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Introducing epistemic uncertainties into seismic hazard assessment for the broader Vittorio Veneto area (N.E. Italy)

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Abstract - The logic tree approach has been used to compute robust seismic hazard estimates for the border area between the Veneto and Friuli - Venezia Giulia regions (N.E. Italy). In order to quantify the epistemic uncertainties, different options for the seismogenic zonation, maximum magnitude, and PGA attenuation relations have been considered. Three seismogenic zonations, representing different levels of our seismotectonic knowledge, were used. Moreover, the maximum magnitude was estimated in three different ways. Since no specific PGA attenuation relations are available for N.E. Italy, a European and an Italian relation were considered. The final logic tree has 16 branches: 3 zonations, 3 maximum magnitude estimates, 2 attenuation relations, 2 branches being empty. The regional hazard assessment was done according to a standard probabilistic approach for a 475-year return period. The results obtained for the different branches show remarkable differences that highlight, moreover, the influence of the seismogenic zonation. The results, evenly weighted, coming from all branches, contribute to the final aggregate seismic hazard map. Two areas (central Friuli and the area N.E. of Vittorio Veneto) show the highest hazard in these maps. One specific analysis interested the Vittorio Veneto test site, where the influence of the different characteristics of the branches in the logic tree have been investigated. In general, the results are rather similar and depend on the combination of the different choices. The average PGA value (mean of the median values) is 0.30 g taking into account the aleatory uncertainty of the attenuation relations, and it becomes 0.33 g, when the epistemic uncertainty is also added.

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1. Introduction

The quantification of the uncertainties (McGuire, 1977) is a crucial point in modern probabilistic seismic hazard assessment (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).

The aleatory variability is the natural randomness in a process. In PSHA, it is considered by taking into account the standard deviation of the relation describing the process. In fact, the randomness in seismic wave propagation (due to different source mechanisms, path, and site effects) is taken into account by the standard deviation of the attenuation relation used. Further aleatory uncertainties regard the source location and the magnitude of the events but are rarerly taken into account in PSHA, being rather limited (Slejko and Rebez, 2002).

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 poor knowledge on the geometry and activity of the seismogenic sources and on the wave propagation model are taken into account considering different seismogenic zonations, attenuation relations, and various methods for calculating the maximum magnitude. The logic tree approach for PSHA (Kulkarni et al., 1984; Coppersmith and Youngs, 1986) was introduced to quantify the epistemic uncertainties. With the logic tree approach various options can be taken into account in the computation: they represent the confidence we have in topics like the seismogenic zonation, the maximum possible magnitude in the seismogenic zones (SZs), the wave attenuation model, etc. Each branch of the logic tree represents a series of choices by which the resulting hazard is conditioned. Each branch can be adequately weighted and combined with the others to obtain the final aggregate result.

Recent seismic hazard estimates (Rebez et al., 1999) for the Eastern Alps (N.E. Italy) show that the most seismic area is expected to be central Friuli and hazard decreases as one moves westwards. The Belluno area, at the border between the Friuli - Venezia Giulia and Veneto regions, represents the western 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 to the Alpine compressional front (Galadini et al., 2002) as well. The use of several seismogenic zonations in PSHA is, consequently, very important for this area.

The seismicity of Friuli (Fig. 1) was widely studied (e.g.: Slejko et al., 1989): the region experienced events with magnitude (macroseismic magnitude M_m or magnitude on surficial waves M_S) 6 and over several times [e.g.: M_m 6.4 in 1348, M_m 6.2 in 1511, and M_S 6.5 in 1976; Camassi and Stucchi (1997)]. In the Belluno area, two earthquakes with magnitude larger than 5.5 occurred during the past centuries: the M_m 6.4 1873 Alpago earthquake and the M_S 5.8 1936 Cansiglio event (Camassi and Stucchi, 1997). Lower seismicity interests the western part, where the major event is the M_m 6.4 1695 Asolo earthquake (Camassi and Stucchi, 1997).

The town of Vittorio Veneto, located near Belluno (Fig. 1), was selected as a 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 seismic risk map will be based on

