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A definition of seismic vulnerability on a regional scale: the structural typology as a significant parameter

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Abstract - In this work a criterion is presented to evaluate the seismic vulnerability on a regional scale based on an a posteriori method. This goal has been reached through the analysis of data collected after the 1976 Friuli seismic event on the base of a Regional Law (17/76) that performed a census of the damage for every building of the area struck by the earthquake. It was possible to derive the typological parameters able to define a degree of vulnerability. To this purpose the original database has been reorganized and processed, in particular to assess the quality of the information. This was done by comparing the earthquake intensity as computed on the base of the judgements given in the forms with the published isoseismal maps. After having characterized the building typologies and the associated vulnerability classes, we statistically evaluated the differences in their behaviour under seismic action. The parameters used are present both in the rich damage assessment forms filled in after the 1976 earthquake, and in the poorer census carried out by ISTAT every 10 years. Six significantly different typological classes were selected; these, once mapped to vulnerability classes, highlight the most vulnerable typologies. The following step is a vulnerability map for the Friuli-Venezia Giulia region at different detail degrees. At the most detailed level, vulnerability evaluation is based on the availability of information for each building or structural aggregate. At the other end, a coarse, less detailed vulnerability map only requires statistical data that identify the structural behaviour for different building typologies. The application of GIS techniques allows the integration of these data with other geographical and geophysical information.

1. Introduction

In the last few years the seismic risk problem has been studied extensively in order to define strategies and methodologies to reduce economical and social losses due to earthquakes (e.g.

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Riuscetti et al., 1999). The seismic risk is defined as the amount of damage expected at a given place as a consequence of a seismic event. It is commonly agreed that this can be due to three factors: hazard, exposition and vulnerability. Seismic hazard characterises the probability of the occurrence of an event of a given intensity in a given time interval and is commonly defined statistically (Grandori et al., 1984, 1991). The exposition estimates the value of objects and people subject to the number of seismic action, therefore tightly linked to the local socio-economic system. Although the vulnerability concept can be applied in a wider sense to infrastructural, organizational and the whole socio-economical aspects of a given territory (Hays et al., 1998), this paper deals in particular with building vulnerability, a good definition of which was given by Sandi (1986): the seismic vulnerability of a building is its behaviour described via a cause-effect law, where the cause is the earthquake and the effect is the damage. It is noteworthy that most of the measures needed to lower the vulnerability, produce additional costs and, therefore, also act on the exposure. Theoretical and practical aspects regarding the different approaches to the vulnerability problem (in particular, the GNDT, 1993 approach) are discussed in a previous paper (Riuscetti et al., 1997).

The development of land planning methods to limit seismic risk has been increased for two fundamental reasons: the first is the complexity of residential settlements, which relates directly to seismic vulnerability. The second is the impossibility, for economical and practical reasons, to restore all the buildings to earthquake-resistant standards; so a priority list must be established, e.g. in areas characterised by higher seismic risk, retrofit operations should be done before areas with a lower risk. Moreover, the process towards a reduction of seismic risk must consider two different realities:

- land-planning for new urbanised areas: in high hazard zones land use is limited to particular buildings and activities;
- reduction of vulnerability for existing residential settlements: in areas with high vulnerability buildings, either a complete retrofit must be carried out, or the entire area must be re-planned in order to lower population density.

The second case is very frequent in Italy, where seismic risk assessment is strictly connected with vulnerability evaluation of buildings mostly of historical and architectural importance. An effective land planning to lower seismic vulnerability of existing residential settlements is a difficult and expensive process, requiring lots of resources. It should therefore be organised over a time scale of several years, establishing activities', priority on different scales.

The criterion we present to evaluate the seismic vulnerability on a regional scale in this work is based on an a posteriori method (see Fig. 1). The starting point is the data set collected after the 1976 Friuli seismic event on the base of a Regional Law (17/76) issued by the government of Friuli-Venezia Giulia Region on 7 June 1976. This law established a census of the damage for every single building of the area struck by the earthquake, with the purpose of evaluating the restoration works (and relative costs) needed to recover damaged buildings or to rebuild destroyed ones. Besides the residential buildings, both in villages and in rural areas, some productive activities like shops and artisan workshops were also catalogued. However, the census did not include industrial plants, hospitals, town halls, schools, barracks or warehouses.

