Probabilistic seismic hazard assessment and deterministic ground shaking scenarios for Vittorio Veneto (N.E. Italy)

D. SLEJKO and A. REBEZ

*Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, Trieste, Italy*

Abstract - Probabilistic seismic hazard estimates have been assessed for the Vittorio Veneto broader area in north-eastern Italy and two deterministic ground shaking scenarios have been computed for the study site, respectively for the design and extreme earthquakes. Different hazard parameters and three soil conditions have been taken into account. The probabilistic estimates will be used to compute a regional seismic risk map. The two deterministic ground shaking scenarios will constrain the ones obtained by complete ground motion modelling and will be used for the detailed damage assessment at Vittorio Veneto in the case of future possible earthquakes. The results, although not very high (the median value on soft soil plus the total uncertainty is 0.64 g in the worst case), refer to shakings that can produce also significant damage. The median ground motion on rock expected in Vittorio Veneto from the two scenario earthquakes are very similar to each other (respectively 0.16 and 0.22 g). An even more interesting aspect is that they do not differ much from the probabilistic estimate for a 475-year return period (0.21 g). These similarities are justified by the characteristics of the seismicity influencing the study site.

1. Introduction

Recent seismic hazard estimates for the eastern Alps (Rebez et al., 2001) show that the most seismic area is central Friuli (north-eastern Italy) and hazard decreases moving westwards. The Belluno area, on the border of the Friuli - Venezia Giulia and Veneto regions (Fig. 1), 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

---

Corresponding author: D. Slejko, Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, Borgo Grotta Gigante 42c, 34010 Sgonico (Trieste), Italy; phone: +39 0402140248; fax +39 040327307; e-mail: dslejko@ ogs.trieste
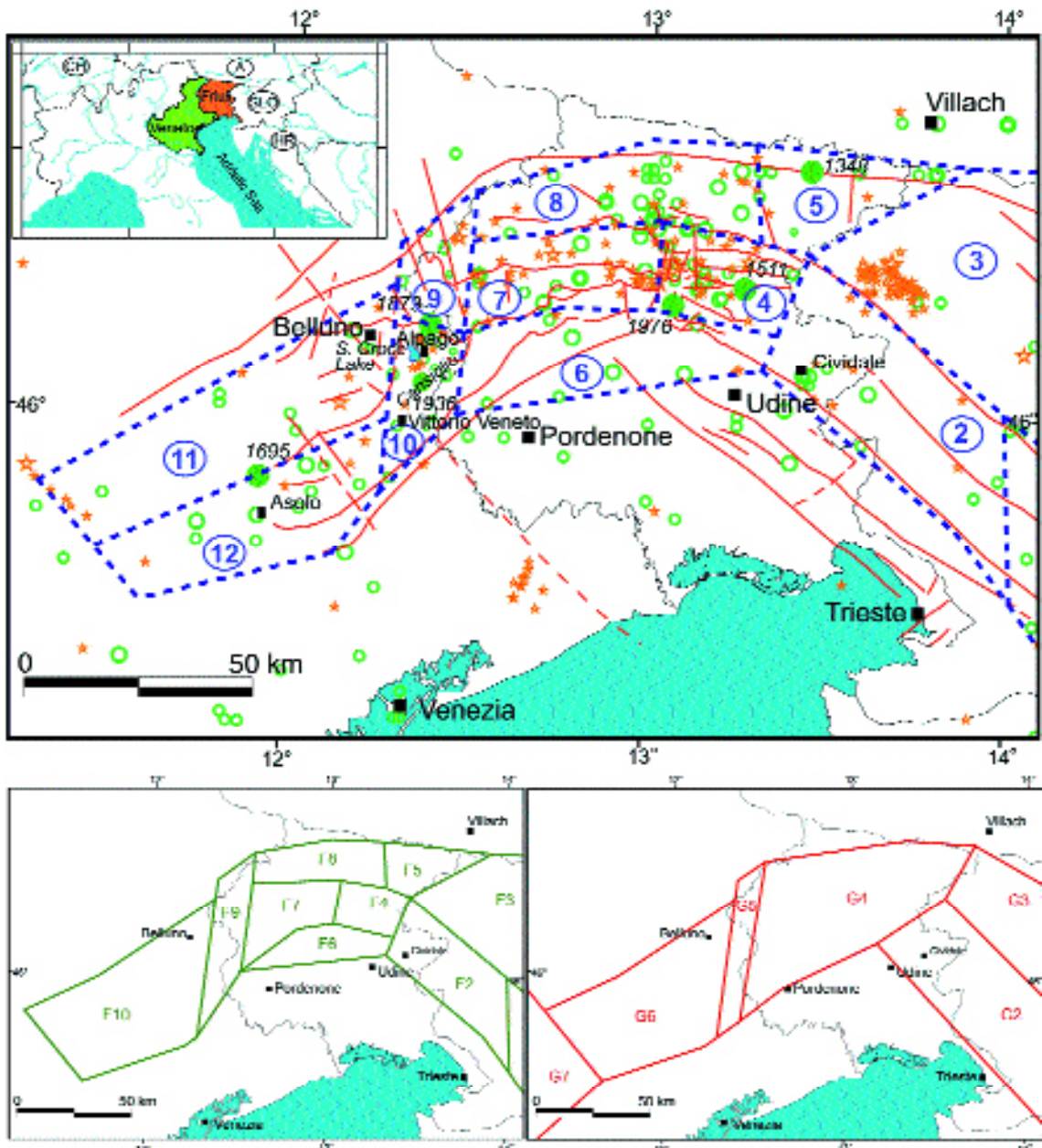
Fig. 1 - Evolution of the seismogenic zonation in the eastern Alps - northern Dinarides: a) SZs proposed in the present work and tectonic setting, dashed blue boxes indicate the SZs, green (solid if major events, the number indicates the date of the quake) circles show the epicentres of the earthquakes of the GNDT catalogue (Camassi and Stucchi, 1996), yellow stars represent the epicentres of the 1977 - 1999 earthquakes (OGS, 1977-1980, 1981-1990, 1991-1999; Renner, 1995), red lines display the main faults; b) SZs according to Carulli et al. (2002); c) SZs according to Meletti et al. (2000).

was associated to a narrow NNE-SSW trending strip (Meletti et al., 2000), which could also be linked to the Alpine compressional front (Galadini et al., 2002). Two large earthquakes occurred there in the last two centuries: the 1873 Alpago quake with magnitude 6.3 and the 1936 Cansiglio event with magnitude 5.8 (Gruppo di Lavoro CPTI, 1999).

The Italian "Gruppo Nazionale per la Difesa dai Terremoti" (GNDT) is financing a national project also for the above cited reasons. Its aim is to compute some damage scenarios for the Vittorio Veneto test site, located about 20 km SSE from Belluno (Fig. 1), as well as a risk assessment for a broader area around the site. The test site was chosen for several reasons other than the seismological one, i. e.: Vittorio Veneto has an architecturally important historical part and can be studied using geophysical surveys because it is not very large. The regional seismic risk map is obtained from probabilistic seismic hazard estimates, while the damage scenarios for Vittorio Veneto are based on a deterministic, complete ground motion modelling. Additional deterministic estimates, hereafter described, are to constrain the basic results for the Vittorio Veneto deterministic ground shaking scenario.

