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Seismic damage curves of masonry buildings from Probit analysis on the data of the 1976 Friuli earthquake (NE Italy)

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ABSTRACT Immediately after the earthquake of May 6, 1976 in Friuli (NE Italy) about 85,000 buildings were inspected and the same number of damage-assessment forms, containing useful information, were produced. A research team from the University of Udine (Italy) collected and reorganized these sheets inputting this information in the Fr.E.D. (Friuli Earthquake Damage) database, and reconstructing connections among seismic action, typology of construction and the level of provoked damage. Generally in the field of risk assessment of major accidents, a Probit analysis is applied to derive experimental relationships useful for the prediction of the accident's consequences. In particular, in this work, seismic damage curves, extrapolated for different typologies of residential masonry buildings, are presented. A combined use of these curves with the EMS98 and GSD scales of seismic damage is proposed to predict the damage scenarios, in terms of direct and indirect consequences, that a future earthquake could produce in an inhabited area with masonry building typologies similar to those present in the Friuli area.

1. Introduction

The problem of relating the severity of an action to its effects, in terms of level of caused damage, exists in many fields of risk analysis. Often, as occurs in the field of industrial safety or toxicology, these relations are derived from statistical analysis of observed damages.

A method for assessing the consequences resulting from an adverse event is the use of a direct effect model. Such a model predicts effects on a specific target based on predetermined criteria (e.g. collapse is assumed if an individual structure is exposed to a certain load level). In reality, the consequences may not take the form of discrete functions (e.g. a fixed input yields a singular output) but may instead conform to probability distribution functions. Therefore, a statistical method for assessing a consequence is also necessary in the seismic field.

At a territorial level the methodology of Damage Probability Matrices (DPM) turns out to be the most suitable (Lagomarsino, 1999). The frequency of the damage levels recorded for each typology and level of intensity is investigated considering a binomial probability function. The DPM methodology requires the retrieval of reliable and exhaustive observed damage data, referred to all defined building typologies, all grades of damage (including no damage), earthquake intensities and soil conditions. Otherwise, other statistical methods or hybrid methodologies must be used (Giovinazzi and Lagomarsino, 2006).

If it is reasonable to assume that the shape of the function relating the magnitude of the action to the level of damage caused by that action is known, a statistical method is applicable [e.g. the Probit analysis - from "probalility-unit" - (Finney, 1971)].

Probit is a non-linear regression model that assumes the cumulative normal function as a regression curve. This assumption could be considered likely according to Spence *et al*. (1991). In particular, Spence *et al*. (1991) observed that the best fit for relative damage curves of all building types and damage states, can be shown to be Gaussian – the cumulative function of a normal distribution. They observed also that for a large number of similar structures it can be assumed that the intensity at which each individual structure passes a given damage threshold will be clustered around an average intensity, with some variations: slightly weaker structures will pass the threshold at a lower intensity and slightly stronger-than-average structures will pass it at higher intensities. This scatter around the mean performance can be assumed to be normally distributed.

Therefore, if a large set of data, in which the action and the effects are recorded, is available, a Probit analysis can be used to extrapolate the response curves, taking into account the different typologies of buildings.

2. Probit analysis

Probit analysis (Finney, 1971; Aldrich and Nelson, 1984) is a statistical technique useful for modelling the relationship between a stimulus and a dichotomous response (yes/no or 0/1). It assumes that, for each receptor, there is a certain level of dose of the stimulus below which it will be unaffected, but above which it will respond. This level of action, known as its tolerance, will vary from subject to subject within the population. The model assumes a non linear S-shaped relationship between stimulus and response and, in particular, uses the normal cumulative function.

If the response Y_i can be only equal to 0 or 1, then the expected value of Y_i is reduced to the probability that Y_i equals 1:

$$E(Y_i) = 1 \cdot P(Y_i = 1) + 0 \cdot P(Y_i = 0) = P(Y_i = 1) \qquad (1)$$

It can be assumed that the damage depends on unobservable (or "latent") continuous index I_i*, determined by the explanatory variables in such a way that the larger the value of index I_i*, the greater the probability of reaching a determinate level of damage.

More formally, it can be defined:

$$I_i^* = \alpha + \beta X_i + \varepsilon_i, \qquad (2)$$

and

Y_i=1 if $I^*_i \geq 0$ (i.e. the damage power is "strong enough"),

Y_i=0 if $I^*_i < 0$ (i.e. the damage power is not "strong enough"),

then:

$$P(Y_i = 1 | X_i) = P(I^*_i \geq 0) = P(\alpha + \beta X_i + \varepsilon_i \geq 0) = P(\varepsilon_i < \alpha + \beta X_i), \tag{3}$$

and, considering a symmetric cumulative function F for ε:

$$P(Y_i = 1 | X_i) = F(\alpha + \beta X_i) = F(Z_i). \tag{4}$$

Moreover, if it is assumed that $\varepsilon \sim N\,(0,1)$ then $F(Z_i) = \Phi(Z_i)$ and

$$P(Y_i = 1 | X_i) = \Phi(\alpha + \beta X_i) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\alpha + \beta Xi} \exp\left[\frac{u^2}{2}\right] du = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{I^*} \exp\left[\frac{u^2}{2}\right] du \tag{5}$$

where I^* is the normal equivalent deviate (N.E.D.) or, simply, Normit.

The Probit variable Y_{Pr} is defined as:

$$Y_{Pr} = I^* + 5. \tag{6}$$

The added value 5 is purely conventional and does not influence the results obtained with the model. It is introduced only to avoid negative values in the calculus.

The relationship between the Probit variable (Y_{Pr}) and the probability (P) is the following:

$$P = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{Y_{\mathrm{Pr}} - 5} \exp\left[\frac{u^2}{2}\right] du. \tag{7}$$

Consequently, if the relationship between percentage and independent variable X is the cumulative normal function, then the relationship between X and Probit is linear (Fig. 1).

