New ground motion attenuation relations for north-eastern Italy and their application to the regional seismic hazard assessment

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ABSTRACT New strong motion attenuation relations are presented for NE Italy. These relations are calibrated on a huge data set of strong- and weak-motion recordings. The comparison of the behaviour of this new regional relation for *PGA* and some others, suitable for the study region, points out its fast attenuation in the far field. Considering some hazard results obtained with different attenuation relations, both in terms of hazard maps and hazard curves for specific sites, the new regional relation drives us to higher *PGA* values, mainly due to its high standard deviation, and, consequently points out the importance of a robust attenuation model in seismic hazard assessment.

1. Introduction

The quantification of the ground motion during an earthquake remains a key issue for engineering seismology. It plays a crucial role, as well, in seismic hazard assessment, where attenuation models for the main parameters [intensity, peak ground acceleration (*PGA*), spectral acceleration (*SA*), etc.] are used. The scarce number of observations, especially in the near field, is a strong limit in the definition of robust attenuation relations (ARs). This is demonstrated by the fact that many recent earthquakes have produced unexpectedly high strong motion records. On the other hand, some strong motion relations (e.g., Ambraseys *et al.*, 1996) overestimate the effect of moderate earthquakes (magnitude lower than 6) in the far field. A further element of debate is if general attenuation relations calibrated on a huge number of data collected world wide (or in similar tectonic domains) are appropriate or if regional differences are significant. An attempt to assess such a point was performed by Douglas (2004): for limited distance and magnitude ranges, he found that regional differences are not significant, but the data are insufficient to draw firm conclusions for the magnitudes of main interest for hazard studies. For all these reasons, it is very important to define robust attenuation relations calibrated on a homogeneous (from the instrumental but also from the geological point of view) set of observations for a wide range of magnitudes.

Two different attenuation relations (for *PGA* and *SA*) were applied in the past for probabilistic seismic hazard assessment (PSHA) in NE Italy (Rebez and Slejko, 2004): a relation calibrated on a huge number of European strong motion records (Ambraseys *et al*., 1996; AMB hereafter) and another one calibrated on a limited number of only Italian strong motion records (Sabetta and Pugliese, 1987; S&P hereafter). More recently, Malagnini *et al*. (2002; MAL in the following) have modelled attenuation in NE Italy area by means of the random vibration theory, and developed attenuation curves for *PGA* and *SA* for weak and strong earthquakes.

In the framework of the activities of the project "Damage scenarios in the Veneto – Friuli area" financed by the Gruppo Nazionale per la Difesa dai Terremoti (GNDT), a new regional empirical relation was defined very recently for NE Italy [Bragato and Slejko (2005); B&S hereafter] and it presents some peculiar characteristics. As the few strong-motion data available for that region come almost exclusively from the 1976 M_L 6.3 Friuli earthquake, the strong motion data set was integrated with weak-motion data and from this very huge data set the regional relation was computed using a sophisticated data processing.

The scope of the present work is to compare the performances of the new regional B&S attenuation relation in simulating the ground motion field with respect to those already used and to quantify the differences when applied for regional PSHA.

2. The new ground motion attenuation relation for NE Italy

B&S have used a large data set of seismometric and accelerometric recordings (3168 vertical and 1402 for each of the horizontal components) collected by various networks in the eastern Alps to estimate empirical ground motion attenuation relations valid in the M_L range 2.5-6.3 for distances up to 130 km. In particular, they have considered data of the 1976 Friuli sequence drawn from the European strong-motion data bank and all the data collected between January 1995 and December 2002 by the Seismometric Network of Friuli-Venezia Giulia [SENF, managed by the Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS)] and the Friuli Accelerometric Network (RAF, managed by the Dipartimento di Scienze della Terra of the University of Trieste). Moreover, B&S have used the data collected by some temporary stations deployed in western Slovenia by URSG (Uprava RS za Geofiziko, Ljubljana, Slovenia) during the 1998 Bovec sequence (main shock M_L 5.6).

B&S have developed attenuation relations for the horizontal and vertical *PGA*, peak ground velocity, Arias intensity, and response *SA* and Fourier amplitude for 46 periods between 0.1 and 2 seconds. Some preliminary tests have shown great differences between the attenuation of weak and strong earthquakes. Then, for all the ground motion parameters, they have adopted a magnitude-dependent attenuation model where both magnitude scaling and distance attenuation decrease for increasing magnitude. It has the functional form

$$log_{10}Y = a + (b+cM_L)\, M_L + (d+eM_L^3)\, log_{10}r \qquad \text{with } r^2 = d^2 + h^2 \qquad (1)$$

where M_L is the local magnitude, d is the Joyner-Boore distance (i.e., the closest horizontal distance to the vertical projection of the rupture on the surface), while a, b, c, d, e and h are parameters estimated by regression on the available data set. In the estimation, B&S have taken into account the bias induced by non-triggering stations and adopted the techniques for Truncated Regression Analysis (TRA) described by Bragato (2004). In particular, for the horizontal *PGA* (in g) they have estimated the relation:

$$log_{10}Y = -3.37 + (1.93-0.203M_L)\, M_L + (-3.02+0.00744\, M_L^{\,3})\, log_{10}r \qquad (2)$$
$$\text{with } r^2 = d^2 + 7.3^2 \quad \text{and } \sigma=0.358.$$