Probabilistic and deterministic hazard estimates have different purposes (see McGuire, 2001, for a complete description): in short, the first are the guidelines for the definition of national seismic zonations, while the second contribute to the construction of damage scenarios for a specific site. In the case of the GNDT project, several products will be prepared to guide the public administration in urban planning, building retrofitting, and emergency preparedness: a regional seismic risk map, based on probabilistic estimates, and damage scenarios at different scales for Vittorio Veneto. These will refer to the two major earthquakes most likely to occur in the region.

The aim of the present paper is to describe the probabilistic seismic hazard assessment (PSHA) for the broader Vittorio Veneto area, for use in the regional seismic risk map, and the additional deterministic ground shaking scenarios for Vittorio Veneto, for use as additional constraints to the deterministic scenarios obtained by complete ground motion modelling. More precisely, two scenario earthquakes are computed in the present work: the most probable one and the extreme one; for both the expected ground shaking in Vittorio Veneto is estimated by taking into account the related uncertainties of the focal parameters.

2. PSHA at the Vittorio Veneto test site

In the standard PSHA (Cornell, 1968; Bender and Perkins, 1987), seismic sources are modelled as seismogenic zones (SZs), where the earthquakes can randomly occur. In addition, the magnitude distribution of the earthquakes inside each SZ and the attenuation relation of the quantity chosen as hazard parameter are needed. Alternative probabilistic approaches do exist (e.g.: Frankel 1995; Mantyniemi et al., 2001) but the use of geological data is there marginal in these cases.

2.1. The new seismogenic zonation

The seismogenic zonation considered in the present study (Fig. 1a) derives from an improvement by Carulli et al. (2002; Fig. 1b) of the Italian seismogenic zonation designed by Meletti et al. (2000; Fig. 1c) and used in a GNDT project of the Nineties in which the seismic

hazard map of Italy was prepared (Slejko et al., 1998) for the revision of the national seismic zonation. The Carulli et al. (2002) seismogenic model was adopted to compute the soil-dependent seismic hazard map of the Friuli - Venezia Giulia region (Rebez et al., 2001) and is further improved here, mainly on the evidence of recent seismicity in north-eastern Italy. The five homogeneous SZs in the eastern Alps - northern Dinarides of Meletti et al. (2000; SZs G2 to G6 in Fig. 1c) were identified in greater detail by Carulli et al. (2002), obtaining nine SZs (SZs F2 to F10 in Fig. 1b). Summarising their main modifications, the subdivision between External (SZ G2) and Internal (SZ G3) Dinarides of Meletti et al. (2000) was maintained, but the respective SZs F2 and F3 have different shapes; in particular, SZ F2 collects the low seismicity of the Cividale area, which is due to normal faulting. The Meletti et al. (2000) SZ G4 of Friuli was divided into five SZs (F4 to F8), of which SZs F4 and F7 collect the major seismicity. In the north-eastern part of the region, the new wedge-shaped SZ F5 connects the Alpine domain to the Dinaric one and represents a possible link to the Vienna basin (Slejko et al., 1989). As the focus of the present study is the Vittorio Veneto area, the geometry proposed by Carulli et al. (2002) for SZ F9, on the border of Friuli and Veneto, where Vittorio Veneto is located, has been subdivided into two smaller zones according to the space distribution of the 1936 Cansiglio seismic sequence (Peruzza et al., 1989) and on the basis of the trend of the main overthrusts (Fig. 1a): the southern part (SZ 10 corresponding to the external front) collects the main seismicity of Alpago-Cansiglio, where the two large earthquakes of 1873 and 1936 occurred. In addition, its eastern border has also been re-shaped to better contain the local seismicity. It is noteworthy that the seismicity reported for both SZs 9 and 10 is very rare before 1850. The western Asolo SZ F10 of Carulli et al. (2002) has been subdivided into two parts (SZs 11 and 12) as well, mainly on the basis of the historical seismicity, which has been reported since 1300 for these SZs and seems to be concentrated in the southern foothills, where the 1695 earthquake with magnitude 6.4 (Gruppo di Lavoro CPTI, 1999) is also located.

In terms of hazard estimates, the Carulli et al. (2002) zonation concentrated the maximum expected shaking at the border with Slovenia (Rebez et al., 2001) reflecting the high seismicity of SZ F4. The modifications introduced in this western part focus on the higher seismicity of the foothills with respect to the northern piedmont belt.

In addition to the 11 SZs described before, a general wide background SZ has been considered: it covers the whole study region (Fig. 1a) and collects all the earthquakes with epicentre outside the actual SZs.

2.2. Hazard computation

The seismicity associated to the different SZs described above has been modelled by taking into account the low magnitude events too. Their contribution to hazard is, in fact, small but not negligible. Fig. 2 summarises two synthetic cases of annual seismicity rates computed from a Gutenberg - Richter (GR) distribution of seismicity with an a-value of 4 and, respectively, a b-value of 1 with maximum magnitude (M_{max}) of 8 (squares in Fig. 2) for the high seismicity SZ and a b-value of 1.2 with an M_{max} of 6.4 (diamonds in Fig. 2) for the moderate seismicity SZ.
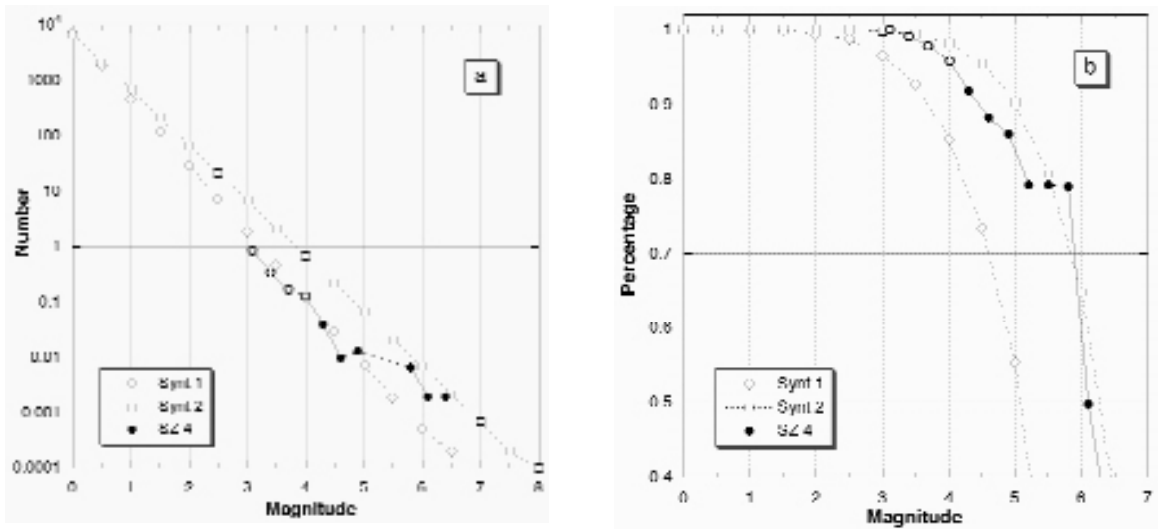
Fig. 2 - Contribution of low magnitude earthquakes to seismic hazard: a) annual (non cumulative) seismicity rates for two synthetic cases (dotted lines with squares for $a = 4$, $b = 1$, $M_{max} = 8$; and with diamonds for $a = 4$, $b = 1.2$, $M_{max} = 6.5$) and for SZ 4 (circles; empty symbols mark the rates for magnitude lower than, or equal to, 4 coming from the data of the OGS seismometric network); b) percentage of a 475-year return period PGA with σ computed with different threshold magnitudes, the dotted lines with squares and diamonds refer to the two synthetic cases, the solid line to the real case of SZ 4. The value 1 (100%) refers to the PGA computed with all rates: 0 and higher for the synthetic cases, 3.1 and higher for SZ 4.