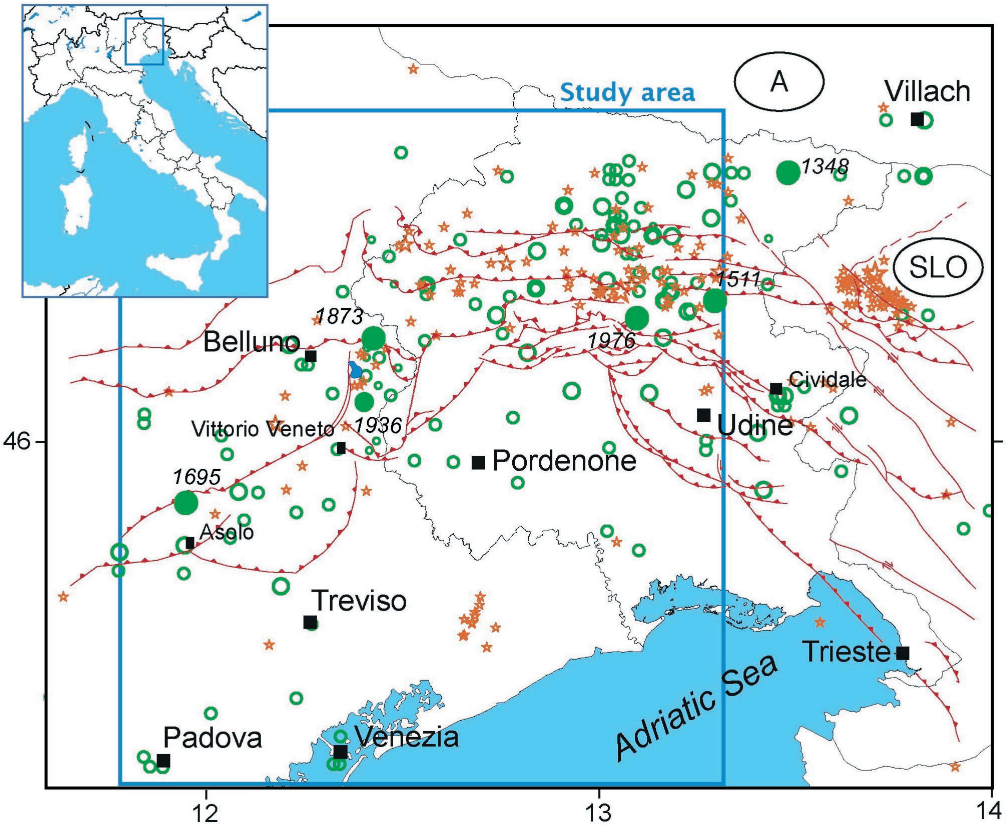

Fig. 1 - Main seismotectonic features of the Eastern Alps region: red solid lines represent faults (Caputo et al., 2002; Zanferrari et al., 2002), green circles (solid for the major events) indicate the epicenters of earthquakes from 1000 to 1976 with intensity larger than, or equal to, VI Mercalli-Cancani-Sieberg (from Camassi and Stucchi, 1997) and yellow stars represent the epicenters of the earthquakes from 1977 to 1999 with local magnitude larger than, or equal to 3.0 (from OGS, 1977-1981, 1982-1990, 1991-1999). The frame indicates the study area.

probabilistic seismic hazard estimates, while the damage scenarios for Vittorio Veneto will be mainly based on a complete deterministic ground shaking modelling.

The aim of the present study is to update the PSHA in the broader Vittorio Veneto area using, for the first time in Italy, the logic tree approach. More precisely, a logic tree with several branches has been constructed (Fig. 2): it consists of three zonations, three methods for maximum magnitude assessment, and two attenuation relations for peak ground acceleration (PGA). The results of the present study will be part of the shaking estimates used by GNDT for the loss assessment at a regional scale.

2. Ingredients for PSHA in the broader Vittorio Veneto area

The regional PSHA was done according to the standard Cornell (1968) approach using the computer formulation by Bender and Perkins (1987). This approach is based on two working hypotheses: the earthquake recurrence times follow a Poisson distribution (made up by

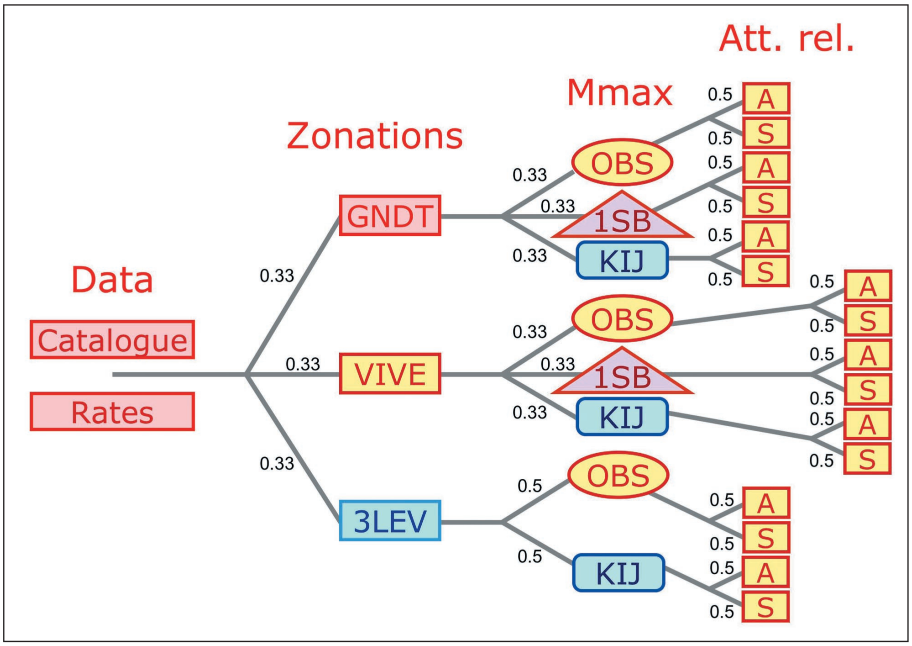

Fig. 2 - Logic tree used for PSHA of the Vittorio Veneto broader area. It consists of 3 seismogenic zonations [GNDT = Meletti et al. (2000); VIVE = Slejko and Rebez (2002); 3LEV = Stucchi et al. (2002)], 3 methods for M_{max} assessment [OBS = maximum observed value; 1SB = Slejko et al. (1998); KIJ = Kijko and Graham (1998)], and 2 PGA attenuation relations [A = Ambraseys et al. (1996); S = Sabetta and Pugliese (1987)]. The number indicates the weight of the branch (see text for details).

independent, non-multiple events, and the process is stationary in time) and the magnitude is exponentially distributed (the Gutenberg - Richter relation holds). In addition, the seismicity is considered uniformly distributed over the 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 the attenuation relation of the chosen parameter of motion.

