Soil characterization and seismic hazard maps for the Friuli Venezia Giulia region (NE Italy)

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ABSTRACT Seismic hazard maps that account for site amplification (soil seismic hazard maps) are very useful because they represent the expected ground motion at the Earth's surface, but need much more information and elaboration than the usual rock hazard maps. The regional soil hazard map has been developed for the Friuli Venezia Giulia region, in north-eastern Italy, by considering the most updated approach. In fact, the structure of the seismic hazard analysis presented here is based on the logic tree approach to achieve a robust statistical computation taking into account, in addition to the aleatory variability, also the epistemic uncertainties. The logic tree adopted for rock and soft soil conditions consists of 54 branches: three seismogenic zonations, representing various levels of our seismotectonic knowledge, three methods for the seismicity rate computation, three statistical approaches for the maximum magnitude estimation, and two PGA attenuation models of different spatial relevance (European and Italian). An additional regional attenuation model was considered only for stiff soil conditions, increasing the number of branches of the logic tree to 81. A consolidated expeditive procedure, widely adopted in the United States, has been used to compute the soil ground motion, properly modified on the basis of specific calibrations based on the local geological conditions and the results of geotechnical soundings. The final result of this study is represented by the map of the expected ground motion in the Friuli Venezia Giulia region, computed considering the different litho-stratigraphic and morphological conditions existing in the area. This map clearly shows the contribution given by the soft sediments along the Alpine valleys and by the steep formation of the moraine amphitheatre in central Friuli. A comparison of these new results with those obtained by applying the amplification factors provided by the most popular seismic codes points out that the actual ground shaking could be notably larger than that obtained by the application of the seismic codes, suggesting a possible future implementation in the regional building code, so far not taken into account.

1. Introduction

For many years now, after-quake investigations have been conducted in most countries by multidisciplinary teams of experts, in order to gather information not only on the effects of the shocks on the buildings but also on the local modification of the seismic action due to the geology of the ground foundation. It appears evident, and on this matter there is a nearly total consensus, that part of the damage is related to the local geological conditions and this is particularly true for the low-medium magnitude earthquakes. The above considerations well describe the situation of the Friuli Venezia Giulia region (and most of the other regions of Italy) where widespread damage was caused by the magnitude 6.4 earthquake of May 6, 1976 (Carulli and Slejko, 2005), that appears to be, on a historical basis, most probably the maximum one.

The building codes (stated on a national frame), on the other hand, have two possible drawbacks: they establish design ground motions that are too low to avoid unwanted damage or are too high for a great part of the territory giving it an excessive level of protection and, therefore, of costs.

Since the costs are so high, this is very often the reason why public administrators (and also private owners of large buildings) skip prevention; we therefore tried to define the expected ground motion all over the regional territory in a more realistic way, taking into account, on a conservative base, the various morphological amplification factors (AFs) which, moreover, are of primary importance in the mountainous areas.

The aim of the present study [see the results of a previous pilot study in Rebez *et al.* (2001)], commissioned by the Regional Civil Protection, is not only to give a picture of the economic relevance of the adoption of the new building code, in terms of possible underestimation of the site effects, but also to provide an instrument for a safer design of regional urbanization and logistics planning. Moreover, it can be considered a useful starting point for planning the location of future critical industrial plants and, through the construction of realistic scenarios, an important support for the organization of the Civil Protection to plan emergency interventions (see Riuscetti, 2008).

2. Seismotectonic framework of the study region

The Friuli Venezia Giulia region, in NE Italy (Fig. 1), represents the north-eastern portion of the deformed margin of the Adria microplate, where a complex interaction between two orogenic chains occurs. The mountainous part comprises the hinge zone between the eastern sector of the Southern Alps and the north-western part of the External Dinarides. Both systems reflect, in shape and in geodynamic evolution, the effects of the collision between the Adria microplate and the European plate, and of the fragmentation of the microplate itself. The southern parts of these mountain chains (Carnian and Julian Prealps) face the Friuli Plain to the south (the eastern part of the Po Plain), which can be considered their foreland basin. The structural units of the Dinaric orogenic belt have a SW vergence, while the Alpine ones have a south and SE vergence [see more description in Slejko *et al.* (1989)].

The stratigraphic succession cropping out in the Friuli Venezia Giulia region (Middle Ordovician to Recent) attains a total thickness of 30 km and can be considered unique in Italy for its geological time span and continuity. It is made mostly of sedimentary rocks that belong to the Adriatic microplate, today cropping out in a mainly E-W oriented structural domain, consequence of the Hercynic, Dinaric and neo-Alpine orogenic events. In these structural compartments, the terrains

Fig. 1 - Tectonic map of the Friuli Venezia Giulia region (modified from Carulli, 2006). The blue lines indicate the main faults. Legenda: AT = Alto Tagliamento line, PM = Polcenigo – Maniago line, MA = Maniago line, M = moraine amphitheatre.

become younger moving southwards from the Italian-Austrian border, in proximity to the Periadriatic Lineament, to the Friuli Plain, a poorly deformed edge of the Adriatic microplate.

The central and external parts of the Carnian and Julian mountain chains (neglecting the more internal part made up of the Hercynian Paleocarnic mountain belt) were emplaced during distinct tectonic phases during the Paleogene p.p. and, with associated maximum deformation, during the Late Miocene-Quaternary. The latter tectonic phase determined the highest crustal shortening of the entire Southern Alps in the Friuli region [up to 1/3 of the original terrain extension

(Castellarin, 1979; Castellarin and Vai 1982)]. The orogenic belt is composed of closely-spaced, generally south-verging overthrusts that originate an embricated structure. The footwall of the southernmost overthrusts (Fig. 1) is made of Neogene successions, in the maximum shortening zone that developed in response to the more recent N-S oriented compressional stresses (Zanferrari *et al.*, 2003).

Modern and recent activity of these tectonic lines is amply documented by geological data (Carulli *et al.*, 1980; Zanferrari *et al.*, 1982; Galadini *et al.*, 2001, 2005) and high-precision topographic measurements (Talamo *et al.*, 1978) of the Pre-Alpine area in particular. Here, this neotectonic activity finds its expression in the extremely high reliefs and in numerous fresh and evident surface ruptures.

The Friuli region was hit by several destructive earthquakes over the centuries, especially in the strip along the foothills, whereas the area of the plain and the Alps are less seismic. The seismic hazard of Friuli is conditioned by the lesser seismicity of the northern area on the border with Carinthia (Austria) and especially by that of the eastern area on the border with Slovenia. Information about several earthquakes which occurred in the distant past is scarce while some strong events of the 20th century (Tolmezzo 1928; Cansiglio 1936; and, above all, Gemona 1976) have been thoroughly studied (Gortani, 1928; Cavasino, 1929; Andreotti, 1937; Carulli and Slejko, 2005).

3. The rock seismic hazard map

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

The PSHA for the studied area has been performed according to the standard approach of Cornell (1968), by using the computer formulation of Bender and Perkins (1987), and replicated several times (one for each singular branch of the logic tree) in order to take into consideration various knowledge hypotheses, given the unavoidable scarcity of data and the non-uniqueness of models.

The Cornell (1968) approach needs the following input data: the geometry definition of the seismic sources, the seismicity models [in terms of average number of earthquakes per magnitude interval, and maximum possible magnitude (M_{max})], and the ground motion prediction equations (GMPEs) of the chosen parameter of ground motion.

In the present study, a logic tree (Fig. 2) with 54 branches has been constructed for the rock

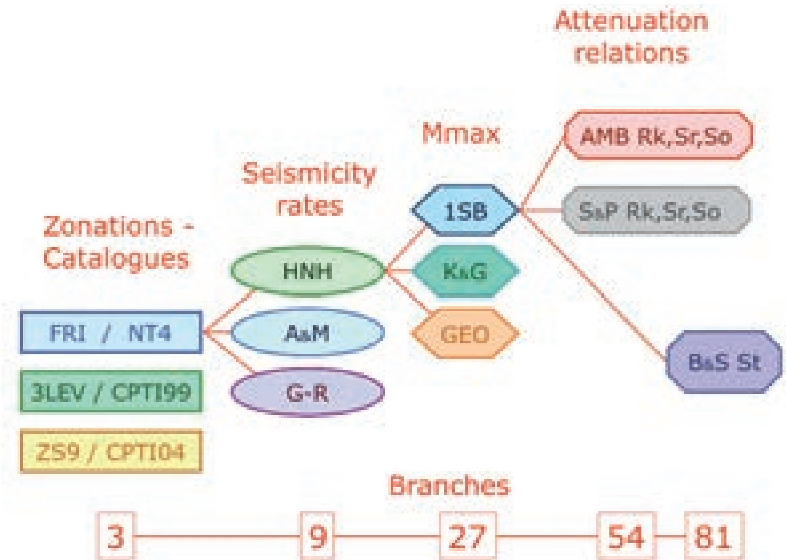


Fig. 2 - The logic tree used for PSHA. It consists of 3 seismogenic zonations and related catalogues: SZ9 [geometry modified from Meletti *et al.* (2008), catalogue CPTI04 (Gruppo di Lavoro CPTI, 2004)]; FRI [geometry modified from Slejko and Rebez (2002), catalogue NT4 (Camassi and Stucchi, 1997)]; 3LEV [geometry modified from Poli and Galadini (written personal communication), catalogue CPTI99 (Gruppo di Lavoro CPTI, 1999)]; 3 methods to compute the seismicity rates: HNH (Slejko et al., 1998); A&M (Albarello and Mucciarelli, 2002); G-R (Gutenberg - Richter fit of the mean values of the two previous rates); 3 methods for M_{max} assessment: 1SB (Slejko et al., 1998); K&G (Kijko and Graham, 1998); GEO [application of the Wells and Coppersmith (1994) relation to the SZs]; and 2 PGA GMPEs; AMB (Ambraseys *et al.,* 1996); S&P (Sabetta and Pugliese, 1987). The additional B&S (Bragato and Slejko, 2005) GMPE was used for stiff soil. Consequently, the number of branches is 54 for rock (Rk) and soft soil (So), and 81 for stiff soil (St). All branches were evenly weighted (see the text for details).

and soft soil hazard maps: it consists of three zonations, three approaches for the seismicity rate definition, three methods for M_{max} assessment, and two GMPEs for horizontal peak ground acceleration (PGA). In the case of the stiff soil hazard map, a further third GMPE, has been considered, increasing the number of branches of the logic tree to 81. It must be pointed out that the application of the logic tree approach requires the tree branches to be mutually exclusive and collectively exhaustive: sometimes this requirement is hardly fulfilled, as will be explained later [see a wide discussion in Bommer and Scherbaum (2008)]. The mean value is taken as final estimate and, in such a way, the variability of the results given by the various branches are smoothed but are quantified by the related standard deviation.

3.1. Seismogenic zonation

In the standard PSHA, seismic sources are modelled as lines (corresponding to actual faults) or seismogenic zones (SZs), where the earthquakes can randomly occur. Three seismogenic zonations have been used for the present PSHA: they represent different levels of seismotectonic interpretation and knowledge (Fig. 3) and almost correspond to those adopted for the seismic hazard assessment of the Vittorio Veneto broader area (Slejko *et al.*, 2008). Two of the models used derive from the Meletti *et al.* (2000) zonation, hereafter referred to as GNDT zonation, which was used for the Italian seismic hazard maps of Slejko *et al.* (1998) and Albarello *et al.*

(2000), and is composed of 80 SZs for the whole of Italy. Each seismogenic zonation is linked to the specific earthquake catalogue used originally to define it. Each catalogue, moreover, was enriched with the data of the recent seismicity [see more discussion in Slejko *et al.* (2008)]. As the reference magnitude in the Italian catalogues is M_S, the M_L of recent earthquakes (OGS, 1977-1981, 1982-1990, 1991-2002) was converted into M_S (Margottini *et al.*, 1993).

The first model (Fig. 3a), hereafter referred to as FRI (Friuli) zonation, is a regional improvement (Slejko and Rebez, 2002) of the GNDT zonation and inherits the original structure of the GNDT zonation but fractioning some zones, considered too large, into smaller ones. These modifications were mainly suggested by the recent instrumental seismicity, located by the regional seismometric network during the last three decades, and by an increased knowledge about the regional structural and tectonic assets. Although some SZs are rather small, the number of earthquakes inside them is sufficient to define their seismicity rates (the poorest SZ 6 has 53 events distributed in 11 classes). The catalogue NT4 (Camassi and Stucchi, 1997) is associated with this zonation and is used to compute the seismicity parameters.

The second zonation (Fig. 3b), hereafter referred to as the ZS9 zonation (Meletti *et al.*, 2008), has been designed for the latest version of the Italian seismic hazard map (Gruppo di Lavoro, 2004). Also this zonation inherits the structure of the GNDT zonation but in this case it simplifies the original design and aggregates small zones in a bigger frame. In this project, the original ZS9 zonation has been modified by adding two zones (SZs 111 and 222 in Fig. 3b) to adequately describe the contribution of the Dinaric front seismicity to the hazard. The catalogue CPTI04 (Gruppo di Lavoro CPTI, 2004) is associated with this zonation and is used to compute the seismicity parameters.

The third model (Fig. 3c), hereafter referred to as the 3LEV (3 levels) zonation (Galadini and Poli, written personal communication) is based on the different concept of confining the seismicity of high, medium and low level into three different strips (Stucchi *et al.,* 2002). All the earthquakes of the presently active front (SZs 101, 102, 103, 104 in Fig. 3c), with a magnitude equal to 6 or higher, are framed in the high seismicity zone. The intermediate zone collects all the earthquakes between magnitude 5 and 6 located at the wider foothill strip (SZs 201, 202, 203 in Fig. 3c). The external zones (SZs 301, 302, 303 in Fig. 3c) collect all the earthquakes with a magnitude lower than 5. The 3LEV zonation is not based only on the information about seismicity but is solidly designed on the basis of main seismogenic structures (Galadini *et al.*, 2005; Burrato *et al.*, 2008) of the studied area. The catalogue CPTI99 (Gruppo di Lavoro CPTI, 1999) is associated with this zonation and it is used to compute the seismicity parameters.

A question arises on the correct application of the logic tree approach: are the three zonations mutually exclusive and collectively exhaustive? If we can state that they are collectively exhaustive, because no other zonations have been proposed so far for the study region, both the FRI and ZS9 zonations derive from the original GNDT one, but the influence of the recent seismicity in the FRI zonation and of the regional tectonic scheme in the ZS9 one modify them notably from the original GNDT zonation.

3.2. Seismicity rates

Seismicity rates have been computed following three different methodologies.

The first method [HNH (higher not highest) in Fig. 2] was developed for the 1996 Italian

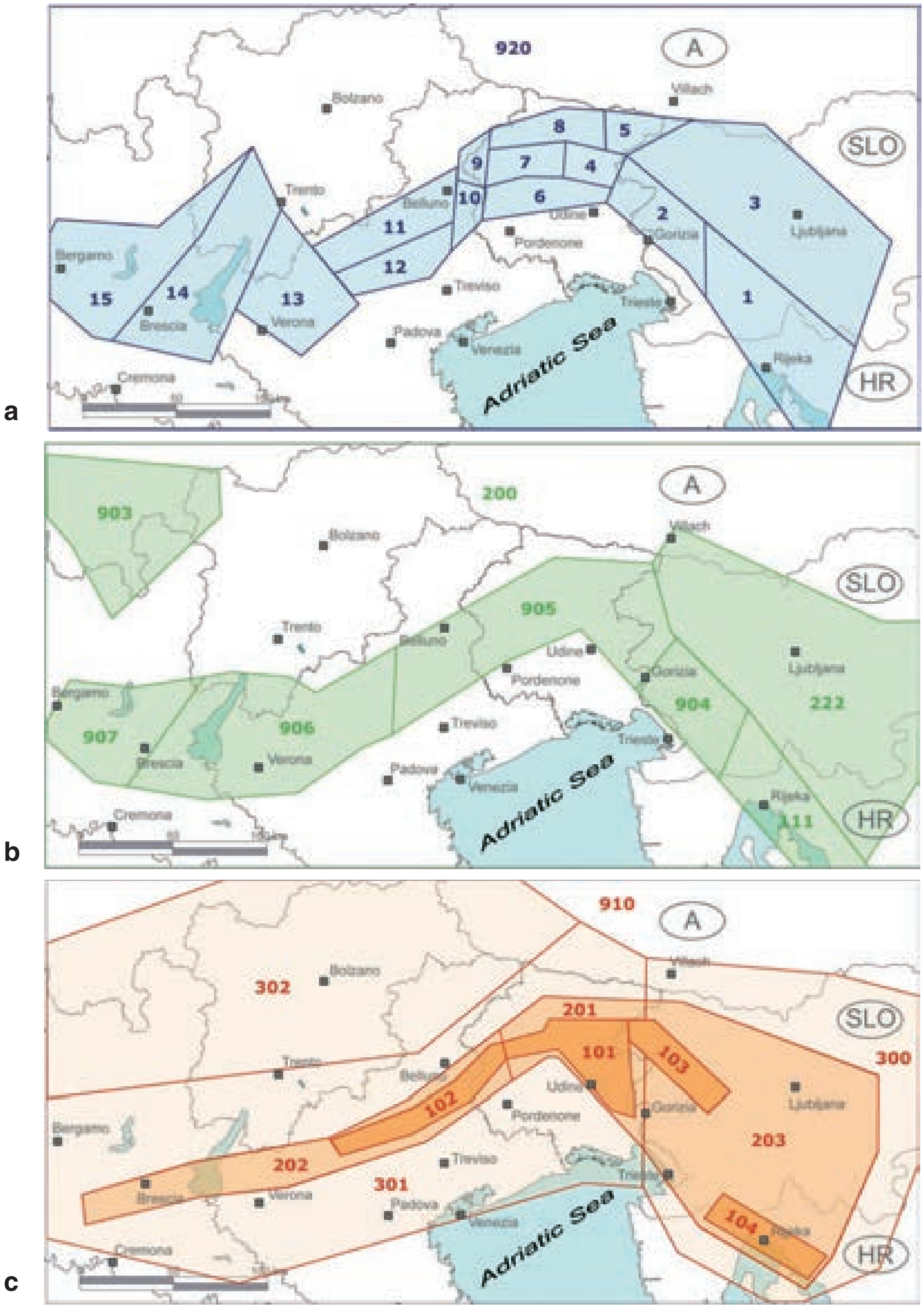


Fig. 3 - The three seismogenic zonations zonation [see Slejko *et al.* (2008) for their complete description] used in the logic tree (Fig. 2): a) the FRI zonation; b) the ZS9 zonation; c) the 3LEV.

seismic hazard map (Slejko *et al.*, 1998) and consists in identifying the higher seismicity rate for each magnitude class compatible with completeness evaluation of the earthquake catalogue, without considering the rates of the other magnitude classes [see Slejko *et al.* (1998) for details].