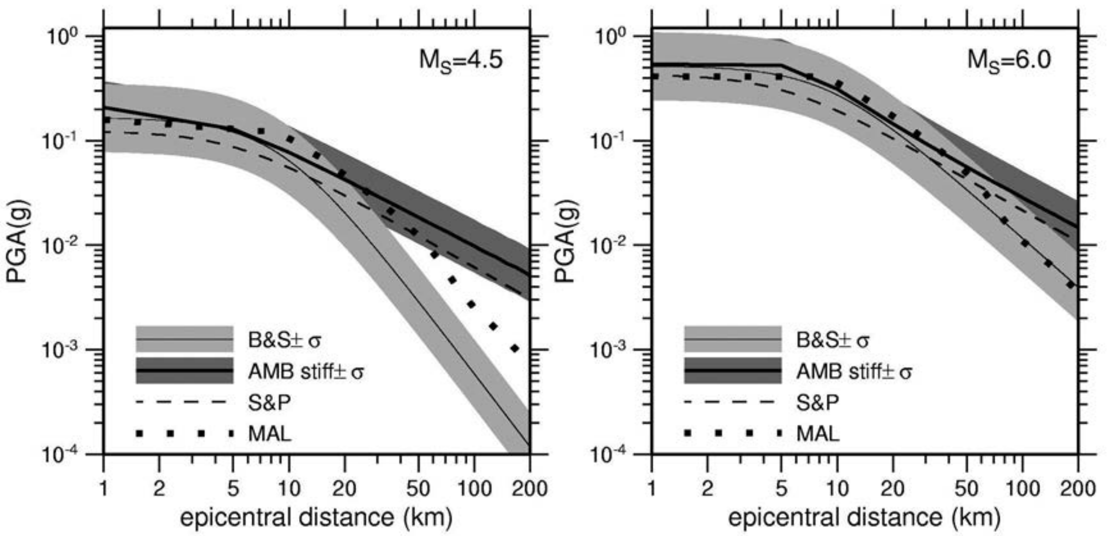

Fig. 1 - ARs suitable for NE Italy drawn for *Ms* 4.5 (left) and 6.0 (right): AMB for stiff soil (solid line), S&B (dashed line), MAL (dotted line) and B&S (thin line). The median *PGA* values +/- 1 σ are also shown for the B&S and AMB ARs.

The same processing was also done considering the epicentral distance and the following relation was obtained for horizontal *PGA* (in g):

$$log_{10}Y = -3.27 + (1.95-0.202\ M_L)\ M_L + (-3.11+0.00751\ M_L{}^3)\ log_{10}r \quad (3)$$
with $r^2 = d^2 + 8.9^2$ and σ=0.399.

In Fig. 1, the attenuation curves obtained from Eq. (2) for two magnitudes (M_S 6.0 and 4.5) are compared with the equivalent curves estimated by S&P, AMB and MAL. S&P (dashed lines in the figure) and AMB (solid lines for stiff soil in the figure) use a magnitude-independent attenuation relation estimated for strong earthquakes (magnitude greater than 4.6 and 4.0 for S&P and AMB, respectively). The AMB relation is calibrated for magnitude M_S while the S&P one for M_L in case of weak quakes and M_S for large ones. In Fig. 1, M_L has been transformed into M_S by the Camassi and Stucchi (1997) relation calibrated on Italian data. We compare the various relations for the epicentral distance, as it is closer to the distance used in PSHA (Bender and Perkins, 1987). For this purpose, the AMB relation has been corrected from fault to epicentral distance for magnitudes larger than 6 (Montaldo *et al*., 2005). The B&S relation is in good agreement with the AMB relation for stiff soil in the near field and it forecasts weaker ground motions in the far field (distances larger than 10 and 30 km for M_S 4.5 and 6.0, respectively). The agreement of the B&S relation with the S&P one is slightly worse for M_S 6.0 in the near field.

The curves by MAL are not simply empirical estimations of attenuation. In fact, the authors have used a subset of the data used in the B&S study (i.e., the accelerometric data of the 1976 Friuli sequence and the seismometric data from the SENF) to parameterise a source-spectral model, to estimate empirical functions for the attenuation of the Fourier amplitude spectra and to evaluate the dispersion-induced ground-motion duration. Then, they have used the random vibration theory to predict the absolute levels of ground shaking. As the MAL relation is defined for magnitude M_W and for distances larger than 10 km, M_W has been converted into M_S with the relation recently used for the seismic hazard map of Italy (Gruppo di Lavoro, 2004) and, in agreement with the cited study, the estimates of the AMB relation for rock have been taken in the near field (1 km) and interpolated for 5 km to the MAL value at 10 km. Furthermore, as the MAL relation is defined for the hypocentral distance, we reduced it to the epicentral one by assuming earthquakes located at 5 km depth. The agreement between the B&S and the MAL ARs is quite good for M_S 6.0 while larger ground motions are estimated by the MAL relation for weaker quakes.