The following expression is normally used to calculate the value Y_{Pr}:

$$Y_{\mathrm{Pr}} = k_1 + k_2 \ln V = a + b \log_{10} V, \tag{8}$$

where k_1 and k_2 (or a and b) are constants, experimentally determined from the information on events that actually occurred. V is a measure of the damaging action (or dose) and, therefore, represents the "causative variable"; it can be just one parameter (e.g. the overpressure in the case of an explosion) or a combination of various parameters (e.g. a combination of concentration and time in a toxic gas release). Once the value of Y_{Pr} is determined, the Probit variable must be converted into a percentage of affected target in order to estimate the real consequences of an adverse event (e.g. the number of people injured or dead, the number of structures collapsed, and so on).

Table 1 relates the Probit value Y_{Pr} to the percentage $P_{\%}$.

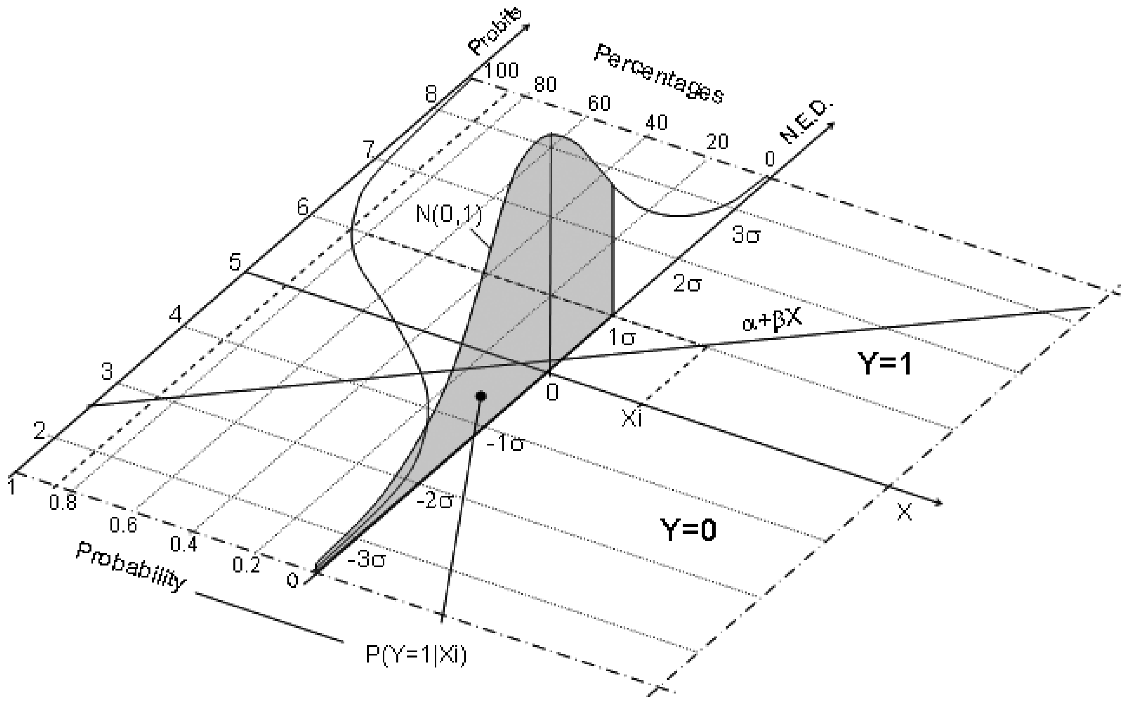


Fig. 1 - Relationships among the independent variable *X*, N.E.D., Probits, percentages and probability $P(Y=1/X_i)$.

A more useful expression to perform the conversion from Probit to percentage is given by (CCPS, 2000):

$$P_{\%} = 50\left[1 + \frac{Y_{\mathrm{Pr}} - 5}{\left|Y_{\mathrm{Pr}} - 5\right|} erf\left(\frac{\left|Y_{\mathrm{Pr}} - 5\right|}{\sqrt{2}}\right)\right]. \tag{9}$$

The Probit analysis is, nowadays, the most widely used procedure for estimating the consequences of certain major accidents on people (Lees, 1996; Vilchez *et al*., 2001). Eq. (9) permits the determination of the percentage of damage of a certain type (no damage, light damage, strong damage, collapsed/dead) in a practical and direct way.

In other words, the Probit approach considers the impact on a vulnerable receptor (e.g. people or buildings) and relates this impact to the probability that a certain damage level will occur, given a specific level of load (causative variable).

This method can also be applied to the seismic risk field in order to evaluate the response (damage) curves. For this case, parameter *V* is considered as an indicator of the severity of the action (for instance referring to instrumental ground motion measures) and the specific quantal response of the target (for instance referring to a specific threshold of building damage).

If under the same seismic load, there are several typologies of buildings with different behaviour, they can be considered as different receptors and a separate Probit analysis, for each

Table 1 - Relationship between Probit value Y_{Pr} (*in italic*) and percentage $P_{\%}$

$P_{\%}$		units									
		0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
tens	**0**	-	*2.67*	*2.95*	*3.12*	*3.25*	*3.36*	*3.45*	*3.52*	*3.59*	*3.66*
	10	*3.72*	*3.77*	*3.82*	*3.87*	*3.92*	*3.96*	*4.01*	*4.05*	*4.08*	*4.12*
	20	*4.16*	*4.19*	*4.23*	*4.26*	*4.29*	*4.33*	*4.36*	*4.39*	*4.42*	*4.45*
	30	*4.48*	*4.50*	*4.53*	*4.56*	*4.59*	*4.61*	*4.64*	*4.67*	*4.69*	*4.72*
	40	*4.75*	*4.77*	*4.80*	*4.82*	*4.85*	*4.87*	*4.90*	*4.92*	*4.95*	*4.97*
	50	*5.00*	*5.03*	*5.05*	*5.08*	*5.10*	*5.13*	*5.15*	*5.18*	*5.20*	*5.23*
	60	*5.25*	*5.28*	*5.31*	*5.33*	*5.36*	*5.39*	*5.41*	*5.44*	*5.47*	*5.50*
	70	*5.52*	*5.55*	*5.58*	*5.61*	*5.64*	*5.67*	*5.71*	*5.74*	*5.77*	*5.81*
	80	*5.84*	*5.88*	*5.92*	*5.95*	*5.99*	*6.04*	*6.08*	*6.13*	*6.18*	*6.23*
	90	*6.28*	*6.34*	*6.41*	*6.48*	*6.55*	*6.64*	*6.75*	*6.88*	*7.05*	*7.33*

typology of building, can be undertaken (e.g. classified in the same vulnerability class) obtaining, for each of them, the relative Probit equations (damage curves).