The second method (A&M in Fig. 2) was developed by Albarello and Mucciarelli (2002) and was adopted for the 2002 Italian seismic hazard map (Albarello *et al.*, 2000). This approach analyses the stationarity of the seismic events in time and associates a probability of completeness to each time period. In this case, the whole earthquake catalogue is used and the seismicity rate of each magnitude class is obtained by properly weighting the rates of the different time periods.

The third method (G-R in Fig. 2), is based on the Gutenberg-Richter (G-R) interpolation (Aki, 1965; Utsu, 1965, 1966) of the mean rates computed by the two previous methods. In this case, the seismicity rates are not obtained individually but are interpolated by a regression fit.

An example of seismicity rates computed with the three methods and for two different SZs is reported in Fig. 4: large fluctuations are produced by the application of the HNH and A&M approaches, while the G-R one produces, obviously, smooth rates.

Also in this case, the question if the three methods are mutually exclusive and collectively exhaustive could be raised. Actually, the seismicity rates could be defined by counting the number of events in several different ways, but the HNH approach can represent them all with conservative constraints, differently from the A&M one, where stationarity in time is evaluated. The G-R method elaborates the results of the other two approaches and, consequently, cannot be considered fully alternative to them but its interpolation remarkably modifies the input rates.

3.3. Maximum magnitude

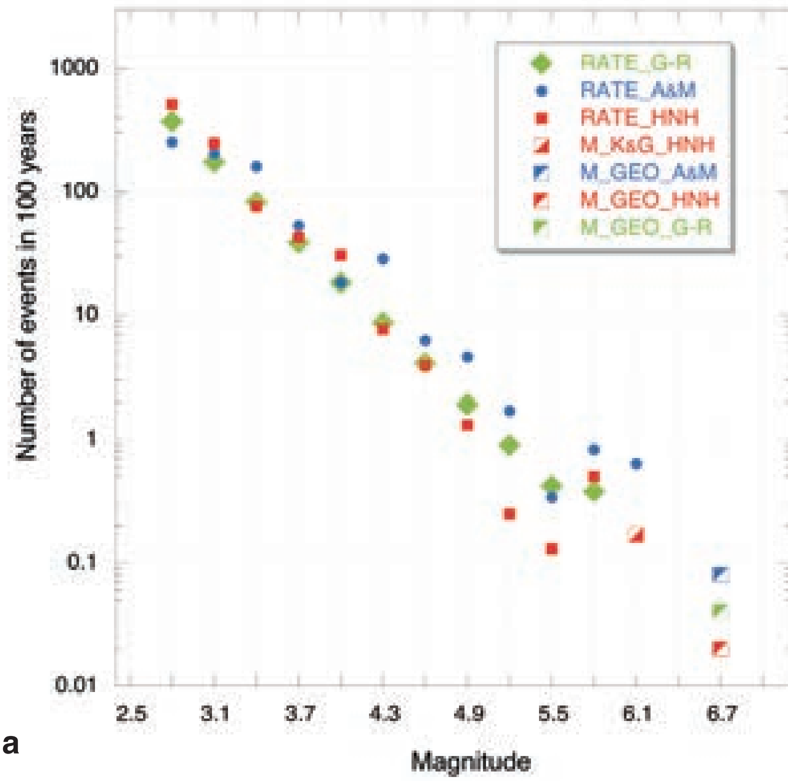
M_{max} is generally considered an important parameter in PSHA although its contribution to the final estimates depends strongly on the return period considered for it. Three different methods to determine M_{max} for each SZ have been applied in the present study and the results have been added to the observed seismicity rates.

The first method [indicated as 1SB (one step beyond) in Fig. 2] identifies M_{max} of a SZ simply increasing the largest magnitude in the earthquake catalogue of that SZ by one magnitude class (in our case 0.3 magnitude units). The related magnitude rate is obtained by the G-R interpolation and is used in the PSHA only if the corresponding return period is longer than the time span of the earthquake catalogue. This M_{max} refers, then, to an earthquake that should have occurred before the time span of the catalogue [see details in Slejko *et al.* (1998)].

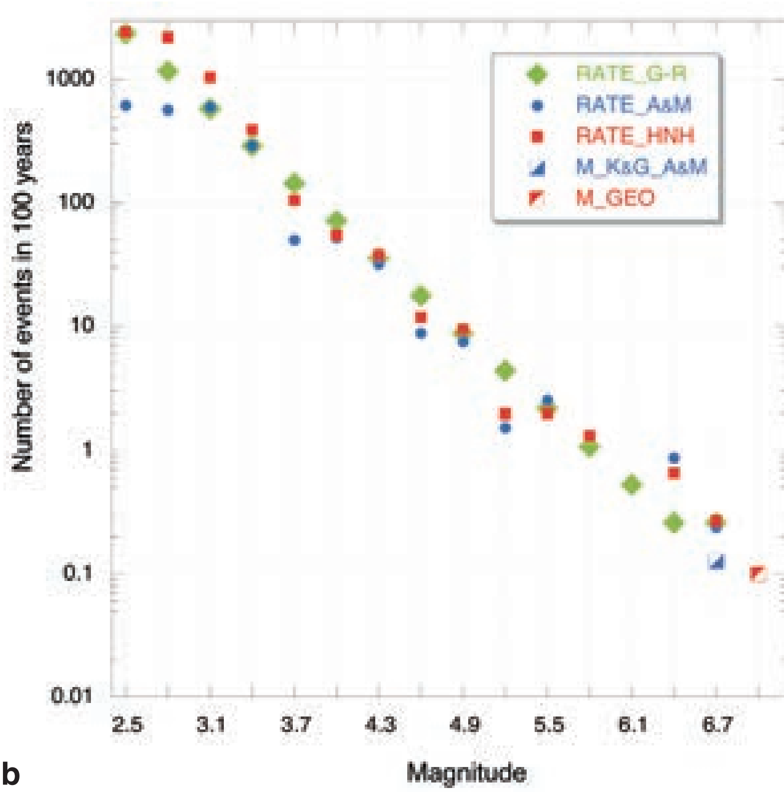
The second method (K&G in Fig. 2) is a statistical computation of M_{max} according to the Kijko and Graham (1998) procedure. The advantages of this method are given by the possibility of treating separately, historical and instrumental portions of the earthquake catalogue and in its almost insensitiveness to lack of data. All rates in the range between the maximum observed magnitude and M_{max} have been added by the G-R interpolation.

The third method (GEO in Fig. 2) is based on geologic-tectonic considerations and computes the (geologic) M_{max} by the Wells and Coppersmith (1994) relation from the maximum fault length present in each SZ. Conversely to the previous case, only the rate of this geological M_{max} has been added.

Fig. 4 shows the M_{max} estimates obtained, when possible, by the different methods (1SB,



a



b

Fig. 4 - Seismicity rates of two SZs (the number of accepted rates has been increased with respect to the original version of the computer code to better shape the SZ seismicity): a) zone 7 of the FRI zonation and b) zone 905 of the ZS9 zonation. Legend: G-R = rates computed by the G-R relation; A&M = rates computed by the A&M method; HNH = rates computed by the HNH method. Half-closed squares indicate M_{max} calculated by a specified approach for each method of seismicity rate computation. The missing M_{max} estimates cannot be assessed according to the fixed rules (see the text for the details). In the case of SZ 905, M_GEO indicates the geological M_{max} according to the HNH, A&M, and G-R rate computation, that coincide.

K&G, GEO) according to the 3 approaches for seismicity rate computation (HNH, A&M, G-R). The same geological M_{max} was calculated regardless of the method applied for seismicity rate computation. It is 6.7 for SZ 7 of the FRI zonation (Fig. 4a) whose rates range between 0.02 and 0.09 (in 100 years). Of the other approaches of M_{max} computation, only the K&G with the HNH rates is applicable. In the case of SZ 905 of the ZS9 zonation, the geological M_{max} is 7.0 with a 0.1 rate (in 100 years) for all (HNH, A&M, G-R) seismicity rate computations (Fig. 4b).

In the case of M_{max}, no doubts exist that the three methods are mutually exclusive and no indication of further alternative approaches are available.

3.4. Attenuation models

In the PSHA, the expected ground motion at each site of the study region is computed by applying GMPEs referring to different soil types, i.e., rock, stiff soil, and soft soil. In our case, horizontal PGA has been obtained by the application of three GMPEs, one calibrated on European strong-motion records (AMB: Ambraseys *et al.*, 1996), the second tuned on Italian strong-motion records (S&P: Sabetta and Pugliese, 1987, 1996) and the third based on strong- and weak-motion records of events in north-eastern Italy (B&S: Bragato and Slejko, 2005). Since the S&P GMPE refers to two different kinds of magnitude according to the size of the earthquake, the M_S magnitudes from the catalogue were converted into local magnitude M_L using the Camassi and Stucchi (1997) relation, when necessary. The B&S GMPE refers to M_L and the proper transformation has been applied as well. Choosing the AMB GMPE with respect to the more recent European GMPEs is motivated both by problems in using the considered computer code of the magnitude dependent aleatory uncertainty present in the most recent GMPEs and by wrong estimates that their use can lead to [see discussion in Musson (2009)].

While the AMB and the S&P GMPEs are defined for all three soil types previously cited, the B&S GMPE is defined only for stiff soil. Comments and details on these GMPEs can be found in Slejko and Bragato (2008) and Slejko *et al.* (2008).

It is not easy to state that the three GMPEs are mutually exclusive because the Italian strong motion data used by Sabetta and Pugliese (1987, 1996) were used also by Ambraseys *et al.* (1996), as part of a much wider database. The GMPEs can be considered collectively exhaustive because no further independent GMPEs were available for the study region at the time this study was conducted, while new Italian GMPEs have been proposed more recently (e.g., Cauzzi and Faccioli, 2008; Bindi *et al.*, 2010).

3.5. Results for the Friuli Venezia Giulia region

While the uniform hazard response spectrum is presently the main parameter considered by the Italian seismic code, at the time of this study the horizontal PGA with an exceedence probability of 10% in 50 years, corresponding to the 475-year return period, was considered in the design of standard buildings. The hazard estimates, shown in Figs. 5a to 5c, are the mean values of all the branches of the logic tree of Fig. 2, no epistemic uncertainty has been added to the mean values. In Fig. 5d, conversely, the epistemic uncertainty has been considered, in the sense that one standard deviation of the Gaussian distribution of the results of the different branches has been added to the mean values.

Fig. 5a refers to rocky conditions and shows the highest values, exceeding 0.35 g, in the central-

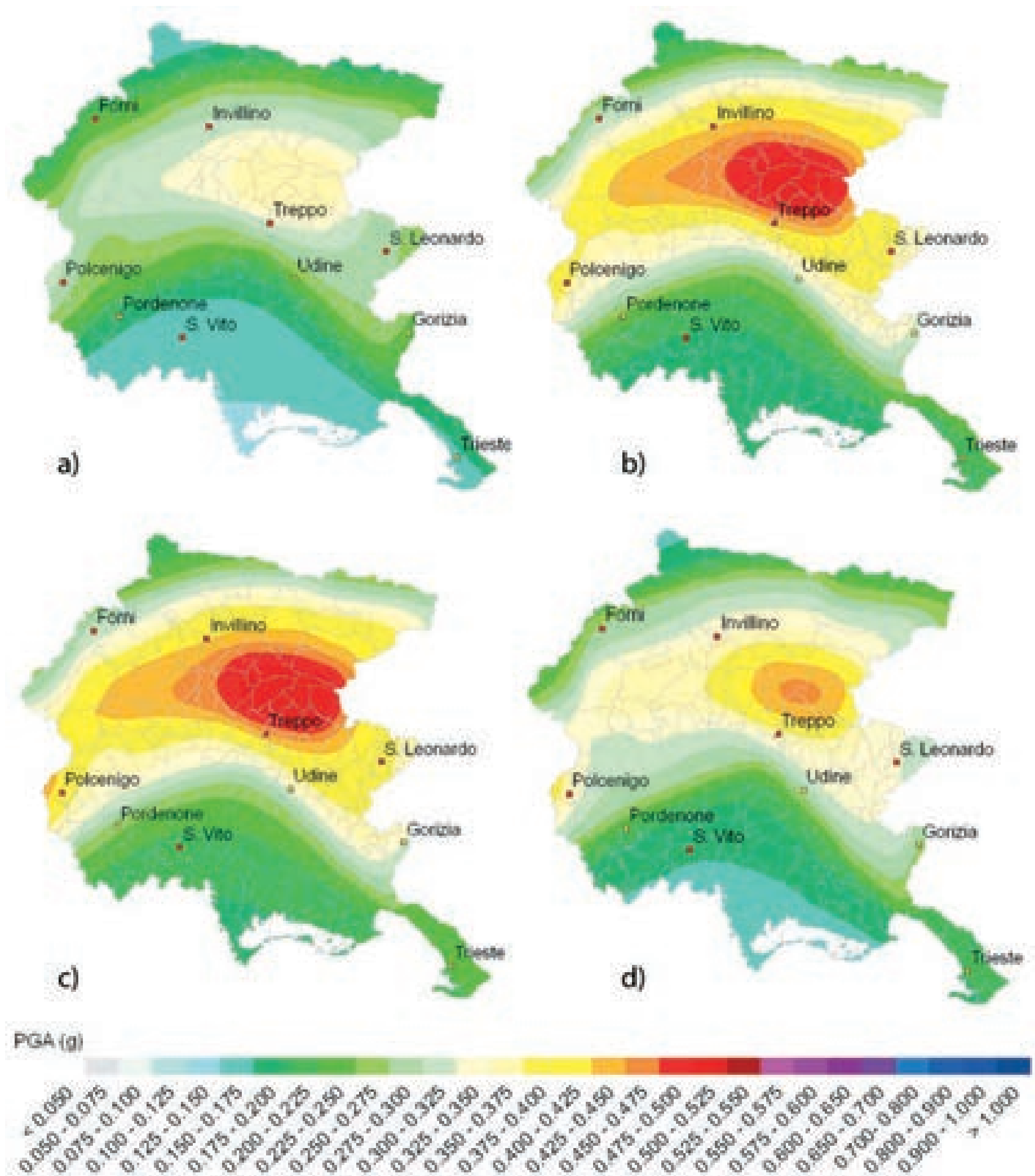


Fig. 5 - PGA with a 475-year return period computed considering the aleatory variability (standard deviation of the GMPEs used): a) rock conditions; b) stiff soil; c) soft soil; d) rock conditions with epistemic uncertainty.

eastern part of the region. Among the main towns, Udine turns out to be the most seismic with an expected PGA of 0.25 g. Values between 0.175 and 0.200 g are forecasted for Pordenone, and between 0.150 and 0.175 g for Trieste.

In addition to the rock seismic hazard map, the computation has also been performed for stiff

(Fig. 5b) and soft (Fig. 5c) soils. The two maps show evident similarities with slightly higher values computed for soft soils (it must be remarked that an additional GMPE was used for the computation of the stiff soil map). In the case of the soft soil map, the maximum PGAs refer to central-eastern Friuli with values as high as 0.50 g. A PGA between 0.325 and 0.350 g is expected in Udine, between 0.25 and 0.275 g in Pordenone, and between 0.225 and 0.250 g in Trieste.

The rock seismic hazard map that accounts for the epistemic uncertainty (Fig. 5d) shows an obvious general increase of values with respect to the map showing the mean values (Fig. 5a); ground motions between 0.450 and 0.475 g are expected in central-eastern Friuli, with an increase of about 0.10 g with respect to the map without epistemic uncertainty (Fig. 5a). The lowest PGAs (between 0.150 and 0.175 g) are now expected along the western Adriatic coast, with an increase of only 0.025 g.

4. Geotechnical characterisation

The term local effects indicates the result of very complex interactions between seismic waves and the local geological conditions, represented by the morphological and stratigraphic characteristics of soil deposits and rock masses and their physical and mechanical properties.

The propagation of seismic waves in soils, from the bedrock to the surface, can be simulated using numerical codes, with the advantage, compared to empirical and/or semi-quantitative methods, that they consider the physical phenomena with more accuracy and, therefore, increase the accuracy in the amplification prediction. Choosing the numerical code to use, depends on the type of site to be analyzed and on the available knowledge (stratigraphy, material properties, and seismic input). The numerical methods (and related codes) to be used in the local response analysis are divided into 1D, 2D, and 3D, depending on the complexity of the subsoil geometry considered.

In the present study, it was sufficient to use a 1D analysis to model plane-parallel situations, with one or more layers, and for an incident seismic motion perpendicular to the free surface, we used the PSHAKE program (Sanò and Pugliese, 1991), which is a modified version of the SHAKE code (Schnabel *et al.*, 1972), universally adopted in this type of analysis. As an input, the program requires a recorded motion on rock, that can be expressed as a response spectrum at a certain degree of probability. It needs also the mechanical properties of the soil in terms of shear wave velocity, density and damping in each layer. Two types of analysis can be performed: linear or linear equivalent. In the first, the characteristics of the materials are independent from the deformation. In the second, curves describing the shear modulus and the damping behaviours as function of the shear deformation are requested for each material.

2D codes are applied where the subsoil has a variable geometry and also the horizontal dimensions must be taken into account, e.g. marginal areas of alluvial valleys. In this case, the seismic motion is caused primarily by the focusing of seismic waves due to a special geometry of the surface (e.g., the ridge of a relief or a canyon) and is influenced by the wavelength of the incident waves and by their angle of incidence.

In the present study we have used the BESOIL code (Sanò, 1996), which is based on the indirect Boundary Element Method. This approach provides information on the physics of diffraction problems because diffracted waves are constructed at the boundaries from which they are radiated. The 2D space is divided into zones, in which the mechanical properties are constant. It does not

Table 1 – Association of the regional lithologies to the NEHRP classes (BSSC, 2004).

