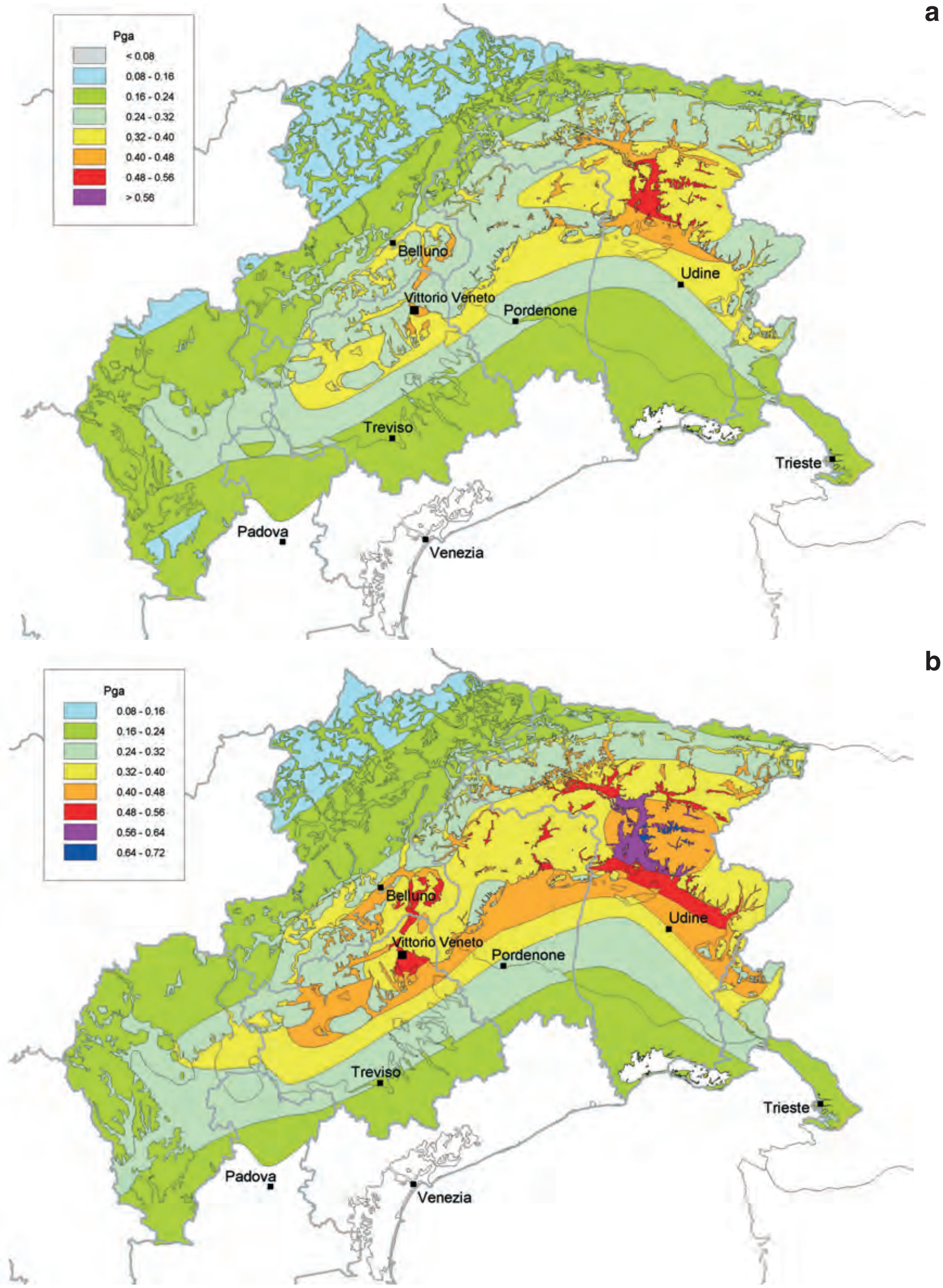


Fig. 6 - Soil *PGA* with a 475-year return period: a) median *PGA* computed taking into account the AR $\sigma_a s$; b) median *PGA* computed taking into account the AR $\sigma_a s$ and adding 1 σ_e (see the text for details).