3. The Friuli Earthquake Damage database

After the May 6, 1976 earthquake in Friuli, about 85,000 damaged buildings were inspected as a subsequent regional law required (LR. 17/76 - Friuli Venezia Giulia Region), and as the same number of sheets were filled and collected. The aim of that data collection was to define the number of non-usable dwellings after the earthquake and to assess the cost of retrofitting. The set of data collected from the sheets contained information both on the damage level provoked on the building and on the characteristics of the building.

Studies made immediately after the earthquake (Giorgetti, 1976) produced an assessment of the MSK isoseismal curves of the event for the entire region affected by the earthquake.

At the beginning of 1990, a research team from the University of Udine acquired all the sheets collected in 1976, and organized them into a database (Friuli Earthquake Damage - Fr.E.D.). On the basis of these data, studies on seismic vulnerability were carried out (Grimaz, 1993; Grimaz *et al*., 1997). Riuscetti *et al*. (1997) and Carniel *et al*. (2001), in particular, elaborated the Fr.E.D.'s data and six meaningfully different classes of vulnerability, corresponding to six different typologies of buildings, were defined (see Table 2).

Grimaz *et al*. (1996) developed an expert system for damage assessment of buildings in the seismic area based on functional criteria and on a scale of synthetic damage judgements (GSD scale). The GSD scale allows us to relate the physical damage to the indirect consequences, as: repairability, usability, and possibility of causing victims. This scale can be also related to the levels of damage assigned during the inspections after the May 6, 1976 Friuli earthquake (Fr.E.D.

Table 2 - Vulnerability typologies with statistically different outcomes derived from the Fr.E.D. database.

Building characteristics					**Vulnerability Typology**
Material		Construction date	Structural context	floors	
masonry	stone	< 1920	detached building or non detached buildings	< 5	T1
		1920-1950	detached building or non detached building	3-5 <5	T2
		1920-1950	detached building	1-2	T3
	stone/bricks	>1950	detached building or non detached building	3-5	T4
		>1950	non detached building	1-2	T5
		> 1950	detached building	1-2	T6

damage classification), and to the EMS98 damage scale (Grünthal, 1998), as it is shown in Fig. 2.

In Fig. 2, a new sub-grade is introduced (G5+) to distinguish the upper part of the G5 grade in the EMS98 scale, corresponding to the complete destruction (this distinction is present in the Fr.E.D. damage classification).

Taking advantage of other information collected from the sheets, for example the address (that permits the identification of the location of each building), the information has been geo-localized and an automatic evaluation of the typology and seismic intensity recorded at the site of each building was defined. This operation allowed the new release of the Fr.E.D. database in which a set of 46,836 buildings with complete information, can be investigated.

Table 3 shows the percentage distribution of buildings of the Fr.E.D. database in the different damage grades for each typology and intensity grade.

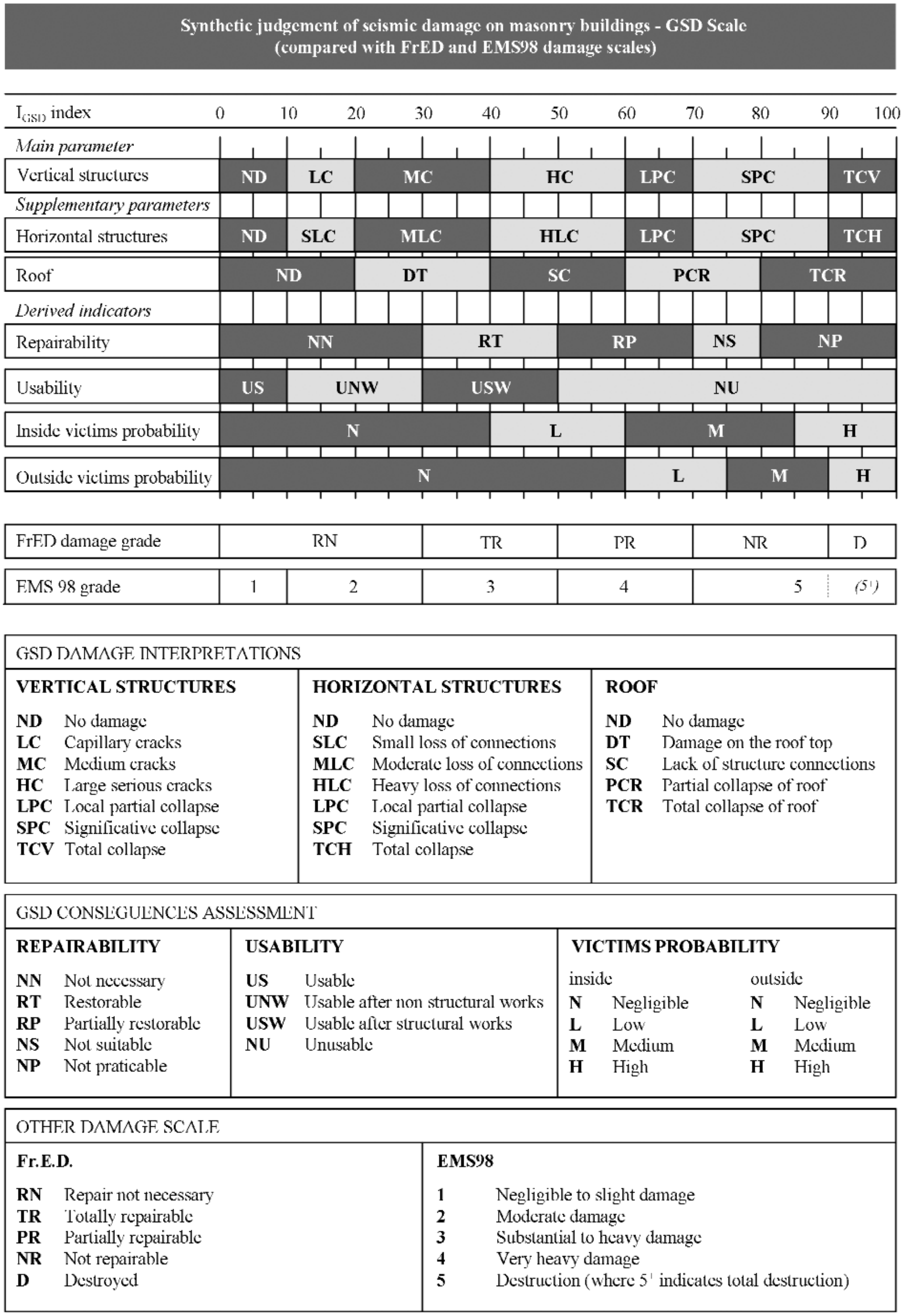
The database does not contain the inventory of buildings not surveyed immediately after the May 6, 1976 Friuli earthquake. This could affect the distribution of the frequencies of damage grades, in particular, in the urban centres with local intensity lower than VIII and, therefore presumably, with a larger number of buildings not surveyed. This makes it difficult to carry out directly a statistical analysis on each level of damage (as in the case of the DPM).