Lithology	NEHRP class
massive rock	A
stratified rock	B
evaporitic rock	C
gravel sediment	C
sand, clay and glacial sediment	D
swamp and peat sediment	E
reclamation and anthropic cover area	E_R[1]

require the schematization of the entire space where the solution is searched, but it requests only the soil free surface and the contour of the areas with uniform mechanical properties, offering a significant computational time reduction. Furthermore, it requires neither the presence of artificial damping elements on the contour, nor restrictive assumptions such as soil parallel plane layers and waves propagating only vertically. In this way waves of any type and with any angle of incidence can be considered.

4.1. Soil classification

As the NEHRP (BSSC, 2004) soil classification is the most detailed among the international building codes, the regional terrains have been assigned to those soil classes, considering mainly the information of the geological map of Friuli Venezia Giulia at a 1:150,000 scale and related explanatory notes (Carulli, 2006). Fifty-one boxes, related to the chrono- and litho-stratigraphic units outcropping in the region, and six highlighting symbols, related to the continental Quaternary sediment textures, are represented in the map legend[2] .

Association to the NEHRP classes (Table 1) has been assigned according to the data deriving from the drills made at some test sites (and particularly to the V_s values of the various lithological conditions found out), to the literature data (Bauer *et al.*, 2001; Holzer *et al.*, 2005), often specific for the litho-stratigraphic units of the regional outcrops (Brambati *et al.*, 1980), as well as according to lithological, sedimentological, and textural similarities.

The class of massive rocks includes all the geological formations constituted mainly by limestones (e.g.: Devonian, Jurassic, Cretaceous, Paleocenic limestones), dolomites (e.g.: Triassic dolomites), vulcanites (e.g.: Carboniferous and Triassic diabases and basalts), which are either massive or with unclear stratification or in banks with a thickness of some metres or some decimetres.

The class of stratified rocks includes all the geological formations constituted mainly by stratified rocks with a thickness of some centimetres or decimetres and particularly the several lithological alternations of thin layers (as flysch and other mainly basin sediments).

[1] This class is differentiated only because we had the areal data on the geological map. In reality, from the seismic point of view, the materials of this class must be regarded as being totally as those of class E.
[2] In the region, a sequence of about 15,000 m of total thickness, almost continuous from the Ordovician to the Present (representing more than 450 MA) outcrops, with many and repeated facies lateral variations.

The map of the NEHRP classes in the Friuli Venezia Giulia region (Fig. 6), has been obtained by transforming the areas of the litho-stratigraphical units mapped on the above mentioned geological map into the corresponding NEHRP classes. According to this map, many of the municipality territories (especially those related to the mountain and hill sectors and those near the relief) are divided into two or more classes. In fact, the hilly municipality territory, often without present and planned settlements, is generally assigned to the A or B classes (in accordance with the prevailing massive or stratified lithology). Conversely, the most populated areas, normally almost flat, are generally placed in correspondence of the river valleys, alluvial terraces, fans, and drifts. They are assigned to the C, D and E NEHRP classes, according to the textures of the locally prevailing Quaternary sediments.

It is interesting to notice in Fig. 6, the two different kinds of rock conditions (class A and B in different gray colours), the presence of morain deposits (class D) in the centre of the region at the transition between relief and plain. The map shows also that all the Alpine valleys in the mountain sector are characterised by stiff soils (class C and D). The majority of urban settlements are located on these soil conditions and local amplifications can be expected.

4.2. Test sites description

The Friuli Venezia Giulia region covers an area of 7,845 km^2, most of it is mountainous (42.5%) or hilly (19.3%) and presents, therefore, a great variability of morphological situations. For these reasons and due to the limited amount of available resources, it has been necessary to proceed with detailed geological and geophysical studies on a limited number of sites and then extend them to the whole region on the base of representative parameters.

In brief, the adopted strategy was as follows:

1. restrict the analysis to the areas of higher seismic risk (Carulli *et al.*, 2003);
2. pinpoint a number of relevant sites for geological and anthropical reasons;
3. intensive campaign of detailed geological and geophysical measurements [1:2000 geological survey, cross- and down-hole S-wave stratigraphy, refraction profiles, H/V spectral ratio [so called Nakamura (1989)] analysis, ReMi method (Louie, 2001)];
4. 1D [PSHAKE (Sanò and Pugliese, 1991)] or 2D [BESOIL (Sanò, 1996)] modelling.

The municipalities involved were: Forni di Sopra, San Leonardo, San Vito al Tagliamento, Treppo Grande, Invillino (Fig. 6). All of them are located in the Udine province, with the exceptions of Polcenigo and San Vito al Tagliamento which are situated in the Pordenone province. Each one of them has been subdivided into "homogeneous" areas mainly on the base of H/V spectra and then parametrized (with the above mentioned techniques and modelling) to obtain the proper S-velocity profiles and local seismic AF. Guided mainly on morphological consideration the whole regional territory was zoned, by analogy, in terms of AF.

With the ultimate aim of estimating the local amplification, these localities were identified so as to characterize the typologies of the soil types, on the basis of new geophysical and geotechnical data ad hoc collected in the field, at a later stage.

A geological map has been drawn for each of the 6 test sites, described later, and all available data (mechanical soundings, geophysical surveys, etc.) referring to an area around the site have been collected and the related soil types have been defined (Table 2). Geoelectrical measurements have been done for the geometric and lithological characterization of the soils and a seismic refraction

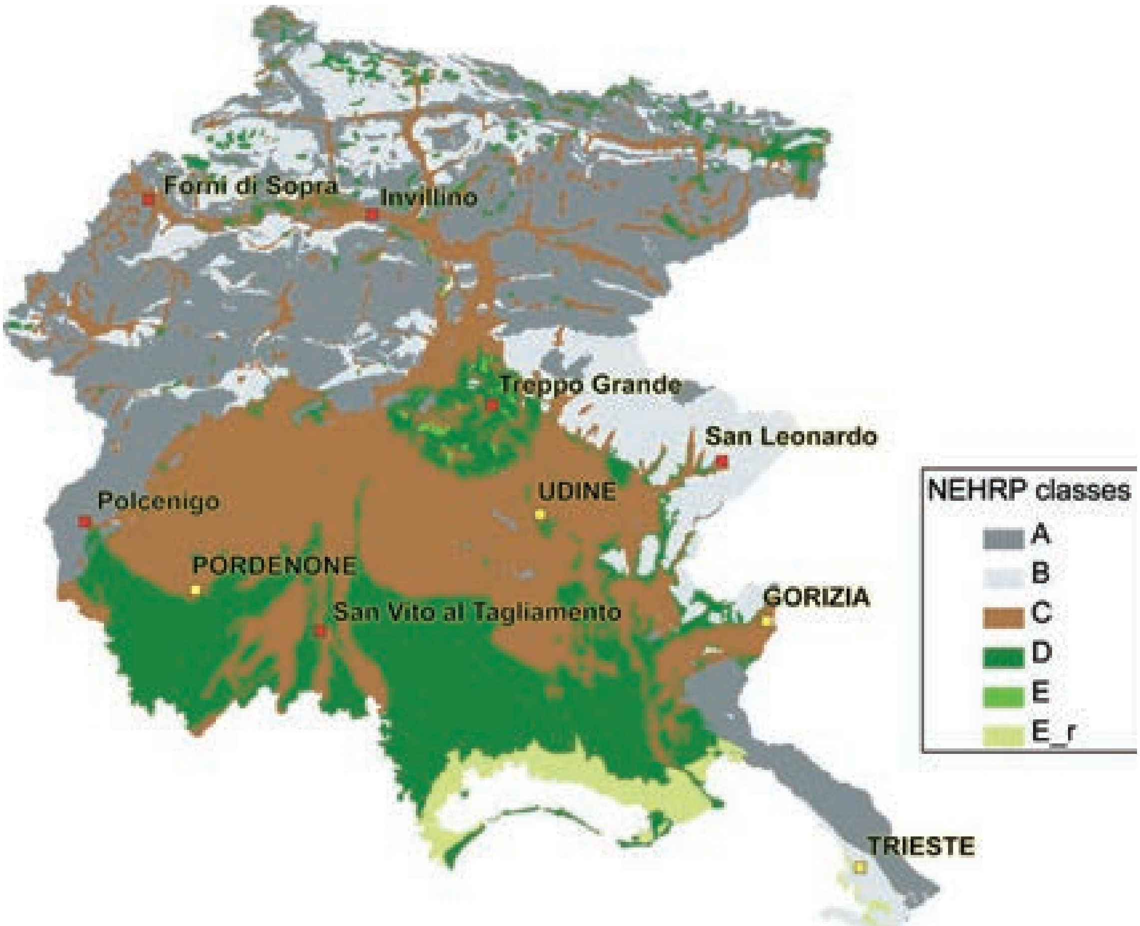


Fig. 6 - Soil map following the NEHRP classification (BSSC, 2004). The class E is present only in limited spots of the moraine amphitheatre of central Friuli. Yellow symbols indicate the main towns in the region and the red symbols show the 6 test sites.

survey has been performed for the V_{30} (velocity of the S waves in the surficial 30 m) quantification. The test sites, where additional down-hole and cross-hole measurements were requested, have been identified on the basis of the results of the previous surveys.

4.2.1. Forni di Sopra

This site is representative of a mountain settlement located on an alluvial fan, with carbonate bedrock outcropping or placed at a shallow depth. From the structural point of view, the area is characterized, at a regional scale, by south-verging imbricate tectonic wedges. It is located on alluvial deposits. The gentle morphology of the mountainsides has been modelled by the glacier action, testified by patches of moraine deposits, and by the presence of highly Triassic erodible lithotypes (limestones, sandstones and siltstones thickly layered). Human intervention for agricultural purposes is also evident in the surface shaping.

The moraines appear as gravelly-sandy sediments with varying amounts of thin material (usually

Table 2 – Test sites and related NEHRP classes.

Test site	NEHRP class
1. Forni di Sopra	D
2. Invillino	C
3. Treppo Grande	D/E
4. San Leonardo	C
5. Polcenigo	D
6. San Vito al Tagliamento	D

greater than 25%). The alluvial deposits are mainly composed of gravel and sand with a high degree of densification. The slope deposits, finally, are made up of debris with sharp elements varying in size from pebbles to large blocks.

The test site can be related to the NEHRP class D (Table 2).

4.2.2. Invillino

This site is representative of a mountain settlement situated on the alluvial plain with relatively deep bedrock and it is located on the mountain course of the Tagliamento River.

Different lithological units overlook the valley located at 340-370 m AMSL:

- to the north, a massive, Mid-Triassic dolomite that looms over the settlement with several hundred metre high sub-vertical walls;
- to the south, the low, northern slopes of Mt. Verzegnis, made up of bituminous laminated dolomite of Upper Triassic age, with a smooth morphology.

Minor relief, above the district of Invillino and elevated a few metres from the plain, borders its southern edge. It consists of Mid-Pleistocene conglomerates, and represents relicts of the paleo floods of the Tagliamento River.

From the structural point of view, this part of the valley is set to the Alto Tagliamento Line (Fig. 1), which brought the dolomite of the left bank of the river to overlap those of the right bank, southwards. The structure does not appear because it is masked by the recent and ancient deposits of the Tagliamento River, which is set on it, but we can assume that it runs at the foot of the northern walls of the Dolomites.

The materials filling the valley are given by gravel deposits, partially sandy, with scattered lenses of finer material, quite similar to those of the present river-bed, which flows a few hundred metres to the south of the site. The pebbles are mainly made up of carbonate with a state of compaction and cementation of very low power in the first metres of the deposit, and may increase in depth. In the absence of mechanical deep surveys, the total thickness of the alluvial deposits is not known but is believed to add up to several tens of metres.

The test site can be related to the NEHRP class C (Table 2).

4.2.3. Treppo Grande

The site is representative of a settlement located on the moraine arc of the Tagliamento River and it extends into an intra-moraine depression of the glacial amphitheatre. The morphology was modelled by the glacial action, with gentle undulations and flat or slightly sloping areas. Isolated peaks emerge locally, evidence of the quiescence phases of the Würmian glacier.

The substrate, consisting of Eocene flysch, is dominated by Quaternary deposits, with very variable thicknesses, represented by glacial and fluvio-glacial deposits, locally covered by detrital layers.

In particular, three units of sediments have been recognized in the investigated site.

- Gravelly-sandy deposits with sometimes dominant silt, with pebbles and locally, boulders. They show an average particle size of 40-60% gravel with 20-35% of sand and 20-35% also of silt and/or clayey silt. Relative density values usually ranging from 0.45 and 0.65 in the first metres of soil, and greater than 0.65 at a greater depth, can be associated to this lithofacies.
- Silty-sandy deposits with small gravel parts, rare pebbles, more or less frequent silty-clayey or silty-sandy intercalations, or thick layers of silt and clay with a mean or, more frequently, compact state of consistency. Silts are limited to 35-50% and may contain a low quantity of clay (5-10%), sand (15-25%) or partly gravel (15-30%). In general, this lithofacies presents average conditions of densification.
- Low sandy-clay loam, with rare included coarse cobbles, with a thickness between 2 and 4 m.

The test site can be related to the NEHRP class D and E (Table 2).

4.2.4. San Leonardo

This site is representative of a settlement situated on the bottom of a valley surrounded by the flysch relief, and it is located in a narrow alluvial plain. The area develops along the hilly strip at an elevation of a few hundred metres. The morphology is variable: gentle, with slopes less than 20% in the presence of easily eroded materials, steeper in correspondence of carbonate banks.

From the lithological point of view, the relief is made up of Paleocenic and Eocenic flysch units, characterized by prevailing carbonate banks placed on well stratified horizons of turbidites. The bank size varies from 10 to several tens of metres.

The bottom of the valley is characterized by alluvial deposits that are joined laterally with deposits of weathering and leaching flysch relief. In general, the alluvial deposits show up as limestone-dolomite gravel, and sand (sometimes with weak cementation) with limited silty-clayey levels. The colluvial deposits are made up of not very thick more or less sandy and clayey silts, sloping down from the mountain to valley sometimes even reaching the first river terraces.

The test site can be related to the NEHRP class C (Table 2).

4.2.5. Polcenigo

This site is representative of a settlement of the western flank of the Tagliamento River and it is placed on hills of Cenozoic molasse. The reliefs are made of molasse deposits with prevailing facies of Upper Miocene conglomerates. The conglomerate consists of predominantly carbonatic round pebbles, variable in diameter. The sandy matrix is abundant and it is welded, together with clasts, by calcareous cement. Sandy and clayey intercalations can be found here as well. The conglomerate is present here in the form of coarse banks with a thickness of about one metre.

From a structural point of view, the area is characterized by the presence of a branch of the Polcenigo-Maniago Line, which brings the carbonate relief of the Pre-Alps to overcome the molasse piedmont hills. They are strongly deformed in a series of tight bends characterizing the local morphology. In fact, depressions surrounded by elongated relief have set at the core of the synclines, or of more erodible lithological units within the conglomerates.

The test site at Polcenigo is located in an almost N-S trending depression filled by alluvial deposits. The test sites can be related to the NEHRP class D (Table 2).

4.2.6. San Vito al Tagliamento

This site is representative of a settlement placed predominantly on gravel at the boundary between the northern and southern Friuli Plain. The morphology of this alluvial plain refers to a wide and flat fan with an average slope of 1.5‰. It was originated in the Quaternary age due to the overlap and the advancement of gravelly-sandy and silty deposits transported from the Tagliamento River. The surficial lithological facies is fairly homogeneous with sandy and sandy-silty soils, and deposits of clean sand or with an abundant silty matrix. The cobbles here are small while clay is almost absent. Overall, the percentage composition of the deposit has more than 50% sand, silt around 40%, and 4-5% of very fine carbonate particles. This facies has moderate geotechnical characteristics, although there is some variability due to both percentage of silt matrix, which determines a different degree of densification, and to different water content, that has a decisive influence on the deterioration of the material. The Tagliamento River and the resurgence ditches determine the hydrographic system. The inputs of the water table are conspicuous, with temporary seasonal fluctuations in relation to the different full-courses, so that as to influence the longitudinal extension of the resurgence area that can vary by several kilometres.

The test site can be related to the NEHRP class D (Table 2).

4.3. Geophysical survey

The Friuli Venezia Giulia region was divided into 6 homogeneous areas, on the basis of lithological and geotechnical properties, and a test site for specific geophysical measurements (down-hole, cross-hole, active seismic prospections) was identified for each area. The stratigraphies of the 6 test sites were obtained using a multidisciplinary approach that integrates results of geological, geophysical, geotechnical, and geomorphological studies to characterize the stratigraphy, lithology, and geomorphology, to determine the shear wave velocity profiles (Fig. 7), and to define the dynamic properties of the soils (Table 3 and Fig. 8).