The dotted lines in Fig. 2b show the results for the horizontal peak ground acceleration (PGA) with a 475-year return period computed considering the standard deviation (σ) of the attenuation relation (Ambraseys et al., 1996). It can be seen that the correct hazard estimate is obtained with the rates referring to magnitude 1.5 and above, in the case of the moderate seismicity SZ, and 3 and above in the case of the high seismicity one. The seismicity lower than magnitude 4 (usual threshold value in engineering seismology) contributes only 2% in the high seismicity SZ, but 15% in the moderate seismicity one. For shorter return periods, the contribution of small-magnitude earthquakes increases. In really low seismicity SZs, the contribution from the small events can be even larger because of non-linear (GR) seismicity distributions (see in Fig. 2 a real case which will be described in the following). A general guideline is not easy to identify but in low seismicity SZs (small M_{max}, high b-value) the small events (magnitude lower than 4) contribute significantly to a correct hazard estimate and an appropriate threshold value can probably be magnitude 3. In the case of hazard estimates without the σ of the attenuation relation, the influence of the small events is very limited and correct estimates can be obtained using only events of magnitude 4 and above (see more discussion about this topic in Reiter, 1990).

The catalogue prepared in the Ninenties in the framework of the GNDT activities (Camassi and Stucchi, 1996) for the hazard assessment of Italy has been used for the seismicity rate computation. Some more recent catalogues (Boschi et al., 1995; Gruppo di Lavoro CPTI, 1999) have been considered as well, but discarded for their lower homogeneity. The Camassi and Stucchi (1996) catalogue has been implemented with the data of local events recorded by the

Seismometric Network of Friuli - Venezia Giulia, which the Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS) has been running since 1977 and whose data were published in the OGS bulletins (OGS, 1977-1981, 1982-1990, 1991-1999; Renner, 1995).

As the probabilistic approach used considers main earthquakes only, some operations were required before introducing these new events into the Camassi and Stucchi (1996) catalogue. In fact, aftershocks were removed by a space-time window (Gardner and Knopoff, 1974) and all M_L magnitudes of the OGS seismometric network were converted into M_S values by the relation calibrated on Italian data (Camassi and Stucchi, 1996). More precisely, the time and space distributions of all events in Friuli since 1976 which followed large and medium magnitude earthquakes (see their list in Table 1) have been graphically analysed for the identification of the time duration and space extension of the sequences. Thus, twelve sequences in the magnitude range 3.1 to 6.4 have been analysed (solid dots in Fig. 3). Taking into account the evident limits of this data set, we consider it suitable for a rough filtering of the aftershocks in Friuli. The lines enveloping the data are reported in Fig. 3: it can be seen that the dispersion is much larger for the space window (Fig. 3b) than for the time one (Fig. 3a). When comparing the time and space windows computed for the Friuli region with those estimated by Gardner and Knopoff (1974) and Knopoff et al. (1981) for California (both reported in Fig. 3 as well), it can be seen that the time window for Friuli is rather similar to the time windows for California, while the space window reflects the behaviour of the Gardner and Knopoff (1974) window but is smaller for all magnitudes. The space and time windows suited for the Friuli aftershocks have been used to decluster the OGS data set.

Most events of the Friuli earthquake data set refer to central Friuli, because of the early geometry of the network, and a few low magnitude events in the peripheral areas may have been
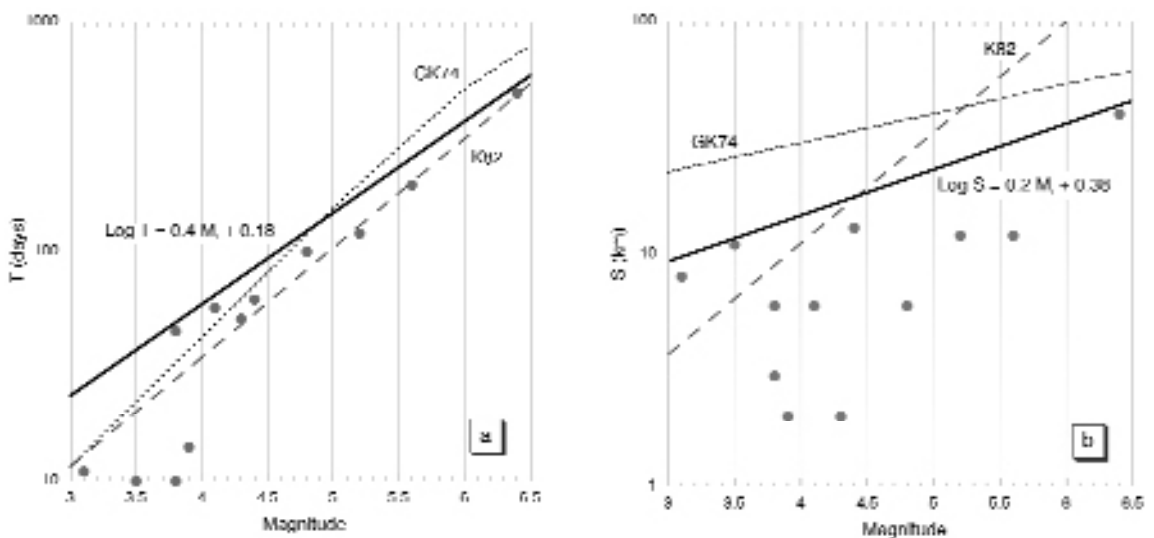
Fig. 3 - Time (T; a) and space (S; b) declustering of aftershocks in Friuli. Solid dots show the data used; the enveloping solid lines indicate the computed windows; the GK74 and K82 lines display respectively the Gardner and Knopoff (1974) and Knopoff et al. (1982) windows calibrated on earthquake sequences in California.

Table 1 - Aftershock sequences in Friuli and neighbouring areas. M_L is the local magnitude, T indicates the sequence duration, and S the distance of the aftershock furthest from the main shock.

Date	M_L	T (days)	S (km)
6 May 1976	6.4	490	40
16 Sep 1977	5.2	120	12
18 Apr 1979	4.8	100	6
27 May 1979	3.1	11	8
14 Aug 1979	3.5	10	11
29 Aug 1986	4.4	62	13
1 Feb 1988	4.1	57	6
11 Jun 1991	3.9	14	2
5 Oct 1991	3.8	45	6
27 Feb 1996	3.8	10	3
13 Apr 1996	4.3	51	2
12 Apr 1998	5.6	195	12

lost. Nevertheless, the heterogeneous detection threshold should not bias the hazard estimates as the low magnitudes have a limited influence in the hazard assessment. Fig. 2 illustrates the above statement: seismic hazard in terms of PGA with a 475-year return period with σ of the attenuation relation has been computed in the central point of SZ 4, eliminating, step after step, the lowest magnitude rate. Solid dots (magnitude greater than 4.0) represent the seismicity rates computed with the Camassi and Stucchi (1996) catalogue data, while the empty dots (magnitude from 3.1 to 4) show those derived from the data of the OGS regional seismometric network (Fig. 2a). It can be seen that the introduction of the low magnitude rates increases the computed hazard by about 8% (Fig. 2b).

