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Advancements from *a posteriori* studies on the damage to buildings caused by the 1976 Friuli earthquake (north-eastern Italy)

S. Grimaz and P. Malisan

SPRINT-Lab, Politecnico di Ingegneria e Architettura, Università di Udine, Italy

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ABSTRACT After the 6 May, 1976 earthquake in Friuli Venezia Giulia (north-eastern Italy), about 85,000 buildings in the affected area were investigated through damage-assessment forms. Researchers of University of Udine collected and re-organized these data, and created the FrED (Friuli Earthquake Damage) database. As a result, more than 45,000 buildings with complete information were geo-localized. This enabled carrying out *a posteriori* studies to characterize both the vulnerability of different typologies of buildings and the effects of the geomorphology on the site seismic response. This paper, after a brief overview on the 1976 earthquakes in Friuli and on the FrED database, summarises the main results of these studies. In particular, the paper compares the results of a statistical analysis of the FrED information at regional scale, with the results obtained, at local scale, through geophysical investigations. The geophysical outcomes highlight that in some scenarios the local seismic response is influenced by local conditions that cannot be recognized from the analysis of FrED at regional scale. Nevertheless, the results of the study provide a preliminary informative warning on the potential amplification factors of the geomorphological regions. These results can be used for in-depth studies for quantifying the amplification factors at local scale.

Key words: earthquake, Friuli 1976, damage, vulnerability, site effects, Probit.

1. The 1976 Friuli earthquakes

The 1976 earthquakes in Friuli (north-eastern Italy) caused severe damage to a large portion of the territory: the devastated area covered about 1,800 km^2 and over one hundred villages were almost destroyed, mainly in the province of Udine, causing 989 deaths (Carulli and Slejko, 2005). The Friuli 1976 seismic sequence started on 6 May, with a M_L = 6.4 earthquake, and continued again on 11 and 15 September, when four main-shocks with magnitude M_L = 5.5, 5.8, 6.1 and 6.0 occurred in rapid succession (Luzi *et al.*, 2017; Slejko, 2018).

Right after the May 1976 earthquakes, a regional law (RL 17/76 - Friuli Venezia Giulia Region) was issued for the inspection of the buildings in the affected area. About 85,000 inspections were carried out on buildings in Friuli, in order to define the number of dwellings not usable after the earthquake and to estimate the cost of retrofitting. Additionally, the regional law recommended some intervention techniques for the retrofitting of damaged buildings.

The September sequence of earthquakes had a demoralizing effect on Friuli inhabitants (Carbonetto, 2018); at the same time, these shocks revealed the inadequacy of the recovery interventions made after the first shock together with the deficiencies in preparedness from both technical and management perspectives. However, acknowledging these critical issues forced administrators, scientists, and technicians to deepen their knowledge and redefine the strategies to cope with the emergency. The supervision of the reconstruction then produced very good results, concerning both the interventions on buildings and the overall management of the situation. On a positive note, the disaster prompted the input of considerable investements, as well as the modernisation and the re-launching of the industrial sector, resulting in increased job opportunities (Geipel, 1980). As result, the entire Friuli region experienced new dynamic trends and accelerated the economic development of the area (Cattarinussi *et al.*, 1981). Thus, the Friuli reconstruction became a successful example in the international panorama and a source of pride for the Friulian people. In 1978, the University of Udine was set up as part of the reconstruction policies. Since then, the 1976 Friuli earthquake has become a central research focus of many researchers of that University; among them, *a posteriori* studies were carried out on the post-earthquake assessment forms of RL 17/76.

2. The post-earthquake assessment reports

On 7 June, 1976 the legislative council of the Friuli Venezia Giulia Region enacted law No. 17, aimed at both identifying usable buildings and restoring damaged ones. Overall, 416 teams of engineers and architects were assigned the task of compiling a specific form (on paper) for each investigated building in the entire shaken area. The compilation of damage forms represented an innovative approach for the management of the earthquake emergency, with no precedent cases in Italian history. This survey lasted three years and 84,780 forms were collected. Each form includes five different sheets that cover all the necessary information needed to pursue the aims of the law:

- **Sheet 1**: this sheet, structured in four sections, contains the general characteristics of the building. Information about the location, address, number of floors, number of sides in common with other buildings, presence of a basement and/or a loft, cellar, number of lodgings, age, presence of outhouses or productive activities are provided. The damage is briefly described as follows: destroyed (D), not repairable (NR), partially repairable (PR), totally repairable (TR) (with the distinction between "with structural work" and "without structural work"). The sheet also reports the estimated restoration cost for each flat, multiple dwelling, outhouse or productive activity with, possibly, notes regarding the restoration;
- **Sheet 2**: this sheet enables acquiring information about the building depending on its typology; it is divided into 4 sections. The first section refers to lived-in houses and includes the number of rooms used, if the house is for rent or not, etc. The second section relates to rural buildings eventually annexed to the house and their volume. The third section provides the same information as the second section but concerning commercial activities. In the fourth, some information with respect to the owner is provided;

- **Sheet 3**: this sheet provides an estimate of the building's volume and the repair costs; there are three distinct sections. In the first section, the volume is associated to each typology of use (civil or rural dwelling, outhouses, and productive activities). In the second section, a summary evaluation of the building before the earthquake based on unitary values according to the typology and the state of preservation is given. The third and fourth sections allow calculating the total amount of restoration costs based on the unitary values of sheet 4 defined by the regional authority;
- **Sheet 4**: this sheet is divided into two parts: 4-A and 4-B. The first is used mainly for civil or rural dwellings, while the second for outhouses and productive activities. It contains an outline used to determine the unitary amount of restoration work; the calculation is organized by structural elements and by typology, first quantifying the percentage of its composition compared to the total building and then evaluating what amount of these elements needs total or partial restoration. The unitary cost for each element was determined a priori;
- **Sheet 5**: this sheet is simply a blank sheet for technicians to make notes and proposals about technical methods for restoration.

The collected data were used as a fundamental decision-making support to define strategies, both for inhabitant assistance and for reconstruction.

This huge amount of data has also been used as a "knowledge tank" for a posteriori studies.

3. The *a posteriori* studies based on the data of the damage assessment forms

At the end of the 1980s, the seismic group of research of the University of Udine began evaluating the lessons learnt from the Friuli earthquake experience from an *a posteriori* analysis of the data of the damage assessment forms. To this end, the researchers acquired and re-organized the data collected by technical investigations, which allowed developing statistical studies on the vulnerability of buildings and on the site effects. The main results of these studies are summarized hereafter.

3.1. Collection and organization of 1976 Friuli earthquake damage assessment forms

At the end of the 1990s, after collecting all the forms, a preliminary organization of the data was carried out to make the data ready to use. In particular, all the information of the forms of some villages in the epicentral area were loaded in an electronic database called FrED (Friuli Earthquake Damage). Thereafter, thanks to the new information and communication technologies, the original database was enlarged, adding all the data of the investigated buildings and, where possible, associating the geographic coordinates for each building. All the information was reorganized in a new version of the FrED database (Di Cecca and Grimaz, 2008). These last operations exploited the information for deeper studies and spatial analyses to a previously unthinkable degree of detail. The analysis of the entire database (84,780 compiled forms) allowed tracing the distribution of the compiled forms over time (from June 1976 to September 1979), distinguishing the assessed damage suffered by buildings (Fig. 1). However, the complete set of information on location, macroseismic intensity, construction typology and level of damage, were available only for about 45,000 buildings in the area affected by the 1976 Friuli earthquakes (Fig. 2).

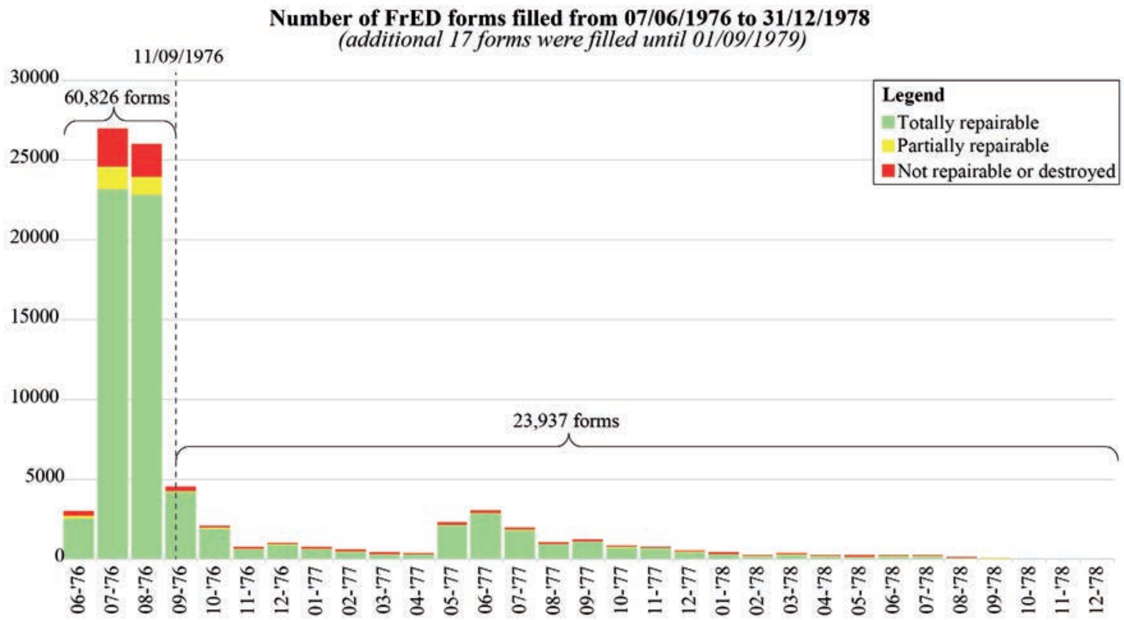


Fig. 1 - Distribution of the FrED forms filled from 7 June 1976 to 31 Decembre 1978. The colours indicate the assessed suffered damage.