2.1. Seismogenic zonations

In the standard PSHA, seismic sources are modelled as SZs, where the earthquakes can randomly occur. Three seismogenic zonations have been used in the present study (Fig. 3): they represent different levels of seismotectonic knowledge. The first model (Fig. 3a), hereafter referred to as the GNDT zonation (Meletti et al., 2000), is the zonation used for the Italian seismic hazard map (Slejko et al., 1998) and is composed of 80 SZs for the whole of Italy. The second zonation (Fig. 3b), hereafter referred to as the VIVE (Vittorio Veneto), is a regional improvement of the previous one based mainly on the distribution of the recent seismicity in N.E. Italy (Slejko and Rebez, 2002). The third zonation (Fig. 3c), hereafter referred to as the 3LEV (3 levels), is based on a different concept: strong earthquakes are linked to regional faults while the lower seismicity is associated to wider areas characterized by a general tectonic

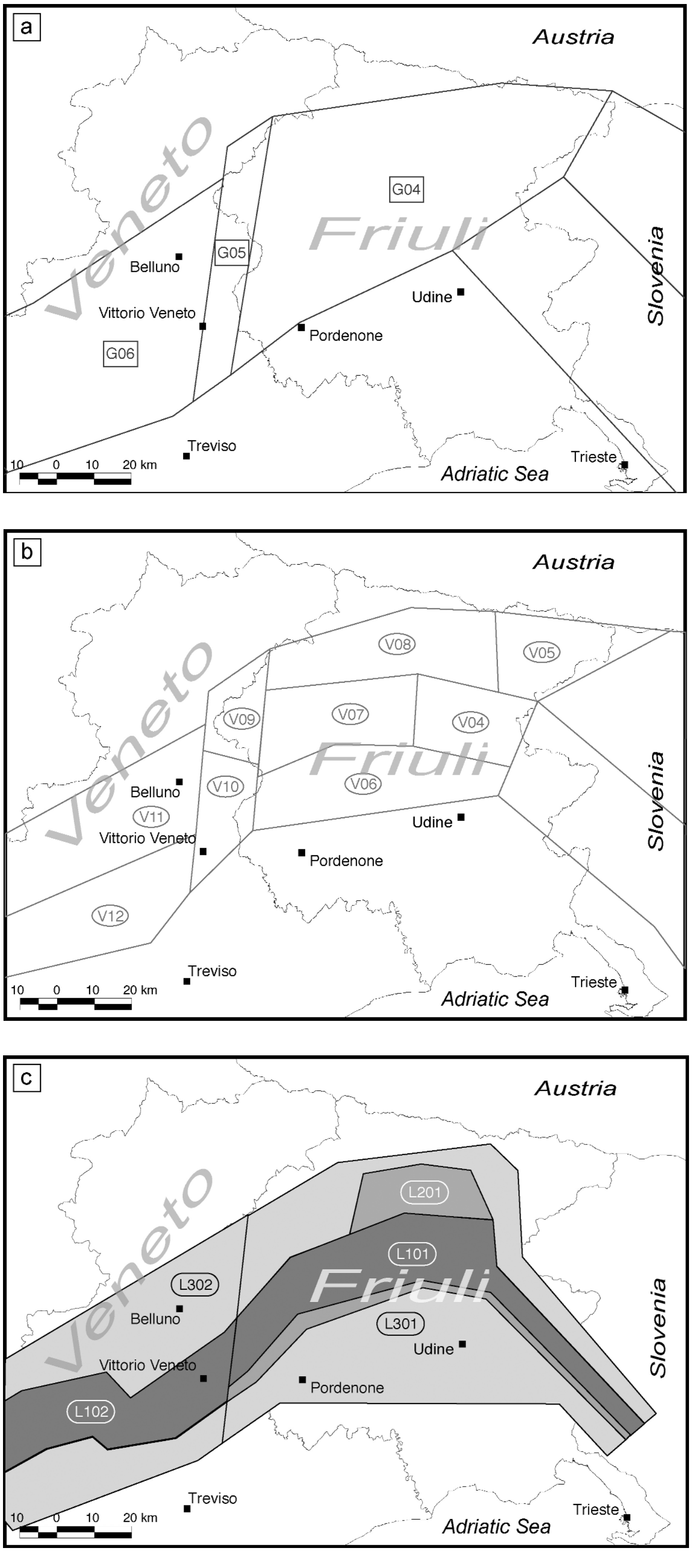

Fig. 3 - The 3 seismogenic zonations used: a) the GNDT zonation (Meletti et al., 2000); b) the VIVE zonation (Slejko and Rebez, 2002); c) the 3LEV zonation (Stucchi et al., 2002).

deformation. More precisely, in this zonation seismicity refers to three zones: the high seismicity ($M \geq 6$) at the presently active front, the intermediate seismicity ($M \geq 5$) at the wider foothill strip, and the low seismicity at the less active belt (Stucchi et al., 2002).

Entering into detail, three SZs of the GNDT zonation were used for the hazard assessment of the Vittorio Veneto broader area (labelled SZs in Fig. 3a). The G04 Friuli SZ is characterised by the high seismicity of the Alpine thrusts at the northern edge of the Adria microplate (Slejko et al., 1999). The G06 Asolo SZ experienced earthquakes of medium magnitude related to the thrusts of the Southalpine belt; among them the M_m 6.4 1695 Asolo quake is the largest event (Camassi and Stucchi, 1997). The G05 Cansiglio SZ represents the transfer between the two previous SZs and is characterised by sinistral strike-slip activity testified by the M_S 5.8 1936 Cansiglio earthquake (Peruzza et al., 1989); another strong event which occurred there is the M_m 6.4 1873 Alpago earthquake (Camassi and Stucchi, 1997).

The VIVE zonation (Fig. 3b) derives from the improvement by Carulli et al. (2002) of the seismogenic zonation of Italy (Meletti et al., 2000). The three SZs of the GNDT zonation were subdivided (Slejko and Rebez, 2002), mainly on the basis of the present-day seismicity, into 9 SZs (labelled SZs in Fig. 3b). The general kinematic framework of the GNDT zonation is not modified, in such a way.

The 3LEV zonation consists of 5 SZs: three in Friuli and two in Veneto. The three SZs in Friuli collect, respectively, the high (SZ L101 in Fig. 3c), the medium (L201), and low (L301) seismicity of the Southalpine and Dinaric belts. The two SZs in Veneto collect, respectively, the high (L102) and the low (L302) seismicity of the Southalpine belt. More precisely, the medium-seismicity SZ is missing because in the high-seismicity SZ the medium magnitude earthquakes ($5 \leq M_S < 6$) were added to the few strong events which occurred there.