The methodology used for assessing the seismicity rates is the same as that followed for the seismic hazard map of Italy (Slejko et al., 1998), where a detailed description can be found. That procedure computes the individual rates directly from the catalogue data without requesting the exponential distribution of seismicity. More precisely, the highest rate, which is in agreement with the completeness of the catalogue, is taken for every magnitude class and, consequently, the approach can be considered cautious, suitable for seismic zonation purposes. That procedure has been applied to all classes of M_S larger than, or equal to, 4 of the Camassi and Stucchi (1996) catalogue. For the lower magnitude classes, which were integrated by the events of the OGS regional network, the whole 1977-1999 data set was assumed as complete, and used to compute the rates. For magnitude 4 the highest of the two rates (from the historical and OGS network catalogues) was chosen.

2.3. Attenuation relations

The choice of a proper attenuation relation is extremely important in hazard assessment but no specific ones are available for north-eastern Italy. Consequently, several attenuation relations have been considered in the present study.

The Ambraseys et al. (1996) attenuation relations were defined for PGA and absolute

spectral acceleration (SA) on the basis of the European strong motion data bank (Ambraseys and Bommer, 1991) and calibrated on 422 triaxial records generated by 157 earthquakes in Europe and adjacent regions in the magnitude M_s range 4.0 to 7.9. The PGA σ is 0.25 while the spectral σ ranges from 0.27 to 0.33 for frequencies from 0.5 to 10 Hz.

The spectral attenuation relations of Sabetta and Pugliese (1987, 1996) were calibrated on 95 Italian strong motion data from 17 earthquakes in the magnitude (M_L for values lower than 5.5, otherwise M_s) range of 4.6 to 6.8; ground shakings are given in terms of PGA and pseudo-velocity (PSV), which can be easily converted into pseudo-SA. The PGA σ is 0.173 while the spectral σ ranges from 0.19 to 0.32 for PSV in the frequency range from 0.25 to 25 Hz.

Chiaruttini and Siro (1981) calibrated PGA attenuation relations on 120 strong motion data from 36 earthquakes of the Friuli 1976 seismic sequence in the magnitude M_L range of 3.4 to 6.2. The PGA σ varies from 0.20 to 0.29 according to the soil type.

All the previous three attenuation relations take into account different soil types; estimates for rock and soil can be derived. The Tento et al. (1992) spectral attenuation relations, on the contrary, do not consider different soil types but refer to an average soil. They were calibrated on 137 Italian strong motion data from 40 earthquakes in the magnitude M_L range of 4.4 to 6.6. The PGA σ is 0.29 (converted from ln into log units) while the spectral σ ranges from 0.29 to 0.40 for PSV in the frequency range from 0.36 to 25 Hz.

In the absence of a logic tree approach (planned for a future stage of the GNDT project for Vittorio Veneto), where several attenuation relations can be used, and in agreement with the choice made for the Italian seismic hazard map (Slejko et al., 1998), the Ambraseys et al. (1996) PGA and SA attenuation relations have been used for the regional PSHA. As we have introduced seismicity rates referring to M_s smaller than 4, the extrapolation of the attenuation relations is applied by the computer program for hazard computation (Bender and Perkins, 1987) and this operation is used cautiously (Ambraseys, 1995).

2.4. Hazard results

The seismogenic zonation of Fig. 1a, with the seismicity rates described previously, and the Ambraseys et al. (1996) attenuation relations have been used for the regional hazard assessment.

Fig. 4 shows the PGA with a 475-year return period with σ of the attenuation relation. While the highest values (larger than 0.36 g) are located in eastern Friuli, a secondary maximum (with PGA larger than 0.32 g) can be seen inside SZ 10 and very close, then, to the Vittorio Veneto test site. This seismic area is determined by the new seismogenic zonation which concentrates the seismicity in the foothills (Fig. 1a).

The results for the Vittorio Veneto test site are reported in Table 2, where, in addition to the PGA, SA at 0.1 s (SA01) and at 0.3 s (SA03), obtained through a similar process as that of the PGA, are shown as well. They again refer to the 475-year return period and, although not very high, deserve attention. The influence of the introduction of the σ of the attenuation relations, which increase the results a lot, and the small differences between the estimates on stiff and soft soil can be seen.
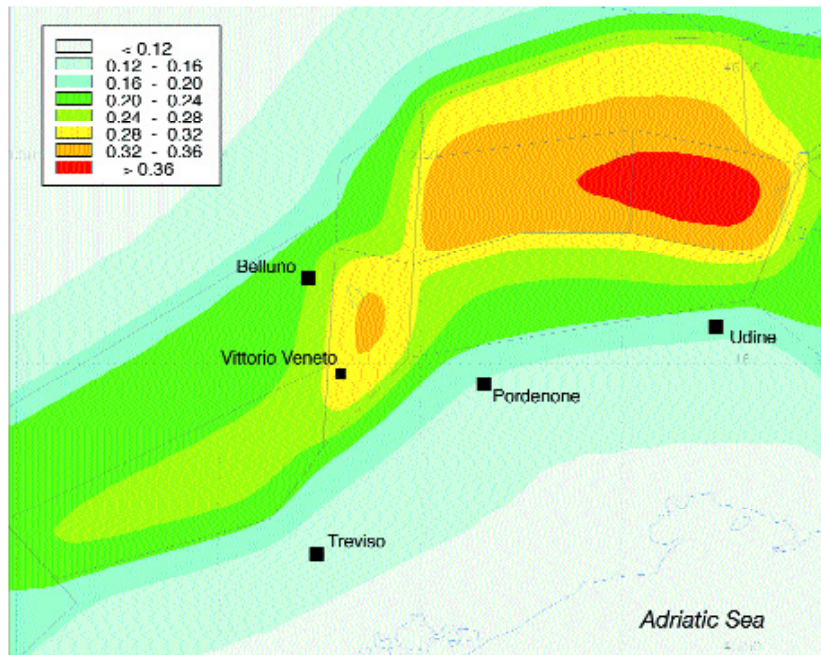
**Fig. 4** - PGA on rock with a 475-year return period, with σ of the attenuation relation (Ambraseys et al., 1996).

3. Disaggregation of the hazard results

Disaggregating probabilistic hazard results is quite a new technique and is useful for identifying the SZ which contributes more to the hazard at the study site (McGuire, 1995; Bazzurro e Cornell, 1999). More sophisticated techniques, where the contribution of each magnitude-distance bin is analysed, have been developed recently and applied to the hazard results for the U.S.A. (Harmsen and Frankel, 2001). These are based on a different probabilistic approach which lies mainly on the spatial distribution of seismicity.

3.1. Disaggregation for SZs

The sensitivity analysis of the previous probabilistic results was done by disaggregating the contribution of each SZ to the hazard of the Vittorio Veneto test site. The LaForge (1996) implementation to the Seisrisk III code (Bender and Perkins, 1987) was used: it gives the percentage of the total hazard (median value as well as median value plus σ of the attenuation relation) caused by each SZ.