Other statistical tools, for instance the Probit, could be used. The concept of tolerance and a dichotomous response of the damage must be introduced. The assumption, on the normal distribution, must be taken and statistically verified.

The Fr.E.D. database provides an experimental data set where the causative variable and the relative damage provoked on a very great number of buildings are known or assessable. It has been possible to apply the Probit analysis on these data, in order to extrapolate the seismic response curves for the different typologies of buildings.

4. The causative variable in the seismic Probit analysis

The Probit analysis assumes that the cumulative function of a building, reaching a specific level of damage is normally distributed if, computed in function of a specific metametric scale of



Synthetic judgement of seismic damage on masonry buildings - GSD Scale
(compared with FrED and EMS98 damage scales)

I_{GSD} index	0	10	20	30	40	50	60	70	80	90 100
Main parameter										
Vertical structures	**ND**	**LC**	**MC**		**HC**		**LPC**	**SPC**		**TCV**
Supplementary parameters										
Horizontal structures	**ND**	**SLC**	**MLC**		**HLC**		**LPC**	**SPC**		**TCH**
Roof	**ND**		**DT**		**SC**		**PCR**		**TCR**	
Derived indicators										
Repairability	**NN**			**RT**		**RP**		**NS**	**NP**	
Usability	**US**	**UNW**		**USW**		**NU**				
Inside victims probability	**N**				**L**		**M**		**H**	
Outside victims probability	**N**						**L**	**M**		**H**
FrED damage grade	RN			TR		PR		NR		D
EMS 98 grade	1	2		3		4		5		*(5¹)*

GSD DAMAGE INTERPRETATIONS

VERTICAL STRUCTURES		**HORIZONTAL STRUCTURES**		**ROOF**	
ND	No damage	**ND**	No damage	**ND**	No damage
LC	Capillary cracks	**SLC**	Small loss of connections	**DT**	Damage on the roof top
MC	Medium cracks	**MLC**	Moderate loss of connections	**SC**	Lack of structure connections
HC	Large serious cracks	**HLC**	Heavy loss of connections	**PCR**	Partial collapse of roof
LPC	Local partial collapse	**LPC**	Local partial collapse	**TCR**	Total collapse of roof
SPC	Significative collapse	**SPC**	Significative collapse		
TCV	Total collapse	**TCH**	Total collapse		

GSD CONSEGUENCES ASSESSMENT

REPAIRABILITY		**USABILITY**		**VICTIMS PROBABILITY** inside		outside	
NN	Not necessary	**US**	Usable	**N**	Negligible	**N**	Negligible
RT	Restorable	**UNW**	Usable after non structural works	**L**	Low	**L**	Low
RP	Partially restorable	**USW**	Usable after structural works	**M**	Medium	**M**	Medium
NS	Not suitable	**NU**	Unusable	**H**	High	**H**	High
NP	Not praticable						

OTHER DAMAGE SCALE

Fr.E.D.		**EMS98**	
RN	Repair not necessary	**1**	Negligible to slight damage
TR	Totally repairable	**2**	Moderate damage
PR	Partially repairable	**3**	Substantial to heavy damage
NR	Not repairable	**4**	Very heavy damage
D	Destroyed	**5**	Destruction (where 5¹ indicates total destruction)

Fig. 2 - Synthetic judgement of damage scenarios on masonry buildings - GSD scale (modified from Grimaz *et al.*, 1996).

Table 3 - Percentage distribution of Fr.E.D.'s buildings for each typology, macroseismic intensity and level of damage recorded.