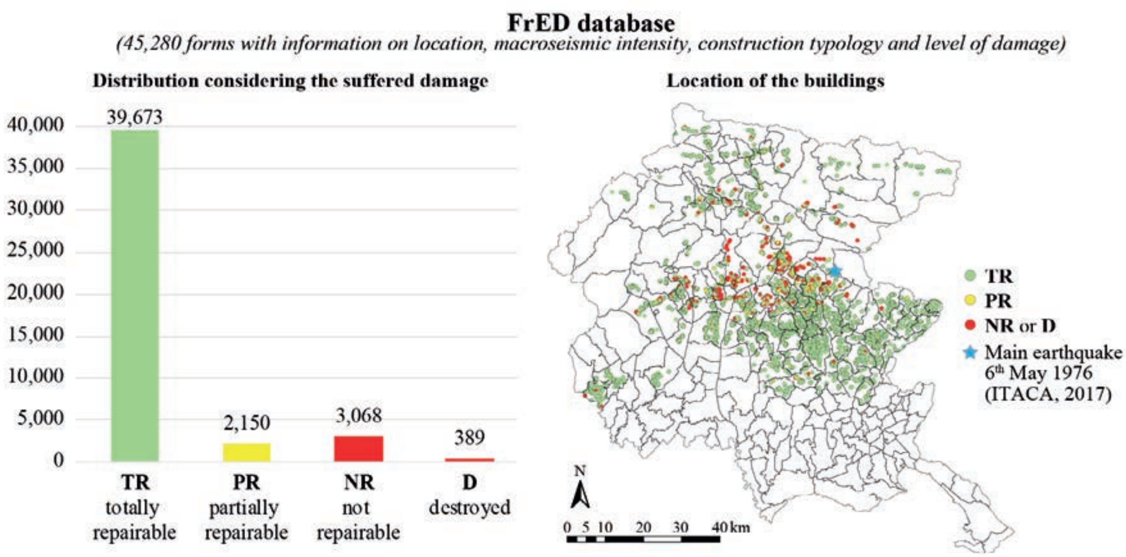


Fig. 2 - Distribution of the damage grades (left) and location of the buildings (right) of the 45,280 forms with information on location, macroseismic intensity, construction typology and level of damage in the FrED database.

3.2. A posteriori *studies on seismic damage and vulnerability*

A first use of the data collected in the forms of RL 17/76 aimed at improving knowledge on seismic vulnerability of masonry buildings. Studies on seismic vulnerability of buildings, mainly in historical centres, were carried out (Grimaz, 1992, 1993). Other studies were aimed at defining a Synthetic Damage Judgement scale (GSD damage index) in order to assign a damage grade from visual inspection or photographic information. Grimaz *et al.* (1996) developed an expert system for damage assessment of buildings in the seismic area based on functional criteria (using the GSD scale). The GSD scale allows researchers to relate the physical damage to indirect consequences: reparability, usability, and possibility of causing victims. This scale was related to the damage levels assigned during the inspections after the 6 May, 1976 Friuli earthquake and proved coherent with the successive classification of seismic damage grades of the EMS98 scale (Grünthal, 1998; Grimaz, 2009a).

Other studies (Riuscetti *et al.*, 1997) were specifically aimed at improving the fragility curves based on the GNDT (National Group for the Defence against Earthquakes) vulnerability index (Benedetti and Petrini, 1984). The index, used extensively in Italy, is based on vulnerability-assessment forms including parameters that take into account the type and configuration of the structural system and the quality of the construction and materials. A weighted sum of these parameters gives a vulnerability index, with values between 0 and 100 for masonry, and -25 and 100 for reinforced concrete (higher values imply high vulnerability). The GNDT index was correlated with the seismic damage derived from the FrED database for three villages in Friuli in the most affected area: San Daniele, Tarcento, and Venzone (province of Udine). A calibration of the fragility curves for different vulnerability indexes was thus derived (Grimaz *et al.*, 1996). These fragility curves were also used among others in European projects to elaborate seismic risk maps (Zonno *et al.*, 2003) and prioritize actions of risk mitigation (Grant *et al.*, 2007).

When the FrED database was completed, the information was used for investigating, through an *a posteriori* method, the seismic vulnerability at regional scale (Carniel *et al.*, 2001). The studies permitted deriving the typological parameters able to define different degrees of vulnerability. Firstly, the researchers compared the earthquake intensity, as computed on the basis of the judgements given in the forms, with the published isoseismal maps (Giorgetti, 1976). Then, they characterized twelve building typologies from the data available in the FrED and ISTAT (Italian Central Statistics Institute) census databases. Statistical analysis allows evaluating the differences in their seismic behaviour. From these comparisons, six statistically significantly different classes were selected. Table 1 resumes the results, evidencing the correspondence between the six vulnerability classes and the different typologies derivable from the ISTAT and the FrED databases.

Thereafter, Grimaz (2009a), adopting a Probit analysis based on the FrED information, derived the seismic damage curves for different typologies of residential masonry buildings (Eq. 1, Table 2):

$$\mathrm{Y}_{\mathrm{Pr}\geq\mathrm{Gn}} = \mathrm{a} + \mathrm{b}\ \mathrm{Log}\left(V\right) = \mathrm{a} + \mathrm{b}\ MSD \tag{1}$$

$$\mathrm{P}_{\%}\left(\mathrm{Y}_{\mathrm{Pr}\geq\mathrm{Gn}}\right) = 50\left[1 + \frac{\mathrm{Y}_{\mathrm{Pr}\geq\mathrm{Gn}}-5}{\left|\mathrm{Y}_{\mathrm{Pr}\geq\mathrm{Gn}}-5\right|}\, erf\left(\frac{\left|\mathrm{Y}_{\mathrm{Pr}\geq\mathrm{Gn}}-5\right|}{\sqrt{2}}\right)\right] \tag{2}$$

$$MSD = 2.10 + 4.35 \log \mathrm{a}_{max} \tag{3}$$

where a_{max} is in g×100 and the validity is $2.5 \leq MSD \leq 8.5$ (Slejko *et al.*, 2008) and

$$MSD = 10.09 + 2.86 \log \mathrm{v}_{max} \tag{4}$$

where v_{max} is in m/s and the validity is $4.5 \leq MSD \leq 9.0$ (Faccioli and Cauzzi, 2006).

Table 1 - Vulnerability typologies with statistically different outcomes derived from the FrED database.

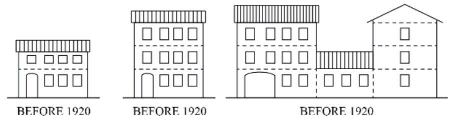
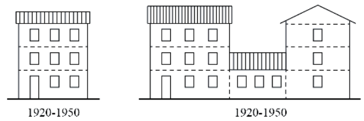
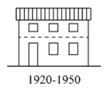
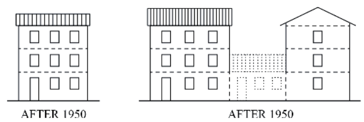
Building characteristics						**Vulnerability typology**	
Material		**Construction period**	**Structural context**	**Floors**			
Masonry	Stone	< 1920	Detached building or non detached building	<5	T1	
Masonry	Stone	1920-1950	Detached building or non detached building	3-5 <5	T2	
Masonry	Stone	1920-1950	Detached building	1-2	T3	
Masonry	Stone/bricks	>1950	Detached building or non detached building	3-5	T4	
Masonry	Stone/bricks	>1950	Non detached building	1-2	T5	
Masonry	Stone/bricks	>1950	Detached building	1-2	T6	

Table 2 - Coefficients of Probit equations derived for the six vulnerability typologies and for each threshold level of damage (modified from Grimaz, 2009a).

		Damage range			
		FrED: TR-D **EMS-98: ≥G3** I_{GSD}**≥30**	**FrED: PR-D** **EMS-98: ≥G4** I_{GSD}**≥50**	**FrED: NR-D** **EMS-98: ≥G5** I_{GSD}**≥70**	**FrED: D** **EMS-98: G5*** I_{GSD}**≥90**
Vulnerability typology	**T1**	a=2.82; b=0.40	a=-1.68; b=0.71	a=-1.73; b=0.67	a=-0.65; b=0.42
	T2	a=3.09; b=0.33	a=-2.28; b=0.73	a=-2.35; b=0.69	a=-1.06; b=0.44
	T3	a=3.48; b=0.26	a=-1.79; b=0.66	a=-1.20; b=0.54	a=-0.24; b=0.34
	T4	a=2.45; b=0.33	a=-2.57; b=0.70	a=-2.02; b=0.60	a=-0.01; b=0.30
	T5	a=2.83; b=0.25	a=-0.97; b=0.47	a=-0.58; b=0.39	a=0.58; b=0.20
	T6	a=4.14; b=0.06	a=-0.45; b=0.40	a=0.11; b=0.34	a=1.17; b=0.12

Validity: 6.5 ≤ MSD ≤ 10. In grey, the equations with $R^2 < 0.7$

Correspondence among FrED damage, EMS98 damage grade and GSD Index

FrED	TR	PR	NR	D
EMS98	G3	G4	G5	(G5*)
I_{GSD}	30	50	70	90

Correspondence and relationships among metametric seismic dose (MSD=Log V) and macroseismic intensity grade (I_{MSK}), a_{max} and v_{max}

MSD	6.5	7	7.5	8	8.5	9	10
I_{MSK}	VI-VII	VII	VII-VIII	VIII	VIII-IX	IX	X

Probit is a statistical technique used widely in the field of risk assessment of major accidents and toxicology for deriving experimental relationships that are useful to predict the accident's consequences. In his work, Grimaz (2009a) proposed a combined use of these curves with the EMS98 and GSD scales of seismic damage. Eq. 1, considering the coefficients derived for the six vulnerability typologies (Table 2), allows calculating the Probit value ($Y_{Pr\geq Gn}$) for different actions (expressed in terms of metametric seismic dose - *MSD* value). The *MSD* value can be defined both using an association with the macroseismic intensity grade (I_{MSK}), and through relationships with the peak ground acceleration (or peak ground velocity) (Eqs. 3 and 4). Eq. 2 permits then to derive from the Probit value ($Y_{Pr\geq Gn}$) the percentage of building suffering the damage ≥ Gn [$P_{\%}(Y_{Pr\geq Gn})$]. In terms of direct and indirect consequences, this enables predicting the damage scenarios that a future earthquake could produce in an inhabited area with similar masonry building typologies to those found in the Friuli area.