Fig. 5 shows the contribution to the Vittorio Veneto 475-year return period PGA on rock given by the various SZs respectively for the median value (0.21 g; Fig. 5a) and median value plus one σ of the attenuation relation (0.31 g; Fig. 5b). The major hazard for Vittorio Veneto comes from SZ 10 (94% and 88%, respectively without and with σ), SZ 12 follows (4% and 8%) and then the background seismicity contributes also.
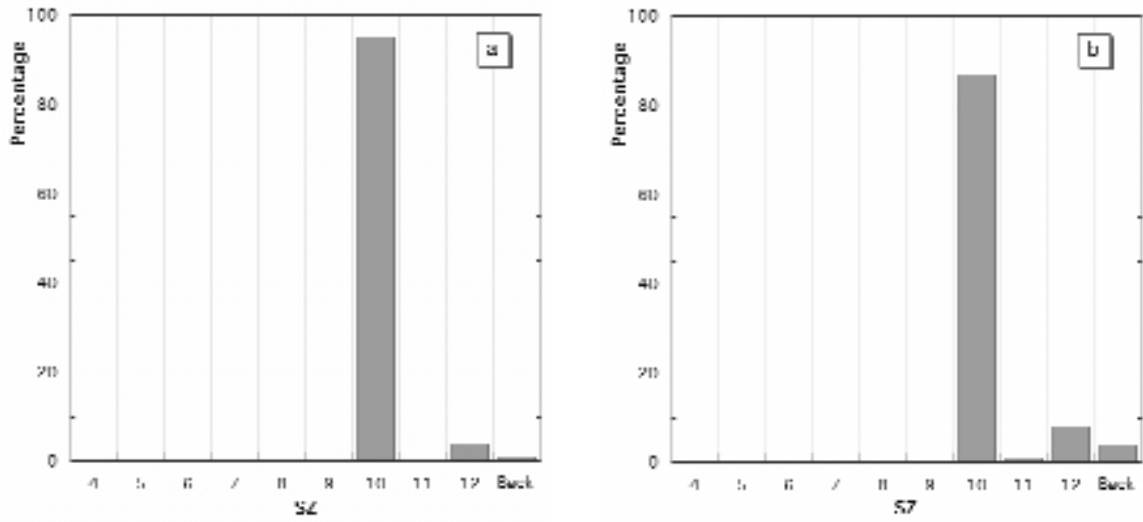
Fig. 5 - Contribution of the SZs to the seismic hazard of Vittorio Veneto: a) median value (0.21 g); b) median value + σ (0.31 g) of the attenuation relation (Ambraseys et al., 1996).

3.2. The maximum magnitude in SZ 10

After having found that SZ 10 is the most hazardous SZ for the Vittorio Veneto test site, it is interesting to investigate its maximum seismogenic potentiality.

According to Kijko e Graham (1998) the estimate of the maximum possible magnitude for a region is done on a statistical basis. The input data which characterise the study region, in our case SZ 10, from a seismological point of view, are: the maximum observed magnitude (6.4 for SZ 10); the magnitude threshold of the catalogue (3.1); the error in magnitude estimates (we fix it at 0.2); the b-value of the GR relation and its related error; the annual seismicity rate of events exceeding the threshold magnitude (0.631 for SZ 10); and the completeness period of the catalogue.

As the annual rates are computed with an algorithm that searches for the highest rate among those in agreement with the length of the completeness period of the related magnitude (see Slejko et al., 1998), we can consider that the annual rates hold for the whole span of the catalogue (1000 years).

Different methodologies are available in literature for assessing the b-value. The least-squares method (LSM), easy to apply, is not considered suitable as magnitude is not error free, cumulative event counts are not independent, and the error distribution of the number
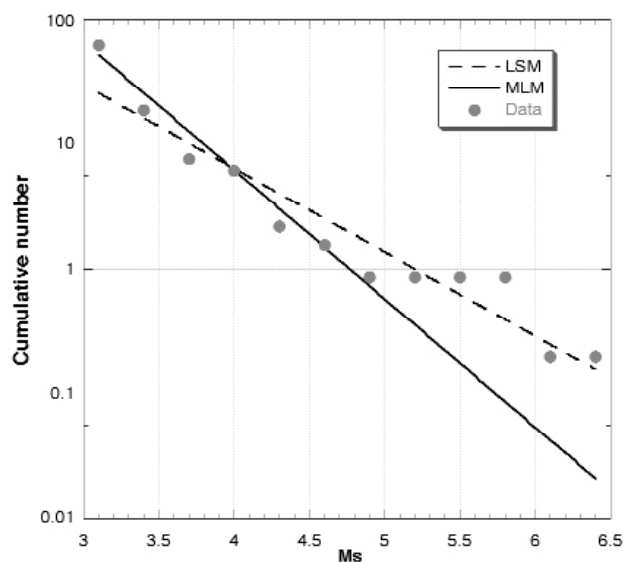
Table 2 - PSHA for the Vittorio Veneto test site. The estimates refer to a 475-year return period and have been computed with and without σ of the attenuation relations (Ambraseys et al., 1996).

Soil type	PGA (g)	PGA + σ (g)	SA01 (g)	SA01 + σ (g)	SA03 (g)	SA03 + σ (g)
rock	0.21	0.31	0.41	0.73	0.44	0.67
stiff soil	0.27	0.40	0.49	0.88	0.57	0.89
soft soil	0.28	0.41	0.44	0.78	0.58	0.92

of earthquake occurrences does not follow a Gaussian distribution. The maximum likelihood method (MLM) has been widely applied (Aki, 1965; Utsu, 1966): Weichert (1980) proposed a general routine suitable also for different completeness periods of the earthquake catalogue. For our purposes, MLM has been applied together with the LSM (Press et al., 1992), which better fits the high magnitude data when all data points are weighted equally.

The range of the seismicity rates used for computing the *b*-value is 3.1 to 6.4. Fig. 6 shows the data used and the two interpolations obtained: it can be seen that they are very different because the data points are not aligned. More precisely, the regression line obtained with the LSM (dashed line) displays an important dispersion everywhere, while that computed with the MLM (solid line) fits the low magnitude points well and passes far away from the high magnitude ones. The non-linear behaviour of the earthquake cumulative number (Fig. 6) is caused by the almost complete lack of events with magnitude larger than 4.6: the catalogue, in fact, reports only 2 events with magnitude 5.8 and above. An explanation for this is not simple: either the GR distribution holds only for small events of SZ 10 and large events behave as characteristic earthquakes (Schwartz and Coppersmith, 1984), or the geometry of SZ 10 is not suited to agree with the accuracy of the earthquake locations. The LSM *b*-value estimate is 0.67 +/- 0.06 while the MLM one is 1.03 +/- 0.10: these latter values have been used in the following computations.

The Kijko and Graham (1998) method gives two estimations for the maximum magnitude: the Tate-Pisarenko (T-P) and the Kijko-Sellevol (K-S) ones. The Bayes version is available for both (T-P-B and K-S-B, respectively): these last are more complicated in the computation but are considered more robust. The results we have obtained for SZ 10 (Table 3) vary between 6.40 and 6.98, with the exception of the T-P case, which gives a much higher value (8.07). The estimate chosen for hazard assessment is 6.75 +/- 0.40 coming from the K-S-B formulation.

Fig. 6 - Seismicity of SZ 10: solid dots = cumulative number of earthquakes in 100 years; solid line = MLM GR fit; dashed line = LSM GR fit.