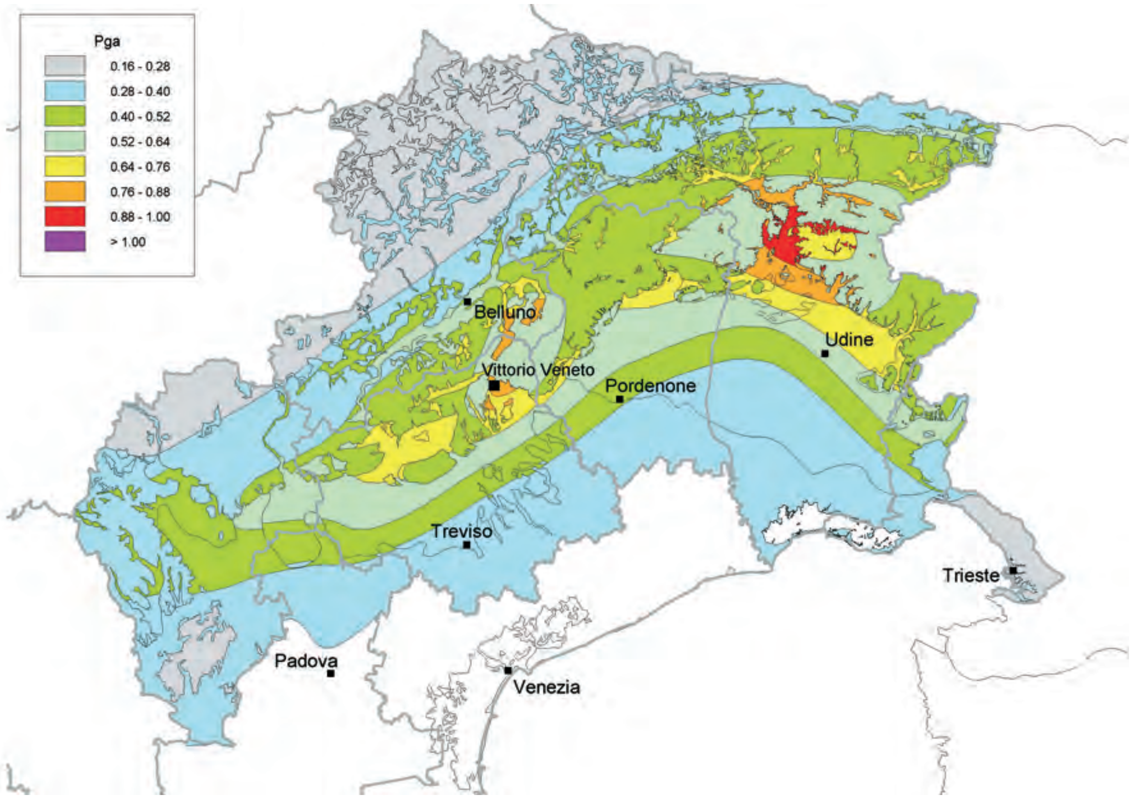


Fig. 7 - Soil *PGA* (median *PGA* computed taking into account the σ_a of the ARs) with a 2475-year return period.

larger than that of the national map, where values between 0.24 and 0.32 g are expected. The difference in the results of the two studies can be explained easily by the different logic trees used. The main source of difference stays in the seismogenic zonations considered. The national map used only the SZ09 zonation, while two additional zonations were taken into account in the present study and both define narrower SZs, collecting the high seismicity (the 3LEV zonation is based on this aspect). As a consequence, the estimated *PGA* is largely higher inside some SZs. Moreover, the HNH method for computing the seismicity rates, not used in the national map, is conservative for definition.