3.3. A posteriori *studies on site effects*

After the revision of the FrED database, Grimaz (2009b) carried out an *a posteriori* quantitative evaluation of local seismic response effects using an inverse Probit analysis of data. In his work, Grimaz (2009b) used the Probit analysis to estimate the relative amplification factors for some different geomorphological scenarios classified in the Gemona and Tarcento areas (province of Udine). These scenarios were identified at local scale, taking into account the topographical and lithostratigraphic features of the areas. Furthermore, Grimaz (2009b) proposed a first estimation of the average relative amplification factors referred to flat rock (Fig. 3), yet he underlined the need for validation by considering all the data available in the FrED database and a classification of the geomorphological scenarios of the whole area affected by the 1976 Friuli earthquake. At the same time, he suggested considering the site effects in a preliminary microzonation, identifying the different geomorphological scenarios within a municipality.

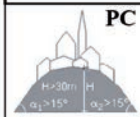
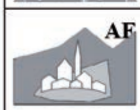
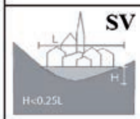
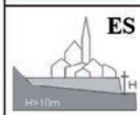
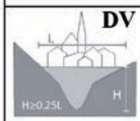
Geomorphological Local scenario (GL)	Estimated Average Relative Amplification Factors referred to RP	
	ARAF a_{max}	ARAF v_{max}
 **RP** Rock flat plain	1.00	1.00
 **SS** Steep slope	2.17	3.44
 **AP** Alluvial flat plain	1.20	1.20
 **MS** Moderate slope	1.22	1.28
 **PC** Peak or crest	2.65	4.88
 **AF** Alluvial fan	1.49	1.74
 **SV** Alluvial shallow valley	2.00	3.04
 **ES** Edge of scarp	2.82	5.44
 **DV** Alluvial deep valley	2.95	5.92

Fig. 3 - Geomorphological local scenarios (GLs) and estimated average amplification factor, for the municipalities of Gemona del Friuli and Tarcento both in the Udine province (modified from Grimaz, 2009b).

Starting from these suggestions, researchers of University of Trieste and Udine (ASSESS report, 2010; Grimaz *et al.*, 2016) proceeded with a classification of the different geomorphological scenarios at regional scale using a semi-automatic GIS procedure. As a result, different geomorphological regions (GRs) for the whole Friuli Venezia Giulia region were identified. In particular, considering homogeneous geological, geomorphological and topographical characteristics, 14 GRs were defined at regional scale. The researchers identified the GRs considering the overlay of the maps with the geological, geomorphological and topographical characteristics; for the calculation, the authors used the mean values calculated for an area of 40×40 m^2. The lithostratigraphic units were subdivided into "hard soil" and "soft soil" as a function of the S-wave velocity (>800 m/s for hard and <800 m/s for soft soil), using the NEHRP soil map defined by Carulli (2006) at 1:150,000 scale. The topographical effects were analysed distinguishing three classes of average slope: <8°, 8°-15°, and >15°. Wherever necessary, the data were "smoothed" in order to identify macro-zones with homogeneous geomorphological behaviour. The resulting map was defined at 1:150,000 scale.

Fig. 4 shows the pictures associated with the identified GRs.

It is worth noting that the GRs are defined at regional scale and differ from the geomorphological scenarios (GLs) identified by Grimaz (2009b) at local scale. The definition of the GRs allowed their adoption in regional hazard maps for the seismic risk evaluation. In particular, Slejko *et al.* (2011) proposed a new regional hazard map (called "site hazard map") for the Friuli Venezia Giulia region, considering also the amplification caused by the different class of GR and using, with a first approximation, the amplification factors proposed by Grimaz (2009b) for the most similar GLs.

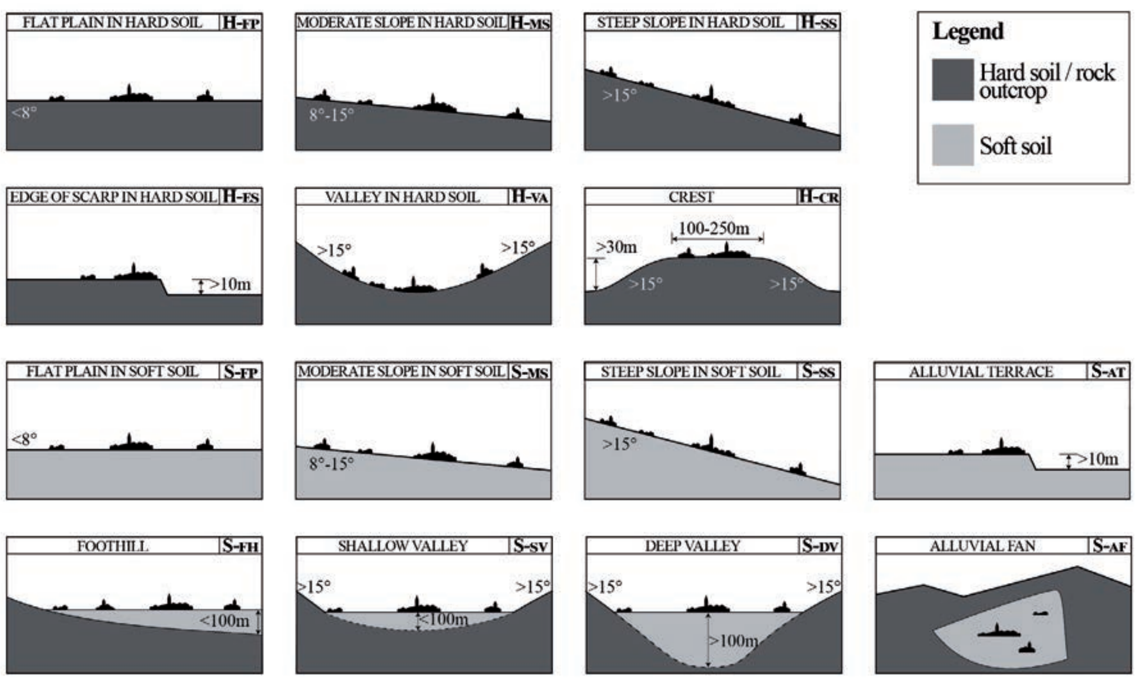


Fig. 4 - GRs identified with the semi-automatic GIS procedure.

4. Recent advancements, confirmations and warnings

After defining the GRs for the Friuli Venezia Giulia territory, the FrED database was integrated by adding to each building also the characteristics of the GR where it was located. This represents the prerequisite for an extensive validation of the site effects by *a posteriori* analysis, considering the information of the FrED database for the affected area. In particular, extensive Probit analyses on the new FrED data were carried out.

Before presenting the results, some considerations on the reliability of data are necessary. First of all, it should be noted that the FrED data were located using the address, which in some cases (i.e. when the address is not complete) produced a clusterization in a specific locations. Furthermore, the GRs are defined at a very large scale (1:150,000), and this has to be considered in the analysis of the integrated information.

In order to investigate the relationship between the GRs and the damage sustained by the buildings after the 1976 Friuli earthquakes, the researchers applied an inverse-Probit analysis on the integrated FrED data. To reduce the effect of the vulnerability of the buildings, a first filter on the FrED data was applied considering only the information for buildings belonging to a specific vulnerability typology, as described in the previous sections. In particular, the vulnerability typology T1 was analysed, as it is the most frequent in the FrED database (Fig. 5) and only the information of the forms filled before the main shocks of September 1976 was considered.

For the typology T1, inspected before September 1976, 27,478 buildings in all were analysed. Fig. 6 shows the overlapping of the GRs map, the isoseismal curves [I_{MSK}, for the 1976 earthquake (Giorgetti, 1976)], and the T1 FrED points used in the present study (classified according to their damage grade).

In order to analyse the data, the territory of each municipality was assumed as an "investigation area". The purpose of this assumption is to limit the potential variability of the seismic action due to the attenuation effects within the analysed area: indeed, the territory of the municipalities is generally small and has a range of distances from the epicentre that enables considering the variability of seismic action mainly related to local effects. The comparative analysis of the damage of buildings located in contiguous GRs within the same investigation area also permits overcoming the loop of an indirect estimate of the ground motion obtained using the relationship of PGA/PGV versus macroseismic intensity.