4.3.1. Seismic data

The seismic surveys were designed to illuminate the structures up to 100 m depth at the 6 test sites. To better define the acquisition parameters we used a commercial software to create synthetic seismograms (Tesseral©), supposing different acquisition parameters. The initial geometrical model was created considering the results obtained by other geophysical surveys performed in the same area (ground penetrating radar and geoelectric surveys). After this study, the receiver and shot intervals range from 2 to 3 m and from 2 to 6 m, respectively. The length of the seismic line is variable from 200 to 300 m, according to the logistic problems. The sample rate of the data is equal to 1 ms. The acquisition system is characterized by 3-C geophones (with a nominal frequency of 10 Hz), while the source is a MiniVib that allowed us to generate both P than S waves. After the field tests, we decided to use a sweep of 12 s ranging from 20 to 300 Hz for both P- and S-energizations. The choice of the source was made so as to limit environmental damage and to have the possibility of generating both P and S energy. The quality of both P and S data generally is high and the

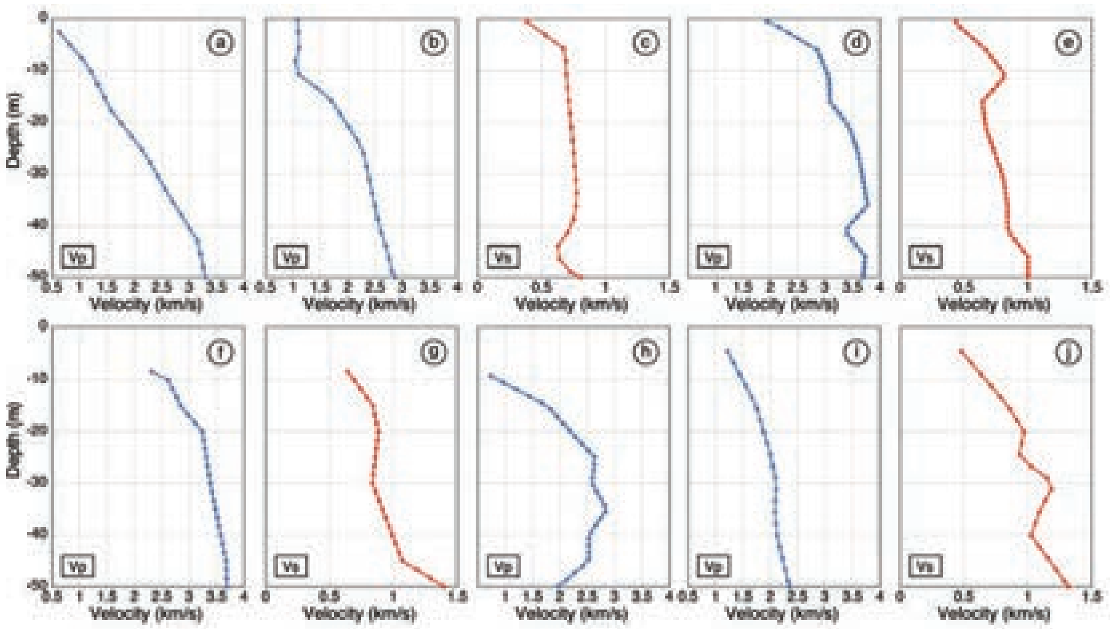


Fig. 7 - V_P and V_S at the test sites: a) V_P at Forni di Sopra; b) V_P at Invillino; c) V_S at Invillino; d) V_P at Polcenigo; e) V_S at Polcenigo; f) V_P at San Leonardo; g) V_S at San Leonardo; h) V_P at San Vito al Tagliamento; i) V_P at Treppo Grande; j) V_S at Treppo Grande. The depth is referred to the surface.

identification of the first arrivals is clearly detected. At the San Vito al Tagliamento site, the quality of the S-wave data is poor, while S-wave data are missing at the Forni di Sopra site due to logistic problems.

The analysis of the seismic data is focalized so as to increase the signal/noise ratio, especially to help the picking of the first arrivals. Particular attention was devolved to reduce the ground roll on the S-wave data in order to better indentify these arrivals.

4.3.2. Tomographic inversion

To obtain the velocity fields, we used a tomographic algorithm. The inversion needs the picking

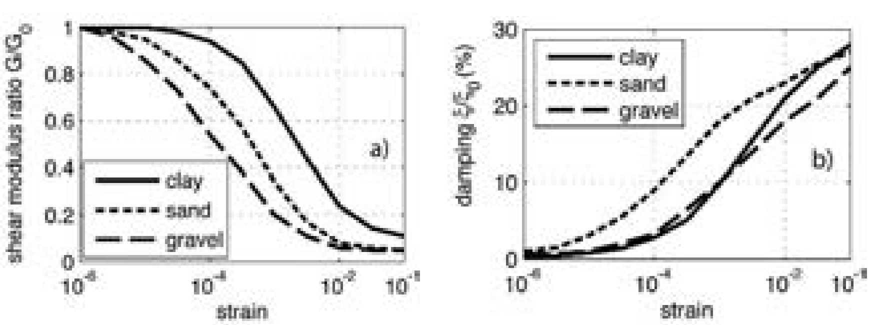


Fig. 8 - Curves of the dynamic properties of materials: a) shear modulus; b) damping.

of the first breaks for all the shots considered for both P and S shots. To avoid errors in picking, the analysis of the apparent velocity of the pick was performed, and the picks with anomalous apparent velocity were not considered (Accaino *et al.*, 2007). The initial velocity model was composed of the topographic surface and deeper surfaces, spaced from 1 to 5 m in depth that smooth the topography until they reach a horizontal surface. Each layer is composed of pixels with a maximum size of 1 m. The initial model was designed using a constant velocity determined site by site, by the slope of the first arrivals.

The inversion was performed with the commercial tomographic software (CAT3D), using a modified version of the minimum time ray tracing (Böhm *et al.*, 1999), and an iterative procedure for the inversion, based on the SIRT algorithm. The ray-tracing algorithm starts from an initial hypothesis for its path and converges to a final geometry through an iterative procedure by using the analytical solution of Snell's law (Böhm and Petronio, 2003). Initially, the first arrivals were inverted using the circular travel of the rays to obtain an initial model close to a real model. Then, using the results obtained in the previous inversion, the arrivals were inverted assuming a ray path of diving waves. Subsequently, to improve the lateral resolution of the velocity model, an inversion was performed using the Staggered Grid method (Vesnaver and Böhm, 2000). This technique provides a better resolution of the inversion without increasing the null space energy of the tomographic system (Vesnaver and Böhm, 2000). In order to check the reliability of the final velocity model, we evaluate the residual time, i.e. the difference between the picked and calculated time after the tomographic inversion.

4.3.3. Velocity profiles

The main target of this study was to obtain an average wave velocity of the shallower structures (above the first 50 m below the topography) on the basis of all the geophysical data acquired. In Fig. 7, the velocity profiles in the middle of the seismic lines are reported, hereafter called V_P and V_S for the compressional and shear wave velocity, respectively.

At the Forni di Sopra site, the V_P (Fig. 7a) reported quite a linear increase of the velocity versus depth from 500 m/s (below the surface) to 3300 m/s (at 50 m below the surface, i.e. 800 m of elevation). No acquisition of V_S was possible, due to organizational problems.

At the Invillino site, the V_P (Fig. 7b) and the V_S (Fig. 7c) summarized the main characteristic of the two velocity fields, indicating variable compressional velocity gradient versus depth with respect to the more simple shear-wave velocity profiles.

At the Treppo Grande site, the V_P (Fig. 7d) indicates a change of velocity gradient at about 30 m in depth, while the V_S (Fig. 7e) shows two velocity inversions at about 20 and 30 m below the surface.

At the San Leonardo site, the V_P (Fig. 7f) indicates a change of velocity gradient at 20 m below the surface. The V_S (Fig. 7g) is more complex, showing, in particular, a velocity inversion at about 30 m below the surface.

At the Polcenigo site, the V_P (Fig. 7h) reported the increase of the velocity versus depth, while the V_S (Fig. 7i) indicates the complexity of the S-wave velocity at this site.

The San Vito al Tagliamento (Fig. 7j) site is characterised by a very variable V_P in depth, showing a layer characterized by low velocity (1900 m/s) with respect the surrounding velocity, at about 45 m below the surface. The recorded data of the V_S was too noisy and not suitable for further

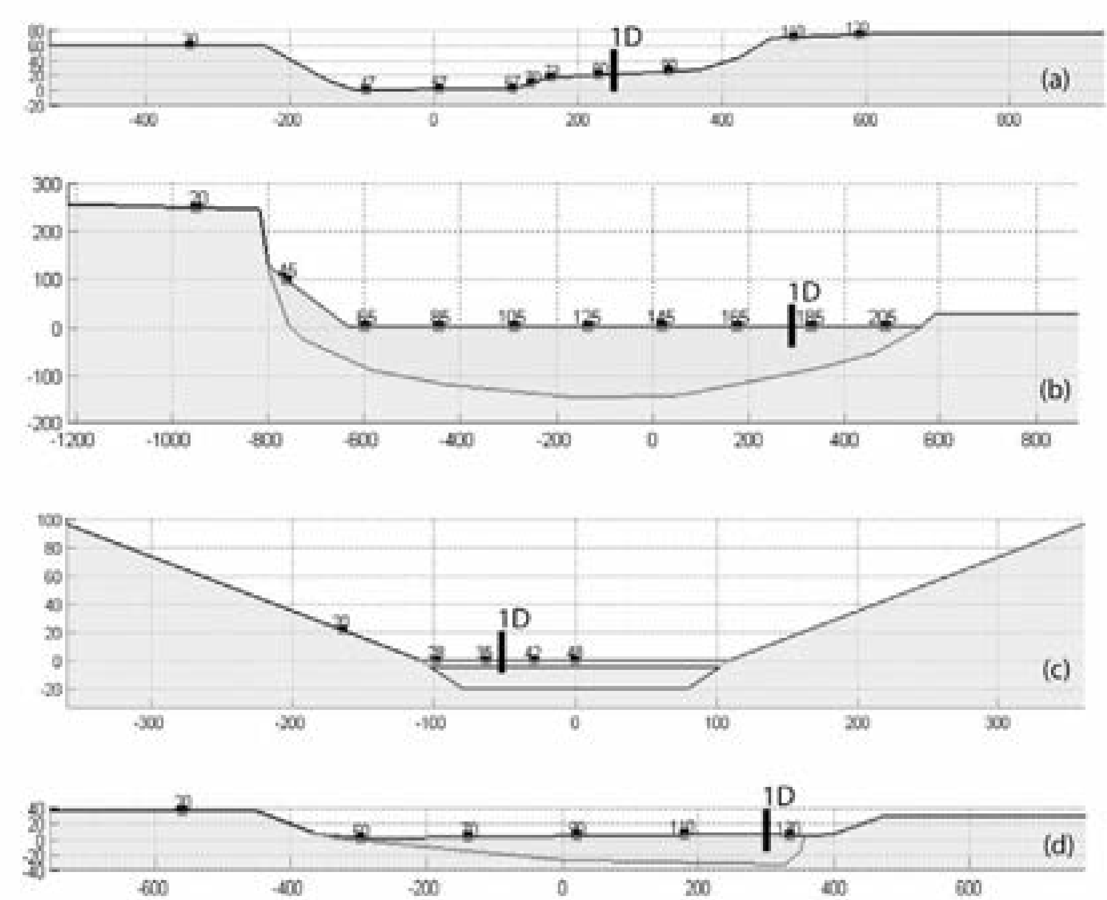


Fig. 9 - 2D modelling site profiles: a) Forni di Sopra; b) Invillino; c) San Leonardo; d) Polcenigo. The numbers indicate the analyzed elements and the 1D segmant identifies the location of the available well, where the 1D modelling has been performed.

processing.

4.4. Lithological amplification

In the present study, the lithological amplification was computed by 1D and 2D modelling based on the results of the specific local geophysical and geotechnical soundings. The AFs obtained were exported to the whole area of which the test site is representative. The location of the wells, used for calibrating the 1D stratigraphies (Table 3) and that of the 2D profiles are illustrated in Fig. 9.

The parameters used in the modelling for each site are: a) a uniform hazard response spectrum with a return period of 475 years and with a 5% damping computed for rock and applied at the bedrock (layer with a V_S greater than, or equal to, 800 m/s in Table 3), and b) mean linear-equivalent behaviour curves for different types of material (e.g. clay, sand, gravel; see Fig. 8), taken from the literature.

The 1D analysis was performed for all sites, while the 2D one was applied only in those situations where the subsoil has a variable geometry (Forni di Sopra, Invillino, San Leonardo, and

Table 3 - Stratigraphic profiles for the 6 test sites.

Site	Depth (m)	Lithology	Density (g/cm³)	Vs (m/s)
Forni di Sopra	0 - 10	Clay	1.08	170
	10 - 20	Sand	1.73	723
	20 - 40	Gravel	2.10	900
	> 40	Rock	2.36	1430
Invillino	0 - 5	Gravel	1.15	200
	5 - 15	Gravel	1.77	700
	15 - 25	Gravel	1.98	750
	25 - 35	Gravel	2.11	750
	35 - 75	Gravel	2.17	750
	> 75	Rock	2.36	800
Treppo Grande	0 - 9	Sand	1.54	300
	9 - 17	Gravel	1.92	700
	17 - 40	Gravel	2.06	850
	> 40	Gravel	2.21	1250
San Leonardo	0 - 5	Gravel	1.98	400
	5 - 20	Gravel	2.17	750
	20 - 35	Gravel	2.36	1100
	> 35	Rock	2.46	1400
Polcenigo	0 - 5	Sand	1.31	400
	5 - 29	Gravel	2.06	700
	29 - 40	Gravel	2.40	1000
	> 40	Rock	2.45	1000
San Vito al T.	0 - 5	Sand	1.54	330
	5 - 15	Gravel	2.03	800
	15 - 25	Gravel	2.17	800
	25 - 39	Gravel	2.21	1260
	> 39	Gravel	2.17	750

Polcenigo) and the results of the 2D modelling were compared with those of the 1D analysis.

The AF is calculated as:

$$AF = \frac{\int_{0.1s}^{0.5s} SA_{output}}{\int_{0.1s}^{0.5s} SA_{input}}$$

that is the ratio between the integral of the output and input spectral acceleration (SA) in the period

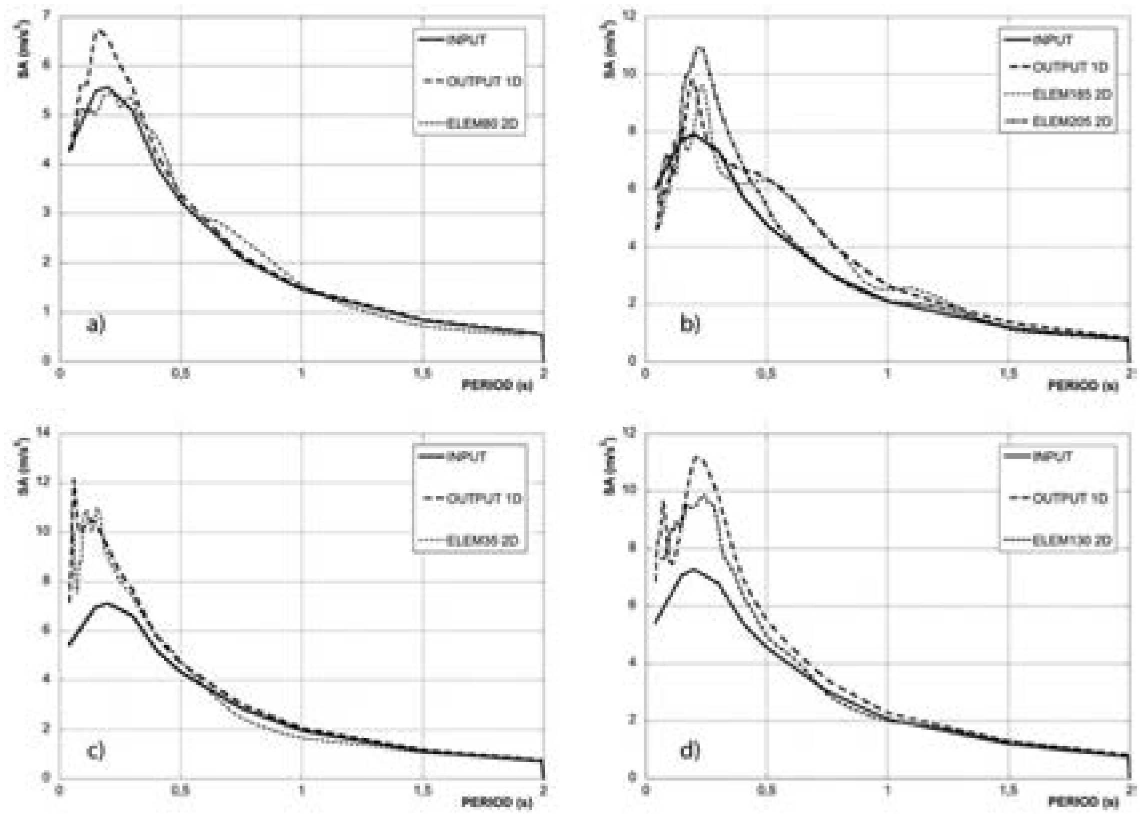


Fig. 10 - Input and output spectra for the test sites: a) Forni di Sopra; b) Invillino; c) San Leonardo; d) Polcenigo. Legend: INPUT = input response spectrum for the 1D and 2D analysis; OUTPUT 1D = output response spectrum for the 1D analysis with PSHAKE (Sanò and Pugliese, 1991); ELEMn 2D = output response spectrum for the n element of the 2D analysis. The position of the n element is shown in Fig. 8.

range between 0.1 and 0.5 s.

For the Forni di Sopra test site the 1D analysis highlights a generally low amplification (see Table 4), in the range of periods between 0.05 and 0.4 s, with a peak around 0.15 s. The AF has a value of 1.12. This test site has been used to evaluate the performance of the 2D modelling to account for morphological effects (Fig. 9a). In fact, not considering the surficial thin layer of low velocity and density that is usually eliminated during the construction of a new building, the stratigraphy has no indication of strong impedance contrasts (Table 3) and, therefore, a 2D analysis is suitable for the identification of any morphological effect. The results (Table 4) confirm the influence, definitely weak in this case (~10%), of the terrain topography on the spatial distribution of the AFs (Fig. 10a). The element n. 80 of the 2D profile is the closest to the location of the 1D stratigraphy; the computed AF is 1.03, a bit lower than that obtained by the 1D modelling (1.12). This is due to the fact that the surficial layer, removed in the 2D analysis, determines a strong impedance contrast.

For the Invillino test site, the 1D analysis shows an amplification limited to a small range of periods, with the main peak at around 0.25 s (Fig. 10b). Element n. 185 of the 2D profile is the closest to the well used for defining the 1D stratigraphic profile (Fig. 9b). For this element, both the

Table 4 - AFs from 1D modelling and for the n elements studied by the 2D modelling; the position of the n element is shown in Fig. 9.

1-Forni di Sopra		2-Invillino		4-San Leonardo		5-Polcenigo	
Element	**AF**	**Element**	**AF**	**Element**	**AF**	**Element**	**AF**
1D	1.12	1D	1.10	1D	1.25	1D	1.37
20	0.96	20	0.95	20	0.93	20	0.98
47	0.97	45	1.06	28	0.97	50	0.98
57	1.04	65	1.09	35	1.24	70	1.22
67	0.91	85	0.99	42	1.27	90	1.33
70	0.97	105	0.95	48	1.30	110	1.32
73	1.07	125	0.97			130	1.26
80	1.03	145	0.98				
90	1.01	165	0.98				
110	1.14	185	1.06				
120	0.97	205	1.21				

spectrum and the AF are very similar to those obtained by the 1D modelling (AF=1.06 and 1.10, respectively, see Fig. 10b and Table 4). Element n. 205, which is located at the border of the valley (Fig. 9b), has, instead, a high main peak and an AF of 1.21 (Table 4 and Fig. 10b): this amplification, which is larger than that of element n. 185, may be attributable to edge effects related to the geometry of the basin.