The 2475-year return period was considered as well, because long return periods are becoming important in the estimation of seismic hazard, especially at a national level (see e. g.: Frankel *et al*., 2002; Adams and Halchuk, 2003). Fig. 7 displays the *PGA* with a 2475-year return period: similarly to the map in Fig. 6a, the AR $\sigma_a s$ have been taken into account in the computation, but no σ_e has been added. Higher *PGA* values are, obviously, displayed but the general pattern does not show remarkable differences with respect to that of the map in Fig. 6a. This testifies that this region is not characterised by strong events with a very long return period. The maximum *PGA* is encountered again along the northern Tagliamento River valley and neighbouring Alpine valleys, with values between 0.88 and 1.00 g. Vittorio Veneto is again involved in local amplifications, which anyway remain below 0.88 g.

8. The hazard map in terms of macroseismic intensity

Most of the fragility curves for the Italian buildings are expressed in terms of macroseismic intensity because this quantity is easily available for the whole territory and, in particular, for the locations where specific surveys were made on the damaged buildings. On the contrary, strong motion data are available only for specific sites. Consequently, for damage assessment it is necessary to transform the *PGA* values of the previous maps into macroseismic intensity.

Several relationships between *PGA* and intensity are available in literature (e.g.: Trifunac and Brady, 1975; Murphy and O'Brien, 1977; Wald *et al*., 1999; Atkinson and Sonley, 2000) and some of them were calibrated for Italian earthquakes (e.g.: Margottini *et al*., 1992; Decanini *et al*., 1995) as well.

In the present study, it was decided to use the data collected during the 1976 Friuli earthquake (Chiaruttini and Siro, 1981) which involves 120 non corrected *PGA* values related to recordings in the free-field or in the basement of small buildings. The related values of macroseismic intensity are expressed in the Modified Mercalli (MM) scale and were taken from Giorgetti (1976), Karnik *et al*. (1978), and (1978). We took the largest of the horizontal components; all values smaller than 0.015 g were discarded to avoid a bias towards the low values. The arithmetic mean was taken for the Tolmezzo station, where two accelerometers were operating. A total of 75 *PGA* - intensity pairs was used for the calibration of the relationship: they span from 0.015 to 0.525 g and from 2.5 to 8.5 MM, where the half degrees indicate uncertainty between two successive degrees.

The model available in literature has the following form:

$$I = a + b \log PGA \quad (1)$$

where *PGA* is expressed in g ·100.

The result we have obtained by the least squares method is:

$$a = 3.409; \quad b = 2.842; \quad R = 0.70 \quad (2)$$

where *R* is the correlation coefficient.

The relation (grey dashed line in Fig. 8a) is conditioned by the numerous low intensity data and does not fit the high intensity data in a satisfactory way: the low *R* value quantifies this situation. Adding 56 *PGA* - intensity pairs, referred to Italian earthquakes (Margottini *et al*., 1992), to the data set did not yield better results also because the data do not increase the *PGA* and intensity ranges.

An orthogonal relation was tried as well: this kind of relation would allow us to move from *PGA* to intensity and vice versa. The orthogonal regression was applied to all data and the following results were obtained:

$$a = 1.235; \quad b = 5.661; \quad R = 0.70. \quad (3)$$

The line obtained (grey solid line in Fig. 8a) is quite distant from the previous one. It must be pointed out that orthogonal relations are applicable only when the error distribution for the two involved quantities is similar (Castellaro *et al*., 2006) and this is not our case.