Typology	Intensity MSK	Fr.E.D.Damage level					
		D (%)	**NR** (%)	**PR** (%)	**TR** (%)	**RN** (%)	**Total (%)**
T1	**VI-VII**	0,011	0,041	0,053	4,247	3,694	**8,045**
	VII	0,021	0,173	0,241	9,578	2,607	**12,621**
	VII-VIII	0,056	0,290	0,307	8,577	3,122	**12,352**
	VIII	0,233	2,451	1,315	10,947	2,417	**17,363**
	VIII-IX	0,117	1,100	0,564	1,943	0,378	**4,102**
	IX	0,083	0,758	0,555	1,597	0,297	**3,290**
	X	0,107	0,521	0,235	0,747	0,077	**1,687**
	Total	**0,628**	**5,334**	**3,271**	**37,636**	**12,591**	**59,459**
T2	**VI-VII**	0,000	0,000	0,004	0,606	0,562	**1,172**
	VII	0,002	0,019	0,019	1,633	0,762	**2,436**
	VII-VIII	0,000	0,011	0,019	1,505	0,754	**2,289**
	VIII	0,013	0,211	0,258	2,511	0,871	**3,865**
	VIII-IX	0,015	0,137	0,154	0,786	0,267	**1,358**
	IX	0,023	0,175	0,167	0,743	0,120	**1,228**
	X	0,056	0,160	0,126	0,470	0,092	**0,903**
	Total	**0,109**	**0,713**	**0,747**	**8,254**	**3,427**	**13,250**
T3	**VI-VII**	0,002	0,000	0,000	0,374	0,485	**0,860**
	VII	0,000	0,006	0,011	0,820	0,442	**1,279**
	VII-VIII	0,004	0,006	0,023	0,856	0,468	**1,358**
	VIII	0,011	0,109	0,098	0,978	0,534	**1,729**
	VIII-IX	0,000	0,034	0,038	0,214	0,081	**0,367**
	IX	0,011	0,030	0,038	0,286	0,092	**0,457**
	X	0,019	0,036	0,066	0,188	0,066	**0,376**
	Total	**0,047**	**0,222**	**0,275**	**3,715**	**2,167**	**6,427**
T4	**VI-VII**	0,000	0,000	0,000	0,028	0,066	**0,094**
	VII	0,000	0,000	0,000	0,162	0,252	**0,414**
	VII-VIII	0,000	0,000	0,002	0,167	0,243	**0,412**
	VIII	0,004	0,015	0,004	0,322	0,474	**0,820**
	VIII-IX	0,002	0,019	0,026	0,188	0,085	**0,320**
	IX	0,006	0,019	0,023	0,252	0,107	**0,408**
	X	0,004	0,023	0,019	0,152	0,090	**0,288**
	Total	**0,017**	**0,077**	**0,075**	**1,270**	**1,317**	**2,756**
T5	**VI-VII**	0,000	0,000	0,000	0,036	0,132	**0,169**
	VII	0,000	0,000	0,000	0,177	0,265	**0,442**
	VII-VIII	0,000	0,000	0,002	0,186	0,384	**0,572**
	VIII	0,000	0,017	0,019	0,305	0,747	**1,089**
	VIII-IX	0,000	0,015	0,015	0,194	0,284	**0,508**
	IX	0,002	0,002	0,026	0,325	0,226	**0,581**
	X	0,006	0,017	0,026	0,286	0,235	**0,570**
	Total	**0,009**	**0,051**	**0,088**	**1,510**	**2,274**	**3,931**
T6	**VI-VII**	0,000	0,000	0,000	0,207	0,542	**0,749**
	VII	0,000	0,002	0,002	0,472	1,328	**1,804**
	VII-VIII	0,000	0,006	0,006	0,453	1,283	**1,749**
	VIII	0,006	0,043	0,032	1,070	3,408	**4,558**
	VIII-IX	0,000	0,023	0,013	0,316	0,688	**1,040**
	IX	0,002	0,038	0,030	0,734	1,149	**1,954**
	X	0,013	0,041	0,051	0,677	1,542	**2,323**
	Total	**0,021**	**0,154**	**0,135**	**3,929**	**9,939**	**14,177**
TOTAL (%)							**100.000**

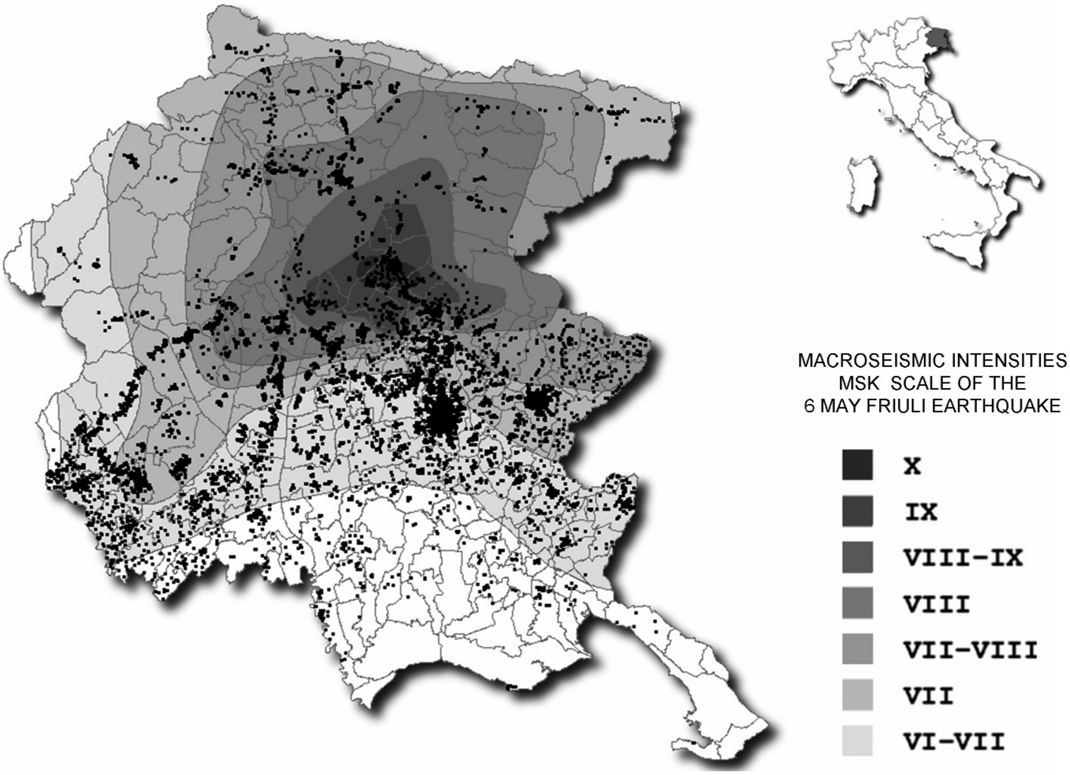


Fig. 3 - Distribution of buildings of Fr.E.D. database (dots) in the different isoseismal areas.

dose. For dose-effect problems, Finney (1971) proposes to use the log-dose. According to the observations made by Spence *et al*. (1991), cited in the introduction, it is reasonable to consider a continuous index (MSD) directly derived from macroseismic intensity grades as metametric scale of dose. This assumption is reliable also because the macroseismic intensity is log-correlated to PGA, PGV or other ground motion parameters, that can be considered causative variables V.

The MSD has been considered as the independent variable X in the Probit analysis. The MSD is directly related to the macroseismic intensity grades of MSK scale. According to Musson *et al*. (2006), even though direct conversion among intensity scales should never be made, the relationship among major twelve-degree scales (such as MSK, MMI and MCS) and EMS-98 is more or less 1:1.