Because of the complexity of sediments of the textural composition and the high spatial variability of the stratigraphy, due to numerous lateral heterogeneities (Fig. 11), the Treppo Grande test site was analyzed using different dynamic properties of the materials and different velocities for the layer above the bedrock. A 1D parametric study was performed by considering the wide variability and uncertainty about the geological and physical properties of the soil at the site. Regarding the stratigraphy, a first layer (9 m thick, see Table 3) with different velocities (400, 300, and 180 m/s) and a bedrock with a V_S of 800 m/s were considered. Degradation curves of the materials for sand, gravel, and clay, taken from literature were used. The AFs obtained from this parametric study (Fig. 12) are presented in Table 5. The highest value, 1.93, is related to a first layer of clay with a V_S of 180 m/s (clay_180 case in Table 5). It should be noted that for materials with a very low V_S (as in the case of clay with a V_S of 180 m/s) the program PSHAKE (Sanò and Pugliese, 1991) works at the limits of its range of applicability, because the linear-equivalent analysis may be unable to model peculiar phenomena as, for example, the sand liquefaction.

For the San Leonardo test site, the 1D analysis shows great amplification at very low periods, with the main peak at around 0.06 s (Fig. 10c), and a general amplification up to 0.4 s. The AF is moderately high, with a value of 1.25. As the valley where the test site is located can be considered symmetric, the 2D modelling was limited to half of it (Fig. 9c). Element n. 35 is the closest computational point to the well used to calibrate the 1D stratigraphy of the site (Table 3). As expected, the amplification and the fundamental frequencies are very similar to those computed by 1D modelling (Table 4 and Fig. 10c) as well as the AF (1.25 from the 1D analysis and 1.24 for the

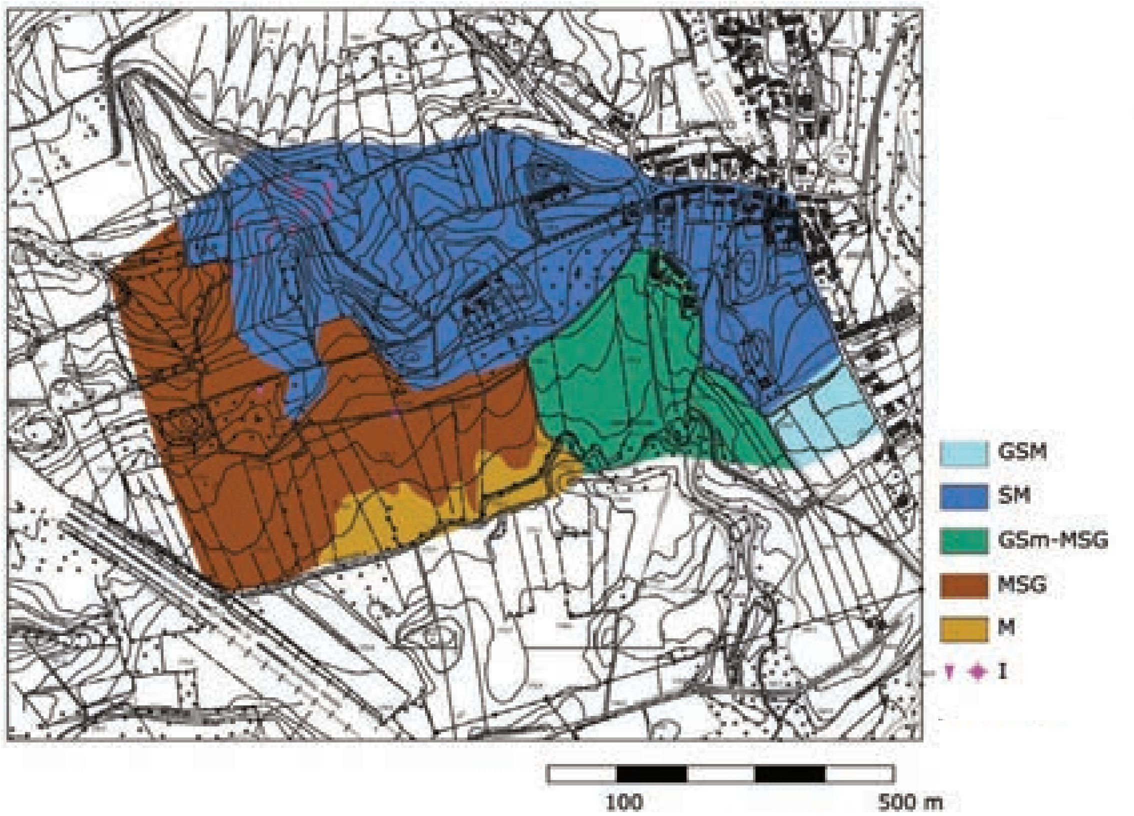


Fig. 11 - Lithological map of the Treppo Grande area with the location of the geotechnical and geophysical investigations (I):
- GSM-SM: gravel-sandy sediments with silt, sometimes with a predominantly cobble and boulders locally, with V_S = 400 m/s;
- GSm-MSG: gravelly-sandy sediments poorly or partially loamy, with V_S = 300 m/s;
- MSG-M: silt sediments from sandy-loamy to loamy-clayey poorly sandy, with V_S = 180 m/s.

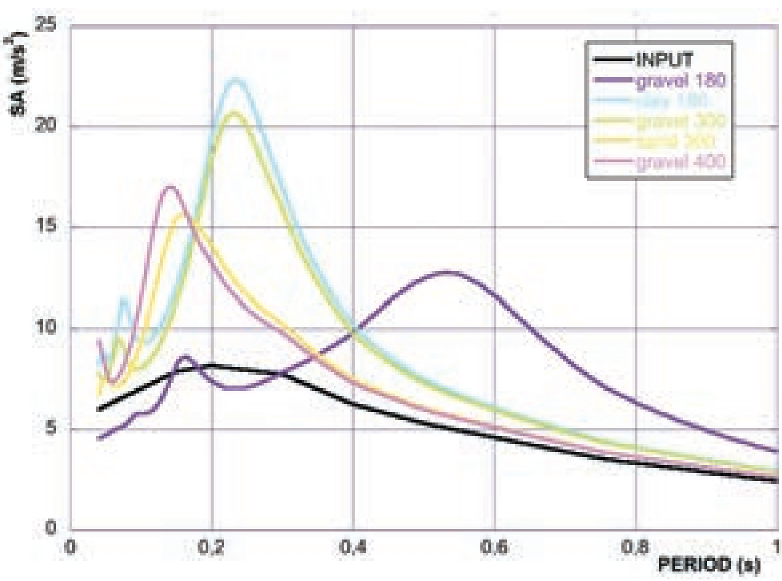


Fig. 12 - Comparison of the Treppo Grande results, due to the variation of the first layer material dynamic properties.

Table 5 - AFs related to the different stratigraphies studied for the test site Treppo Grande. The colours refer to the curves in Fig. 12.

Lithology	AF
gravel_180	1.23
clay_180	1.93
gravel_300	1.81
sand_300	1.44
gravel_400	1.45

element n. 35 of the 2D analysis). In this case, it does not seem that there are morphological influences at the border of the valley and the AFs are quite near to 1.0 (Table 4).

At the Polcenigo test site, the 1D analysis and the 2D one for element n. 130, located at the proximity of the geognostic well used to calibrate the site stratigraphy (Fig. 9d), gave similar curves, especially for the periods of maximum amplification (Fig. 10d), with the 1D analysis, showing greater amplification at low periods. This may be because the code BESOIL (Sanò, 1996) develops only a linear analysis, and, consequently, it needs a preliminary 1D analysis (attenuated V_S and increased damping) to take into approximate account any non-linear effects.

For the San Vito al Tagliamento test site, it was decided to consider only the 1D analysis because of the simple conformation of the subsoil (the adopted stratigraphy is shown in Table 3). The results obtained by applying the 1D modelling are illustrated in Fig. 13, where the main amplification can be seen at low periods, with two maxima at 0.06 and 0.12 s, while for periods longer than 0.3 s there is not any notable amplification. For this reason, the AF is not very high (1.12).

As a summary, Table 6 reports the AFs computed for the 6 test sites and exported to the whole regional territory.

5. Morphological characterization

The territory of the Friuli Venezia Giulia region is very complex from the geomorphological

Table 6 - Table of classification of soils and lithological AFs.

NEHRP Class	NEHRP V30 (m/s)	NEHRP AFs	Italian and EC8 Class	Italian and EC8 V30 (m/s)	EC8 AFs	Italian AFs	Local AFs
A - Hard rock	>1500	0.8					0.8
B - Rock	760-1500	1.0	Rock	>800	1	1	1
C - Very dense soil and soft rock	360-760	1.2	Stiff	800-360	1.2	1.25	1.2
D - Stiff soil	180-360	1.5	Soft	360-180	1.15	1.25	1.7
E - Soft soil	<180	2.1	Very soft	<180	1.35	1.35	1.9

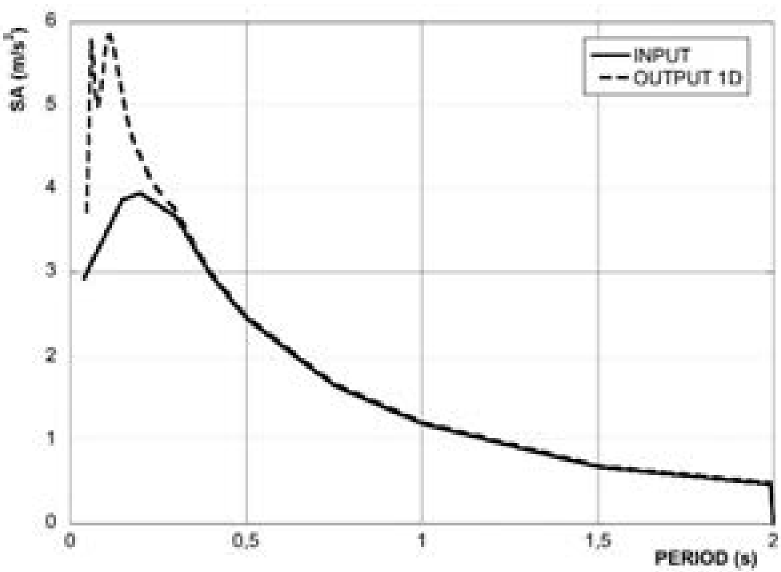


Fig. 13 - Input and output spectra for the San Vito al Tagliamento test site.

point of view: we find an Alpine sector (about 3,200 km^2), a hilly sector (about 1,400 km^2), a plain (about 2,800 km^2), a coastal lagoon area (about 160 km^2), and the Karst (about 200 km^2). Mountain areas occupy the northern part, forming a large mountain arc variously intersected by deep valleys, whose orientation is guided by the structural framework and whose morphology is related to the geotechnical characteristics of the outcropping geological formations. The hills are represented by some isolated reliefs gradually sloping down towards the plains and a series of moraine arches. Limited by the Alpine arc, the Friuli Plain degrades into the sea from 300 m AMSL in the foothills and 150 m AMSL in the moraine amphitheatre. The morphology of the plain is gently moved by a few large terraced fans and by small reliefs either isolated or connected with the Alps. The whole lagoon of Marano and Grado, defined towards the sea by a strip of sand banks and dune relief, extends between the delta of the rivers Isonzo and Tagliamento.

The study of the morphology of the region, for the purposes of the possible effects of seismic amplification, has been set according to two approaches with their own independent management and use, preparatory to one another. It has been aimed at the regional breakdown of the entire surface in steepness classes on the one hand, and at the identification of different morphological situations on the other, developing a Slope Map and a Map of Morphotypes.

Nearly half (43%) of the regional territory shows a slope between 0° and 2° (Fig. 14), indeed as expected given the extent of the Friuli Plain. 45% of the territory falls in the range of a slope between 8° and 50°, with 20% in the slope range between 20° and 35°, corresponding to most of the villages of the hilly strip and part of the mountain one. The smaller percentages are related to often inaccessible high mountain areas, with a slope between 50° and 90° (4%), and to link bands of the northern Friuli Plain with the hills with a slope between 2° and 8° (8%).

5.1. Map of the regional morphotypes

The definition of the surficial morphological features of the territory, as potential seismic

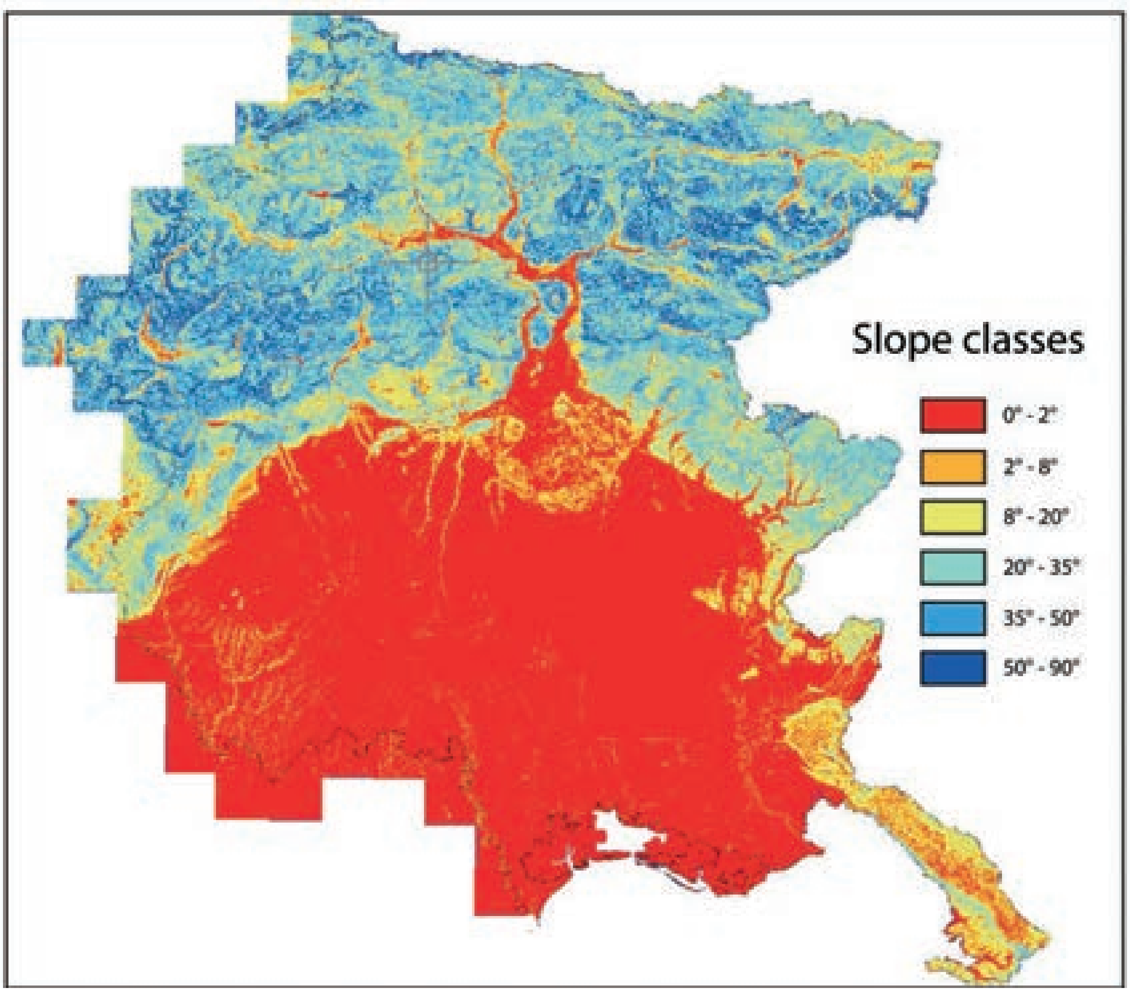


Fig. 14 - Slope map.

amplifiers, was based on the Di Bucci *et al.* (2005) approach. This approach was not considered rigorously because it refers mainly to specific morphological types common to the Apennines. The Di Bucci *et al.* (2005) methodology has been adapted to fit the reality of the geomorphological features of Friuli Venezia Giulia. Consequently, nine significant morphological cases have been identified in the study region (Fig. 15): they are referred to as “morphotypes” (morphological scenarios).