The ARs by B&S have a quite large standard deviation (σ) if compared to those by S&P (0.169 and 0.190 for the Joyner-Boore and epicentral distances, respectively) and AMB [0.25 for the Joyner-Boore distance, comparable to that of its most recent version (Ambraseys *et al*., 2005)]. The difference is justified by the inclusion of weak-motion earthquakes. The inverse dependency of σ on magnitude is well known. Douglas and Smit (2001) find that it increases approximately from 0.2 to 0.4 for magnitudes decreasing from 7.9 to 2.6. To make the various ARs comparable, we have revised the σ of the B&S AR considering only data for magnitude larger than, or equal to, 4.0. The new values have been computed by fitting the distributions of the residuals of the logarithm of the predicted values minus the observed values of *PGA* to a normal distribution. The subset of B&S data for magnitude larger than, or equal to, 4.0 is still unbalanced towards low magnitudes: it has only 31% of records for magnitude larger than, or equal to, 5.5, while the same percentage for S&P and AMB is 67% and 45%, respectively. Then, in the fitting we have weighted the data in order to give equal representation to different magnitude classes. In this way, the σ of Eqs. (2) and (3) reduces to 0.302 and 0.324, respectively. The σ of the MAL relation is not reported in Malagnini *et al*. (2002): the value 0.2 has been taken in the following elaborations in agreement with the value used in the seismic hazard map of Italy (Gruppo di Lavoro, 2004), some authors of which are authors of the MAL AR as well.

3. Comparison between observed and predicted *PGAs* and among seismic hazard estimates

Some analyses are proposed here to compare the different ARs available for NE Italy. The first illustrates the differences between the actual observed *PGA* values recorded for some recent earthquakes in the eastern Alps. The second compares the seismic hazard estimates at a regional scale obtained by different ARs, while in the third some specific sites have been chosen to investigate the differences obtained in the related hazard curves.

In all the following comparisons, it must be remembered that the B&S relation is defined for a rigid soil, similar to the stiff soil of the seismic Eurocode 8 [EC8; CEN, (2002)] or to the soft rock (class C) of the NEHRP provisions (BSSC, 1997).

In agreement with the soil classes of the EC8, the AMB relations were defined for three different soils, on the basis of the shear wave velocity averaged over the upper 30 metres of the site (V_{30}): rock [V_{30} >750 m/s, equivalent to hard rock and rock (classes A and B) of the NEHRP provisions (BSSC, 1997)], stiff soil [360≤V_{30}≤750 m/s equivalent to soft rock (class C) of the NEHRP provisions], and soft soil [180≤V_{30}≤360 m/s, equivalent to stiff soil (class D) of the NEHRP provisions]. For the very soft soil [V_{30}<180 m/s, equivalent to soft soil (class E) of the NEHRP provisions] no sufficient data were available to define a relation. The different attenuation in stiff and soft soils resulted negligible.

The S&P relations were defined for three soil categories according to V_{30} and the thickness (H) of the soil layer: stiff soil (V_{30}>800 m/s or V_{30}<800 m/s with H<5 m, almost equivalent to the rock of AMB), shallow soil (V_{30}≤800 m/s and 5≤H≤20 m) and deep soil (V_{30}≤800 m/s and H>20 m). In this case, the same attenuation was obtained for horizontal *PGA* in the case of stiff and deep soil sites.

The MAL relation was defined for rock but, since the authors used a subset of the data used by B&S, some doubts remain if to associate it to the EC8 rock or to stiff soil (class B and C, respectively, of the NEHRP provisions).

3.1. Comparison between observed and predicted PGAs

In Fig. 2, the curves predicted by Eq. (2) (solid lines) are compared with the *PGA* values observed for the main shock of the 1976 Friuli sequence (bottom left panel) and for the three strongest earthquakes which have occurred in the area since 1995. In particular, the top right panel refers to the recent earthquake of July 12, 2004 in western Slovenia (only data from the RAF network are reported), not considered by B&S. In general, the agreement between the curves and the data is good: in fact, almost all observations remain within one σ. In Fig. 2, we have also reported the corresponding curves by AMB (dashed lines). With the exception of the 1976 Friuli earthquake, such curves overestimate *PGA* at intermediate and long distances, starting from about 10 km.

3.2. Comparison among regional seismic hazard estimates

The ARs used here for PSHA refer to the epicentral distance [Eq. (3) for B&S]. As told before, the AMB relation has been corrected from fault to epicentral distance for magnitudes larger than 6 (Montaldo *et al*., 2005). According to B&S, their relation is not well constrained for magnitude exceeding 6.5 and, consequently, the S&P relation replaces it for large magnitudes. Parameterisations other than the attenuation models have been maintained fixed in the hazard maps shown here and correspond to those used for PSHA of the broader Vittorio Veneto area (Slejko *et al*., 2007) according to the Cornell (1968) approach in the Bender and Perkins (1987) formulation. More precisely, the logic tree approach was used to take into account the epistemic uncertainties and it consists of 27 branches (3 seismogenic zonations, 3 methods for seismicity rate computation, and 3 approaches for maximum magnitude assessment: see the details in Slejko *et al*., 2007). Consequently, the aleatory uncertainty is quantified by the σ of the ARs, while the epistemic uncertainty is given by the standard deviation of the individual estimates related to the different branches of the logic tree. According to the SSHAC (1997), the averaging process should be done on the probability values and the *PGA* is computed accordingly. The method used here is simpler (average of the *PGA* values) and, according to some tests done, leads to almost the same estimates (differences are less than 10%, usually around 4%, also for very long return periods).