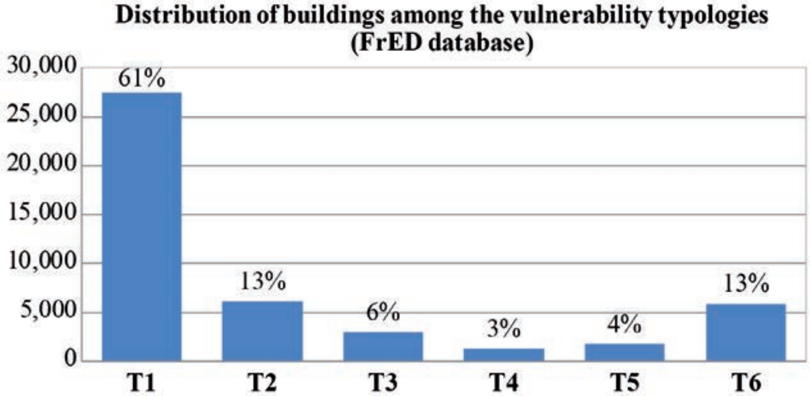


Fig. 5 - Distribution of vulnerability typologies in the FrED database.

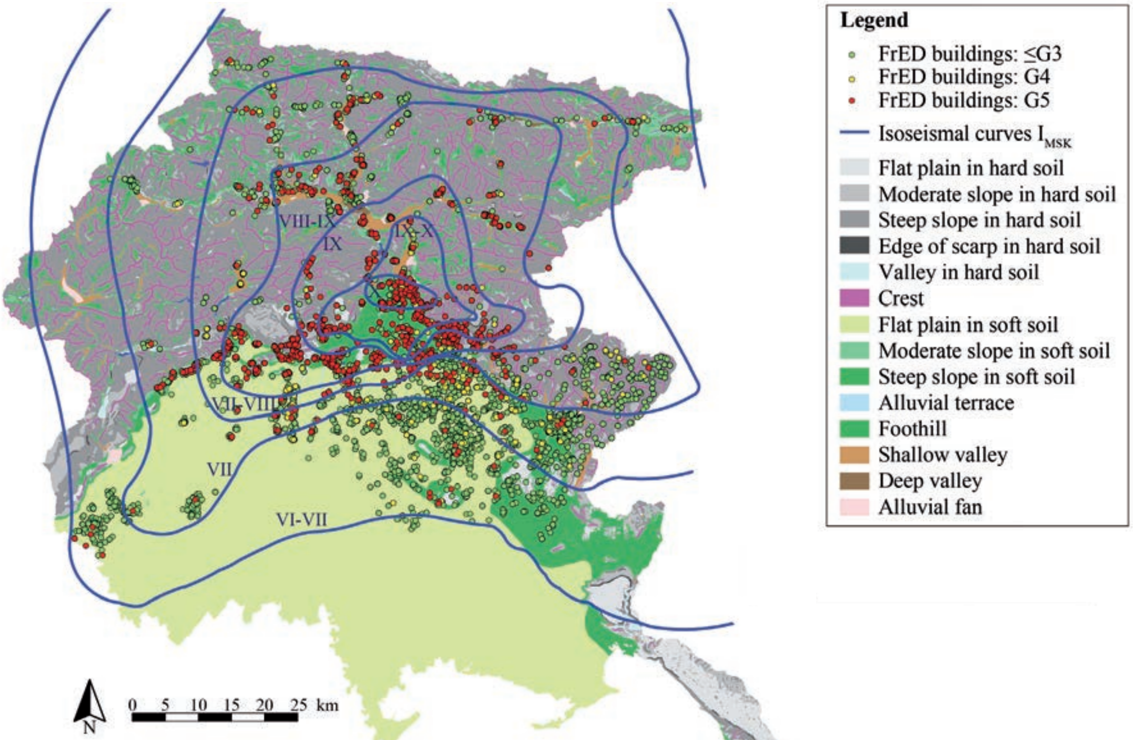


Fig. 6 - GRs, FrED buildings and isoseismal curves.

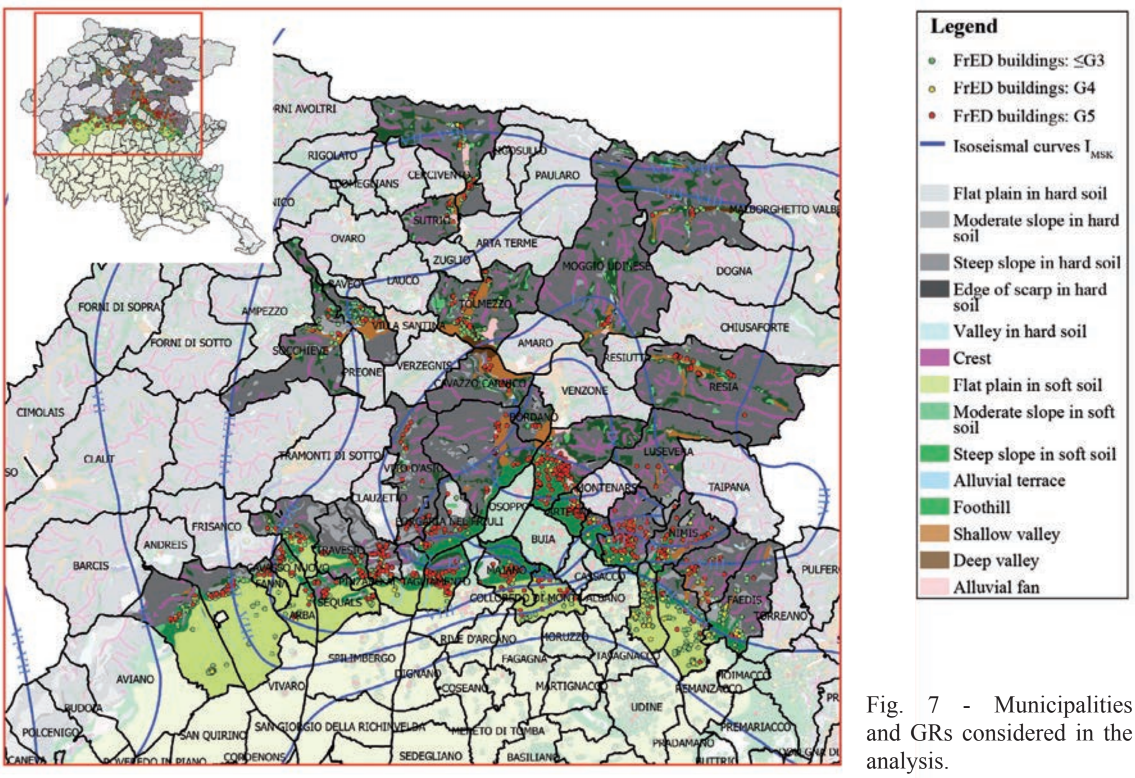


Fig. 7 - Municipalities and GRs considered in the analysis.

A municipality is included in the analysis when both the lowest I_{MSK} of the municipality is at least VII, and data show the presence of at least two GRs with useful information. A GR has useful information when there are both at least 10 buildings in the GR and more than two buildings with damage ≥G4. The application of the above criteria leads to the identification of the municipalities in Fig. 7 and Table 3. Overall, the analysis considered 35 municipalities.

The analysis of the data for each municipality has a similar approach to that presented by Grimaz (2009b). First of all, considering the data relative to the vulnerability typology T1 on the entire region, the regional inverse curves of Probit were derived, considering both acceleration (Eqs. 5 and 6), and velocity (Eqs. 7 and 8).

$$\log PGA = (0.25 \pm 0.04)\, X_{Probit|T1 \geq G4} - (0.73 \pm 0.16) \quad R^2 = 0.89 \tag{5}$$

$$\log PGA = (0.26 \pm 0.04)\, X_{Probit|T1 \geq G5} - (0.69 \pm 0.16) \quad R^2 = 0.88 \tag{6}$$

$$\log PGV = (0.44 \pm 0.07)\, X_{Probit|T1 \geq G4} - (2.48 \pm 0.29) \quad R^2 = 0.89 \tag{7}$$

$$\log PGV = (0.46 \pm 0.07)\, X_{Probit|T1 \geq G5} - (2.40 \pm 0.28) \quad R^2 = 0.88 \tag{8}$$

Table 3 - Inverse Probit data for the 35 municipalities considered in this study. The italics highlight the cases with less than 30 buildings.