The advantage of the a posteriori approach is the possibility of an immediate validation "in

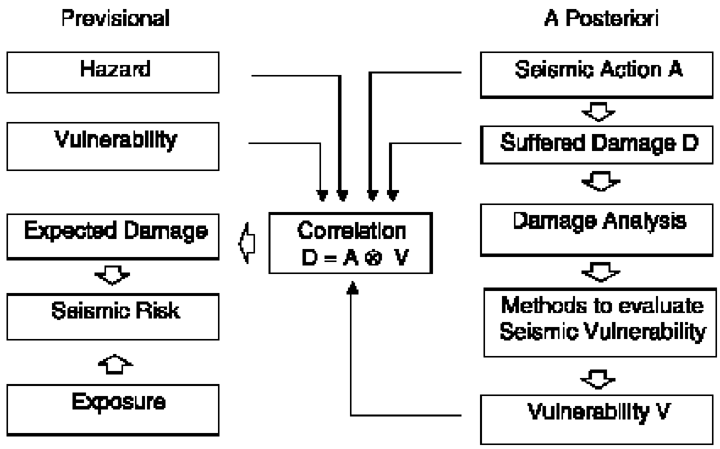

Fig. 1 - A sketch illustrating the a posteriori approach to the seismic risk evaluation.

the field" of the different hypotheses and procedural choices. The final purpose is a vulnerability map of the Friuli-Venezia Giulia region (NE Italy) at several levels of detail, going from the single building, through structural blocks, villages and municipalities, up to the whole region. At each level a procedure is defined in order to minimize the amount of input data required. For this reason, while the most detailed level is based on a very complete data acquisition, such as the filling of vulnerability forms for each building, at the most coarse (regional) level the required data is only of statistical type, trying to catch the common behaviour of structural typologies rather than those of single buildings.

This research is part of the project that will lead to the "Seismic risk map of Friuli-Venezia Giulia region", a joint venture between the Universities of Udine and Trieste and the OGS - Istituto Nazionale di Oceanografia e di Geofisica Sperimentale of Trieste.

2. Typological methods to evaluate vulnerability

The "typological methods" for vulnerability evaluation are based on the identification of classes of buildings characterised by similar typological or functional indicators; typical examples are the materials used to build vertical structures and roofs, or the geometrical parameters of the buildings. The typological methods aim at associating each class with a vulnerability function (curve or matrix). The verification of the hypotheses used to define such vulnerability functions is carried out statistically on the base of damage caused by past earthquakes. This is why such methods belong to the wider class of a posteriori analyses.

The relationship between the computed vulnerability and the real behaviour of a building under seismic action is not an easy one. In fact, the three parameters, physical vulnerability (V), suffered damage (D) and causing seismic action (A) can only be related in the following formulation, which is very generic:

$$D = A * V$$

A fundamental contribution to a posteriori methods was given by the Friuli 1976 earthquake. For this M_s 6.5 event a large amount of data and documentation on the damage suffered by existing buildings is available. Most of these data have been collected thanks to the Regional Law n. 17/76. Although this data set was not built with the aim of giving an evaluation of actual vulnerability, it ended up being an immense data source for the derivation of the correlation between building typologies and suffered damage. Of course the analysis of existing buildings can extend the results of this study and evaluate the expected damage for future earthquakes, together with reliable estimates of the costs needed to reduce seismic risk.

It is important to point out that typological methods are applicable only for the evaluation of the vulnerability for large areas, such as complete residential settlements. In this framework, random errors in the vulnerability evaluation become negligible thanks to the high number of samples. The goal of this approach is therefore mainly for a land-planning able to reduce seismic risk. On the contrary, these methods are not suitable, and should not be used for a detailed analysis of each building in the area of interest. As we will see in detail later, for large area vulnerability estimates, data coming from ISTAT's (Italian Institute for Statistical Studies) periodical census can be used (Picco, 1997). In fact, although ISTAT census data are collected for completely different purposes, they provide, as a sort of side effect, a periodic (10 years) snapshot of the buildings most important typological features.

3. The 1976 earthquake damage data (FRED)

In order to better access the Friuli earthquake huge amount of data, a database was built, called FRED (FRiuli Earthquake Damage), built from very heterogeneous document sources, and organised in layers focused on different detail levels. The section of the database which is relevant to the a posteriori analysis described in this paper collects data digitized from the Damage Assessment Forms (DAF's). For practical reasons, the database includes only the most relevant data contained in the original DAF's, originally thought up mainly for the economical purpose of estimating the reconstruction costs.

3.1. Damage assessment forms

According to the Regional Law n. 17/76, teams of three technicians (engineers, surveyors, architects) carried out the census, filling a DAF report for each building, which included a detailed description of its characteristics, the damage suffered and the works needed for restoration.

There were however some exceptions, e.g. in municipalities classified as destroyed (see Fig. 2, cfr. Italian Law DPR - Decreto Presidente Repubblica - n. 0714, 20 May 1976) the census considered all buildings, while in municipalities classified as deeply damaged or damaged only not irreparably damaged buildings were examined.