1. Morphotype Plain (Fig. 16): it is a very large homogeneous area whose width exceeds 250 m and with a slope of between 0° and 8°. This morphotype covers approximately 49.1% of the region.
2. Morphotype Slope (Fig. 17): it is an area with a slope between 8° and 35°, located between crests and flat areas, including plain areas or valley bottom. This morphotype covers approximately 28.6% of the region.
3. Morphotype Wall (Fig. 17): it is an area whose slope exceeds 35°, located between crests

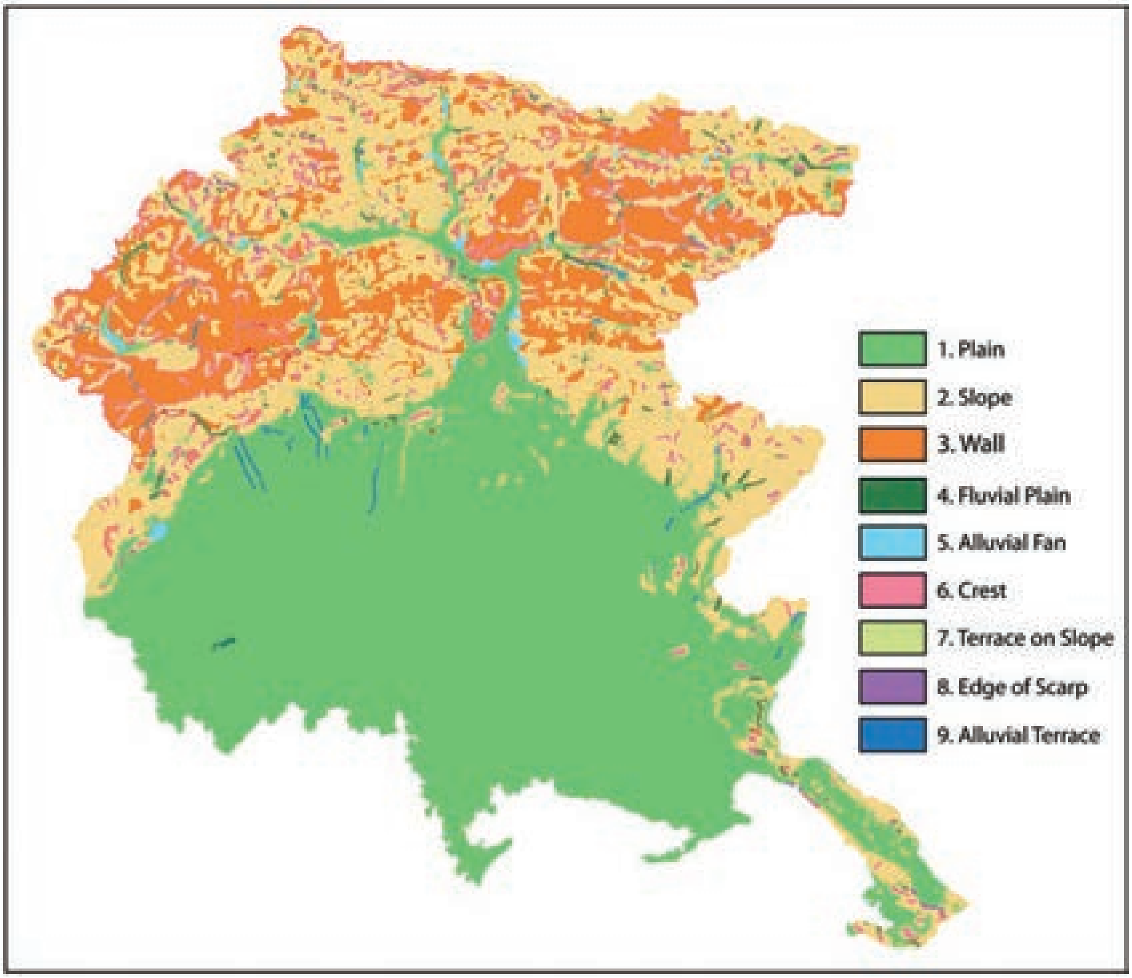


Fig. 15 - Map of the morphotypes.

and flat areas, including plain areas or valley bottom. This morphotype covers approximately 20.1% of the region.

4. Morphotype Fluvial Plain (Fig. 16): it is an almost flat area, up to 250 m wide (when width exceeds 250 m it becomes Plain), with a slope of less than 8°, located between two walls (then it becomes deep fluvial plain), or slopes (then it becomes shallow fluvial plain). This morphotype covers approximately 0.7% of the region.
5. Morphotype Alluvial Fan (Fig. 18): it is an alluvial fan area with a slope of between 2° and 35°. This morphotype covers approximately 0.4% of the region.
6. Morphotypes Crest (Fig. 18): it is an almost flat area (mainly between 0° and 20° of slope), bounded by walls or slopes, with a width between 100 and 500 m. This morphotype covers approximately 0.1% of the region.
7. Morphotype Terrace on Slope (Fig. 17): it is an almost flat area, up to 250 m wide (when width exceeds 250 m it becomes Plain) with a slope less than 8°, located along a slope or

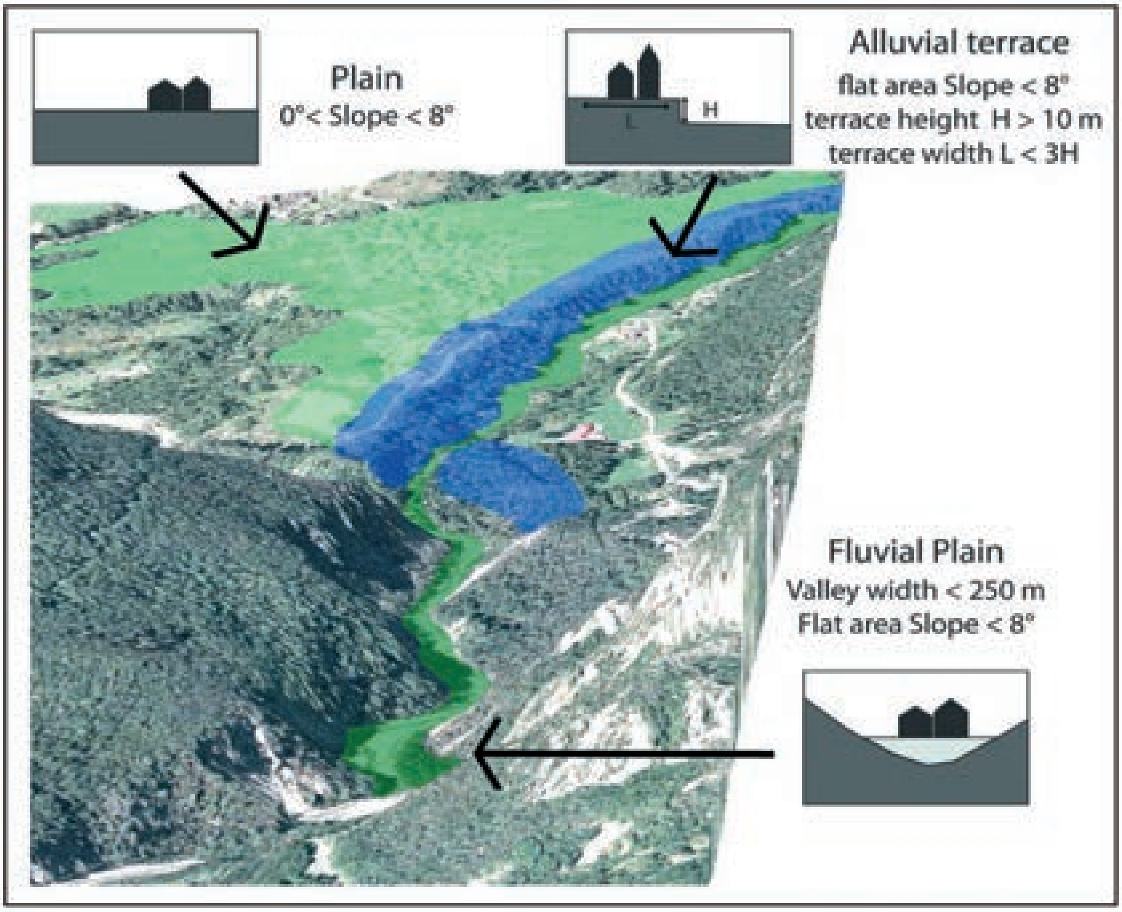


Fig. 16 - Morphotypes Plain, Fluvial Plain, Alluvial Terrace.

a wall. This morphotype covers approximately 0.1% of the region.

8. Morphotype Edge of Scarp (Fig. 18): it is an almost flat area in a mountain domain (e.g.: moraine terraces, plateaus in mountain areas, etc.) which spatially extends for at least 100 m between two slopes or walls and is marked by a sharp change of slope. This morphotype covers approximately 0.1% of the region.
9. Morphotype Alluvial Terrace (Fig. 16): it is an alluvial terrace with a slope less than 8° and a difference in altitude more than 10 m between the terrace edge and the slope foot, including the foot of the escarpment (the distance from the terrace edge should not exceed three times the terrace height). This morphotype covers approximately 0.1% of the region.

These morphological classifications of the Friuli Venezia Giulia territory are completely new and are basic documents for many modellings. They represent an important tool for land managing and for mitigation works against slope failure and landslides.

5.2. Morphological amplifications

In order to obtain a quantitative estimation of the morphological amplification, a statistical

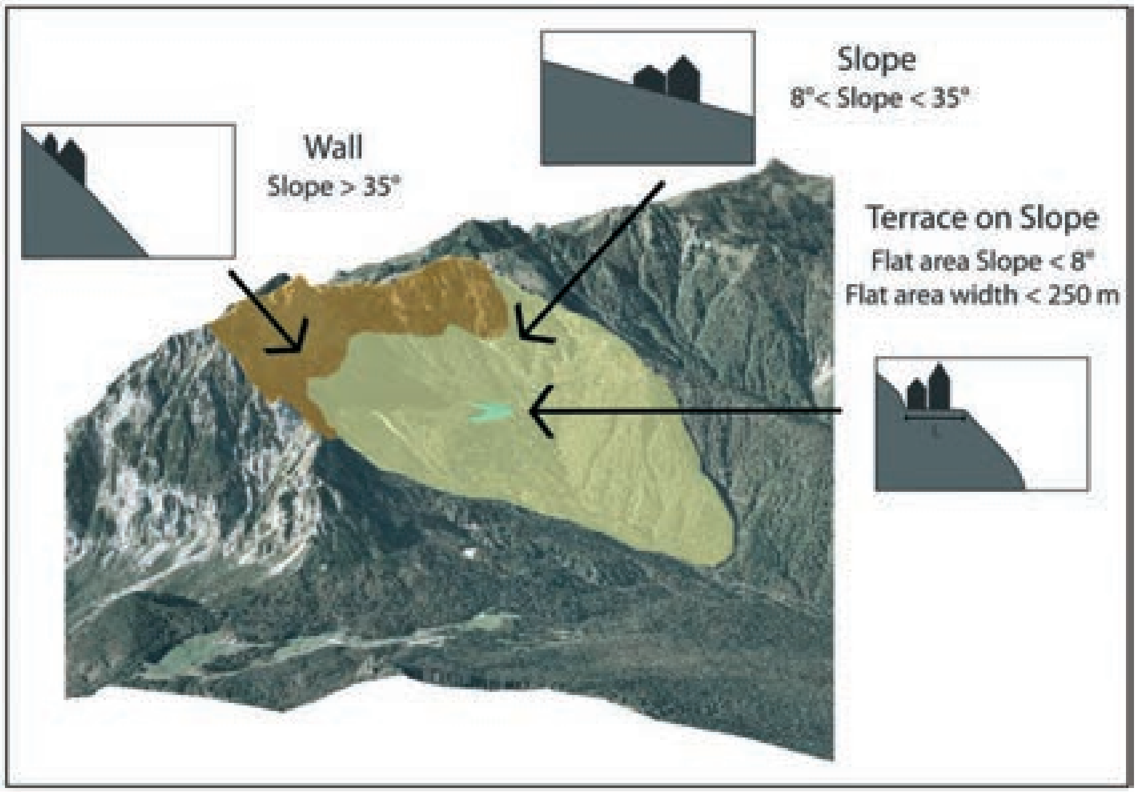


Fig. 17 - Morphotypes Slope, Wall, Terrace on Slope.

method, based on observed seismic damage of buildings, has been adopted. In particular, the Probit analysis, a technique widely applied in the field of industrial safety and toxicology, has been used. The Probit analysis permits us to obtain empirical correlations between specific levels of effect magnitude and its causal agent (Finney, 1971). These correlations are usually used both for estimating the effect produced by an adverse agent on a specific target and for defining the level of the adverse action able to cause a specific effect on the target. This typology of statistical analysis could be applied also in the seismic field if the action is represented by ground motion, the effect is defined referring to different thresholds of damage when sufficient data are available. This is possible in the Friuli region because, immediately after the 1976 earthquake (Carulli and Slejko, 2005), the regional authorities organized a survey aimed at collecting the damage data in the affected area in order to quantify the necessary funds for the reconstruction (Fig. 19). A "damage assessment report" was filled out for about 85,000 residential or mixed buildings, given information on location, type, and characteristics of each building and on the damage level suffered. The seismic risk research team of the University of Udine reorganized the information, implemented the Fr.E.D. (Friuli Earthquake Damage) database and proceeded with the geo-localization of more than 45,000 buildings (Di Cecca and Grimaz, 2009).

Studies on the Fr.E.D. database information (Riuscetti *et al.*, 1997; Carniel *et al.*, 2001; Grimaz, 2009a) led to the definition of criteria for a seismic vulnerability classification of

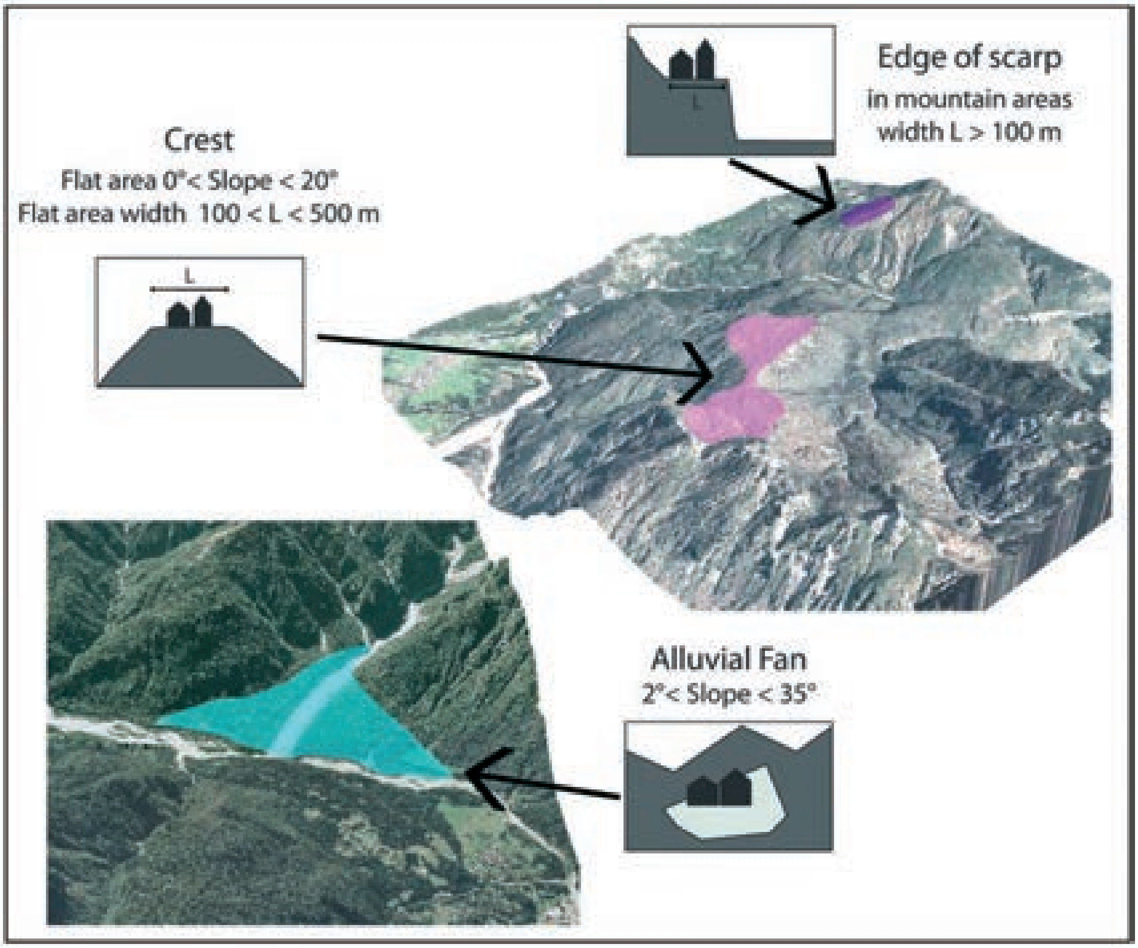


Fig. 18 - Morphotypes Alluvial Fan, Crest, Edge of Scarp.

residential buildings in the area. In particular, six typological classes of masonry buildings, significantly different in terms of vulnerability, were defined taking into account the year of construction, the number of floors, and the presence of shared walls. The largest class (more than 27,000 buildings), represented by masonry buildings built before 1920 with less than 5 floors, permits us to have a significant number of buildings characterized by the same vulnerability and located in different morphological scenarios.

The data related to buildings with an equal class of vulnerability and located in different adjacent morphological scenarios (that, therefore, could be considered at the same epicentral distance), were processed using the Probit analysis to compare the level of damage.

In particular, the analysis was carried out on the data of the Gemona and Tarcento municipalities, both in the Udine Province. Taking into account the morphotype classification, the areas studied were divided into sub-areas, corresponding to different morphological scenarios, and maps representing both the position of the damaged buildings and the level of damage, were implemented. The intensity of the action leading to such damage was quantified

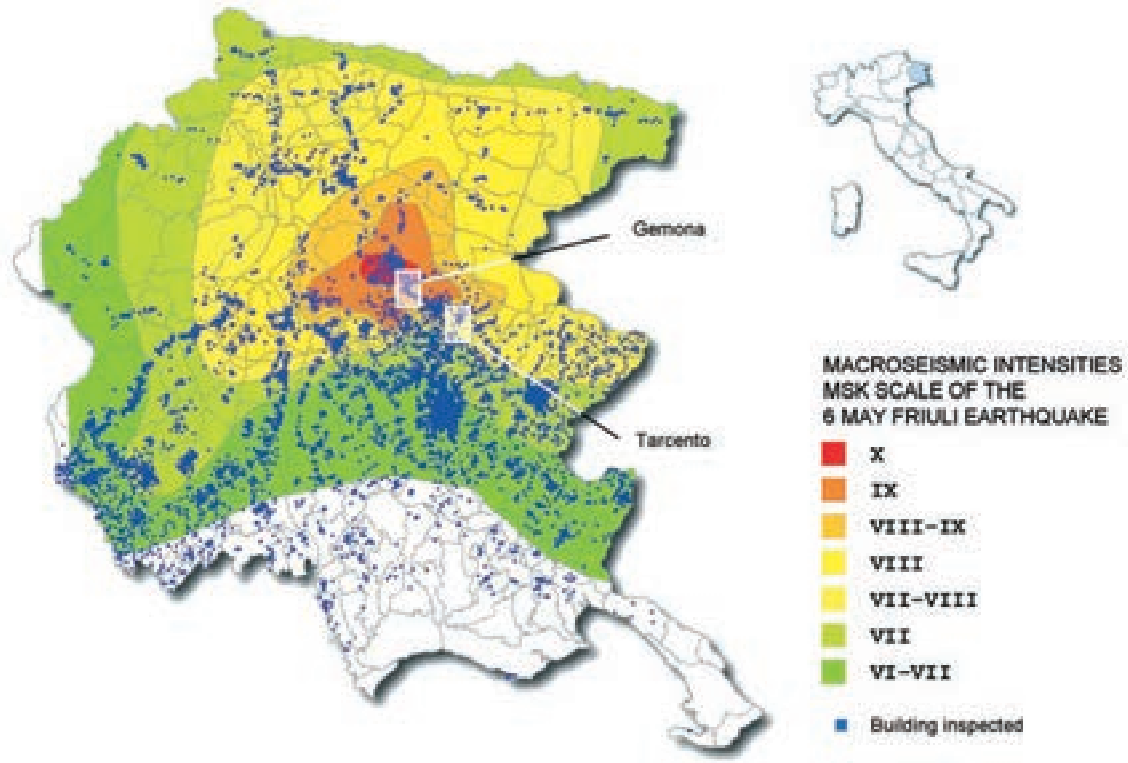


Fig. 19 - Distribution of buildings inspected after the 1976 Friuli earthquake [Fr.E.D. database; Di Cecca and Grimaz (2009)]. Rectangles show the two areas of study where the information of buildings with the same vulnerability located in different morphotypes have been processed by Probit analysis.

by applying the reverse Probit equation. In particular, using the relationship between macroseismic intensity and PGA proposed by Guagenti e Petrini (1989), it has been possible to link the level of observed damage with the corresponding PGA value. The level of action obtained for each scenario was compared with the action level estimated for an adjacent area, classified as “plain” and considered as a reference scenario. In this way, a set of relative AFs for the different morphotypes was defined (Table 7).