Considering the mean value of each intensity class, the following result was obtained:

$$a = 1.635; \quad b = 5.189; \quad R = 0.94. \tag{4}$$

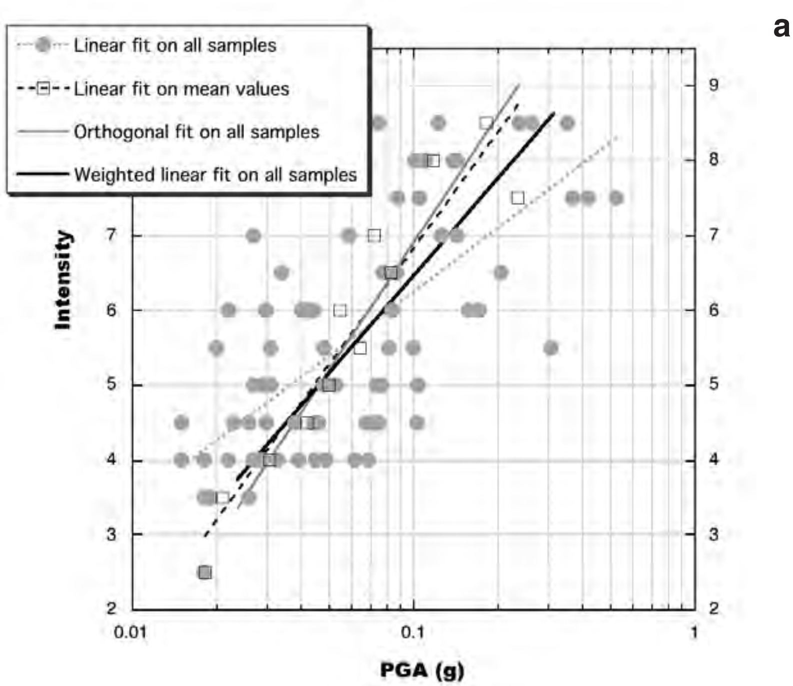
The high intensities are better reproduced in this last case (black dashed line in Fig. 8a) although the quantity of samples are not taken into account. To overcome this effect, a weight, proportional to the square of the inverse of the number of samples, was introduced and the fit with all data was repeated obtaining the following result:

$$a = 2.099; \quad b = 4.351; \quad R = 0.86. \tag{5}$$

The line obtained (black solid line in Fig. 8a) is in the middle of the other lines. Fig. 8a shows all the results obtained: it can be seen that all the regressions are rather close to each other with the exception of the one with all data. The *R* value increases notably when introducing the weights, while, as expected, the highest *R* value refers to the regression on mean values. The choice of the relation, more suitable to transform *PGA* into intensity data, is not easy and our decision was driven by the need to adequately reproduce the high values (more critical for damage assessment) but also to take into account the representativeness of the samples (in terms of number of samples in each intensity class). As a consequence, the weighted fit on all values was selected to translate the *PGAs* of the previous maps into intensity values: this relation is considered valid for the *PGA* range 0.015 to 0.525 g and for the intensity range III to IX MM. When comparing this new relation with others from literature (Fig. 8b), it can be seen that it is almost identical to the one proposed by Margottini *et al*. (1992) for Italian data and quite similar to that suggested by Sabetta *et al*. (1998), but rather different to that by Faccioli and Cauzzi (2006), where the Italian data set was integrated with Mediterranean data for high intensities.

The above relation has been used to transform the *PGA* maps for rock, stiff and soft soil (Fig. 5) into intensity maps. Taking into account the soil typologies identified in the study region (Fig. 4), the adequate intensity value has been associated to the different area units using the potentialities of a GIS and the final intensity hazard map has been constructed (Fig. 9). In this case, the uncertainty associated to the relation between *PGA* and intensity has not been considered because the map displays median values of intensity. In the map we have underlined also the areas where the attribution of intensity between two degrees is uncertain. As in previous maps, in terms of *PGA*, the most hazardous zones are the northern Tagliamento River valley and a few other valleys in central Friuli; an intensity exceeding IX MM is expected here. Moreover, it is interesting to point out the increase of intensity expected in the foothill strip (IX MM) because of the bad typology of the terrain.