Municipality	GR	Buildings	≥G4	≥G5	PGA (m/s²)			PGV (m/s)		
					⊢	•	⊣	⊢	•	⊣
Arba	***H-MS***	*20*	*7*	*6*	*2.11*	*2.86*	*4.03*	*0.23*	*0.40*	*0.69*
	S-FP	121	8	5	1.10	1.43	1.85	0.07	0.12	0.18
	S-FH	*29*	*2*	*1*	*1.10*	*1.41*	*1.79*	*0.08*	*0.11*	*0.17*
Artegna	***H-MS***	*14*	*4*	*1*	*1.40*	*2.07*	*3.01*	*0.12*	*0.23*	*0.43*
	S-FH	185	77	29	1.84	2.62	3.85	0.19	0.34	0.66
	S-AF	*16*	*8*	*3*	*1.97*	*2.90*	*4.50*	*0.21*	*0.41*	*0.87*
Attimis	**H-SS**	35	29	28	3.53	6.37	12.36	0.57	1.61	4.68
	S-SV	153	25	20	1.56	2.01	2.62	0.14	0.21	0.33
Bordano	**S-SS**	44	25	20	2.64	3.80	5.63	0.34	0.65	1.22
	S-SV	140	27	19	1.66	2.09	2.66	0.15	0.23	0.34
Castelnovo del Friuli	**H-FP**	65	46	30	2.76	4.28	6.88	0.39	0.80	1.83
	H-MS	*10*	*5*	*5*	*2.47*	*3.76*	*6.15*	*0.31*	*0.64*	*1.42*
	H-SS	74	15	11	1.69	2.15	2.77	0.16	0.24	0.36
	H-VA	63	24	15	2.13	2.77	3.61	0.24	0.37	0.59
	H-CR	*10*	*4*	*2*	*2.00*	*2.71*	*3.74*	*0.22*	*0.36*	*0.63*
	S-FH	*10*	*3*	*2*	*1.97*	*2.49*	*3.19*	*0.21*	*0.31*	*0.46*
Cavasso Nuovo	***H-MS***	*11*	*6*	*4*	*2.49*	*3.48*	*4.89*	*0.32*	*0.56*	*1.01*
	H-SS	39	6	5	1.52	1.99	2.61	0.13	0.21	0.32
	H-CR	*13*	*3*	*0*	*0.43*	*1.44*	*2.67*	*0.02*	*0.14*	*0.35*
	S-FP	67	3	2	0.96	1.30	1.73	0.06	0.10	0.16
	S-MS	73	13	10	1.61	2.07	2.68	0.14	0.22	0.34
	S-SS	81	3	2	0.90	1.24	1.67	0.05	0.09	0.15
	S-FH	203	55	40	1.90	2.43	3.16	0.19	0.30	0.45
Cavazzo Carnico	**H-SS**	63	19	10	1.85	2.38	3.09	0.19	0.29	0.45
	S-SV	77	31	20	2.20	2.88	3.77	0.26	0.40	0.64
	S-DV	*11*	*2*	*1*	*1.54*	*1.93*	*2.41*	*0.14*	*0.20*	*0.29*
Colloredo di Monte Albano	**S-FP**	177	54	27	1.83	2.38	3.11	0.19	0.29	0.46
	S-MS	*19*	*3*	*2*	*1.54*	*1.92*	*2.42*	*0.13*	*0.20*	*0.28*
Enemonzo	**S-MS**	64	3	3	0.98	1.40	1.92	0.06	0.11	0.19
	S-SV	73	8	7	1.34	1.78	2.34	0.10	0.17	0.27

Table 3 - continued.

Municipality	GR	Buildings	≥G4	≥G5	PGA (m/s²)			PGV (m/s)		
					⊢	•	⊣	⊢	•	⊣
Faedis + Povoletto	H-SS	55	3	2	1.03	1.37	1.80	0.07	0.11	0.17
	H-CR	71	16	15	1.76	2.37	3.28	0.17	0.29	0.48
	S-FP	247	18	7	1.03	1.39	1.82	0.07	0.11	0.18
	S-FH	230	14	4	0.87	1.27	1.74	0.05	0.10	0.17
Fanna	S-FP	180	20	6	1.08	1.52	2.03	0.07	0.13	0.22
	S-FH	295	32	6	0.91	1.43	2.02	0.06	0.12	0.22
Forgaria nel Friuli	*H-FP*	*18*	*3*	*3*	*1.56*	*2.12*	*2.90*	*0.14*	*0.24*	*0.39*
	H-SS	71	53	39	2.99	4.70	7.50	0.46	0.94	2.13
	S-MS	59	53	45	3.75	6.71	12.16	0.69	1.75	4.97
	S-SS	50	2	2	0.93	1.34	1.84	0.05	0.10	0.18
	S-FH	69	34	28	2.45	3.46	5.06	0.30	0.55	1.02
Gemona del Friuli	*S-SS*	*10*	*3*	*3*	*1.97*	*2.75*	*4.03*	*0.21*	*0.37*	*0.69*
	S-FH	259	113	72	2.25	2.99	4.00	0.27	0.43	0.71
	S-SV	65	20	10	1.83	2.38	3.13	0.19	0.29	0.46
	S-AF	277	153	119	2.60	3.68	5.32	0.33	0.61	1.11
Lusevera	*H-SS*	*13*	*11*	*3*	*2.10*	*4.35*	*9.96*	*0.24*	*0.90*	*3.51*
	H-CR	*11*	*4*	*4*	*2.14*	*3.06*	*4.64*	*0.24*	*0.45*	*0.88*
	S-SV	*24*	*5*	*2*	*1.49*	*1.96*	*2.56*	*0.13*	*0.20*	*0.32*
Magnano in Riviera	*S-SS*	*13*	*2*	*1*	*1.45*	*1.82*	*2.26*	*0.12*	*0.18*	*0.26*
	S-AT	*19*	*4*	*0*	*0.43*	*1.40*	*2.57*	*0.02*	*0.13*	*0.33*
	S-FH	71	24	9	1.72	2.36	3.31	0.17	0.28	0.51
Majano	H-FP	38	10	5	1.75	2.23	2.87	0.17	0.26	0.40
	S-FP	90	36	24	2.22	2.89	3.76	0.26	0.40	0.63
	S-FH	363	164	107	2.29	3.07	4.12	0.28	0.45	0.75
Maniago	*H-SS*	*22*	*3*	*3*	*1.45*	*1.96*	*2.66*	*0.12*	*0.21*	*0.34*
	S-FP	116	7	7	1.07	1.51	2.04	0.07	0.13	0.21
	S-MS	*21*	*4*	*3*	*1.65*	*2.10*	*2.71*	*0.15*	*0.23*	*0.35*
	S-FH	228	20	14	0.95	1.45	2.04	0.06	0.12	0.21
Meduno	H-MS	84	3	3	0.89	1.30	1.80	0.05	0.10	0.17
	S-FP	*25*	*4*	*1*	*1.16*	*1.67*	*2.30*	*0.08*	*0.16*	*0.27*
	S-MS	72	8	4	1.30	1.63	2.03	0.10	0.15	0.22
	S-FH	202	27	3	0.84	1.45	2.15	0.05	0.12	0.24
Moggio Udinese	*H-MS*	*28*	*21*	*19*	*3.19*	*5.22*	*9.00*	*0.48*	*1.13*	*2.72*
	H-SS	*17*	*9*	*9*	*2.54*	*3.92*	*6.52*	*0.32*	*0.69*	*1.57*
	S-MS	*23*	*15*	*12*	*2.88*	*4.25*	*6.41*	*0.40*	*0.79*	*1.52*
	S-SS	38	12	11	2.02	2.76	3.93	0.21	0.37	0.66
	S-SV	*21*	*5*	*5*	*1.80*	*2.47*	*3.51*	*0.18*	*0.31*	*0.54*
	S-AF	*21*	*13*	*10*	*2.78*	*4.01*	*5.86*	*0.38*	*0.71*	*1.31*
Montereale Valcellina	*H-MS*	*19*	*3*	*3*	*1.54*	*2.08*	*2.84*	*0.13*	*0.23*	*0.38*
	S-MS	36	2	2	1.04	1.47	1.99	0.07	0.12	0.20
	S-FH	140	10	7	1.13	1.49	1.94	0.08	0.13	0.19
Nimis	H-MS	47	26	16	2.42	3.44	4.97	0.31	0.54	1.04
	H-SS	116	46	18	1.84	2.58	3.71	0.19	0.33	0.62
	S-MS	31	30	20	3.29	7.47	19.34	0.54	2.24	11.19
	S-FH	174	63	36	2.02	2.64	3.48	0.22	0.34	0.56
	S-SV	52	36	23	2.70	4.15	6.61	0.38	0.76	1.71
Paluzza	S-MS	112	2	2	0.71	1.09	1.57	0.03	0.07	0.13
	S-SS	75	6	6	1.19	1.65	2.21	0.08	0.15	0.24
	S-SV	178	17	8	1.20	1.54	1.95	0.09	0.13	0.20

Table 3 - continued.