For all the three zonations, the earthquake catalogue prepared in the framework of the GNDT activities (Camassi and Stucchi, 1997) was used to characterise the SZs from the seismicity point of view. As this catalogue ends in 1980, additional data were taken from the bulletins of the Friuli - Venezia Giulia seismometric network (OGS, 1977-1981, 1982-1990, 1991-1999). All main events with magnitude exceeding 1.7 were considered for the period 1977 to 1999. In the case of double entries (from the GNDT catalogue and from the OGS bulletins), preference was given to the GNDT data. 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). The seismicity rates have been computed following the approach developed for the seismic hazard assessment of the Italian territory (Slejko et al., 1998), with the exception of the low magnitude rates, that were computed considering the period of operation of the regional seismometric network complete (1977 - 1999).

2.2. Maximum magnitudes

A detailed analysis of the seismicity in the SZs has been carried out to identify the maximum expected earthquake for each SZ, to be introduced into the PSHA. This analysis is restricted to the only two SZs (out of the 5 SZs used for the hazard assessment) in the 3LEV zonation where earthquakes larger than 6 can occur. The maximum magnitude was estimated in 3 different ways.

The first way simply takes the maximum observed magnitude M_x (Table 1) in each SZ as maximum magnitude (branch labelled OBS in Fig. 2). It is based on the concept that earthquakes in Italy are expected to have a return period smaller than 1000 years, which is the time length of the earthquake catalogue (Camassi and Stucchi, 1997).

The second is the "one step beyond" approach (branch labelled 1SB in Fig. 2) used for the Italian seismic hazard map (Slejko et al., 1998). It extrapolates the observed seismicity rates by one step (0.3 magnitude units) according to the Gutenberg - Richter *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)]. It was not possible to define a maximum magnitude according to the "one step beyond" method for the 3LEV seismogenic zonation (Table 1) because the maximum magnitudes computed for SZs L101, and L102 refer to events with a return period of less than 1000 years which should, then, be contained in the catalogue: consequently the related branches remain empty in the logic tree.

The third way applies the Kjiko and Graham (1998) statistical approach (branch labelled KIJ in Fig. 2). This approach computes the maximum magnitude for a source on a statistical basis using as input data: M_x, the threshold magnitude M_0 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 Gutenberg-Richter relation and its standard deviation σ, the annual rate (i.e.: the number of earthquakes with magnitude greater than, or equal to, M_0) and the catalogue time span which is considered complete. This last parameter was set at 1000 years as the methodology used for the seismicity rate computation (Slejko et al., 1998) scans the whole catalogue and chooses the period which is most seismic in agreement with the return period of each magnitude class, a priori estimated. The whole input data is reported in Table 1.

Different methodologies for assessing the *b*-value 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, 1966): 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.

Both estimates of the *b*-value have been considered for the assessment of the maximum magnitude for the different SZs. The Kijko and Graham (1998) approach considers four formulations for this computation: the most robust Bayesian Kijko-Sellevol formula has been applied here. The results are reported in Table 1 and it can be seen that the increase, with respect to M_x, is very limited (in general 0.1 for both LSM and MLM), due to the long completeness period (1000 years) considered. With the more detailed VIVE zonation, higher maximum magnitudes are obtained in some SZs with respect to the other two less detailed zonations. For the hazard computation, the maximum magnitudes coming from the MLM *b*-values were used

Table 1 - Seismicity parameters and M_{max} obtained with the "one step beyond" method (Slejko et al., 1998) and the Kijko and Graham (1998) approach for the *SZs* according to the least-squares method (LSM) and the maximum likelihood method (MLM). M_X is the maximum observed magnitude; M_0 is the threshold magnitude; rate is the annual number of earthquakes equal to, or larger than, M_0; b is the b-value and σ its standard deviation; M_{max} is the maximum magnitude and σ its standard deviation.

ZS	M_X	M_0	Rate	1SB	LSM				MLM			
				M_{max}	b	σ	M_{max}	σ	b	σ	M_{max}	σ
GNDT												
G04	6.4	3.4	2.01	6.7	0.92	0.05	6.5	0.2	0.83	0.04	6.4	0.2
G05	6.4	3.4	0.19	6.7	0.63	0.08	6.6	0.3	0.48	0.07	6.5	0.2
G06	6.4	3.4	0.36	6.7	0.92	0.09	6.7	0.3	0.69	0.07	6.5	0.2
3LEV												
L101	6.4	3.4	2.10		0.92	0.05	6.5	0.2	0.85	0.04	6.4	0.2
L202	6.4	3.4	0.46		0.60	0.04	6.5	0.2	0.55	0.06	6.5	0.2
VIVE												
V04	6.4	3.1	1.60	6.7	0.84	0.05	6.5	0.2	1.01	0.06	6.6	0.2
V05	6.4	3.1	0.20	6.7	0.65	0.04	6.6	0.3	0.68	0.11	6.7	0.3
V06	5.2	1.9	1.98	5.5	0.66	0.04	5.2	0.2	0.81	0.04	5.3	0.2
V07	5.8	2.5	5.42	6.1	0.84	0.05	5.8	0.2	0.92	0.03	5.8	0.2
V08	5.8	2.5	2.13	6.1	0.87	0.04	5.9	0.2	0.88	0.03	5.9	0.2
V09	4.3	1.9	2.05	4.6	1.08	0.12	4.3	0.2	1.06	0.05	4.3	0.2
V10	6.4	3.1	0.63	6.7	0.67	0.06	6.5	0.2	1.03	0.10	6.7	0.4
V11	4.9	2.2	2.44	5.2	0.91	0.05	4.9	0.2	0.81	0.04	4.9	0.2
V12	6.4	3.1	0.28	6.7	0.69	0.08	6.6	0.3	0.59	0.08	6.5	0.3

with a fixed return period of 1000 years. There is no need to introduce a further branch of the logic tree with the maximum magnitude coming from the LSM b-values as they do not differ very much.