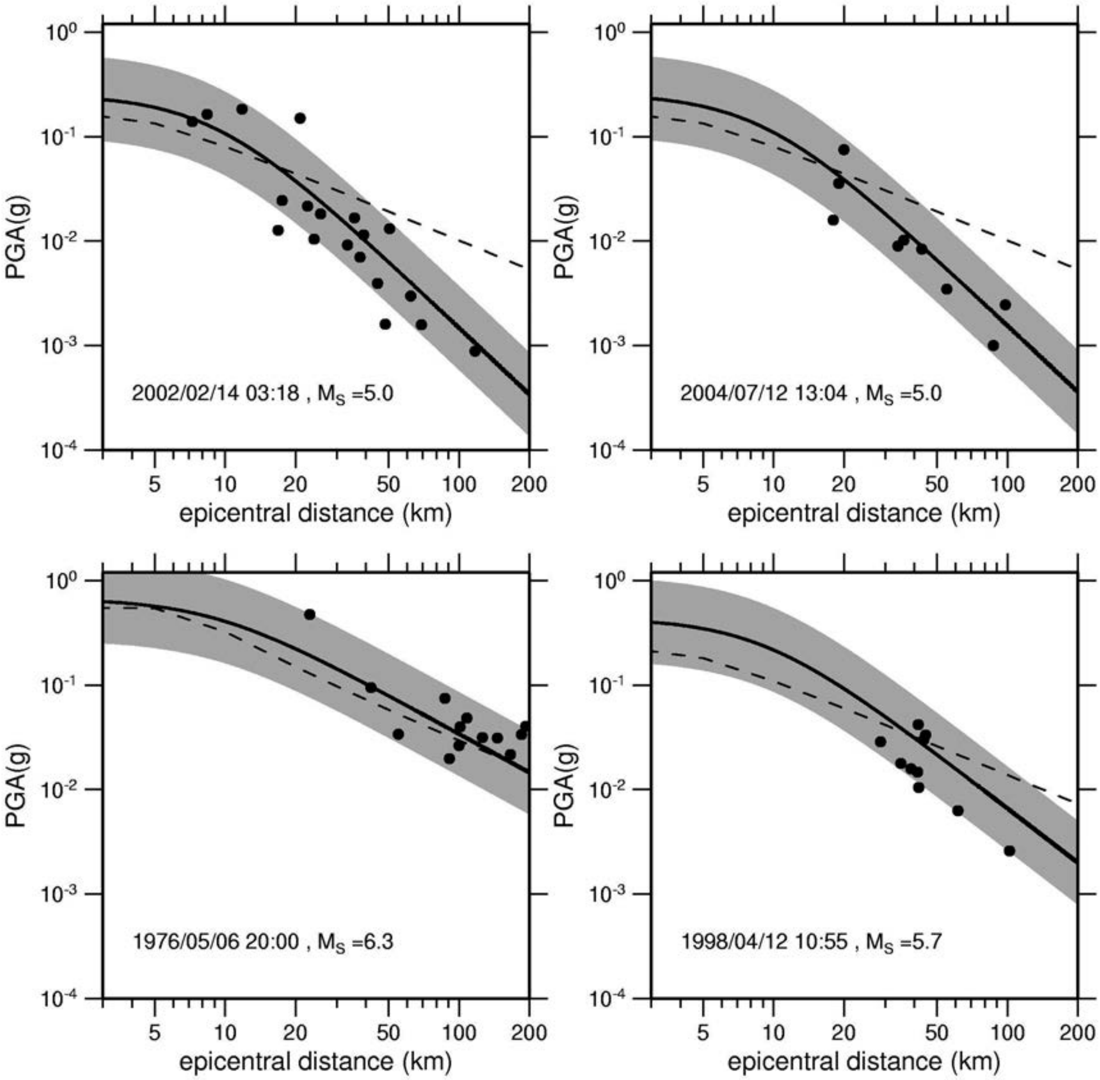

Fig. 2 - *PGA* value observed for the main shock of the 1976 Friuli sequence and for the strongest earthquakes that have occurred since 1995 in the study area (solid dots). The attenuation curves are those predicted for the same magnitude by B&S (solid lines) and AMB (dashed lines). The grey strip represents the σ of the B&S relation.

Fig. 3 shows the hazard results, in terms of median *PGA* with a 475-year return period taking into account the AR σs (reduced in the case of the B&S relation), while the epistemic standard deviation is not considered. The estimates refer to similar terrains, when possible: rigid soil for the B&S AR, EC8 rock (NEHRP class B) for the MAL AR, EC8 stiff soil (NEHRP class C) for the AMB AR, and deep soil for the S&P AR (see the previous description). The results obtained using the B&S relation (Fig. 3a) shows the maximum *PGA* (larger than 0.55 g) in central Friuli. The area with values larger than 0.40 g has a pronounced south-westward elongation, along the Veneto foothills and encompasses Vittorio Veneto, where values larger than 0.45 g are expected.