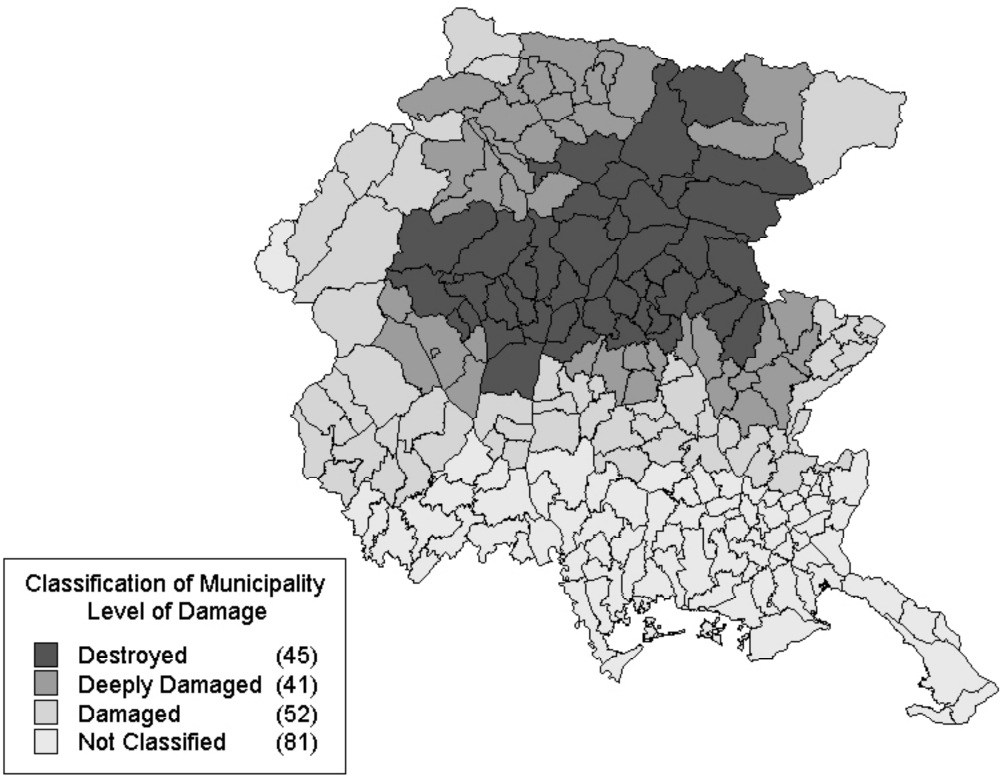

Fig. 2 - Classification of the Friuli Venezia Giulia municipalities with respect to the damage suffered during the 1976 earthquake.

The DAF is composed of five different parts (or sheets), hereafter described.

PART 1. - Contains the general characteristics of the building: localisation, address, number of floors, number of fronts in common with other buildings, presence of a basement and/or a garret, number of lodgings, age, presence of outhouses or productive activities. The damage suffered is briefly described: destroyed, not restorable, partially restorable, totally restorable with structural works, totally restorable without structural works. The form also reports the estimated restoration cost for each flat, rural habitation, outhouse or productive activity, with, possibly, notes regarding the restoration.

PART 2. - This part describes the single units forming the building, like lodgings, rural habitations, outhouses and productive activities; of course there can be more than one sheet 2 for each sheet 1.

PART 3. - Includes a section used to compute the volume of the building associated to each typological use (civil or rural habitation, outhouses, productive activities); a second section gives a summary evaluation of the building before the earthquake, based on unitary values according to the typology and the state of preservation. The third and fourth sections allow the computation of the total amount of restoration costs based on the unitary values of part 4.

PART 4. - This part is divided into two sections: one for civil or rural habitations and one for outhouses and productive activities. It contains an outline used to determine the unitary amount of restoration works; the calculation is organised by structural elements and by their 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 structural element was determined a priori.

PART 5. - This part lists some information about technical methods for restoration works proposed by the technical surveying team.

Given the data contained in the DAF, it is possible to outline the following procedures to evaluate seismic vulnerability:
- derive from the DAF data descriptive parameters able to classify buildings into "seismically homogeneous" typological classes. These parameters should be indicators of vulnerability, and should have a correspondence in the ISTAT census data (see next paragraph);
- for each typological class, identify damage suffered for a particular seismic action;
- define a criterion to classify typological classes based on their vulnerability;
- extend the vulnerability evaluated for buildings damaged by the 1976 earthquake to all existing buildings.

4. Census data (ISTAT)

Every ten years ISTAT carries out a General Census to obtain a periodic snapshot of the Italian situation at the greatest territorial detail. Of course the ISTAT census is not calibrated to the requirements of building evaluation in a seismically active zone. However, it still represents an irreplaceable source of information for a coarse evaluation on a territorial scale and it has the remarkable advantage of being repeated periodically, to control the time variations of the residential patrimony.