2.3. Attenuation relations

No specific attenuation relations of PGA are available for N.E. Italy because the Chiaruttini and Siro (1981) one was calibrated only on the data of the 1976 Friuli seismic sequence. Consequently, the most popular European and Italian relations were considered in the present study. More precisely, the Ambraseys et al. (1996) relation (branch labelled A in Fig. 2), calibrated on European strong-motion data, and the Sabetta and Pugliese (1987) one (branch labelled S in Fig. 2), calibrated on Italian data, were used.

Since the Sabetta and Pugliese (1987) relation refers to two different kinds of magnitude according to the size of the earthquake, the M_S magnitude from the catalogue was converted into local magnitude M_L using the GNDT relation (Camassi and Stucchi, 1997), when necessary. Both attenuation relations were extrapolated outside their range (Ambraseys, 1995) as seismicity rates of magnitude classes below 4.5 were used in the hazard computation.

The Ambraseys et al. (1996) 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 center of the mass of the small circular elements into which the SZ is subdivided. This distance is rigourously neither the epicentral distance nor that of the causative fault, but in practice can be assumed to be equal to either.

The two relations provide different results, as can be seen in Fig. 4: the Sabetta and Pugliese (1987) relation always gives larger PGA median values, with the exception of the very near field (in the case of earthquakes with low-to-medium magnitude). The same features hold also when the standard deviations of the two relations are considered. It is worth pointing out that we have considered the Sabetta and Pugliese (1987) relation as referred to the epicentral distance because the one referred to the fault distance is more similar to the Ambraseys et al. (1996) relation.

3. Seismic hazard results

Sixteen branches constitute the logic tree (Fig. 2): 3 zonations, 3 maximum magnitude estimates, 2 attenuation relations, but 2 branches are empty because it was not possible to assess the maximum magnitude according to the "one step beyond" approach for the 3LEV zonation. All possible branches were evenly weighted: this means that a larger weight is given to the results coming from the 3LEV zonation simply because they are less numerous than those

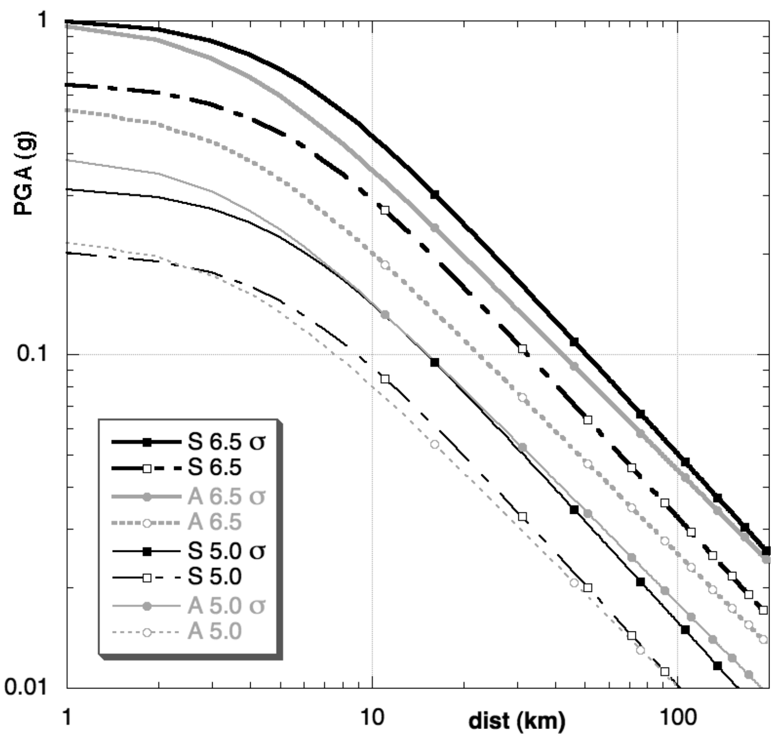

Fig. 4 - Comparison between the Ambraseys et al. (1996: A) and the Sabetta and Pugliese (1987; epicentral distance: S) PGA attenuation relations with and without their σ for M_S 6.5 and 5.0. For the Sabetta and Pugliese (1987) relation the proper conversion (Camassi and Stucchi, 1997) between M_S and M_L has been used.

coming from the GNDT and VIVE zonations (see details in Fig. 2).

Hazard refers to rock and has been computed for a return period of 475 years: this is now a standard practice in seismic design. The initial choice of the 475 years was relatively arbitrary (Algermissen and Perkins, 1976), but seems to have been justified on the basis of considerations about safety of structures using this return period as a basis for design in the U.S. model seismic code (Perkins, personal communication). The aleatory uncertainty of the attenuation relation has been taken into account by introducing its standard deviation in the computation.

3.1. PSHA for the broader Vittorio Veneto area

The results corresponding to the 16 branches are displayed in Figs. 5 and 6: they show evident differences that highlight the influence of the various choices made. In particular, the introduction of the maximum magnitude according to the "one step beyond" (Slejko et al., 1998) and the Kijko and Graham (1998) approaches (Figs. 5b, 5e, 6b, 6e and Figs. 5c, 5f, 5h, 6c, 6f, 6h, respectively) obviously leads to higher results than when considering that the maximum magnitude has been already experienced during the last 1000 years (Figs. 5a, 5d, 5g, 6a, 6d, and 6g), although these differences are rather small. The influence of the seismogenic zonation used is notable because it determines the area of higher hazard: this refers to all of Friuli for the GNDT zonation (Figs. 5a, 5b, 5c, 6a, 6b, and 6c), it is concentrated in central Friuli for the VIVE zonation (Figs. 5d, 5e, 5f, 6d, 6e, and 6f), and it is elongated along the foothills from central Friuli to the west of Vittorio Veneto for the 3LEV zonation (Figs. 5g, 5h, 6g, and 6h). The use of the Sabetta and Pugliese (1987) attenuation relation, coupled with the introduction of the maximum magnitude, gives higher estimates (Fig. 6) than the Ambraseys et al. (1996) relation (Fig. 5) for the narrow transfer SZs V09 and V10 for the VIVE zonation (Figs. 6e and 6f). This relation emphasises, in some cases, the hazard around Vittorio Veneto (Figs. 6c, 6g, and 6h).