It is also possible to relate MSD to average values of ground peak acceleration a_{max} and peak ground velocity v_{max} using relationships available in literature. In this work, it has been decided to use the relationships derived directly from the data of the region of study presenting the best coefficients of correlation. Table 4 shows the correspondence among MSD and average values of a_{max} and v_{max} estimated by relationships proposed by Slejko *et al*. (2008) and Faccioli and Cauzzi's (2006) obtained analysing earthquakes of the Mediterranean and the Venetian-Friulian area respectively.

Table 4 shows the correspondence among the MSD index, the macroseismic intensity grades in

Table 4 - Corrispondence among metametric seismic dose index MSD, macroseismic intensity grade I_{MSK}, and EMS98, peak ground acceleration and peak ground velocity.

MSD	**6.5**	**7**	**7.5**	**8**	**8.5**	**9**	**10**
I_{MSK}	VI-VII	VII	VII-VIII	VIII	VIII-IX	IX	X
EMS-98	6-7	7	7-8	8	8-9	9	10
$\bar{a}_{max}^{(*)}$ (m/s^2)	1.01	1.31	1.71	2.23	2.90	*3.78*	*6.42*
$\bar{v}_{max}^{(**)}$ (m/s)	0.06	0.08	0.12	0.19	0.28	0.42	*0.93*

(*) from Slejko *et al.* (2008): validity: 2.5 ≤ MSD ≤ 8.5
$MSD = 2.10 + 4.35 \log a_{max}$ $R^2= 0.74$ where a_{max} (g*100) (10)

(**) from Faccioli and Cauzzi (2006): validity: 4.5 ≤ MSD ≤ 9
$\log v_{max} = -3.53+0.35MSD$ $R^2= 0.61$ where v_{max}(m/s) (11)

the estimations outside the ranges of validity of the relationships are in italic

the different scales and the average values of a_{max} and v_{max} defined using the relationships cited above.

The majority of the buildings in the Fr.E.D. database are represented by masonry buildings. The hysteretic behaviour of this type of building suggests relating the damage primary to the energy of ground shaking.

Even if PGV, v_{max}, is better related to the energetic content of ground motion than PGA, also a_{max}, has been considered as a causative variable in Table 4. This is because hazard maps generally give PGA values. Probit equations could be used for predictive assessments using MSD values derived from PGA reported in the hazard map.

5. Probit response curves and prediction of post-earthquake scenarios

Table 5 shows the results of Probit analysis for six different typologies of buildings. In particular, it gives the coefficient of Probit equations referred to the threshold level of damage for each investigated case.

Even if the results hide the uncertainty regarding the definition of local intensity, the coefficients of the obtained correlation indicate that the assumption on the normal cumulative distribution is generally acceptable with the exception of the cases marked with a grey background in Table 5.

The relationships obtained for the six typologies have been verified as meaningfully different, using a t-Student test with an interval of confidence of 95%. The set of data has also been analyzed separately for different homogenous areas (e.g. Alpi area, Prealpi area, Friulian flat plain area). It has been verified with the same test of confidence, that the relationships presented above can be applied to all sub-regions.

The Probit relationships derived above permit a rapid prediction of the post-earthquake damage scenario. In fact, knowing or assuming the severity of the seismic action in terms of MSD, the Probit function, relative to each cumulative level of damage, can be calculated using Eq. (12) of Table 5, for each typology of building present in that area.

The percentage of every cumulative class of damages can be obtained from the respective

Table 5 - Probit equation coefficients derived for each typology and for each threshold level of damage.

$Y_{pr} = a+b\ log_{10}\ (V)=a+b\ MSD$				for $6.5\leq MSD\leq 10$			(12)	
Damage range	Probit	coefficients	T1	T2	T3	T4	T5	T6
Fr.ED: TR-D EMS98: ≥**G3** $I_{GSD} \geq 30$	$Y_{Pr\geq G3}$	a b R^2	2.82 0.40 *0.90*	3.09 0.33 *0.90*	3.48 0.26 *0.87*	2.45 0.33 *0.74*	2.83 0.25 *0.70*	4.14 0.06 *0.28*
Fr.ED: PR-D EMS98: ≥**G4** $I_{GSD} \geq 50$	$Y_{Pr\geq G4}$	a b R^2	-1.68 0.71 *0.89*	-2.28 0.73 *0.90*	-1.79 0.66 *0.90*	-2.57 0.70 *0.86*	-0.97 0.47 *0.73*	-0.45 0.40 *0.87*
Fr.ED: NR-D EMS98: ≥**G5** $I_{GSD} \geq 70$	$Y_{Pr\geq G5}$	a b R^2	-1.73 0.67 *0.88*	-2.35 0.69 *0.91*	-1.20 0.54 *0.86*	-2.02 0.60 *0.84*	-0.58 0.39 *0.69*	-0.11 0.34 *0.83*
Fr.ED: D EMS98: **G5⁺** $I_{GSD} \geq 90$	Y_{PrG5^+}	a b R^2	-0.65 0.42 *0.96*	-1.06 0.44 *0.92*	-0.24 0.34 *0.62*	-0.01 0.30 *0.86*	0.58 0.20 *0.71*	1.17 0.12 *0.60*

The relationships with R^2 <0.7 are in grey

Probit unit Y_{Pr} using Table 1 or Eq. (9). The percentage of each single damage of EMS98 grade, G_K, can be estimated as follows:

$$P_{\%}(G_{K|Tj}) = P_{\%}\left(Y_{\mathrm{Pr}\geq G_k|Tj}\right) - P_{\%}\left(Y_{\mathrm{Pr}\geq G_{k+1}|Tj}\right) \quad \text{for K=3,4,} \tag{13}$$

$$P_{\%}(G_{K|Tj}) = P_{\%}\left(Y_{\mathrm{Pr}\geq G_K|Tj}\right) \quad \text{for K=5 and } 5^{+}, \tag{14}$$

where:

$P_{\%}$ is the percentage of buildings suffering the G_k grade of damage

G_k is the K grade of damage in the EMS98 scale

T_j is the typology j with j from 1 to 6

$Y_{Pr\geq Gk/Tj}$ is the Probit of threshold damage ≥ G_k for the j typology of buildings.