As in most Italian fragility curves macroseismic intensity is expressed in Mercalli - Cancani - Sieberg (MCS) scale degrees, it is worth considering the relation between the MM and the MCS scales. The MM scale, widely used in the U.S.A., and the Medvedev - Sponheuer - Karnik (MSK) scale, popular in Europe, can be considered equivalent (Murphy and O'Brien, 1977). According to Console and Gasparini (1977) some differences exist between the MCS and MSK scales, but



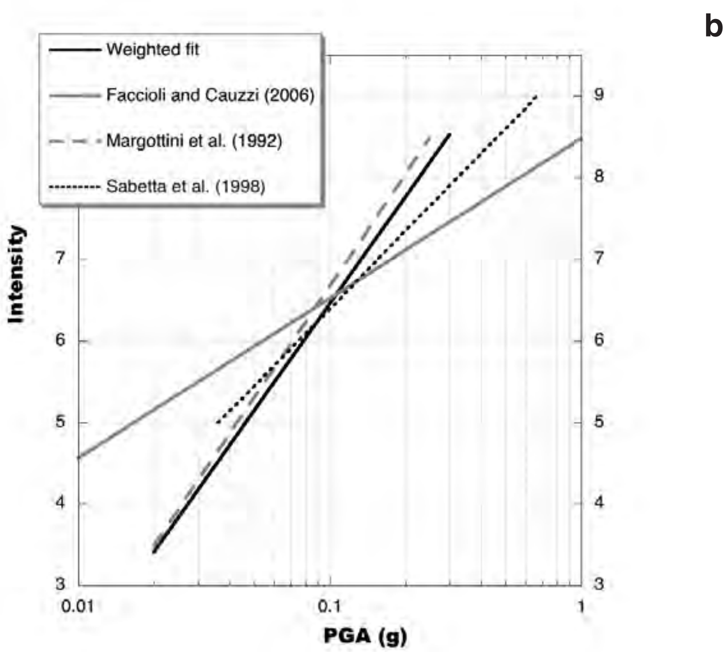


Fig. 8 - Relation between *PGA* and macroseismic intensity: a) calibrated on the data of the 1976 Friuli earthquake, grey solid circles = samples; open squares = mean values; grey dashed line = linear fit on all data; grey solid line = orthogonal fit on all samples; black dashed line = linear fit on mean values; black solid line = weighted linear fit on all samples; b) comparison of the proposed relation (black solid line) with others from literature: grey long-dashed line = Margottini *et al.* (1992), black short-dashed line = Sabetta *et al.* (1998), grey solid line = Faccioli and Cauzzi (2006).