Municipality	GR	Buildings	≥G4	≥G5	PGA (m/s^2)			PGV (m/s)		
					|–	•	–|	|–	•	–|
Pinzano al Tagliamento	**H-MS**	100	41	16	1.86	2.62	3.80	0.19	0.34	0.65
	H-SS	*22*	*14*	*2*	*1.54*	*2.98*	*5.89*	*0.14*	*0.46*	*1.40*
	S-FP	50	2	0	0.43	0.96	1.60	0.02	0.06	0.14
	S-FH	148	59	19	1.73	2.50	3.74	0.17	0.32	0.63
Pontebba	**S-SS**	109	19	17	1.59	2.11	2.82	0.14	0.23	0.37
	S-SV	65	4	3	1.08	1.45	1.91	0.07	0.12	0.19
	S-AF	29	*3*	*2*	*1.31*	*1.67*	*2.11*	*0.10*	*0.15*	*0.23*
Ragogna	**H-SS**	38	7	5	1.63	2.07	2.64	0.15	0.22	0.33
	S-FP	112	23	20	1.70	2.24	3.01	0.16	0.26	0.42
	S-MS	115	61	42	2.50	3.44	4.75	0.32	0.55	0.96
	S-SS	*14*	*8*	*6*	*2.65*	*3.73*	*5.32*	*0.35*	*0.63*	*1.11*
	S-FH	269	72	49	1.89	2.38	3.03	0.19	0.29	0.42
Reana del Rojale	**S-FP**	521	17	3	0.64	1.04	1.54	0.03	0.07	0.13
	S-FH	98	8	5	1.20	1.53	1.94	0.09	0.13	0.19
Resia	**H-SS**	135	34	32	1.84	2.49	3.48	0.18	0.31	0.54
	S-SS	144	11	11	1.17	1.62	2.17	0.08	0.15	0.24
	S-AT	31	13	9	2.28	2.99	3.96	0.27	0.43	0.67
	S-SV	272	96	84	2.11	2.89	4.12	0.23	0.40	0.72
Sequals	**S-FP**	203	77	65	2.17	2.97	4.22	0.24	0.42	0.75
	S-FH	301	73	66	1.81	2.42	3.33	0.18	0.30	0.50
Socchieve	**S-MS**	83	9	7	1.33	1.73	2.24	0.10	0.16	0.25
	S-SV	106	3	2	0.82	1.15	1.59	0.04	0.08	0.13
Sutrio	**S-SV**	126	4	2	0.85	1.15	1.54	0.05	0.08	0.13
	S-AF	72	3	3	0.94	1.35	1.86	0.06	0.11	0.18
Tarcento	**H-FP**	57	6	4	1.32	1.68	2.13	0.10	0.15	0.23
	H-MS	*22*	*17*	*8*	*2.49*	*4.27*	*8.05*	*0.32*	*0.82*	*2.41*
	H-SS	81	46	27	2.40	3.46	5.12	0.30	0.55	1.09
	H-CR	63	36	23	2.50	3.56	5.16	0.33	0.58	1.11
	S-MS	58	10	6	1.58	1.95	2.40	0.14	0.20	0.28
	S-FH	664	255	167	2.17	2.81	3.63	0.25	0.38	0.60
	S-SV	135	67	42	2.34	3.22	4.47	0.29	0.49	0.86
Tolmezzo	**H-SS**	37	8	8	1.73	2.36	3.30	0.16	0.28	0.49
	S-MS	31	6	6	1.66	2.26	3.14	0.15	0.26	0.45
	S-SV	297	20	14	1.11	1.47	1.92	0.08	0.12	0.19
	S-AF	70	21	7	1.58	2.20	3.07	0.14	0.25	0.45
Travesio	**S-FP**	96	11	11	1.36	1.85	2.49	0.11	0.19	0.30
	S-FH	384	88	59	1.78	2.22	2.81	0.17	0.25	0.37
Trasaghis	**H-SS**	164	92	69	2.62	3.68	5.23	0.34	0.61	1.08
	S-SS	*17*	*5*	*3*	*1.92*	*2.42*	*3.05*	*0.20*	*0.29*	*0.44*
	S-FH	40	25	19	2.79	4.03	5.86	0.38	0.72	1.34
	S-SV	149	59	38	2.18	2.84	3.71	0.25	0.39	0.62
	S-AF	71	28	22	2.21	2.98	4.12	0.25	0.42	0.72
Vito d'Asio	**H-MS**	122	98	93	3.41	5.94	11.09	0.54	1.42	3.89
	H-SS	106	66	59	2.79	4.28	6.90	0.38	0.80	1.73
	S-SV	31	21	15	2.81	4.22	6.41	0.41	0.78	1.62

Then, the data of the selected municipalities were analysed by separating the buildings among the different GRs. Table 3 shows the data for each municipality evidencing the effects of each GR. For each GR, the procedure identifies the total number of buildings and the buildings suffering a damage ≥G4 and ≥G5. The cases in which the total number of buildings is lower than 30 (therefore a statistically inadequate number of samples) are reported using italics. The inverse Probit equations obtained at regional level were applied to estimate the seismic action [in terms of peak ground acceleration - (PGA), or peak ground velocity - (PGV)] that caused those effects (Table 3).

The data of Table 3 allowed us to estimate the amplification factors (AF) for the different GRs applying the following criteria, for each municipality:

- presence of the GR H-FP (flat plain in hard soil): this GR is considered as reference and by definition: $AF_{H\text{-}FP} = 1$; in fact, there should be no amplification of the seismic motion for this GR. For each municipality the estimated AF is calculated by dividing the values of acceleration (or velocity) of each GR, with the value of acceleration (or velocity) of the GR H-FP. The estimation of AF is direct and therefore the reliability can be considered good;
- absence of the GR H-FP (flat plain in hard soil): another GR is assumed as a "temporary reference", and the data obtained for the other municipalities are used to relate the amplification to the H-FP case. A notable example is the municipality of Trasaghis, where there is no GR H-FP, but only H-SS, S-SS, S-FH, S-SV, and S-AF. In this case, a specific GR is considered as "temporary reference", and in particular the GR S-SV. The procedure calculates the amplification of each GR of the municipality with respect to S-SV. Then, analysing the data of all the municipalities, it is recognized that Tarcento has information concerning both the "temporary reference" (S-SV) and H-FP GR, and then the value of the AF from H-FP to S-SV is used to relate the values of Trasaghis to the reference site H-FP. This procedure can also be applied twice (passing through different "temporary references" GRs); in these cases, there is no direct link with the GR H-FP. The estimation is indirect and its reliability is lower than in the direct case.

Using the above procedure, two "paths" were used to estimate the AFs considering as potential "temporary reference" S-FP, S-SV and S-FH. The first path adopts, as "temporary reference", S-FP and S-sv, which could be directly linked to H-FP through the data of Majano and Tarcento, and uses for three municipalities a double link from S-FH to S-SV and then to S-FH. The second path considers as temporary reference S-FH (linked to S-FH through the data of Forgaria nel Friuli, Majano and Tarcento), and uses a double link from $S\text{-}_{SV}$ to S-FH and then to S-FH. Table 4 shows the estimated AFs from S-FH to the "temporary reference" GRs considering both PGA and PGV.

Figs. 8 and 9 show the outcomes of the procedure after the analysis of the data of all the municipalities following the two different paths. The figures show the outcomes with different markers and colours, considering the municipalities with and without the GR H-FP.

4.1. Discussion on the results of the statistical analysis

Figs. 8 and 9 summarize the results of statistical analysis for each investigated GR and show a large variability of the estimated AFs, especially for the GRs H-MS H-SS, S-MS and S-SS. It is important to remember that the variability could be intrinsically associated to the characteristics of data input (FrED information) and in particular could derive from:

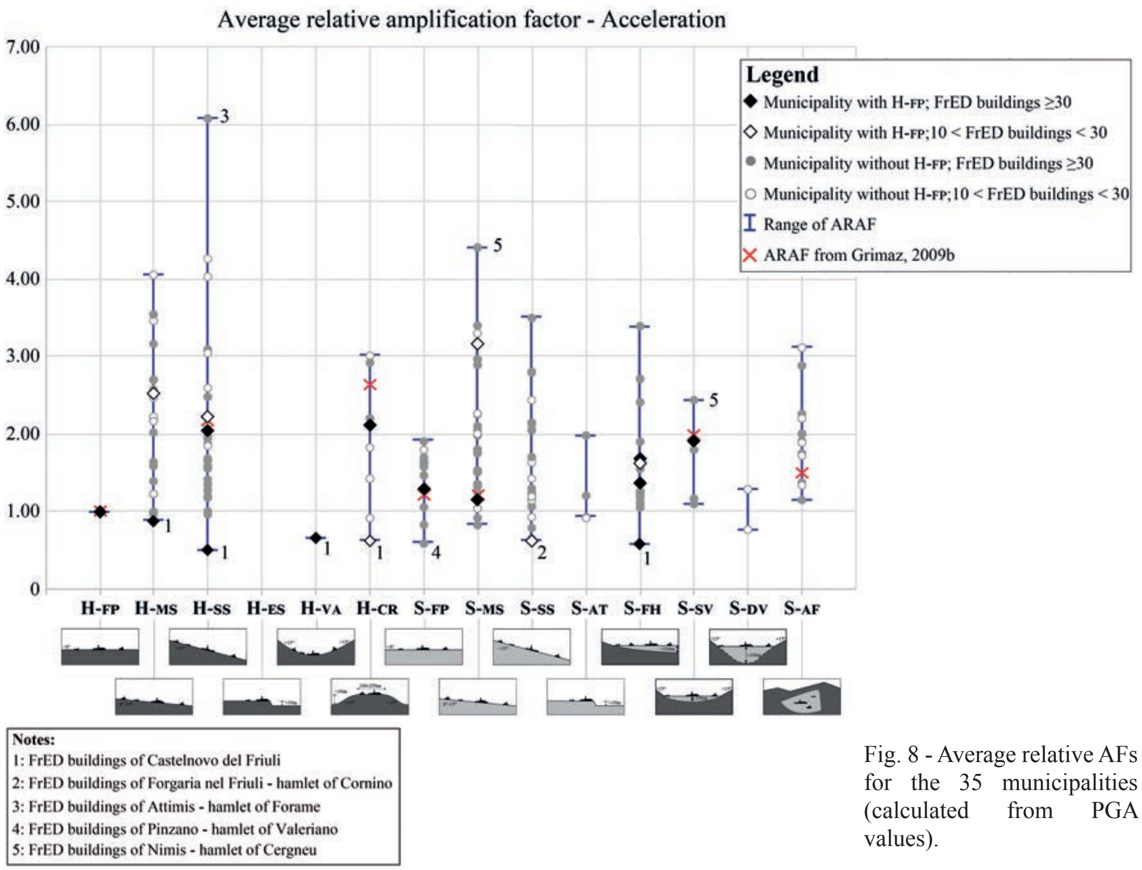


Fig. 8 - Average relative AFs for the 35 municipalities (calculated from PGA values).