The values of seismic action obtained must be considered as the “action at the site” deriving from the overall AF f_T, which can be interpreted as the result of the combination of the lithological AF f_{GL} (related to different soil NEHRP classes) and the morphological AF f_{MF} (related to different surface topography and/or geometry of the buried bedrock). Under the hypothesis that $f_T = f_{GL} \cdot f_{MF}$. it is possible to isolate the morphological contribution and to define a morphological AF referred to the rock site, taking into account the different lithological amplification due to the soil typology in the studied sites (f_{GL}=1.0 for soil NEHRP class B and f_{GL}=1.2 for soil NEHRP class C). The calculated morphological AFs f_{MT} are shown in Table 8.

A notable difference of level of ground motion has been detected between the morphotypes: “shallow fluvial plain” and “deep fluvial plain”. This result suggested an extension of the studies for a better definition of the morphotypes in a seismic amplification perspective. Recently, a

Table 7 - Ground motion estimation derived from an inverse Probit analysis on the 1976 Friuli earthquake damage data, referring to different morphotypes in Tarcento and Gemona areas (see Fig. 19), and computation of the relative AF.

Site: TARCENTO			
Reference morphotype	*NEHRP class of soil*	*estimated PGA*	
Plain	C	0.08 g	
Morphotype	*NEHRP class of soil*	*Estimated PGA*	*AF*
Fluvial plain (deep)	C	0.31 g	3.90
Fluvial plain (shallow)	C	0.15 g	1.84
Alluvial terrace	C	0.32 g	4.04
Wall	B	0.23 g	2.92
Slope	C	0.08 g	0.97
Crest	B	0.26 g	3.28
Site: GEMONA			
Reference morphotype	*NEHRP class of soil*	*estimated PGA*	
Plain	C	0.16 g	
Morphotype	*NEHRP class of soil*	*Estimated PGA*	*AF*
Alluvial fan	C	0.25 g	1.58
PGA estimated from the 1976 Friuli earthquake damage by inverse Probit analysis *AF = estimated PGA on morphotype / estimated PGA on reference plain morphotype*			

more detailed definition of geo-morphotypes has been proposed (Grimaz *et al.*, 2010b), deeper studies on the Fr.E.D. information have been developed, by considering different relationships between macroseismic intensity and PGA (Cauzzi and Faccioli, 2008), and more accurate estimates of the AFs have been obtained by applying statistical analysis (Grimaz, 2009b). Nevertheless, the order of magnitude of the values of the morphological AFs are substantially confirmed.

6. Soil hazard maps

The first expeditious soil hazard map (frequently presented in the literature, e.g.: Romeo *et al.*, 2000) has been computed by simply assigning the expected PGA (see Figs. 5a to 5c) to the different soil types of Fig. 6 by GIS technologies. Table 6 illustrates the soil correspondence in the different building codes while rock, very shallow and deep alluviums of the Sabetta and Pugliese (1987, 1996) GMPEs have been assimilated to rock, and the shallow alluvium has been assimilated to soft soil. In such a way, a soil seismic hazard map has been constructed by the direct application of soil dependent GMPEs (Fig. 20). The map [first presented in Rebez *et al.* (2001) and improved in Slejko *et al.* (2008)] clearly points to the importance of the pertinent soil type. In fact, the hazard is notably higher in the plain and along the Alpine valleys than in the mountain sectors. The largest PGA is expected along some Alpine valleys of Friuli and a PGA between 0.475 and 0.525 g is reached along the northern Tagliamento River valley and a few other valleys close by. A large part of the region, along the piedmont strip, shows PGAs between

Table 8 - Morphological AFs derived from Probit analysis on the data of the 1976 Friuli earthquake compared with topographic AFs suggested by EC8 (CEN, 2002).

Morphotypes	f_{MT}	EC8
Plain	1.0	1.0
Slope	1.0	1.0
Alluvial fan	1.6	≥1.2
Fluvial plain (shallow)	1.8	≥1.2
Wall	3.5	≥1.4
Edge of scarp*	(3.5)	≥1.4
Terrace on slope*	(3.5)	≥1.4
Fluvial plain (deep)	3.9	≥1.2
Crest	4.0	≥1.4
Alluvial terrace	4.0	≥1.4
(*) Morphotypes not investigated because not present in the areas of study. The value was arbitrarily assigned equal to the wall value		

0.325 and 0.475. The town of Pordenone is characterized by an expected ground motion around 0.25 g, it is about 0.30 g for the town of Udine and around 0.15 g are forecasted for the town of Trieste. A similar PGA, around 0.3 g, is expected in 3 of the test sites (Forni di Sopra, San Leonardo, and Polcenigo), it is slightly higher than that forecasted for the San Vito al Tagliamento test site (around 0.20 g) but notably lower than that calculated for Invillino (around 0.4 g) and Treppo Grande (around 0.45 g).

A more reliable situation, adherent to the specific characteristics of the Friuli Venezia Giulia region has been obtained by applying the local soil AFs (Table 6) expressly defined in the present study (Fig. 21).

The processing procedure of this map is similar to the previous one but considers the intersection between the soil map (Fig. 6) and the rock PGA one, where the PGA is discretized according to the scale considered (Fig. 5a). The predicted acceleration values in this case are rather different than those obtained by applying different GMPEs, and several sectors of limited size are emphasized. An emblematic example is given by central Friuli (around the Treppo Grande test site), where values larger than 0.57 g are now estimated (they are lower than 0.50 g considering GMPEs), while the close N-S valley of the Tagliamento River shows lower ground motions now. Also the Karst, area located to the north of Trieste, is characterized by a lower PGA when considering the local AFs than those obtained by GMPEs.

A more severe situation is pictured in Fig. 22 where the expected ground motions are computed by adopting the regional morphological AFs (Table 8). The computation of hazard using these AFs leads to definitely higher expected accelerations. The maximum predicted PGAs (between 0.80 and 0.90 g) involve the whole northern-central part of the Friuli Venezia Giulia region where PGA values above 1.0 g are expected locally.

The aggregate seismic hazard map using both lithological (Fig. 21) and morphological (Fig. 22) AFs computed in this study is shown in Fig. 23. High ground motions (PGA between 0.65

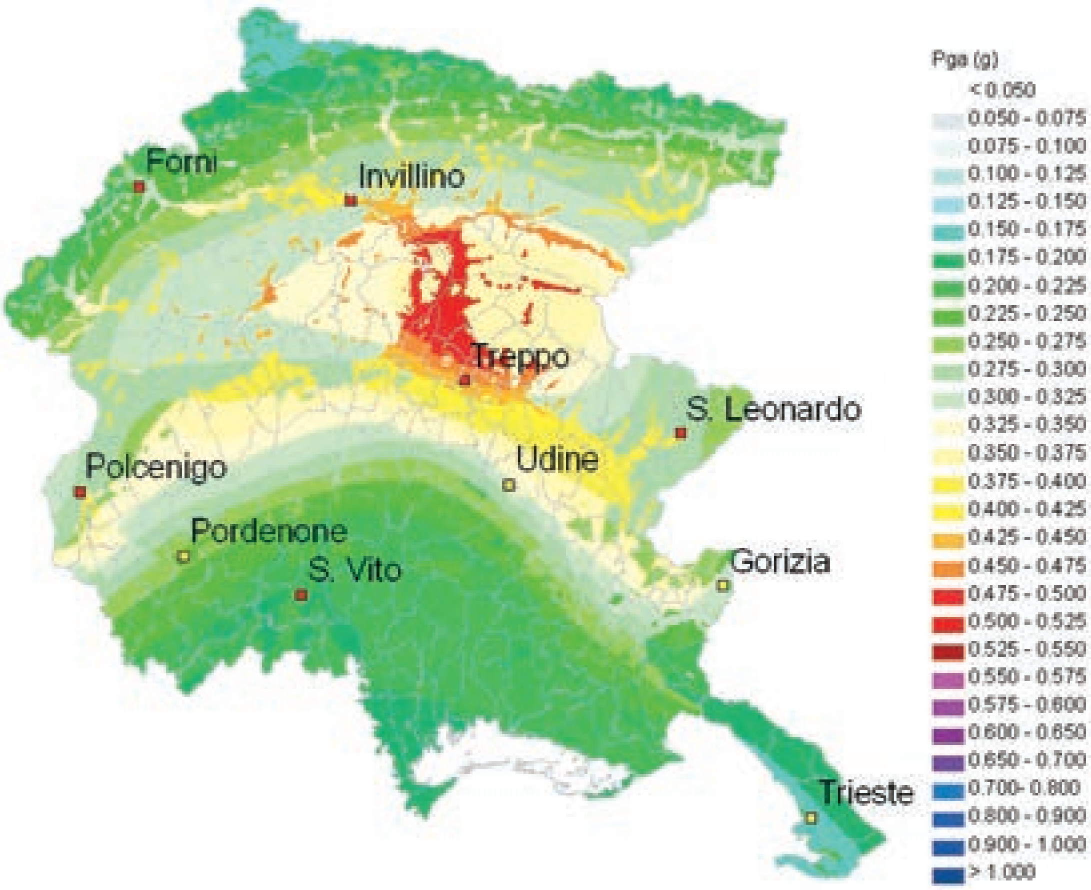


Fig. 20 - Soil seismic hazard map of the Friuli Venezia Giulia region representing the PGA with a 475-year return period computed by considering different soil-dependent GMPEs (see maps in Figs 4a to 4c).

and 0.70 g) appear in the mountain sector of this map given the strong influence of the morphological AFs (the rock is dominant and, consequently, the lithological contribution is very limited). In the plain area, conversely, the role of the lithological AFs is notable and the aggregate map (Fig. 23) is not much different than the map of lithological AFs only (Fig. 21). It must be noticed that for wide parts of the mountain sector Fig. 22 shows larger values than Fig. 23 due to the application of the lithological AF, which is smaller than 1 for hard rock (Table 6).

7. Comparison with maps obtained through building codes

It is quite interesting to see how the lithological AFs and the morphological ones agree with those defined in some building codes and the differences that they produce in the soil hazard estimates. Three building codes have been considered in the present study: the Italian building guidelines (Ministro delle Infrastrutture, 2008), the NEHRP provisions (BSSC, 2004) developed for the U.S., and the European seismic code EC8 (CEN, 2002). It must be pointed out that the

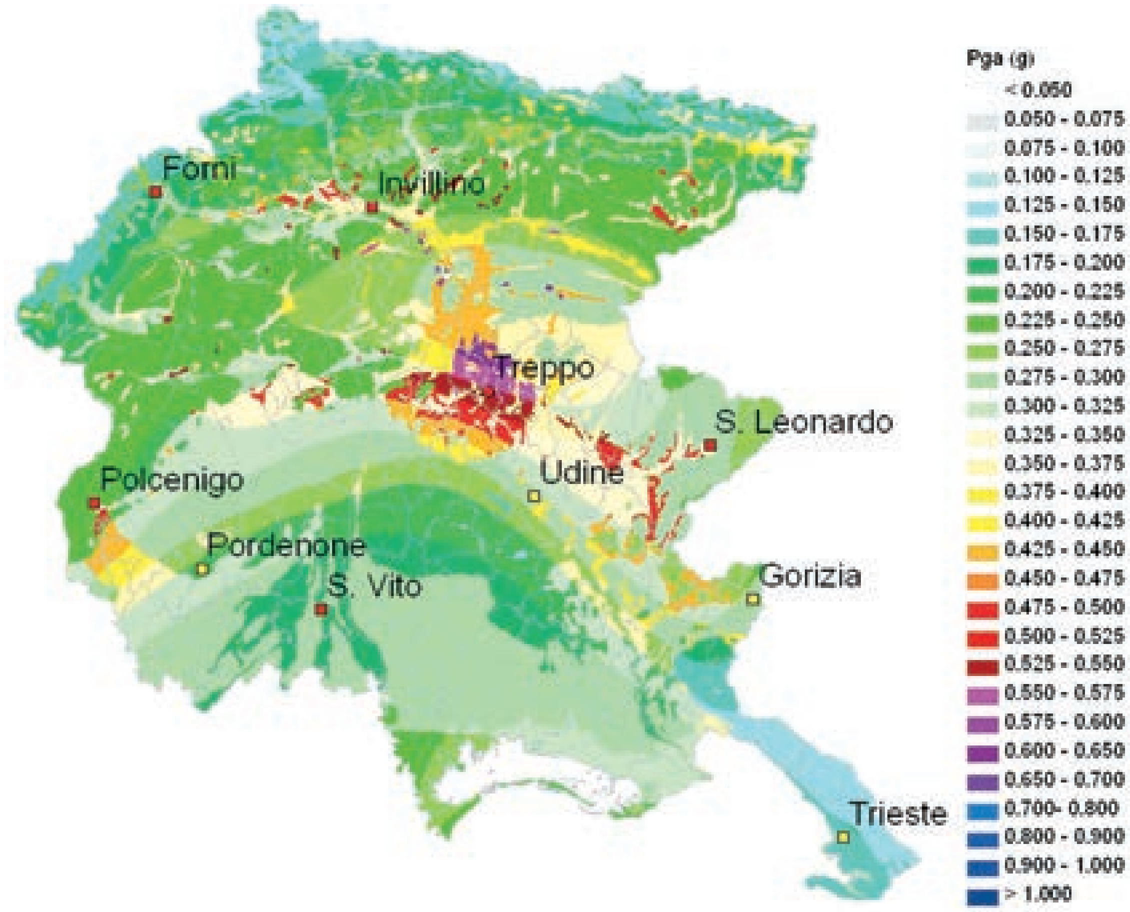


Fig. 21 - Soil seismic hazard map of the Friuli Venezia Giulia region representing the PGA with a 475-year return period computed by considering regional lithological AFs (see Table 6).

Italian code (Ministro delle Infrastrutture, 2008) is based on the European code EC8 and, consequently, the differences in both lithological (Table 6) and morphological (Table 8) AFs are very small. The procedure applied to construct the soil seismic hazard maps follows the one described before, i.e.: the proper AFs of the building codes have been applied to the rock PGA values of Fig. 5a according to the soil types defined in Fig. 6 or the map of the morphotypes summarized in Fig. 15.

The description of the soil classes according to the three building codes, together with the related AFs, are reported in Table 6. In addition to the different names given to similar soils, the difference between the U. S. and European classifications refers to the rock that is not differentiated in the Italian (Ministro delle Infrastrutture, 2008) and EC8 (CEN, 2002) codes while a subdivision into hard rock and rock is considered by the NEHRP (BSSC, 2004) provisions. In the case of the Italian and European codes, both classes A and B of the NEHRP (BSSC, 2004) classification have been assimilated to rock, class C to stiff soil, and classes D and E to soft soil (see Table 6). The results obtained by applying the Italian, NEHRP, and EC8

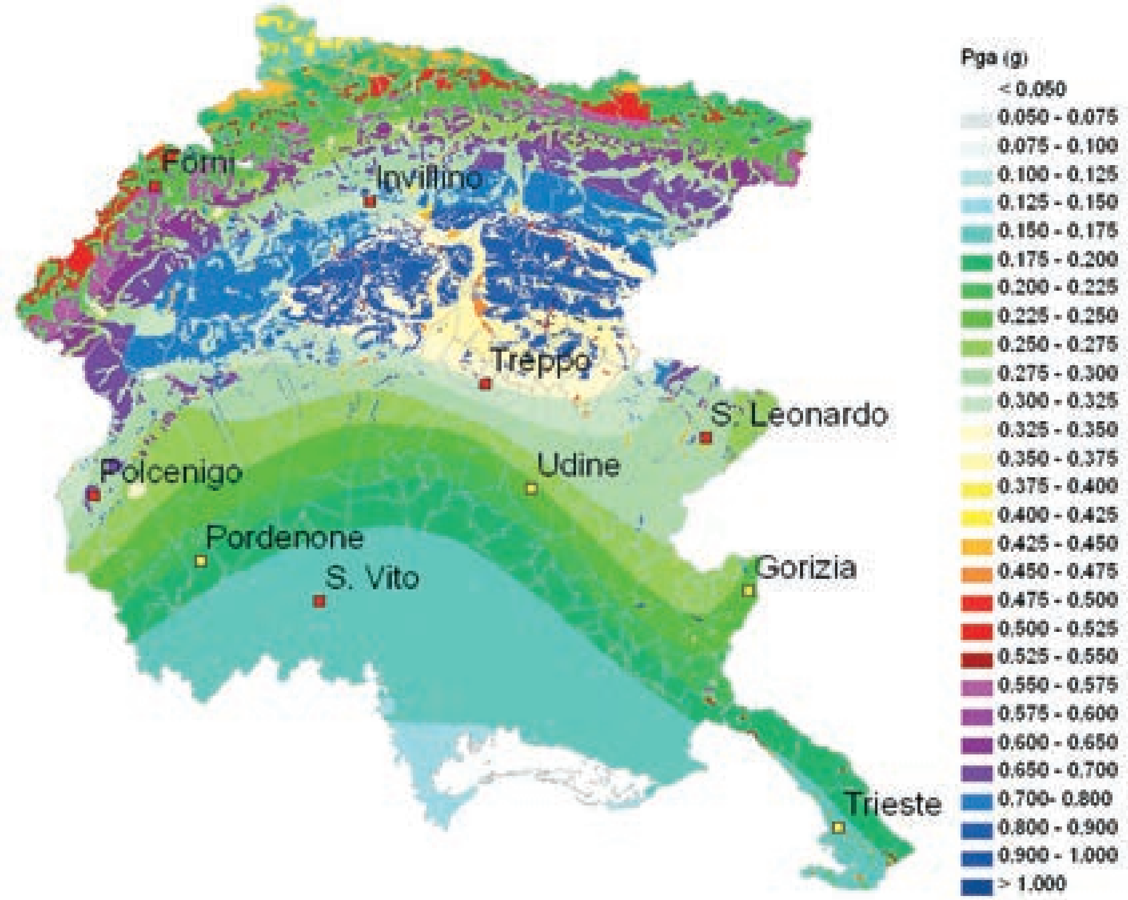


Fig. 22 - Soil seismic hazard map of the Friuli Venezia Giulia region representing the PGA with a 475-year return period computed by considering regional morphological AFs.

lithological AFs (Table 6) are reported in Fig. 24. The three maps are quite similar (especially the Italian and the European ones). The NEHRP map (Fig. 24c) shows lower ground motions than the other two maps in central Friuli, where the highest PGAs are reached, but higher values along the sea coast and in the northernmost Southalpine sector, where the lowest values are encountered. All these maps, moreover, show, on average, lower values than those obtained by GMPEs (Fig. 20).