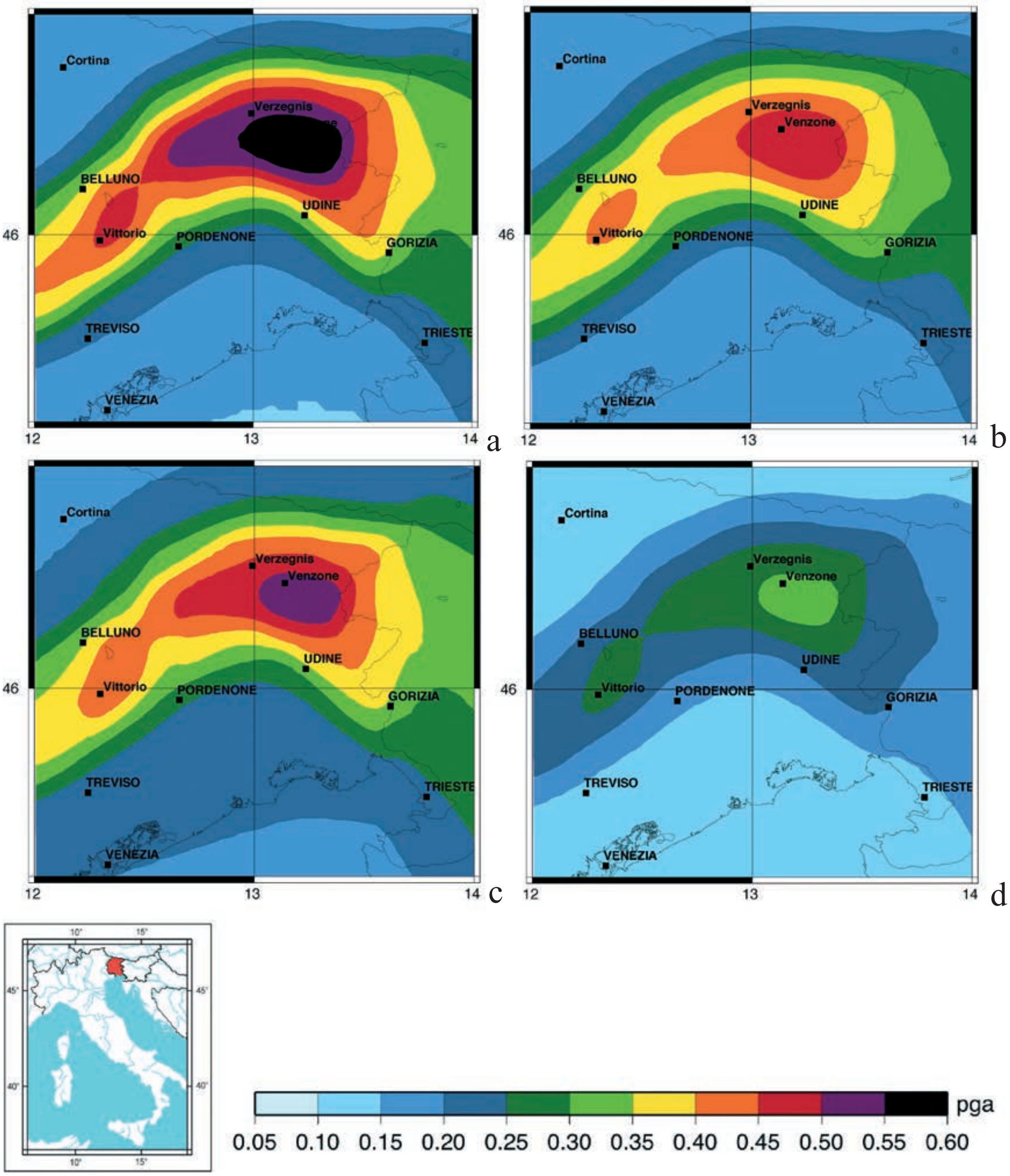

Fig. 3 - Median *PGA* with a 475-year return period in NE Italy, with AR σ, according to different ARs: a) B&S for a rigid soil; b) MAL for rock; c) AMB for stiff soil; d) S&P for deep soil.

Fig. 3b shows the hazard results obtained with the MAL relation. The general features of the map are very similar to those displayed by the previous map (Fig. 3a) but the *PGA* values are lower. The maximum *PGA* reached in central Friuli is now, in fact, between 0.45 and 0.50 g and the Vittorio Veneto area is characterised by *PGAs* larger than 0.40 g. Fig. 3c shows the hazard results obtained with the AMB relation for stiff soil. The map shows remarkable similarities to the previous ones (Figs. 3a and 3b) and slightly higher *PGAs* than those with the MAL relation can be seen in central Friuli (values larger than 0.50 g). Moreover, the attenuation is less rapid with the AMB relation and a higher *PGA* is forecast from the seismic areas at long distances. Fig. 3d shows the hazard results obtained with the S&P relation for deep soil. Although the general features of the map are very similar to those displayed by the previous maps, the *PGA* values are much lower. The maximum *PGA* reached in central Friuli is now, in fact, only between 0.30 and 0.35 g.

To better pinpoint the different behaviours of the considered ARs, *PGA* estimates for a 475-year return period, without considering the AR σs, have been computed as well. It is worth noting that these maps, shown in Fig. 4, do not represent, consequently, the results of a fully probabilistic approach. The higher ground motions are forecast by the MAL relation (*PGA* larger than 0.35 g in central Friuli; Fig. 4b), followed by those obtained by the AMB relation for stiff soil (*PGA* larger than 0.30 again in central Friuli; Fig. 4c). The results with the B&S relation (Fig. 4a) are sensibly lower and remain below 0.30 g. Even lower ground motions are obtained using the S&P (Fig. 4d) relation for deep soil (values below 0.25 g). The faster attenuation with distance of the B&S AR is again evident.