Table 3 - Ground shaking scenarios for the Vittorio Veneto test site: *MM* is the maximum observed magnitude, *Mm* is the threshold magnitude, σ*M* is the error on magnitude, *b*-val is the *b* parameter of the GR relation, σ*b* is its error, *a*-val is the *a* parameter of the GR relation (annual seismicity rate for *Mm* and above), *t* is the completeness period of the catalogue (see the text for a complete description). The Tento et al. (1992) attenuation relation refers to an average soil.

```
Input data:

  MM     Mm     σM    b-val    σb    a-val    t
  6.4    3.1    0.2   1.030  0.100  0.631   1000


MAXIMUM MAGNITUDE           TYPE      MAX MAG        σ
                            T-P         8.07       1.69
                            T-P-B       6.40       0.20
                            K-S         6.98       0.62
                            K-S-B       6.75       0.40
```

```
SCENARIO 1 FOR THE DESIGN EARTHQUAKE

LAT = 46.00 N   LON = 12.38 E
MAG = 6.0 (+/- 0.2) DIST = 6.1 km (+/- 2.0)
```

Relation	rock	rock+σ	rock+tσ	soft	soft+σ	soft+tσ
			PGA (g)			
Ambraseys et al. (1996)	0.215	0.382	0.409	0.286	0.509	0.545
Sabetta & Pugliese (1987)	0.222	0.331	0.361	0.328	0.489	0.532
Chiaruttini & Siro (1981)	0.184	0.285	0.302	0.498	0.886	0.964
Tento et al. (1992) ave	0.263	0.514	0.535			
Mean	0.221	0.378	0.402	0.344	0.599	0.644
SD	0.028	0.085	0.086	0.092	0.166	0.185
			ARIAS INTENSITY (m²/s³)			
Sabetta & Pugliese (1996)	3.480	8.681	10.465	6.104	15.226	18.355

```
SCENARIO 2 FOR THE EXTREME EARTHQUAKE

LAT = 46.10 N   LON = 12.46 E
MAG = 6.75 (+/- 0.4) DIST = 17.9 km (+/- 5.0)
```

Relation	rock	rock+σ	rock+tσ	soft	soft+σ	soft+tσ
			PGA (g)			
Ambraseys et al. (1996)	0.142	0.253	0.279	0.189	0.336	0.371
Sabetta & Pugliese (1987)	0.169	0.252	0.295	0.250	0.372	0.435
Chiaruttini & Siro (1981)	0.173	0.268	0.309	0.419	0.746	0.907
Tento et al. (1992) ave	0.170	0.333	0.361			
Mean	0.164	0.276	0.311	0.257	0.447	0.519
SD	0.013	0.033	0.031	0.098	0.173	0.226
			ARIAS INTENSITY (m²/s³)			
Sabetta & Pugliese (1996)	3.670	9.155	13.908	6.437	16.057	24.393

3.3. Disaggregation for M/d bins

As previously established, SZ 10 determines the seismic hazard of Vittorio Veneto, it is, therefore, now possible to define the design earthquake for the study site. This has been done following the Bommer et al. (2000) approach, which was originally proposed by McGuire (1977): the design earthquake is defined in terms of an M-d pair by simultaneously solving the attenuation equations for the design values of some hazard parameters. This approach is better suited when only one SZ conditions the seismic hazard of the study site, as in our case. The use of three different hazard parameters, among the many available (PGA, PSV, SA at different frequencies, etc.), is suggested (Bommer et al., 2000); in our case, as Vittorio Veneto is inside SZ 10, three parameters quantifying the hazard from local seismicity have been taken: PGA, SA01, and SA03. Disaggregation in terms of M-d pairs has been done for the median values on rock (PGA = 0.21 g, SA01 = 0.41 g, SA03 = 0.44 g; see Table 2), to avoid the data scattering throughout the analysed parameters. The intersection points of the three curves identifies the 5.9 - 6.1 magnitude range and the 6 - 7 km distance range: the design earthquake for Vittorio Veneto is, then, a 6-magnitude event with a 6-km epicentral distance (Fig. 7). These values agree with the characteristics of SZ 10, which is 0 to 50 km from Vittorio Veneto and has a magnitude of 6.75 as maximum earthquake.

4. Deterministic ground shaking scenarios for the design and the extreme earthquakes

The definition of the epicentral coordinates and related errors for the scenario earthquake is very important. Two different hypotheses have been analysed: the design earthquake for Vittorio
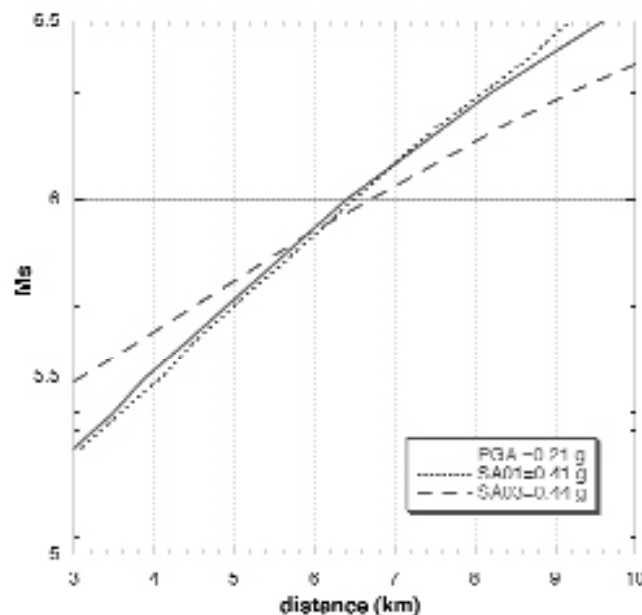
Fig. 7 - M-d bins in agreement with the probabilistic seismic hazard estimates (median values on rock) of PGA (0.21 g), SA01 (0.41 g), and SA03 (0.44 g; see Table 2).

Veneto ($M = 6.0$; distance = 6 km; epicentral error = 2 km, fixed arbitrarily) and the maximum expected earthquake of SZ 10 ($M = 6.75$). For this last one, the instrumental location of the 1936 earthquake (Slejko et al., 1989) has been adopted. The motivation of this choice is that the only strong events which occurred in SZ 10 (the 1873 and 1936 earthquakes) occurred rather close each other (Fig. 1a) and the epicentre of the most recent event is surely better assessed than that of the previous one. The tectonic information available (Galadini et al., 2002) confirms there is a fault capable of producing large quakes. The related epicentral error (2.5 km) has been doubled for precaution. The computational part consists of the definition of maximum horizontal PGA, SA01, SA03, and the Arias intensity for the Vittorio Veneto test site.

A special care in this study is paid to quantify the uncertainties in the hazard results. In order to do this, both the epistemic and aleatory uncertainties (McGuire and Shedlock, 1981; Toro et al., 1997) have been considered. The first one by taking into account several attenuation models, the second by quantifying its two orthogonal (modelling and parametric) parts (Toro et al., 1997).

Although in this study the Ambraseys et al. (1996) attenuation relations for PGA and SA are preferred for the PSHA, the other attenuation relations previously cited have been considered for the scenarios and the average value of the estimates obtained with its standard deviation has been computed. The only attenuation relation available for the Arias intensity is that proposed by Sabetta and Pugliese (1996). Although the difference between M_s and M_L is smaller than 0.3 in the range of our interest (Camassi and Stucchi, 1996) and is thus absorbed by the related σ, the M_s values of the two scenario earthquakes have been transformed into M_L for the application of the Chiaruttini and Siro (1981) and Tento et al. (1992) attenuation relations. All the attenuation relations were calibrated for distances from the fault (at least for large earthquakes as those considered in our two scenarios) with the exception of the Chiaruttini and Siro (1981) one, which was calibrated for hypocentral distances (with an average depth of 6 km) also in the case of the Friuli 1976 main shock (M_L 6.2 according to Chiaruttini and Siro, 1981).