The results coming from all branches, weighted according to the scheme of Fig. 2, contributed to the final aggregate seismic hazard map (Fig. 7). More precisely, three maps are shown: the first with the average PGA value (mean of the median estimates) without taking into account aleatory and epistemic uncertainties (Fig. 7a), the second with the aleatory uncertainty (i.e. in our case, introducing only the σ of the attenuation relations into the hazard computation: Fig. 7b: this map comes directly from those in Figs. 5 and 6), and the third with both aleatory (of the attenuation relation, only) and epistemic uncertainties (Fig. 7c). The quantification of the epistemic uncertainty was done by computing the mean value of the results obtained from the different branches of the logic tree (displayed in Fig. 7b) and its standard deviation for each cell of the study area. These last values were added to the mean values to obtain the final map with all the uncertainties (Fig. 7c). It must be pointed out, anyway, that the values shown in the first two maps (Figs. 7a and 7b) were obtained by averaging the results of the 16 individual branches and, depend, then, on the epistemic uncertainties, although these last quantities are added only in the last map (Fig. 7c). The general features of the three maps are, of course, similar, with two areas of maximum hazard: central Friuli and the area around Vittorio Veneto. These two areas have similar PGA values when no uncertainties are taken into account, while, in the other cases, the area with the highest PGA corresponds to central Friuli, where the 1976 earthquake also occurred. More precisely, in the map with only the aleatory uncertainty (Fig. 7b) central Friuli exceeds 0.32 g while the area around Vittorio Veneto, as well as all the piedmont belt, remains below that value. The most hazardous area of the study region (PGA larger than 0.36 g) is shifted slightly eastwards, when the epistemic uncertainties are also taken into account, and the hazard around Vittorio Veneto clearly appears with PGA values larger than 0.32 g.

A general agreement holds between the present results and those obtained in previous works. The hazard map of Italy computed in the framework of the GNDT activities (Slejko et al., 1998), in fact, shows PGA values between 0.20 and 0.24 g in Friuli and in the Vittorio Veneto area; these values increase to 0.28 - 0.36 g when the standard deviation of the attenuation relation is considered. The hazard map of Italy prepared in the following years (Albarello et al., 2000) displays only the PGA computed by taking into account the standard deviation of the attenuation relations and in that case the PGA values for Friuli and Vittorio Veneto are between 0.25 and 0.30 g.

3.2. PSHA for the Vittorio Veneto test site

Since, as mentioned before, in the GNDT project some damage scenarios are planned for the Vittorio Veneto test site, a specific analysis has interested this site, where the influence of the different characteristics of the branches in the logic tree have been investigated (Fig. 8). In general, the results depend on the combination of the different choices and the only piece of evidence is that lower hazard is obtained with the GNDT zonation because the SZs are rather large. The Sabetta and Pugliese (1987) attenuation relation amplifies the effects of the introduction of the maximum magnitude in the case of the VIVE zonation, because it gives higher PGA values than the Ambraseys et al. (1996) relation for large magnitudes. Considering a normal distribution of the results obtained at Vittorio Veneto, the different estimates lead to a mean value of 0.30 g with a standard deviation of 0.03 g.

4. Conclusions

The logic tree approach has been used to compute seismic hazard in the broader Vittorio Veneto area. Three seismogenic zonations, three methods to assess the maximum magnitude in the SZs, and two PGA attenuation relations have been considered (Fig. 2).

The individual results for the broader Vittorio Veneto region (Figs. 5 and 6) show that the major influence in the PGA estimates is given by the seismogenic zonation used, which modifies the shapes of the areas with the higher hazard remarkably. The aggregate seismic hazard map (Fig. 7) reduces the individual differences and points out the higher PGAs in central Friuli and around Vittorio Veneto.

The scattering of the individual results for Vittorio Veneto varies between 0.25 and 0.34 g