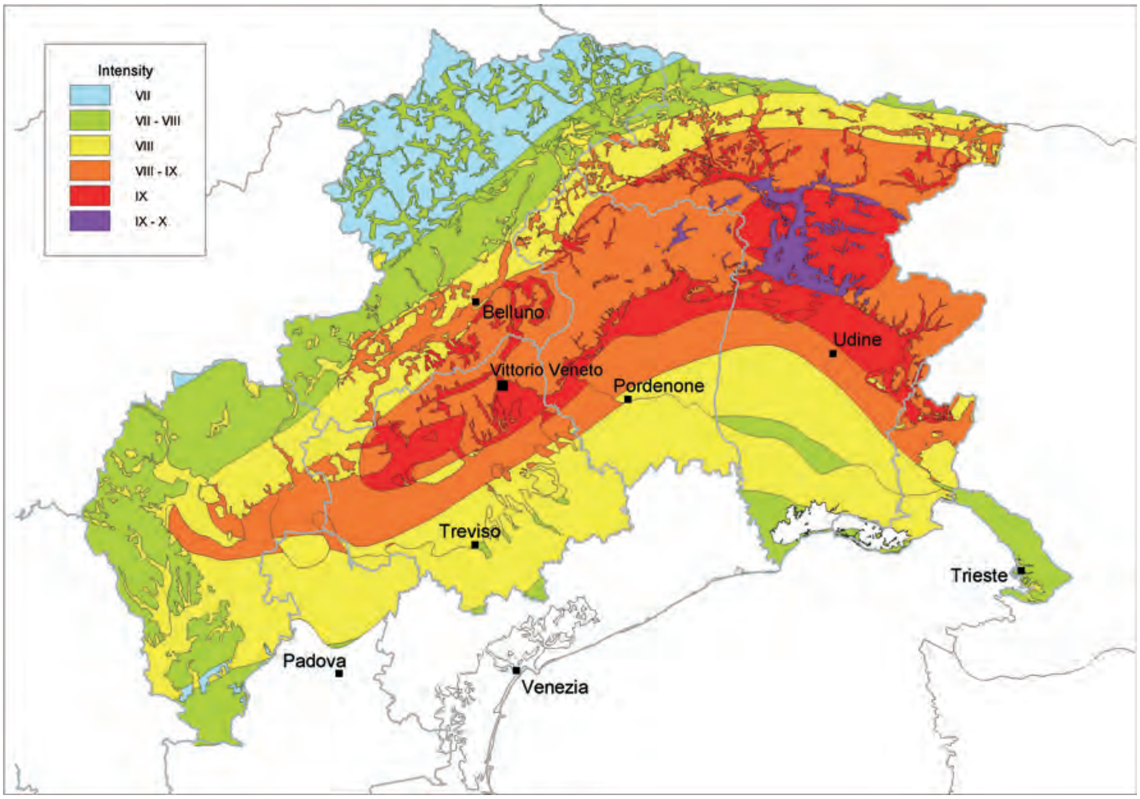


Fig. 9 - Macroseismic intensity with a 475-year return period obtained from the *PGA* values with aleatory variability (Fig. 5; see the text for details).

these differences refer to degrees larger than VIII and remain limited inside the possible uncertainty of the intensity attribution (areas of uncertainty between two degrees in Fig. 9). According to Musson *et al*. (2006), the two scales can be considered more or less equivalent and the chief difference between these scales is not so much the level of shaking represented by each degree, but the extent to which the wording of the scale guides the user into making the correct intensity assignment. As a consequence, the map in Fig. 9 can be considered valid also in terms of MCS intensity for damage assessment purposes.

9. Results for the Vittorio Veneto test site

As mentioned before, since in the GNDT project is focused on the Vittorio Veneto test site, a specific analysis has interested this locality, and the influence of the different characteristics of the branches in the logic tree have been investigated. All the following considerations refer to the stiff soil typology of the terrain which is dominant in Vittorio Veneto. In Fig. 10, the solid dots indicate the hazard estimates related to a 475-year return period, while the empty squares those related to a 2475-year return period. The large double-coloured dots and squares indicate the mean values of the previously cited estimates, and the vertical bars one standard deviation of