The comparison between the maps of Fig. 24 and the one constructed by considering lithological AFs, estimated ad hoc for the study region (Fig. 21) points out some remarkable differences that are due, and justified, by the differences in the values of the AFs themselves (Table 6). Referring to the Italian and EC8 soil classes, the local AFs are almost equal to the NEHRP, Italian, and EC8 ones for rock and stiff soil; they are much higher for soft soil (1.7 while codes vary from 1.15 to 1.5) and in the middle between the NEHRP, and EC8 and Italian ones for very soft soil. The related maps reproduce these differences. In fact, the morain amphitheatre in central Friuli, which is characterized by a soft soil (see Fig. 6), displays a much higher expected

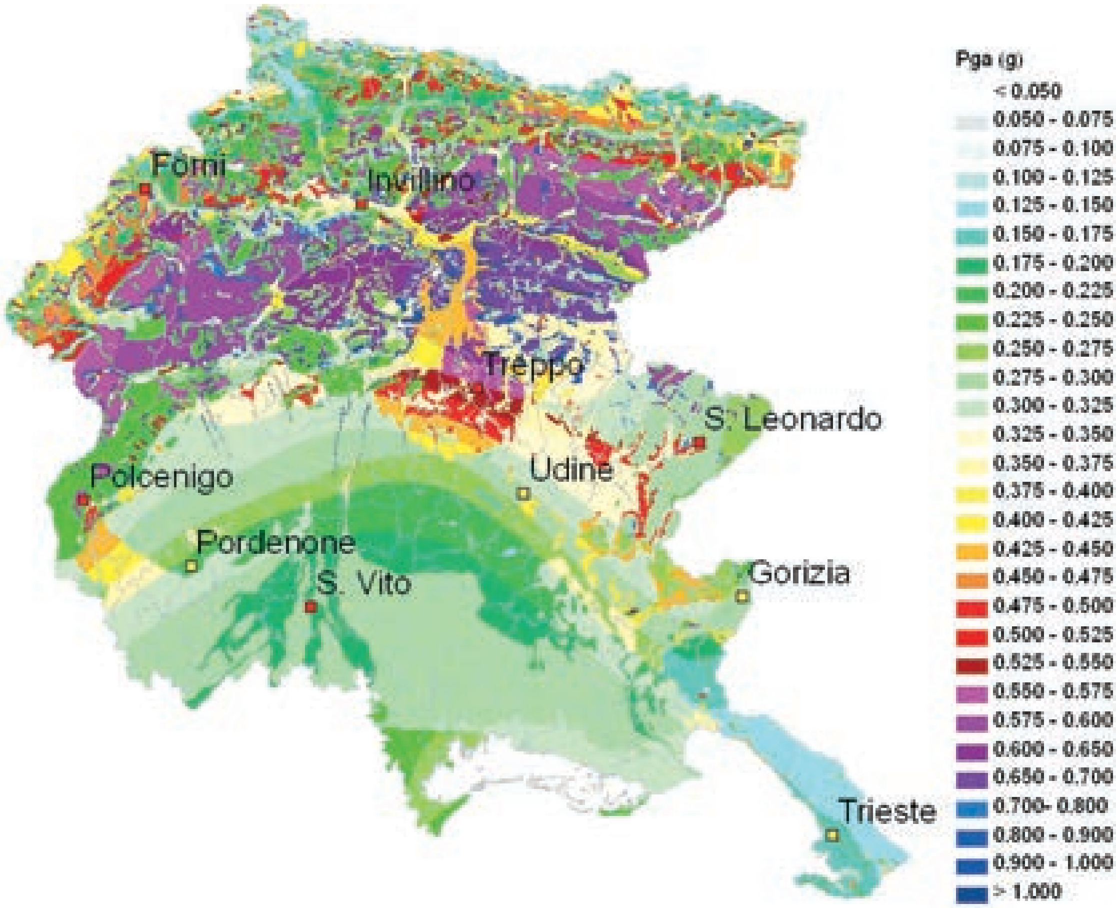


Fig. 23 - Soil seismic hazard map of the Friuli Venezia Giulia region representing the PGA with a 475-year return period computed by considering regional lithological and morphological AFs.

shaking in the map obtained by local AFs (Fig. 21) than in all the other ones (Fig. 24) and slightly lower values all around it. For the same reason, the same feature can be seen also along some Alpine valleys and the edges of the Friuli piedmont belt as well as in the Friuli Plain. In conclusion, it is the higher value of the local AF for soil that determines the main difference of the new regional map and those following the code provisions. Fig. 25 summarizes all the results obtained for the 6 test sites, together with those referring to the main towns (Trieste, Udine, Gorizia, and Pordenone) in the study region. Most of the settlements here considered (Gorizia, Pordenone, Udine, Invillino, and San Leonardo) are located on stiff soil (according to the EC8 classification) and for them the ground motion, calculated on the basis of the AFs of the Italian code, is slightly larger. For Trieste, where most of the town is located on rock (flysch), all estimates give the same result. The local AFs drive to the highest results for the settlements located on soft soil: Forni di Sopra, Treppo Grande, Polcenigo, and San Vito al Tagliamento.

The NEHRP provisions do not define morphological AFs while the Italian seismic code accepts those defined by the EC8. Consequently, only this map is presented (Fig. 26) and

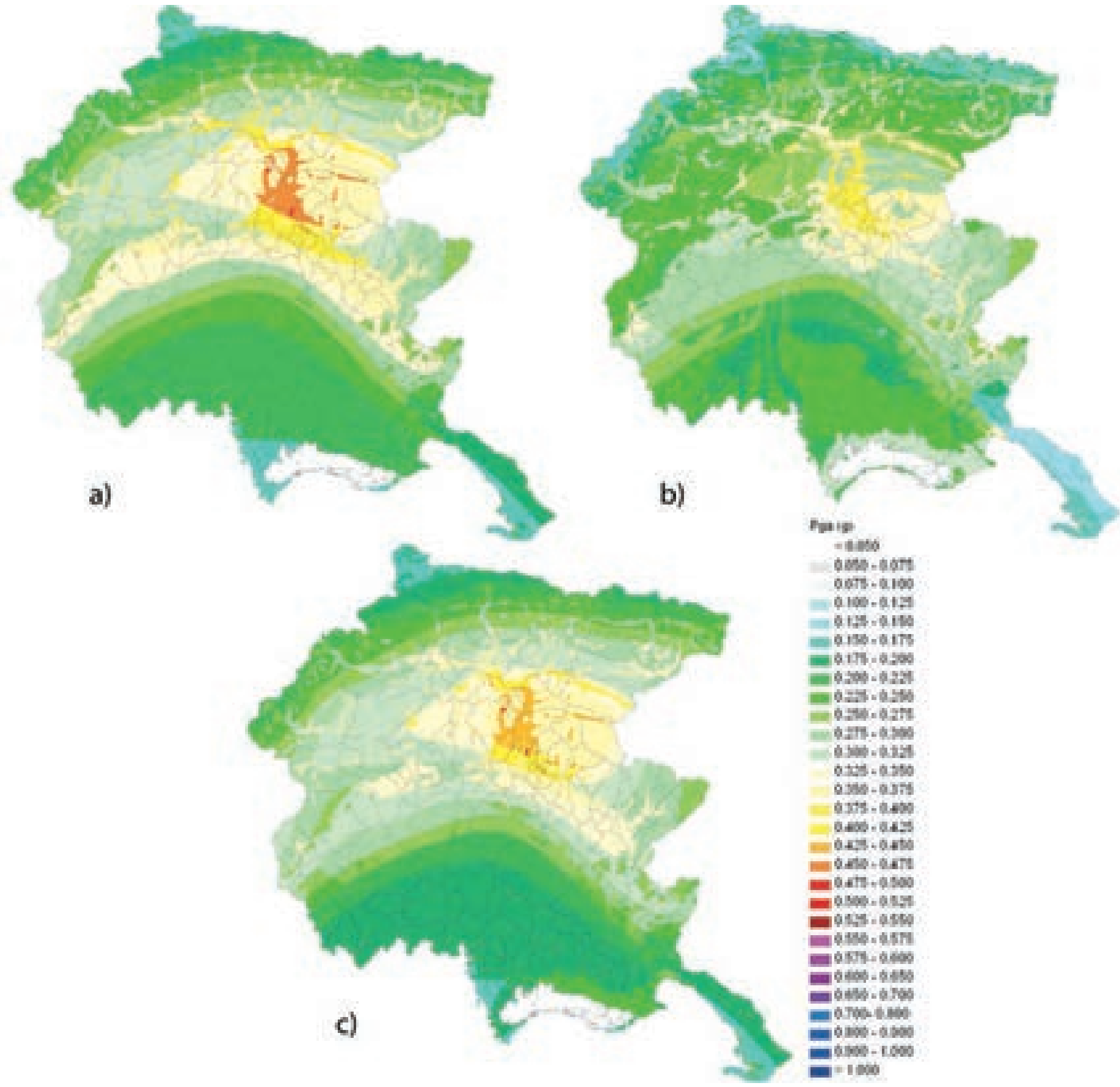


Fig. 24 - Soil seismic hazard map of the Friuli Venezia Giulia region representing the PGA with a 475-year return period computed by considering building code lithological AFs (see Table 6): a) Italian (Ministro delle Infrastrutture, 2008); b) NEHRP (BSSC, 2004); c) EC8 (CEN, 2002).

considered as comparison to the map constructed by considering the local morphological AFs (Fig. 22). It is worth noting that the EC8 AFs are defined as minimum values: also for this reason they are remarkably lower than those calculated on the basis of local data (Table 8). It derives that in the whole mountain region the expected PGAs computed according to the local AFs are notably higher than those obtained by the application of the EC8 code. As a final remark on the maps which account for morphological AFs, we can say that a direct comparison between the two maps cannot be made because the one considering the EC8 AFs defines minimum values. The

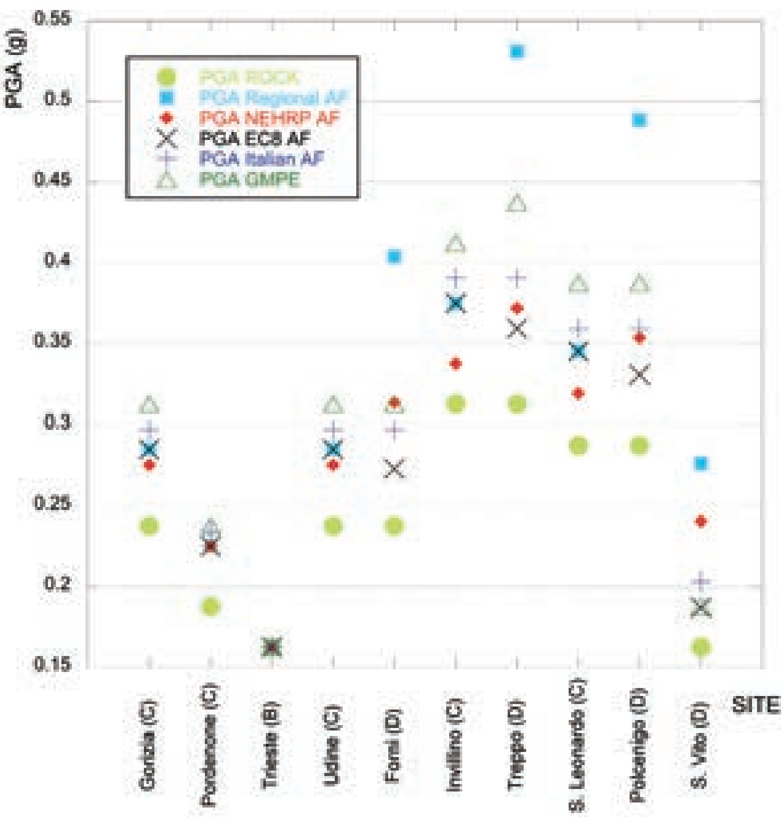


Fig. 25 - PGA with a 475-year return period for rock and specific soil (lithological AF only) for the 6 test sites and the main towns in the Friuli Venezia Giulia region. The letter in brackets after the site name indicates the soil type.

areas with the largest difference are located in the mountain sector of central Friuli, where also the most severe PGAs are expected. From a practical point, this fact is not crucial because those are areas with a very low or null urbanization.

8. Discussion and conclusions

The aim of this work was to give the regional government the possibility of adapting the national seismic zonation to the peculiarity of the geological and morphological structure of the territory in order to avoid underestimation of the hazard or (still worse from some aspects) overestimates leading to countermeasures requesting resources that are unavailable or that could be better spent in other fields.

Because of the morphology of the region and the effects of the reconstruction after the 1976 Friuli earthquake, the areas of highest “residual” risk are mainly mountainous or hilly. For this reason, we devoted a great deal of work to the study of local amplification effects due to the geometry and stratigraphy of the terrains overlying the seismic bedrock.

Strong evidence in the results shows that the expected ground accelerations (and other ground motion parameters) are in most cases higher than those, already high, deriving from the national

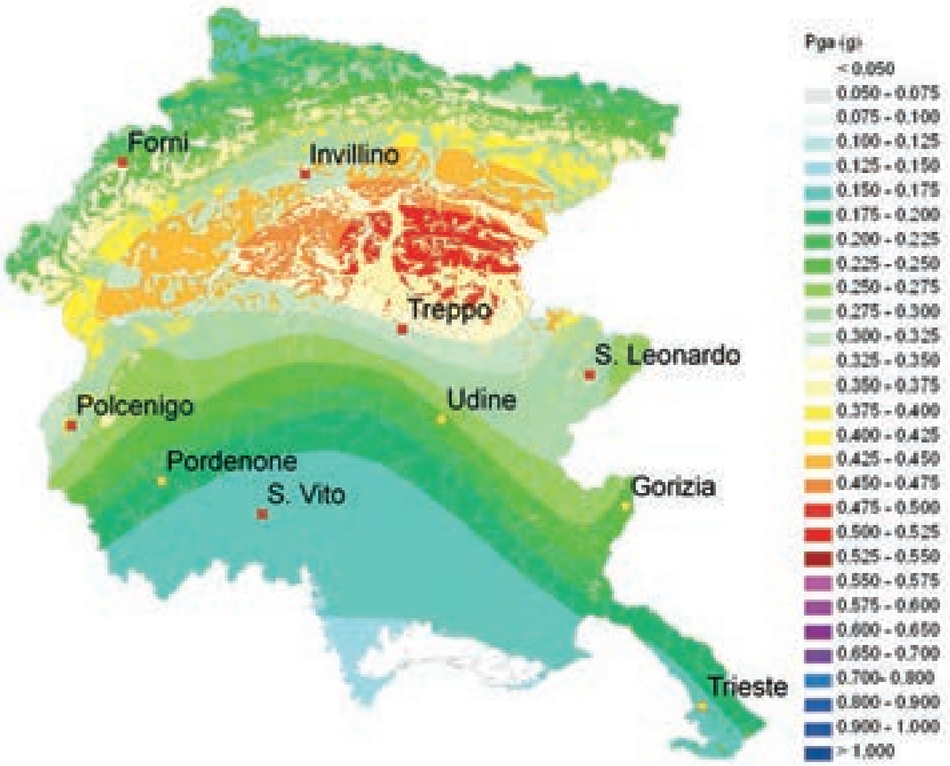


Fig. 26 - Soil seismic hazard map of the Friuli Venezia Giulia region representing the PGA with a 475-year return period computed by considering the EC8 (CEN, 2002) building code morphological AFs (see Table 8).

code suggesting a possible implementation in a future regional building code of specific local features, not taken into account so far.

We believe that many aspects of the hazard assessment deserve further investigation. For instance, the relation between fault length and magnitude looks lousy and not well founded on the physics of the phenomenon where the deformable volumes delimited by the faults, also if they are difficult to calculate, may be more consistent with the now prevailing elastic rebound theory of earthquake generation. Another question regards the statistical evaluation of the maximum magnitude when the calculation of even one fraction of the standard deviation leads to values that considerably exceed the maximum historical record that, in our country is about 2,000 years old and therefore must be considered as a significant sample of the population.

Acknowledgements. This research was performed in the frame of the activities of the project "Seismic zonation of the Friuli Venezia Giulia region" financed by the Civil Protection of the Friuli Venezia Giulia Region. Many thanks are due to Dario Albarello, University of Siena, and Carlo Meletti, INGV Pisa, for reviewing the manuscript and suggesting important improvements.

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