For a complete quantification of the aleatory uncertainty, the assessment of its modelling and parametric parts is needed (Kijko and Graham, 1999). The first is simply given by the σ of the computed regression. The second depends on the errors associated with the parameters of the relation: magnitude and distance. The results obtained are reported in Table 3, where the columns "rock" and "soft" show the median values, while columns "rock+σ" and "soft+σ" display the median values plus one σ of the attenuation relation. In the additional columns "rock+tσ" and "soft+tσ" the median values plus their total standard deviations representing the aleatory variability on parameters (epicentre location and magnitude), and modelling (data scatter with respect to the calculated regression) are reported. More precisely, in agreement with the previous considerations and the results obtained for the maximum magnitude, an epicentral error of 5 km, a magnitude error of 0.4 and the σ of the attenuation relations have been introduced in the scenario computation of the extreme event; while for the design earthquake scenario a location error of 2 km and a magnitude error of 0.2 have been used (see Table 3). The variations of the PGA values are rather large and this fact strongly influences the standard deviation of the average estimates (Fig. 8).

For the scenario of the design earthquake, a median value of 0.22 g on rock has been
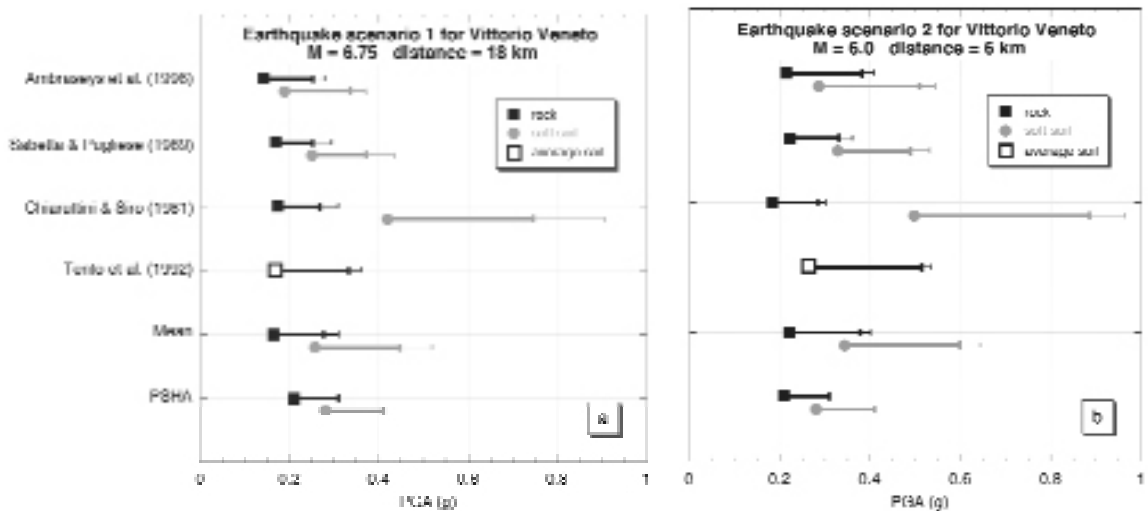
Fig. 8 - Deterministic ground shaking at the Vittorio Veneto test site in terms of PGA computed for the design ($M_S = 6.0$, distance = 6 km; a) and extreme ($M_S = 6.75$, distance = 18 km; b) scenario earthquakes, considering different attenuation relations. Black squares refer to rock, grey circles to soft soil, the Tento et al. (1992) relation refers to an average soil. The bars indicate the positive part of the aleatory modelling uncertainty (heavy line) and to the total (parametric plus modelling) uncertainty (light line). The probabilistic hazard estimates referred to a 475-year return period are indicated with PSHA.

calculated at Vittorio Veneto. This becomes 0.40 g taking into account the total uncertainty; these values increase respectively to 0.34 g and 0.64 g for soft soil. The expected value for the scenario of the extreme earthquake is 0.16 g (0.31 g with total σ) on rock, and 0.26 g (0.52 g with total σ) on soft soil. The similarity of these estimates for the two key events expected at Vittorio Veneto is remarkable. If we compare the median results for the two scenarios with the median ones from the PSHA (0.21 g for rock and 0.28 g for soft soil; Table 2), we see a very good agreement (Fig. 8) and this agreement partly holds, also, when we compare the values with σ. The differences depend on the fact that in the scenario construction also the Tento et al. (1992) attenuation relation for an average soil was considered. The larger discrepancies refer to soft soil, where the Chiaruttini and Siro (1981) relation gives very high values. Furthermore, among the several PGA attenuation relations that have been considered in the scenario constructions, the one by Ambraseys et al. (1996), which was used in PSHA, gives the lowest values in almost all situations.

5. Conclusions

Vittorio Veneto is located in a seismic area (inside SZ 10), which is very important for the seismic hazard of north-eastern Italy. Furthermore, the town is famous from an artistic point of view and deserves special attention for its risk mitigation.

In the framework of a specific GNDT project, Vittorio Veneto was chosen as test site and some damage scenarios are planned for it. A PSHA has been performed for the broader Vittorio

Veneto area (Fig. 4), hence the seismic hazard parameters characteristic for Vittorio Veneto have been derived (Table 2). The median PGA on rock with a 475-year return period is estimated as 0.21 g; the value with σ of the attenuation relation, although not very high (0.31 g), refers to a possible damage.

In addition, the deterministic ground shaking at Vittorio Veneto has been computed for the design and extreme earthquakes in terms of PGA and Arias intensity (Table 3). Both earthquakes are expected to produce a similar ground shaking in Vittorio Veneto: 0.33 g and 0.40 g for PGA on rock, when all uncertainties are taken into account (Fig. 8). This is due to the fact that Vittorio Veneto is located inside a SZ and the most dangerous fault is located some tens of kilometres apart.

What is, furthermore, interesting to notice (Fig. 8) is that the median PGA of the two scenario earthquakes and the probabilistic estimates are in excellent agreement for rock (0.16 g and 0.22 g with respect to 0.21 g) as well as for soft soil (0.26 g and 0.34 g with respect to 0.28 g). This testifies that the probabilistic estimates for a 475-year return period for Vittorio Veneto are close to the maximum possible ground motion (assuming that the locations chosen for the scenario earthquakes are correct), because of the characteristics of the seismicity, dominated by local earthquakes. Taking into account the errors associated with the computation, the scenario estimates are higher than the probabilistic ones. This is due to the fact that in the former uncertainties on location and magnitude were considered in addition to those on attenuation.

References

Aki K.; 1965: *Maximum likelihood estimate of b in the formula logN=a-bM and its confidence limits*. Bull. Earthquake Res. Inst., **43**, 237-239.

Ambraseys N.N.; 1995: *The prediction of earthquake peak ground acceleration in Europe*. Earthquake Eng. Struct. Dyn., **24**, 467-490.

Ambraseys N.N. and Bommer J.J.; 1991: *Database of European strong ground-motion records*. European Earthquake Engineering, **5(2)**, 18 - 37.

Ambraseys N.N., Simpson K.A. and Bommer J.J.; 1996: *Prediction of horizontal response spectra in Europe*. Earthquake Eng. Struct. Dyn., **25**, 371-400.

Bazzurro P. and Cornell C.A.; 1999: *Disaggregation of seismic hazard*. Bull. Seismol. Soc. Am., **89**, 501-520.

Bender B. and Perkins D.M.; 1987: *Seisrisk III: a computer program for seimic hazard estimation*. U.S. Geological Survey Bulletin 1772, Denver CO, 48 pp.

Bommer J.J., Scott S.G. and Sarma S.K.; 2000: *Hazard-consistent earthquake scenarios*. Soil Dynamics and

Earthquake Engineering, **19**, 219-231.

Boschi E., Ferrari G., Gasperini P., Guidoboni E., Smriglio G. and Valensise G.; 1995: *Catalogo dei forti terremoti italiani dal 461 a. C. al 1980*. Istituto Nazionale di Geofisica SGA storia geofisica ambiente, Roma, 973 pp.