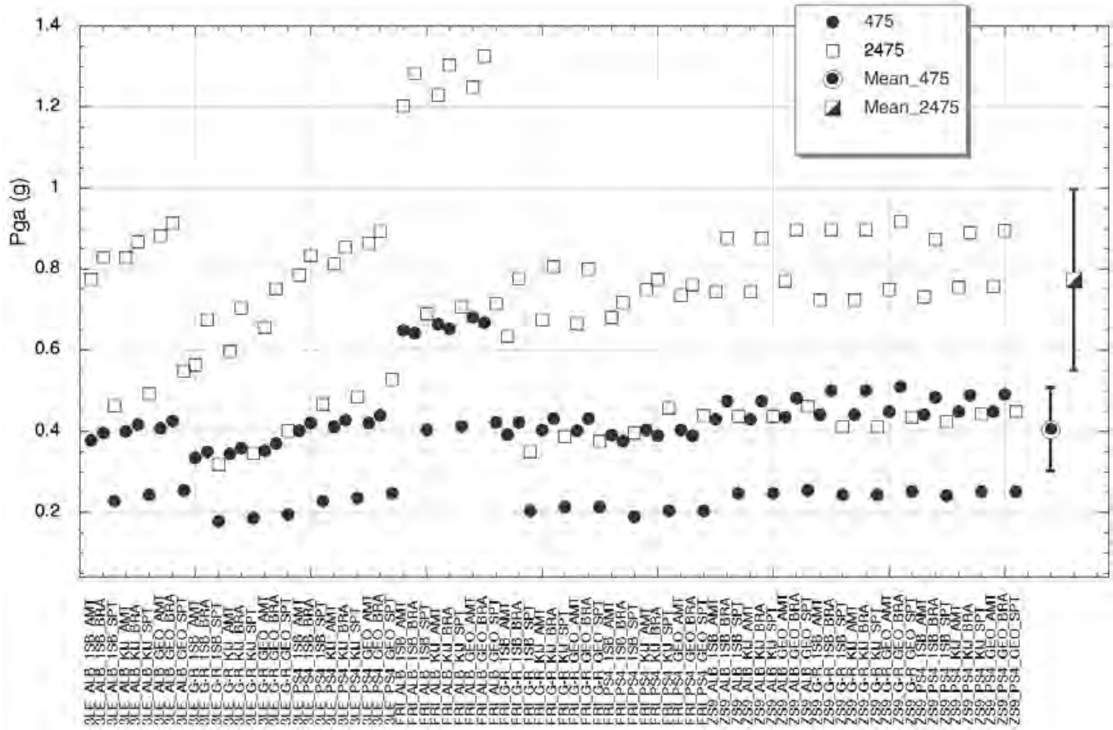


Fig. 10 - *PGA* for Vittorio Veneto (stiff soil) with a 475-year return period (solid dots) and with a 2475-year return period (open squares). The large double-coloured dot and square indicate the average *PGA* with a 475- and 2475-year return period, respectively, computed taking into account the aleatory variability of the AR $\sigma_a s$, the vertical bars display one standard deviation of the estimates (σ_e).

those estimates.

In general, the results depend on the combination of the different choices but two features can be seen: 1) slightly larger differences in the estimates are obtained with the 3LEV zonation; 2) the S&P AR drives to lower *PGAs* [mainly because of its lower σ_a and because the stiff soil in Vittorio Veneto was treated as rock (for correctness this should have been done only where H > 20 m, see previous discussion)]. The combination of the A&M approach for the seismicity rate computation with the FRI zonation produces very high *PGA* estimates: this is explained by the fact that this approach takes the very last years as a complete period when the earthquake catalogue of the SZ is poor (SZs with a small area as in the case of SZ 10, where Vittorio Veneto is located, in the FRI zonation, Fig. 3c).

Considering the $\sigma_a s$, the final median *PGA* value with a 475-year return period in Vittorio Veneto is 0.40 (+/-0.10) g (compare with Fig. 6a). This estimate is larger than that obtained by Rebez and Slejko (2004a), who computed 0.30 g with a standard deviation of 0.03. The difference is motivated by the rich logic tree used in the present elaboration (81 branches instead of only 16), that allowed us to capture the possible uncertainties involved in the PSHA.

For the longer return period of 2475 years, the median *PGA* value is 0.77 (+/-0.22) g (compare