The comparison among the obtained results points out that the median *PGA* computed with the B&S relation is lower than that computed with the MAL relation and the AMB one for stiff soil and higher than that obtained by the S&P relation for deep soil. It is worth noting that no difference is expected for rock and deep soil from the S&P AR. When the σs of the ARs are introduced, the results with the B&S relation are the highest in the seismic areas and this is due to its high σ. As the B&S relation shows a rather fast attenuation with distance (Fig. 1), the *PGA* values computed do not differ significantly with those obtained with the other ARs in the aseismic areas (they are even lower with respect to those given by the AMB AR).

Considering the values reported by the recent Italian seismic hazard map (Gruppo di Lavoro, 2004) for NE Italy, it is evident that the hazard shown by the present study is by far larger than that displayed by the national map, where *PGAs* lower than 0.275 g refer to this territory. This difference is explained by several issues (in a few words it can be said that the logic tree considered in the two studies is remarkably different, mainly in the way of computing the maximum magnitude and the seismicity rates; see more discussion in Slejko *et al*., 2007), among which the introduction of the B&S AR plays surely an important role.

3.3. Comparison among seismic hazard curves

An additional comparison has been made by considering some specific sites (see their location in Figs. 3 and 4) and computing the complete hazard curve for them. Vittorio Veneto, test site of the specific GNDT project “Damage scenarios in the Veneto – Friuli area”, is one of the sites; it is characterised by stiff soil conditions. The other sites have been selected according to their soil typology and hazard level. More precisely, two sites with almost the same hazard level

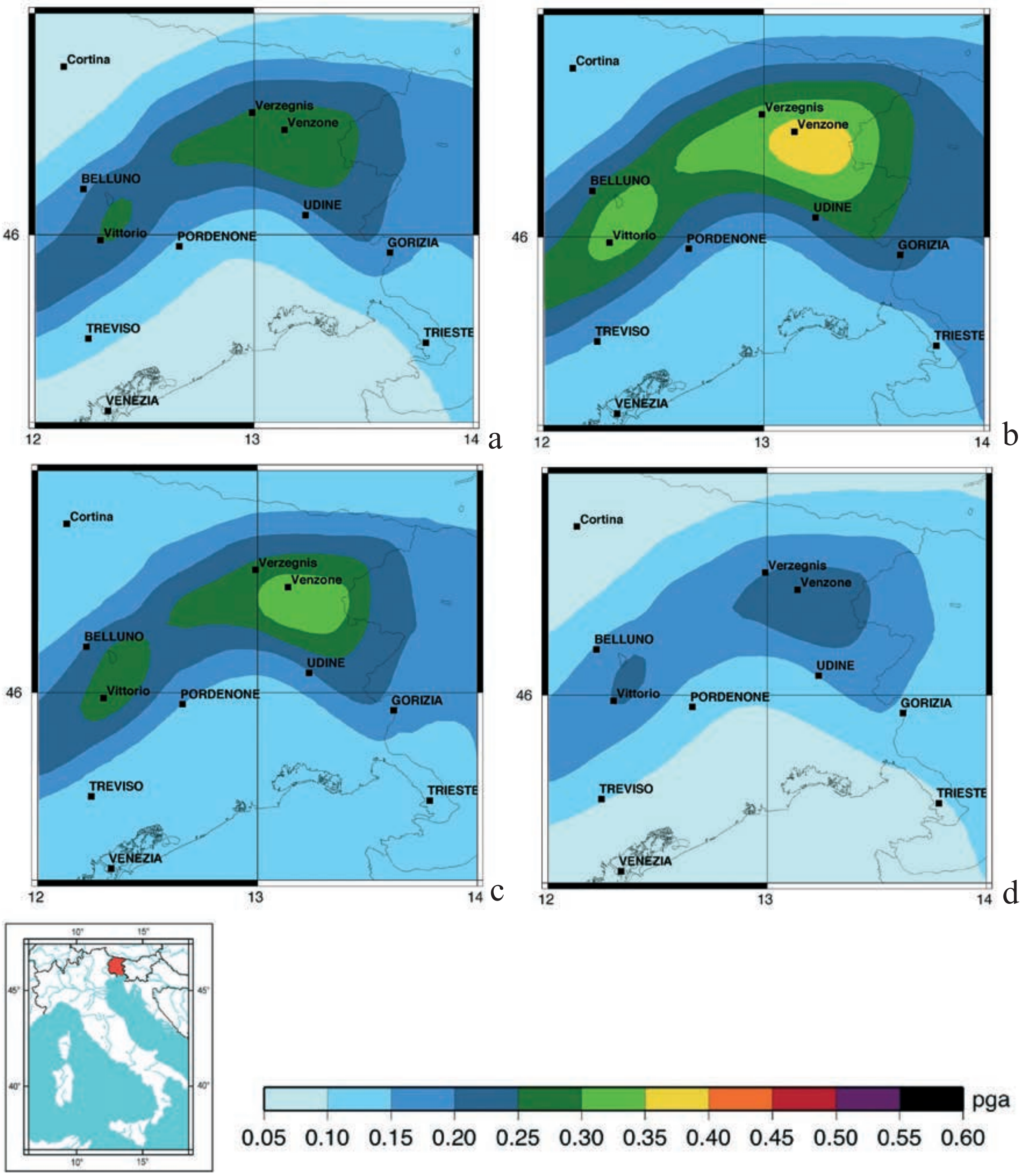

Fig. 4 - Median *PGA* with a 475-year return period in NE Italy according to different ARs: a) B&S for a rigid soil; b) MAL for rock; c) AMB for stiff soil; d) S&P for deep soil.