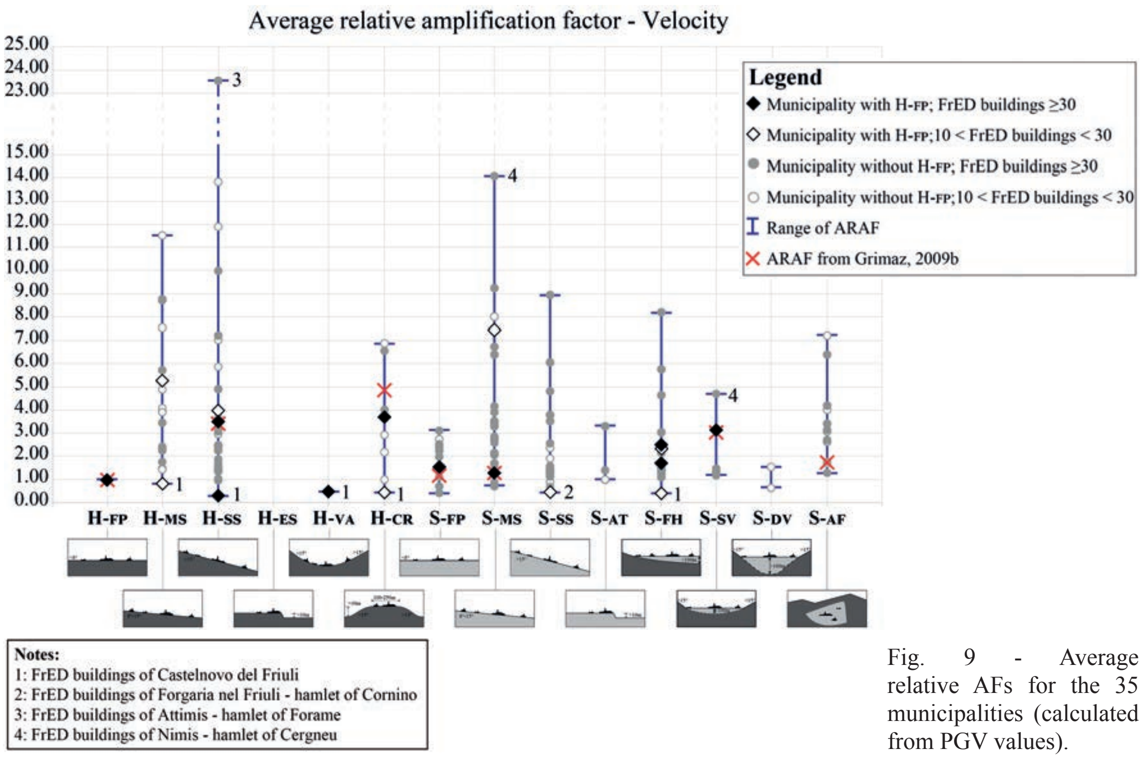


Fig. 9 - Average relative AFs for the 35 municipalities (calculated from PGV values).

Table 4 - Values adopted to link the “temporary reference” values to the GR H-FP.

Temporary reference GR / H-FP	AF PGA	AF PGV	Municipalities used for the evaluation
S-FP / H-FP	1.29	1.57	Majano
S-SV / H-FP	1.92	3.14	Tarcento
S-FH / H-FP	1.56	2.19	Average of the values of Tarcento, Majano, Forgaria nel Friuli

a) approximations related to the high dispersion of the relationship between ground motion parameters and macroseismic intensity;
b) incompleteness of information in the FrED database in the epicentral area (the inspection forms were not compiled for the collapsed buildings);
c) potential poor localization of the FrED buildings [the automatic procedure of geolocalization somewhere produced groups of buildings clustered in a single point, for example in the middle of a street (see Di Cecca and Grimaz, 2008)];
d) poor details deriving from the semi-automatic procedure and related to the scale of definition of the GRs;
e) potential variations of the buildings vulnerability (the vulnerability typology T1 includes a large variability of buildings, with the common characteristics of “being built before 1920”);
f) buildings on slopes (H-MS, H-SS, S-MS, S-SS) could have their foundations on different levels. Higher grade of damage observed in these GRs could derive from a higher vulnerability of buildings and not from an amplification of the ground motion;
g) the correlation between strong motion parameter and damage does not take account of the vertical component. Grimaz and Malisan (2014) evidenced that the vertical component could have a strong role in the damaging, especially in the epicentral area and for friction-resisting structures (T1 typology);
h) the damage observed and recorded on the inspection forms could refer to the damage derived from a different series of main-shocks and not only caused by a single shock. As evidenced by Grimaz and Malisan (2017), the cumulative damage could affect the goodness of the Probit equations;
i) the damage, at local level, could have a possible strong correlation to the direction of the impinging waves with respect to the orientation of the buildings, especially in the areas being characterized by directional effects;

Nevertheless, it is worth noting that the direct estimations (black rhombus) give very close values to the ones estimated by Grimaz (2009b) (red “x”).

The analysis of the distribution of data in Figs. 8 and 9 also highlights the presence of some outliers that should be investigated with in-depth local analysis. In particular, four cases deserve specific analysis (with reference to the notes in Figs. 8 and 9):

1. data derived from the municipality of Castelnovo del Friuli: the data in Table 3 show that the ground motion values that caused the recorded damage in the H-$_{FP}$ are significantly larger than the values calculated for the other GRs in the same municipality. Some anomalies and outliers are also evident. Studying the distribution of the FrED buildings, it is possible to assert that there is no significant variation of the distance from the epicentre of the earthquake (and therefore, that the expected ground motion, calculated without the geomorphological effects, is about the same

for all points). High values of PGA and PGV for H-FP affect the AFs calculated for all the other GRs. This is the reason for unexpected values showing potential de-amplification. A specific study on this anomaly is illustrated in the next section;

2. data derived from the municipality of Forgaria nel Friuli, for the S-SS GR: the evaluation shows a potential de-amplification for the sites in the S-SS GR with respect to the H-FP GR. Two observations can be made on this point: first, the data is calculated with reference to H-FP GR, where there are only 18 FrED buildings (therefore, the outcomes might not be reliable); second, a detailed analysis of the FrED buildings of Forgaria nel Friuli and of the S-SS GR shows that all the buildings are located in the hamlet of Cornino: an in-depth study both on site potential amplification and on buildings vulnerability could enhance the knowledge on this (apparent) anomaly;
3. data derived from the municipality of Attimis, for the H-SS GR: the outcomes show a very large amplification for the H-SS GR. The detailed check of the FrED points shows that all the buildings of Attimis in the H-SS GR were located in the hamlet of Forame; a deeper evaluation of the vulnerability of buildings is necessary, to verify if the destruction was caused by a high vulnerability or by large seismic motion amplification (or both);
4. data derived from the municipality of Nimis, for the S-MS and S-sv GRs: the outcomes show a rather large amplification, especially for S-MS. The FrED data show that the S-ms and S-sv GRs are defined by the data of the hamlet of Cergneu. It is known that Cergneu was almost completely destroyed by the earthquake. It has to be verified if the destruction was caused by a high vulnerability or by large seismic motion amplification (or both).

5. On-site study

Considering the observations derived from the statistical analysis, the authors decided to study in depth the anomalies associated to the GR H-FP of Castelnovo del Friuli, through on-site surveys. Fig. 10 shows the data of PGA and PGV (with the confidential interval) calculated for Castelnovo del Friuli. The figure highlights the large variability and the (relative) high values derived for the H-FP regions.

A specific site survey was planned to investigate the reason for this anomaly and, specifically, to understand why the GR H-FP shows such a large amplification: the variation could be associated both to local building vulnerability characteristics and to local site conditions. The vulnerability assessment was done through a quick (and visual) evaluation of the buildings, analysing in particular the constructions belonging to the T1 typology. The survey did not reveal a meaningful variation of the buildings vulnerability, neither in the GR H-FP nor in the whole municipality. The assessment of the potential amplification in the GR H-FP was carried out through specific ambient noise measurements analysed through the HVSR technique (Fig. 11) [for a short review of the technique, see Fäh *et al.* (2001) and Mucciarelli and Gallipoli (2001)]. The measurements were carried out using seismometers with three orthogonal components (we used a Lennartz LE 3Dlite-1s seismometer and a Lennartz M24 compact LP digitizer). The HVSR technique enables studying, among other parameters:

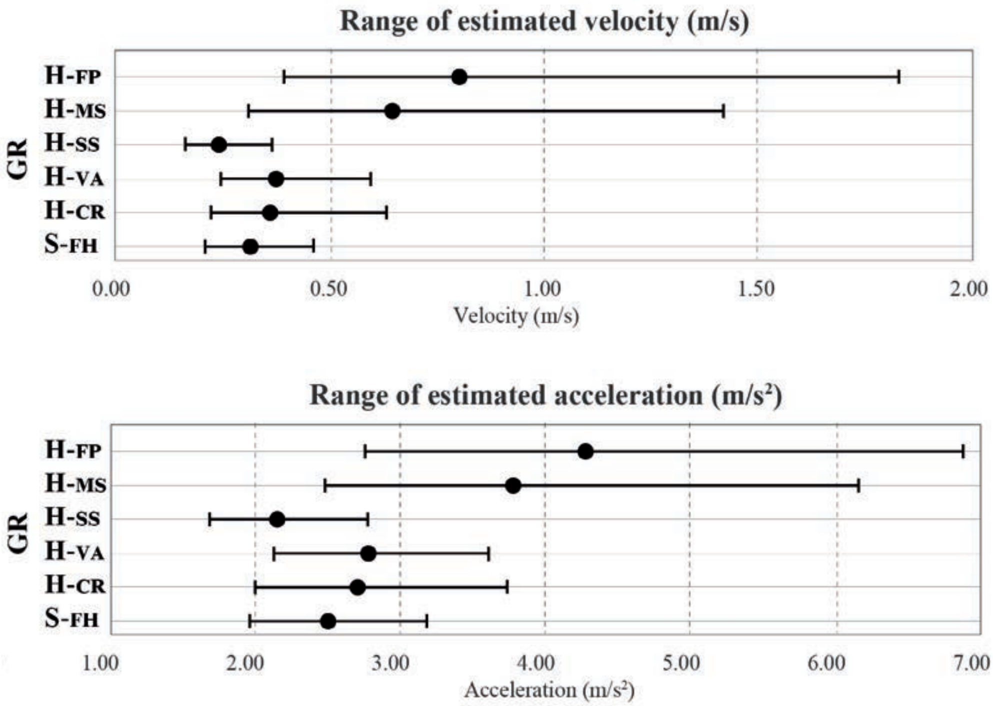


Fig. 10 - Ranges of estimated velocity and acceleration calculated for the GRs of Castelnovo del Friuli.