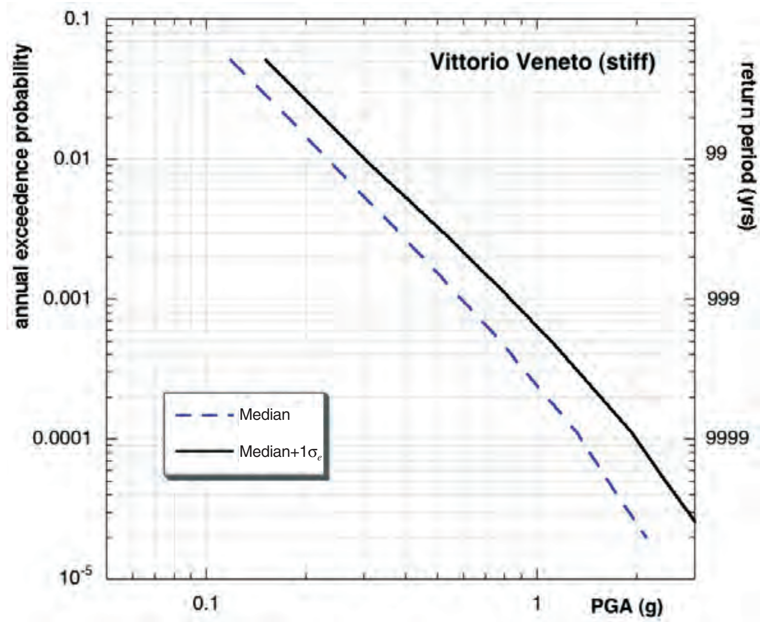


Fig. 11 - Complete hazard curves for Vittorio Veneto: dashed line = median *PGA* values computed taking into account the AR $\sigma_a s$; solid line = median *PGA* value computed taking into account the AR $\sigma_a s$ and adding one σ_e.

with Fig. 7). The patterns of the two graphs are not very different from each other and this suggests that no important contribution to hazard is expected in Vittorio Veneto from the long return period seismicity.

Fig. 11 displays the complete hazard curves for Vittorio Veneto, considering and not considering the epistemic uncertainty. The expected asymptotic behaviour is not evident in the two curves: this suggests that higher values are reachable considering even smaller probability levels, although the annual exceedence probability of 10^{-5} is already very small indeed.

10. Conclusions

This investigation aimed at producing the basic input for the analysis of expected damage in the broader Vittorio Veneto area (see Meroni *et al*., 2008). Consequently, the performed PSHA has considered all the possible uncertainties related to the input parameters involved in the computation by the application of the logic tree approach. Three seismogenic zonations and related earthquake catalogues, three methods for the computation of the seismicity rates, three approaches to assess M_{max} in the SZs, and two *PGA* ARs for rock and soft soil and three for stiff soil, have been considered (Fig. 2).

The hazard estimates refer to three soil categories: rock, stiff, and soft soil (Fig. 5). On the basis of the soil characterisation at a regional scale (Fig. 4), it was possible to construct the soil seismic hazard maps (Fig. 6), where the site amplification with respect to rock is roughly quantified.

All the maps for a specific terrain (Fig. 5) point out to the relatively high *PGA* expected around Vittorio Veneto. Fortunately, no high soil amplification pertains to that area (Fig. 6). Hazard maps have been computed for two return periods: 475 and 2475 years. The first (Fig. 6) is considered the European standard reference in building design, the second (Fig. 7) represents one of the new products for seismic zonation in North America. The *PGA* estimates have been transformed into intensity values (Fig. 9) for separate analyses of the expected damage (see Meroni *et al*., 2008). All maps point out to the expected high ground shaking along the northern Tagliamento River valley and along a few other Alpine valleys. All maps show also some areas with relatively high hazard around Vittorio Veneto, caused by the presence of different soil typologies there.

The computed *PGA* with a return period of 475 years in Vittorio Veneto (stiff soil conditions) is 0.40 (+/-0.10) g (Fig. 10), becoming 0.77 (+/-0.22) g when referred to the 2475-year return period.

The results obtained are slightly higher than those computed preliminarily by Rebez and Slejko (2004a) within the same project and are higher also than those of the Italian seismic hazard map (Gruppo di Lavoro, 2004). The difference is motivated by the more articulated logic tree used in the present study, aimed at capturing the uncertainties inside the PSHA.

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