Percentage of buildings suffering a damage of grade ≤G3 can be obtained from:

$$P_{\%}(G_{\leq 3|Tj}) = 100 - \sum_{K=4}^{K=5} P_{\%}\left(Y_{\mathrm{Pr}G_k|Tj}\right). \tag{15}$$

The percentage of buildings with a damage of grade less than, or equal to, G3, referring to the GSD scale, corresponds to the buildings recording a level of damage permitting their usability directly or after nonstructural or structural interventions. Therefore Eq. (15) can be used for a rapid estimation of buildings that will reasonably maintain their usability or permit a rapid restoration after an earthquake.

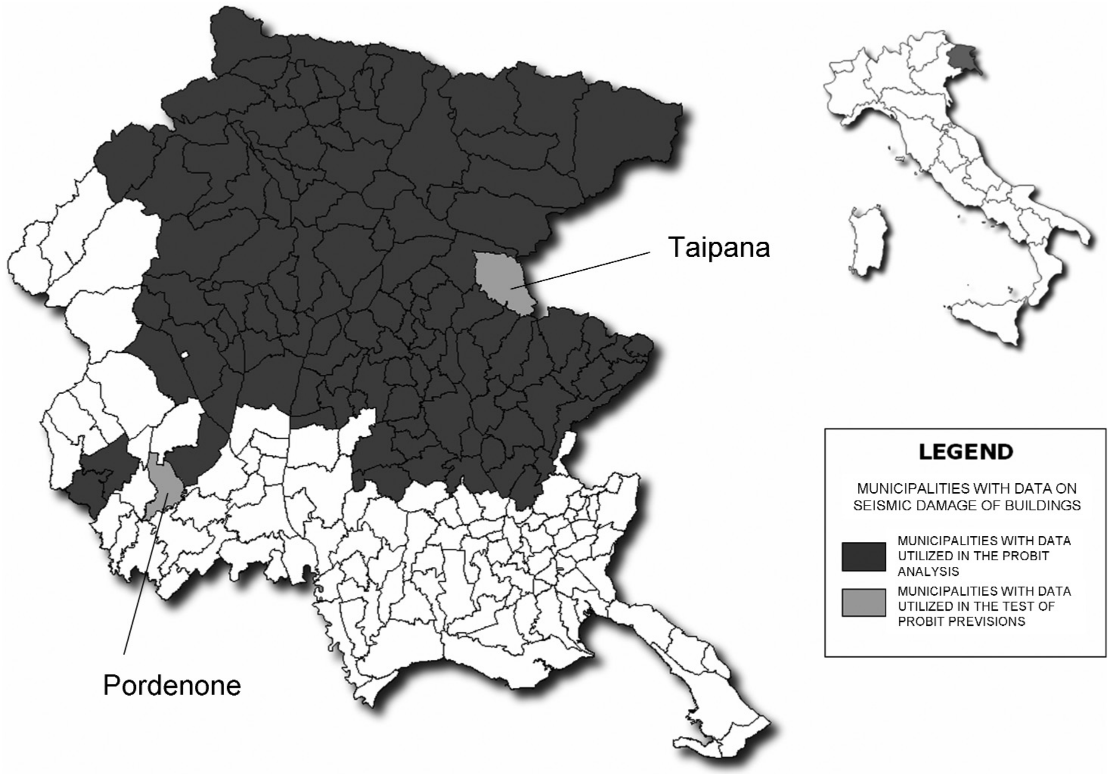


Fig. 4 - Municipalities with damage data utilised in the Probit analysis and as site test in the predictive damage scenario application.

Otherwise, the percentage defined by Eq. (14) can be used assuming $K = 5$ and $K = 5^+$ to estimate, respectively, the percentage of buildings with a medium or high probability of causing victims.

6. Test of predictive assessment

Two municipalities were considered as test sites (Fig. 4): Taipana (in the NE of the region, mountainous area) and Pordenone (in the middle of region, flat plan area). They were not considered in the set of data on which the Probit analysis was carried out. Therefore, considering that they have a sufficient number of damaged buildings with different construction typology, they were used to test the reliability of Probit relationships presented above.

Probit equations were applied to the two test municipalities and both Probit values and corresponding percentages have been calculated. In order to test Probit equations as a predictive tool for damage scenarios, the cases shown in Table 6, where the number of buildings are greater than 30, have been analysed.

The results obtained are reported in Tables 7, 8, and 9. They show deviations between observed and predicted damage scenarios of less than 10%.

After the earthquake, 984 homeless vs. 1215 dwellers were recorded in Taipana municipality,

Table 6 - Number of buildings within the two testing areas.

Municipality	I_{MSK}	MSD	$\bar{a}_{max}$ (m/s^2)	$\bar{v}_{max}$ (m/s)	stone			brick/stone			total
					T1	T2	T3	T4	T5	T6	
Taipana (UD)	VIII-IX	8.5	2.90	0.28	532	130	37	15	8	19	741
Pordenone (PN)	VII	7	1.31	0.08	219	49	35	110	15	55	483

The typologies with less than 30 buildings are in grey

Table 7 - Predictive evaluation of percentage of damage by Probit equations.