- the presence of a significant impedance contrast in the site, that may cause an increment of the seismic action on the ground surface; in the HVSR curve, a peak with amplitude larger than about two usually reveals the presence of a significant impedance contrast;
- the natural frequency(ies) of the ground, useful for the identification of potential double-resonance effects, between site and building; the double resonance could severely increase the damage on buildings.

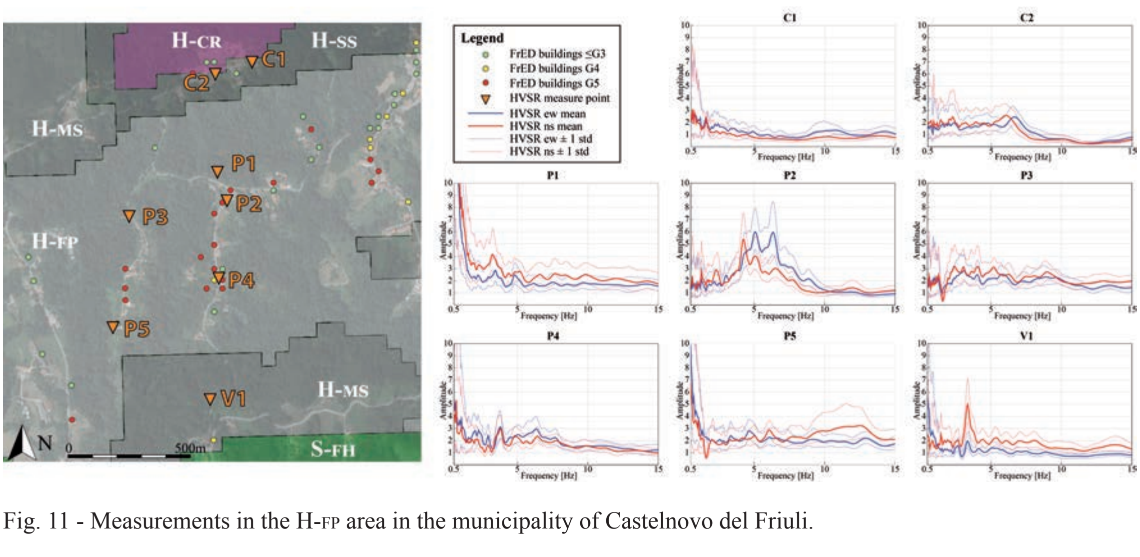


Fig. 11 - Measurements in the H-FP area in the municipality of Castelnovo del Friuli.

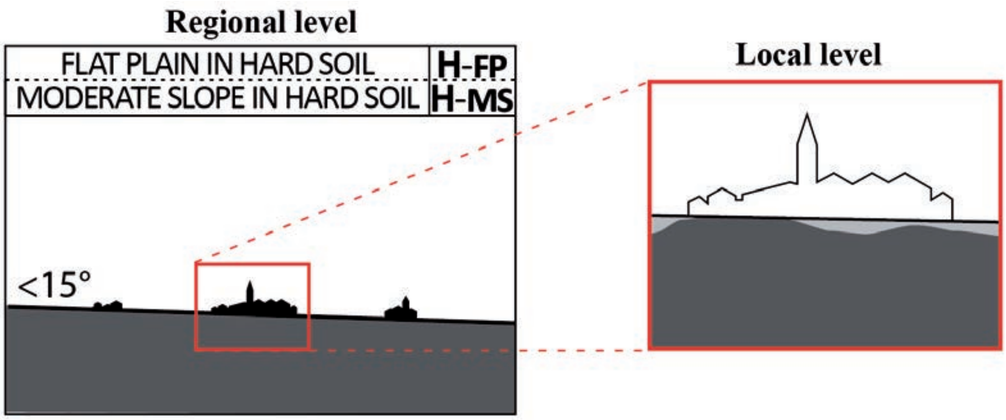


Fig. 12 - The scale of GRs does not permit identifying local stratigraphic characteristics.

These parameters allow the quick identification of local site conditions that could increase the damage, and therefore cause the large variability of the ground motion parameters derived from the FrED database. The choice of the locations of the measurements was guided by the analysis of the FrED data. The green, yellow and red dots in Fig. 11 represent the buildings of the FrED database having G3, G4, and G5 damage grade, respectively. The HVSR measurements were done in the area with more G4 and G5 cases.

The HVSR curves in Fig. 11 show the presence of peaks at relatively high frequencies, and values of the H/V ratio larger than two, for a wide portion of the curves. This indicates the presence of a soft layer in the local stratigraphy. Furthermore, the fundamental frequency range of the site has the same range of fundamental frequencies that are typical of masonry buildings with 1-2 floors (5-10 Hz), therefore implying the presence of potential double-resonance effects. These observations could explain why this area, even if it is classified as GR H-FP at regional scale, showed greater damage than the surrounding GR. This implies that the GRs are not sufficiently detailed to be used for local analysis and could not represent the presence of local stratigraphic characteristics (Fig. 12).

6. Final considerations

The studies on the damage to buildings after the 1976 earthquakes in Friuli allow extracting useful information for prevention purposes. This paper summarizes the results obtained using the FrED database and presents some new outcomes.

The FrED database allowed distinguishing six vulnerability typologies (for masonry buildings) for the region. The data allowed defining a Synthetic Damage Judgement scale, in order to assign a damage grade from visual information (rapid survey or photographic information). The FrED data were also used for the improvement of the fragility curves based on the GNDT vulnerability index. Thanks to a Probit analysis, the FrED data also allowed the definition of relationships that permit estimating the potential consequences of a future earthquake in an inhabited area with similar masonry building typologies to those in the FrED database. The outcomes were used to compile the risk map of Friuli Venezia Giulia (Carulli *et al.*, 2003).

The FrED data were used for an *a posteriori* study on site effects in the municipalities of Gemona del Friuli and Tarcento. This study allowed assessing the effect of local GLs on the damage together with the evaluation of the regional probit curves.

The definition of the GRs for the whole region allowed the study of the effects of topographical, geological, and stratigraphic variations at regional scale. Indeed, the distribution of the damage after the 1976 earthquakes for a specific building vulnerability typology is studied in this work, considering the different GRs, using the inverse Probit analysis. Based on the outcomes, the authors would make a number of comments, as follows:

- the semi-automatic procedure adopted for the definition of the GRs and the large scale of definition of the GRs (1:150,000) do not allow identifying local variations, which could affect the seismic ground motion and cause local site effects;
- the outcomes should be interpreted bearing in mind the main limitations of the data used for their evaluation and in particular: the incompleteness of the FrED database in the epicentral area; the potential poor localization of the FrED buildings; the variations of the buildings vulnerability (considering both the building geometry, the structural typology and the structural material characteristics);
- the data derived for the municipalities near the epicentral zone, should account for the potential effect of the vertical component of the seismic ground motion that could severely affect the constructions, especially those in the T1 vulnerability typology (mainly characterized by friction-resisting structures). Furthermore, the correlation between damage and seismic action could be affected by the effects of cumulative damage of buildings, caused by multiple seismic shocks (aftershocks) with significant intensity.

The above considerations explain the reason for the large variability of the AF ranges obtained from the statistical analysis of FrED data. Nevertheless, the analyses developed at regional level provide some indications (warnings) concerning the seismic effects of the different GRs. As illustrated in the previous sections, the data allow identifying anomalies (or "unexpected results"), that can guide in-depth local analysis (concerning both local site effects and local building vulnerability). An in-depth study, based on geophysical investigation and developed at local level, showed that the apparent anomalies evidenced in correspondence of some GRs are related to local characteristic of the sites.

An overall analysis of the data shows that the outcomes are a good estimate of those calculated by Grimaz (2009b) when considering the direct estimations; even though the two methods adopt different approaches to identify the geomorphotypes (the GRs adopt a semi-automatic procedure, with results at regional scale, while the GLs were identified locally, with in-depth studies).

As a conclusion, the outcomes of the statistical analysis for the different GRs presented in this work can be considered a preliminary informative warning on the range of potential amplification associated to the sites in the different GRs. The range of potential amplification can address specific in-depth studies to more accurately quantify the AFs at local scale.

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Corresponding author: Stefano Grimaz
SPRINT-Lab - Laboratorio di Sicurezza e Protezione Intersettoriale, Politecnico di Ingegneria e Architettura, Università degli Studi di Udine
Via Cotonificio 108, 33100 Udine, Italy
Phone: +39 0432 558731 ; e-mail: stefano.grimaz@uniud.it