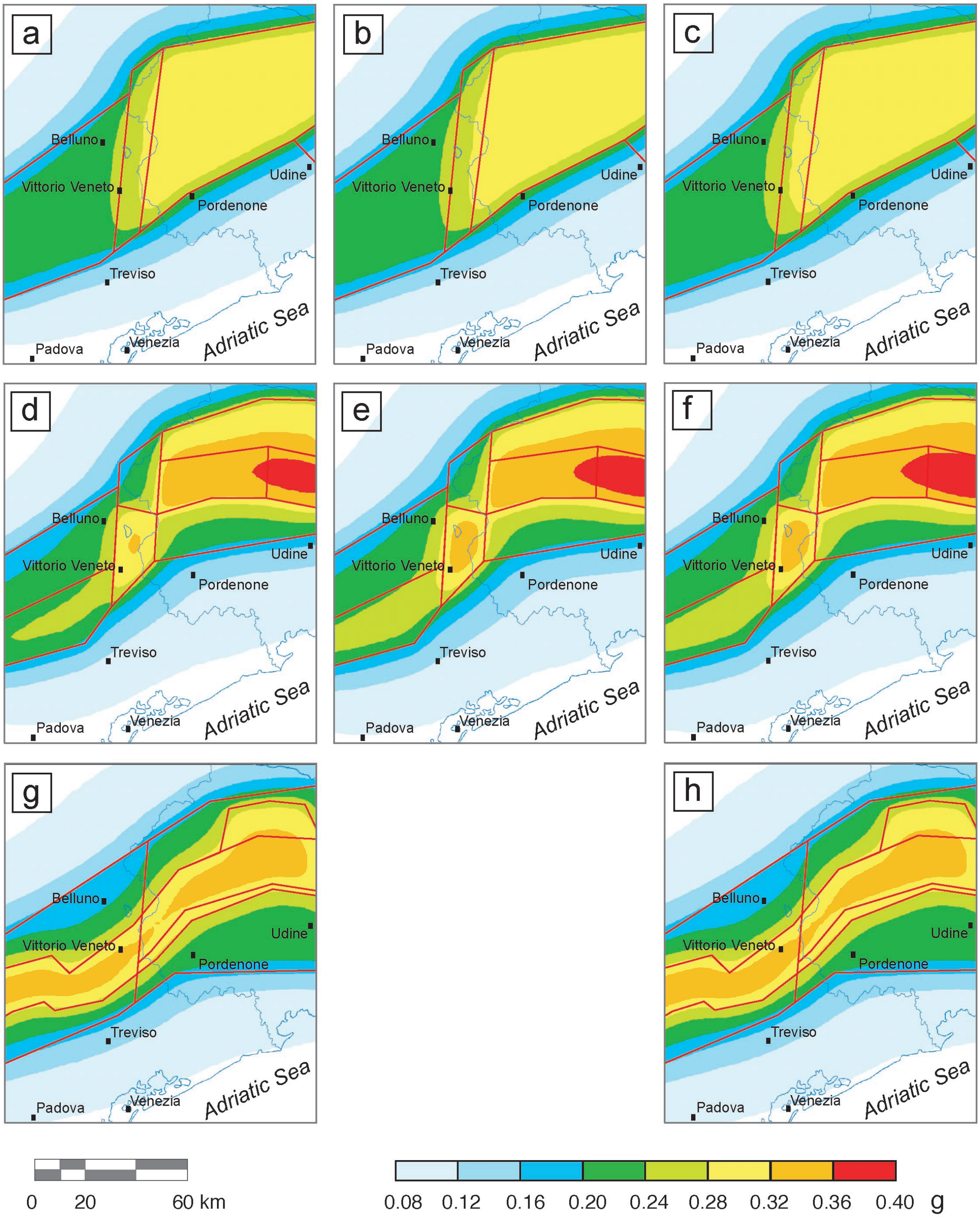

Fig. 5 - PGA for rock with a 475-year return period with σ of the attenuation relation used (Ambraseys et al., 1996). The upper (a, b, c), central (d, e, f), and lower (g, h) rows show the results, respectively, with the GNDT, VIVE, and 3LEV SZs, that are also displayed in the figures. The left (a, d, g), central (b, e), and right (c, f, h) columns indicate the results, respectively, from the OBS, 1SB, and KIJ approaches for maximum magnitude.