Typology of buildings	Probit equations	Taipana		Pordenone	
		Y_{Pr}	P $_{\%}$	Y_{Pr}	P $_{\%}$
T1	$Y_{\geq G3}$= 2.82 + 0.40 MSD	6.20	88.5	5.60	72.5
	$Y_{\geq G4}$= -1.68 + 0.71 MSD	4.35	25.7	3.28	4.3
	$Y_{\geq G5}$= -1.73 + 0.67 MSD	4.00	15.8	2.99	2.3
	Y_{G5^+}= -0.65 + 0.42 MSD	2.91	1.9	2.28	0.3
T2	$Y_{\geq G3}$= 3.09 + 0.33 MSD	5.91	81.8	5.41	67.8
	$Y_{\geq G4}$= -2.28 + 0.73 MSD	3.92	13.9	2.83	1.5
	$Y_{\geq G5}$= -2.35 + 0.69 MSD	3.52	6.9	2.49	0.6
	Y_{G5^+}= -1.06 + 0.44 MSD	2.68	1.0	2.02	<0.1
T3	$Y_{\geq G3}$= 3.48 + 0.26 MSD	5.68	75.2	5.29	61.3
	$Y_{\geq G4}$= -1.79 + 0.66 MSD	3.82	11.8	2.83	1.5
	$Y_{\geq G5}$= -1.20 + 0.54 MSD	3.39	5.4	2.58	0.8
	Y_{G5^+}= -0.24 + 0.34 MSD	2.63	0.9	2.12	0.2
T4	$Y_{\geq G3}$= 2.45 + 0.33 MSD	5.27	60.5	4.77	40.7
	$Y_{\geq G4}$= -2.57 + 0.70 MSD	3.36	5.0	2.32	0.4
	$Y_{\geq G5}$= -2.02 + 0.60 MSD	3.08	2.7	2.18	0.2
	Y_{G5^+}= -0.01 + 0.30 MSD	2.51	0.7	2.07	0.1
T5	$Y_{\geq G3}$= 2.83 + 0.25 MSD	4.96	48.2	4.58	33.6
	$Y_{\geq G4}$= -0.97 + 0.47 MSD	3.02	2.4	2.31	0.4
	$Y_{\geq G5}$= -0.58 + 0.39 MSD	2.72	1.2	2.14	0.2
	Y_{G5^+}= 0.58 + 0.20 MSD	2.24	0.3	1.94	<0.1
T6	$Y_{\geq G3}$= 4.14 + 0.06 MSD	4.63	35.4	4.54	32.1
	$Y_{\geq G4}$= -0.45 + 0.40 MSD	2.98	2.2	2.38	0.5
	$Y_{\geq G5}$= -0.11 + 0.34 MSD	2.76	1.3	2.26	0.3
	Y_{G5^+}= 1.17 + 0.12 MSD	2.16	0.2	1.98	<0.1

The equations with R^2 < 0.7 are in grey

Table 8 - Comparison between a predictive evaluation by Probit equations and damage observed on stone buildings.

Stone masonry buildings							
		Municipality					
Typology	EMS 98 grade	Taipana			Pordenone		
		Observed (%)	Predicted (%)	Error (%)	Observed (%)	Predicted (%)	Deviation (%)
T1	≤G3	71.6	74.3	2.7	97.2	95.7	-1.5
	G4	11.7	9.9	-1.8	0.5	2.0	1.5
	G5 *of which* *(G5$^+$)*	16.7 *(1.9)*	15.8 *(1.9)*	-0.9 *0.0*	2.3 *(0.5)*	2.3 *(0.3)*	-0.3 *-0.2*
T2	≤G3	88.5	86.1	-2.4	100.0	98.5	-1.5
	G4	9.2	7.0	-2.2	0	0.9	-0.9
	G5 *of which* *(G5$^+$)*	2.3 *(0.8)*	6.9 *(1.0)*	4.6 *0.2*	0 0	0.6 *(0.3)*	-0.6 0.3
T3	≤G3	83.8	88.2	4.4	91.4	98.5	7.1
	G4	8.1	6.4	1.7	5.7	0.7	5.0
	G5 *of which* *(G5$^+$)*	8.1 *0*	5.4 *(0.9)*	2.7 0.90	2.9 0	0.8 *(0.2)*	2.1 0.2

corresponding to a percentage of about 79% of the local population. No casualties were recorded. The predictions obtained by Probit equations, using the GSD scale correlations, estimate a percentage of about 94% of unusable buildings. Considering that about the 12% of the buildings of Taipana were not inhabited, the prediction is in good accordance with the situation really observed. In Pordenone's post-earthquake scenario no homeless people were recorded. The results of the Probit equation reported in Table 9, show that the total of the damage levels predicted are within categories of usable or rapidly restorable buildings, as was actually observed.

7. Conclusions

A set of Probit equations, utilizable as seismic response curves, has been derived from the data set collected after the May 6, 1976 Friuli earthquake. The coefficients of correlation obtained confirm the goodness of the initial assumption about the normal distribution of the damages for the most part of the cases investigated.

Probit analyses have shown lower coefficients of correlation for cases of total destruction of 1-2 floor masonry detached buildings constructed after 1920 and causes of the destruction of 1-2 floor masonry non-detached buildings constructed after 1950. Probit curves are not reliable for low damage grade estimation for the case of more recent 1-2 floor masonry detached buildings.

The test of these predictive tools on two municipalities has shown a good agreement with observed damage and has reported maximum deviations of less than 10%.

The combined use of the GSD scale and EMS98 permits the rapid prediction of consequence

Table 9 - Comparison between of predictive evaluation by Probit equations and damage observed on brick-stone buildings.

Brick-stone masonry buildings				
Typology	EMS 98 grade	Pordenone		
		Observed (%)	Predicted (%)	Deviation (%)
T4	≤G3	100.0	98.5	-1.5
	G4	0	0.7	-0.7
	G5 *of which* *(G5⁺)*	0 0	0.8 *(0.2)*	-0.8 0.2
T6	≤G3	100.0	99.5	-0.5
	G4	0	0.2	-0.2
	G5 *of which* *(G5⁺)*	0 *0*	0.3 *0*	-0.3 *0.0*

scenarios in an area struck by an earthquake, in terms of both direct and indirect consequences.

The obtained results suggest that this type of tool could be implemented in a GIS as a very rapid tool permitting the prediction of damage scenarios on a territorial scale.

It is interesting to observe that the MSD could be related to ground motion causative variables, for instance PGV or other parameters related to the energetic content, capable of defining the damage caused to masonry buildings. As the actual hazard maps give the PGA, the MSD in the Probit equation expressed in terms of a_{max} is, actually, more directly applicable.

The Probit equations (damage curves) with high coefficient of correlation presented in this paper can be considered as rapid tools usable for seismic risk assessments in areas presenting masonry building typologies similar to those here investigated.

Nevertheless, the variability of building typologies on the territory is great and it might be opportune to study other sets of data in order to derive Probit equations for other building typologies.

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