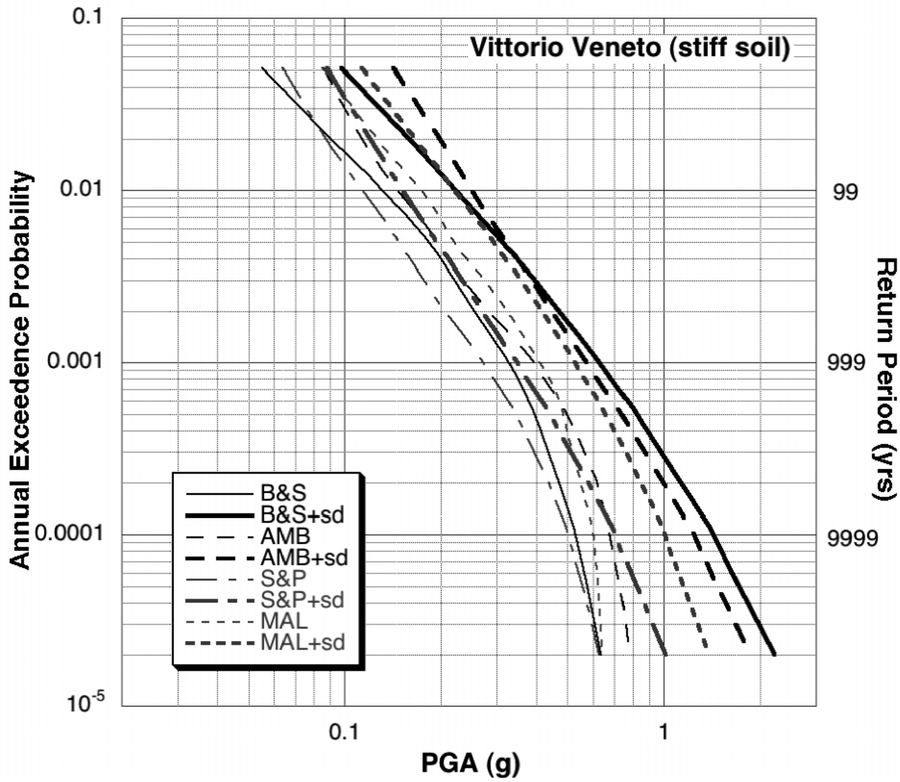

Fig. 5 - Hazard curves for the Vittorio Veneto site (see its location in Figs. 3 and 4) computed by the B&S (solid line), S&P (dot-dashed line), AMB (dashed line), and MAL (dotted line) ARs without (thin lines) and with (thick lines) AR σ. The choice of the ARs is in agreement with the soil type of the site (stiff soil; see the text for the details).

(see Figs. 3 and 4) have been chosen in the high hazardous central Friuli (Venzone and Verzegnis), one along the seaside (Trieste), and one in the mountains (Cortina), the last two far from the seismic bulk and with almost the same hazard level (see again Figs. 3 and 4). Trieste (the hilly part of the town, a few kilometers from the coast) and Verzegnis are characterised by rocky conditions while Cortina and Venzone are located on a stiff soil.

Figs. 5 and 6 show the calculated hazard curves for an annual exceedence probability from 10^{-1} to 10^{-5}, not considering and considering the aleatory uncertainty. It is worth noting, once again, that the hazard curves obtained without taking into account the AR σs cannot be considered the result of a fully probabilistic approach but are reported here to illustrate the behaviour of the different ARs. The illustrated features are quite interesting. In Vittorio Veneto (Fig. 5), a site characterised by a medium level of hazard, the mean ground motion estimates calculated with the B&S relation are the lowest for very short return periods (less than 90 years) and remains lower than those with the AMB and MAL relations, always. When considering its (reduced) σ (0.324), the hazard calculated with the B&S relation is lower than that computed with the AMB relation and similar to that obtained with the MAL relation for short return periods (less than 600 years). The features displayed by the low seismic sites of Cortina (Fig. 6a) and Trieste (Fig. 6b) are rather similar to each other and lower but not very different from those of Vittorio Veneto (Fig. 5). In