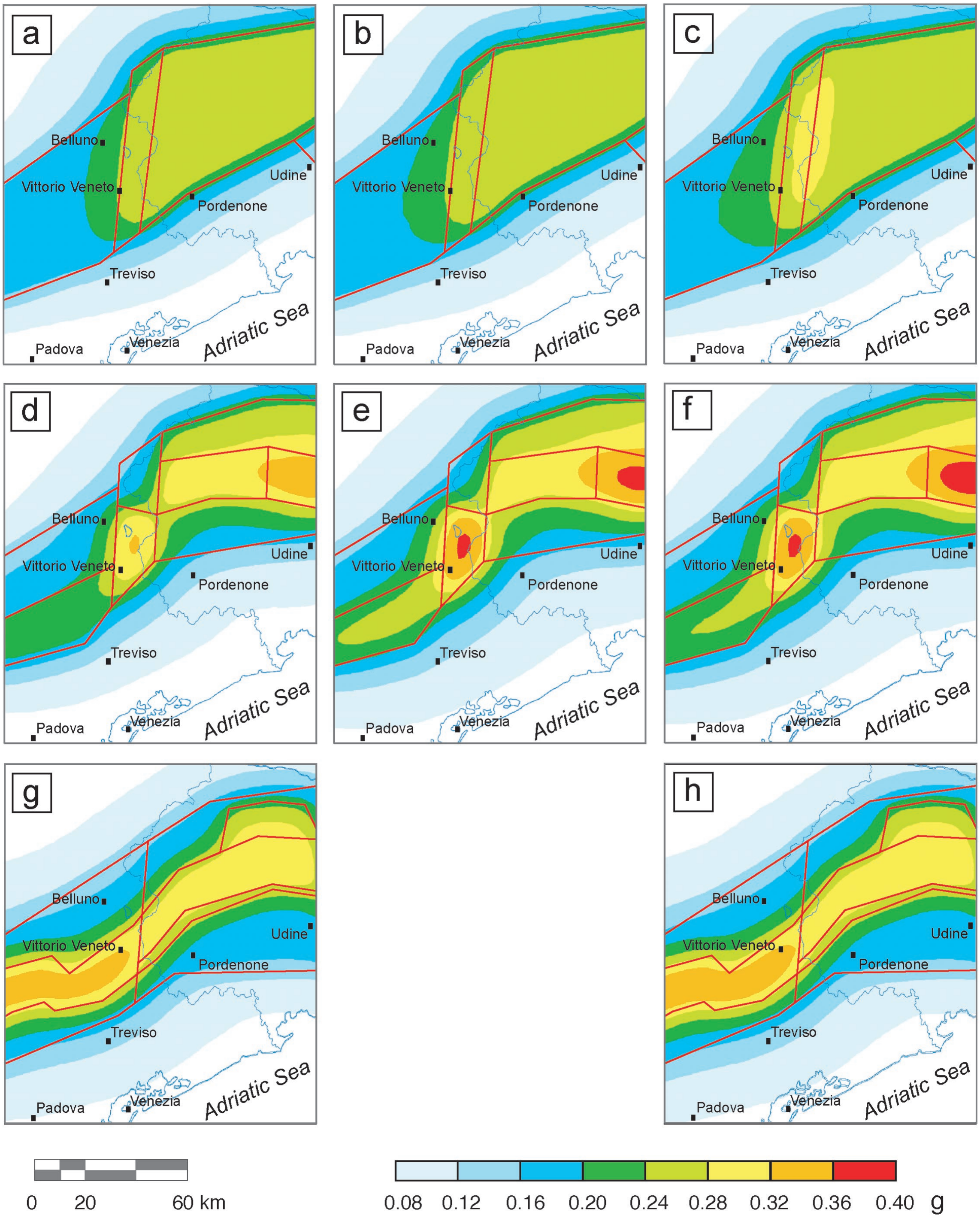

Fig. 6 - PGA for rock with a 475-year return period: with σ of the attenuation relation used (Sabetta and Pugliese, 1987). The upper (a, b, c), central (d, e, f), and lower (g, h) rows show the results, respectively, with the GNDT, VIVE, and 3LEV SZs, that are also displayed in the figures. The left (a, d, g), central (b, e), and right (c, f, h) columns indicate the results, respectively, from the OBS, 1SB, and KIJ approaches for maximum magnitude.

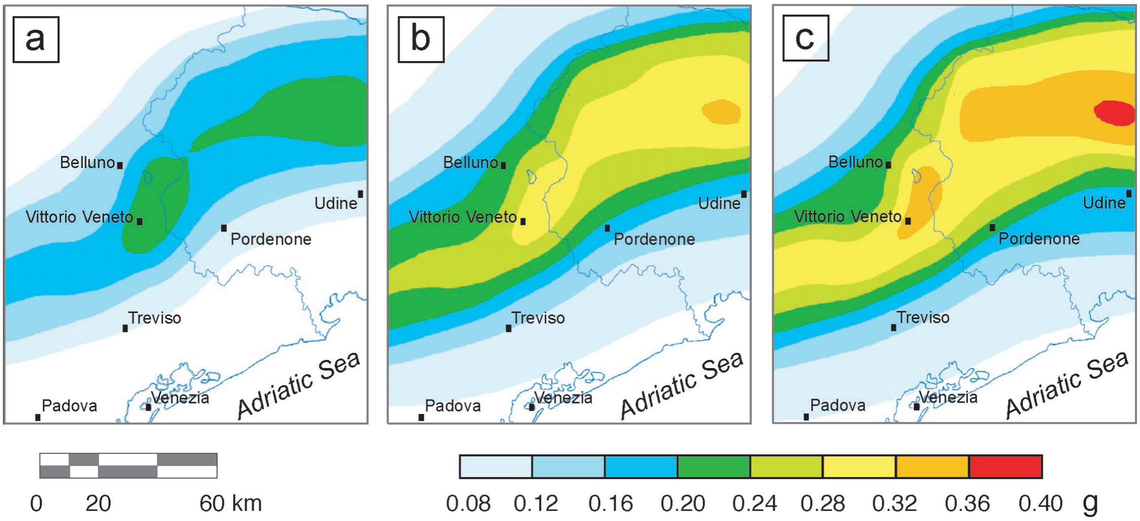

Fig. 7 - Aggregate PGA for rock with a 475-year return period: a) without σ of the attenuation relations used (Sabetta and Pugliese, 1987; Ambraseys et al., 1996); b) with σ of the attenuation relations (Sabetta and Pugliese, 1987; Ambraseys et al., 1996); c) with aleatory and epistemic uncertainties (see the text).

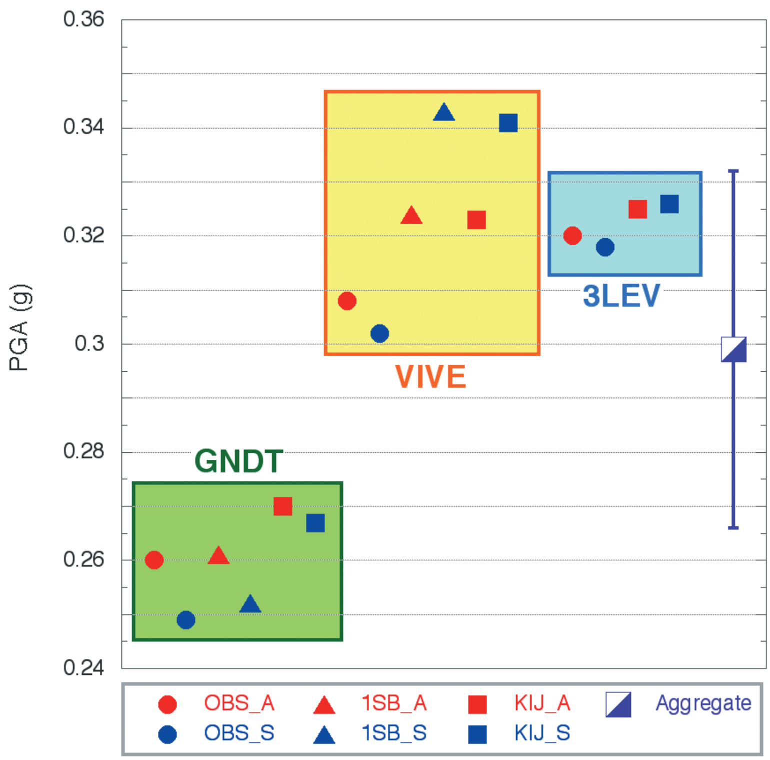

Fig. 8 - Comparison among the individual results of PGA for rock with a 475-year return period with σ of the attenuation relations (Sabetta and Pugliese, 1987; Ambraseys et al., 1996) for the Vittorio Veneto test site. Key: OBS, 1SB, KIJ = maximum magnitude with the observed, “one step beyond”, and Kijko and Graham (1998) approaches; A, S = Ambraseys et al. (1996) and Sabetta and Pugliese (1987) attenuation relations; GNDT, VIVE, 3LEV = SZs according to Meletti et al. (2000), Slejko and Rebez (2002), and Stucchi et al. (2002).

with 0.30 g as mean value with 0.03 g as standard deviation (Fig. 8).

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