Carulli G.B., Cucchi F., Rebez A., Peruzza L., Slejko D. and Codermatz R.; 2002: *Seismic hazard in the Friuli - Venezia Giulia region (NE Italy) considering different soil typologies*. Mem. Soc. Geol. It., **57**, 401-408.

Camassi R. and Stucchi M.; 1996: *NT4.1, un catalogo parametrico di terremoti di area italiana al di sopra della soglia del danno*. C.N.R. GNDT, Milano, 86 pp.

Chiaruttini C. and Siro L.; 1981: *The correlation of peak ground horizontal acceleration with magnitude, distance, and seismic intensity for Friuli and Ancona, Italy and the Alpide belt*. Bull. Seism. Soc. Am., **71**, 1993-2009.

Cornell C.A.; 1968: *Engineering seismic risk analysis*. Bull. Seism. Soc. Am., **58**, 1583-1606.

Frankel A.; 1995: *Mapping seismic hazard in the Central and Eastern United States*. Seismol. Res. Lett., **66**, 8-21.

Galadini F., Poli M.E. and Zanferrari A.; 2002: *Sorgenti sismogenetiche responsabili di terremoti distruttivi nell'Italia nord-orientale*. In: Slejko D. and Rebez A. (a cura di), G.N.G.T.S. 21° Convegno Nazionale - Riassunti estesi delle comunicazioni, Tipografia Mosetti, Trieste, pp. 27-30.

Gardner J.K. and Knopoff L.; 1974: *Is the sequence of earthquakes in southern California, with aftershocks removed, Poissonian?* Boll. Seism. Soc. Am., **64**, 1363 - 1367.

Gruppo di Lavoro CPTI (Boschi E., Gasperini P., Valensise G., Camassi R., Castelli V., Stucchi M., Rebez A., Monachesi G., Barbano M.S., Albini P., Guidoboni E., Ferrari G., Mariotti D., Comastri A., Molin D.); 1999: *Catalogo Parametrico dei Terremoti Italiani*. ING, GNDT, SGA, Bologna, 92 pp.

Harmsen S. and Frankel A.; 2001: *Geographic deaggregation of seismic hazard in the United States*. Bull. Seismol. Soc. Am., **91**, 13-26.

Kijko A. and Graham G.; 1998: *Parametric-historic procedure for probabilistic seismic hazard analysis. Part I: estimation of maximum regional magnitude m_{max}*. Pure Appl. Geophys., **152**, 413-442.

Kijko A. and Graham G.; 1999: *Parametric-historic procedure for probabilistic seismic hazard analysis. Part II: assessment of seismic hazard at specific site*. Pure Appl. Geophys., **154**, 1-22.

Knopoff L., Kagan Y.Y. and Knopoff R., 1982: *b-values for foreshocks and aftershocks in real and simulated earthquake sequences*. Bull. Seism. Soc. Am., **72**, 1663-1679.

LaForge R.; 1996: *Seisrisk III Mods*. Web page at ftp://ghtftp.cr.usgs.gov/pub/hazmaps/sr3mods/ README.SRIII. LaForgeMods

Mantyniemi P., Kijko A. and Retief P.; 2001: *Parametric-historic procedure for seismic hazard assessment and its application to northern Europe*. Boll. Geof. Teor. Appl., **42**, 41-55.

McGuire R.K.; 1977: *Seismic design spectra and mapping procedures using hazard analysis based directly on oscillator response*. Earthq. Engin. Struct. Dyn., **5**, 211-234.

McGuire R.K.; 1995: *Probabilistic seismic hazard analysis and design earthquakes: closing the loop*. Bull. Seismol. Soc. Am., **85**, 1275-1284.

McGuire R.K.; 2001: *Deterministic vs. probabilistic earthquake hazards and risks*. Soil Dynamics and Earthquake Engineering, **21**, 377-384.

McGuire R.K. and Shedlock K.M.; 1981: *Statistical uncertainties in seismic hazard evaluations in the United States*. Bull. Seismol. Soc. Am., **71**, 1287-1308.

Meletti C., Patacca E. and Scandone P.; 2000: *Construction of a seismotectonic model: the case of Italy*. Pure Appl. Geophys., **157**, 11-35.

OGS; 1977-1981: *Bollettino della Rete Sismologica del Friuli - Venezia Giulia*. OGS, Trieste.

OGS; 1982-1990: *Bollettino della Rete Sismometrica dell'Italia Nord-Orientale*. OGS, Trieste.

OGS; 1991-1999: *Bollettino della Rete Sismometrica del Friuli - Venezia Giulia*. OGS, Trieste.

Peruzza L., Iliceto V. and Slejko D.; 1989: *Some seismotectonic aspects of the Alpago - Cansiglio area (N.E. Italy)*. Boll. Geof. Teor. Appl., **31**, 63-75.

Press W.H., Teukolsky S.A., Vetterling W.T. and Flannery B.P.; 1992: *Numerical recipes in Fortran - the art of scientific computing. Second edition*. Cambridge University Press, Cambridge MA, 963 pp.

Rebez A., Carulli G.B., Codermatz R., Cucchi F., Peruzza L. and Slejko D.; 2001: *Soil Type dependent spectral seismic hazard in Friuli – Venezia Giulia (NE Italy)*. Boll. Geof. Teor. Appl., **42**, 121-138.

Reiter L.; 1990: *Earthquake hazard analysis: issues and insights*. Columbia University Press, New York, 252 pp.

Renner G.; 1995: *The revision of the northeastern Italy seismometric network catalogue*. Boll. Geof. Teor. Appl., **37**, 329 - 505.

Sabetta F. and Pugliese A.; 1987: *Attenuation of peak horizontal acceleration and velocity from Italian strong-motion records*. Bull. Seism. Soc. Am., **77**, 1491-1513.

Sabetta F. and Pugliese A.; 1996: *Estimation of response spectra and simulation of nonstationarity earthquake ground motion*. Bull, Seism. Soc. Am., **86**, 337 - 352.

Schwartz D.P. and Coppersmith K.J.; 1984: *Fault behavior and characteristic earthquakes: examples from the Wasatch and San Andreas fault zones*. J. Geophys. Res., **89**, 5681-5698.

Slejko D., Carulli G.B., Nicolich R., Rebez A., Zanferrari A., Cavallin A., Doglioni C., Carraro F., Castaldini D., Iliceto V., Semenza E. and Zanolla C.; 1989: *Seismotectonics of the eastern Southern-Alps: a review*. Boll. Geof. Teor. Appl., **31**, 109-136.

Slejko D., Peruzza L. and Rebez A.; 1998: *Seismic hazard maps of Italy*. Annali di Geofisica, **41**, 183-214.

Tento A., Franceschina L. and Marcellini A.; 1992: *Expected ground motion evaluation for Italian sites*. In: Proc. 10th World Conf. Earth. Eng., Madrid, vol. **1**, pp. 489 - 494.

Toro G.R., Abrahamson N.A. and Schneider J.F.; 1997: *Model of strong motions from earthquakes in central and eastern North America: best estimates and uncertainties*. Seismol. Res. Lett., **68**, 41-57.

Utsu T.; 1966: *A statistical significance test of the difference in b-value between two earthquake groups*. J. Phys. Earth, **14**, 37-40.

Weichert D.H.; 1980: *Estimation of the earthquake recurrence parameters for unequal observation periods for different magnitudes*. Bull. Seismol. Soc. Am., **70**, 1337-1346.