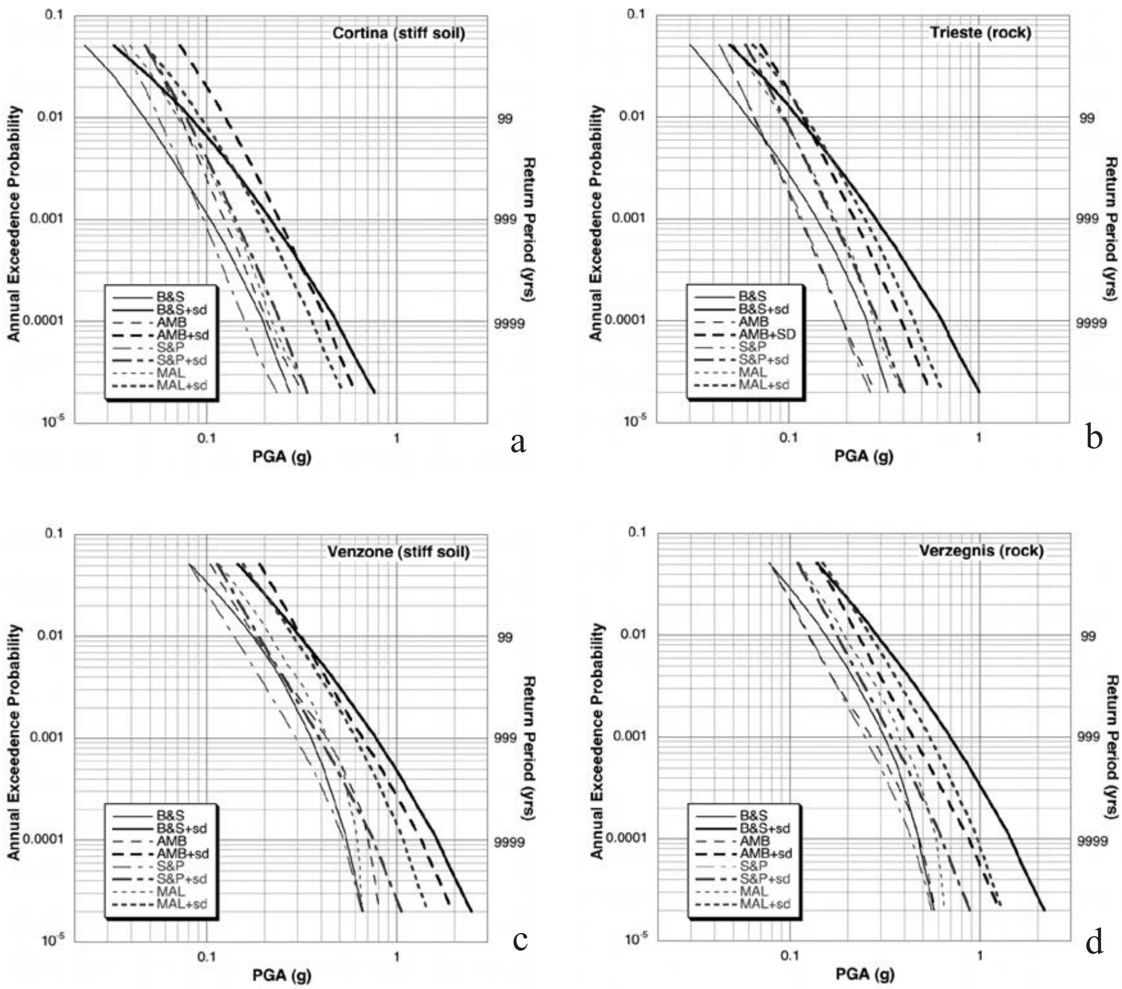

Fig. 6 - Hazard curves for some specific localities in NE Italy (see their location in Figs. 3 and 4) computed by the B&S (solid line), S&P (dot-dashed line), AMB (dashed line), and MAL (dotted line) ARs without (thin lines) and with (thick lines) AR σ. The choice of the ARs is in agreement with the soil type of the sites: a) Cortina (stiff soil); b) Trieste (rock); c) Venzone (stiff soil); d) Verzegnis (rock).

both localities the B&S relation drives to the lowest mean hazard for short return periods (lower than 600 and 900 years for Trieste and Cortina, respectively); for the mountainous site (Fig. 6a), it never exceeds that obtained by the AMB and MAL relations. The high σ of the B&S relation (also considering its reduced value 0.324) produces the highest hazard estimates for return periods greater than 700 and 7000 years for Trieste and Cortina, respectively. A different situation is illustrated by the two highly seismic sites, which are again not very different to each other. In Venzone (Fig. 6c), the mean hazard calculated by the B&S relation is higher only than that obtained by the S&P AR while in Verzegnis (Fig. 6d) it is only lower than that obtained by the MAL AR. The high σ of the B&S relation again produces, almost always, the highest hazard estimates.

To conclude this site analysis, we can say that the seismicity level of the studied locality remarkably conditions the hazard obtained with the different attenuation relations. The B&S relation drives to higher hazard in highly seismic sites and, in all cases, a more severe situation is pictured increasing the return period. No evident differences can be seen, on the contrary, considering the soil characteristics (see the similarities of the two low and the two high hazard sites, respectively).

4. Conclusions

The great importance of the AR in PSHA has been evidenced also by the analyses performed for the Vittorio Veneto broader region. Both the regional hazard maps and the site hazard curves have shown the different *PGA* values obtained considering different attenuation models. The B&S relation, which was calibrated on regional strong- and weak- motion recordings, shows a faster attenuation in the far field than the other relations considered, while in the near field it gives similar *PGA* values. These aspects, together with the quite high aleatory uncertainty related to the B&S relation, drive to hazard estimates that are higher than those obtained with the other relations suitable for the study region.

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