The parameters that describe the characteristics of buildings currently included in the ISTAT census are very simple and qualitatively correspond to the ones contained in the DAF's, as we requested (see previous paragraph). This allows one to define the criteria for seismic vulnerability evaluation of the buildings, essentially masonry ones, on the base of non-specific surveys already carried out at a national level. Parameters such as the number of floors and the number of common walls, the construction material and the age of construction allow a typological classification of the buildings into different categories, for which a vulnerability index must be estimated. The fundamental problem in the processing of ISTAT census building parameters is that they are referred to family living units rather than to the buildings (as the ISTAT's main goal is to study families). A heavy pre-processing of the available data is therefore necessary to relate these typological parameters to the buildings, which are our main interest. Luckily, the 14th General Census of the population and the living units, planned for October 2001, will also include a census of the existing residential buildings. In this census, information will be collected for each building, such as the number of floors, number of walls common to other buildings, the building material and the age, i.e the same parameters that up to the 13th General Census were associated to the family living units.

5. First data processing

The parameters to define the typological classes extracted from the DAF's are the following:
MUNICIPALITY (municipality of the building);
CODE: survey team code plus a sequential number; these two values give a unique identification to each building;
DATE: date when the DAF was filled in;
AGE: age of the building: before 1850, 1850 -1920, 1920 -1950, after 1950, unknown;
FLOORS: number of floors. A garret sufficiently high to be suitable for living, is considered as another floor. Code 0 indicates an unknown number of floors;
BASEMENT: absent, partial, total, unknown;
FRONTS IN COMMON with neighbours. Code 0 means isolated building;
MATERIAL: The DAF's contain only information relative to the typological composition of vertical structures, on the base of the percentages of masonry (%PIE), brick (%LAT) and columns (%PIL). On the base of the main materials derived from these percentages, the building is classified as shown in Table 1;
DAMAGE: a synthetic description, using Table 1 classes.

6. DAF classification

In order to assess the quality of the information contained in each DAF, and of the processing of the results as a consequence, the following parameters are taken into account:

Table 1 - Definition of a typological composition classification of buildings, and classes of suffered damage as described by the survey teams.

BUILDING		DAMAGE	
PIE	masonry	D	destroyed
PPIL	masonry + column	NR	non repairable
LAT	brick	RP	partially repairable
LPIL	brick + column	RT-ST	totally repairable with structural interventions.
PLAT	brick + masonry	RT-NS	totally repairable with no-structural interventions
INT	framed	NS	not damaged no interventions needed.
CA	reinforced concrete		

- the date when the DAF was filled in;
- the completeness of the data in the DAF, stressing, in particular, the data relative to the typological features of the buildings.

6.1. Useful DAF's

The first classification has the purpose of extracting only the DAF's for which damage may be referred to a single seismic action, i.e. the one of May 1976. Only the DAF's filled in before the aftershock of 11 September 1976 are therefore considered Useful DAF's.

6.2. Complete DAF's and incomplete DAF's

From a preliminary analysis of useful DAF's, it is evident that the information is not always complete, mainly due to the surveying procedure itself (e.g. damaged but repairable buildings were described better than non-damaged or destroyed ones) or to several difficulties encountered in the field by the survey teams. The useful DAF's where therefore subdivided into:
- complete DAF's, i.e. useful DAF's with all parameters relative to the typological features of the buildings filled in;
- incomplete DAF's, i.e. useful DAF's with at least one of such parameters missing.

6.3. Representative municipalities

For what concerns the municipalities, a first filter selects them on the base of the following criteria:
- the municipality is classified as destroyed according to the Regional Law 15/76;
- the municipality has a percentage of useful DAF's greater than, or equal to, 70% with respect to the total number of filled DAF's;
- the municipality has a number of useful DAF's greater than 100.

All the 45 municipalities destroyed satisfy these criteria and are therefore considered Representative Municipalities of the damage suffered from the May 1976 seismic event. Moreover, a degree of representativeness is assigned on the base of the percentage of useful DAF's: HIGH (90% - 100%), MEDIUM (80% - 90%), LOW (70% - 80%), NOT REPRESENTATIVE (0% - 70%).

6.4. Significant municipalities

The goal of the second filter is to find a relationship between damage and structural typology. For this reason, it focuses on the DAF's with intermediate damage classes (RP, RT-ST and RT-NS), as they guarantee a high percentage of complete DAF's. More precisely, the criteria is based on the percentage of complete DAF's for the single damage classes. This should be greater than 85% with respect to the total number of DAF's of the damage class itself. All the samples relative to municipalities that satisfy both the first and second filter (which we will call Significant Municipality) may be used to carry out reliable a posteriori studies on the relationship between the degree of damage suffered and the typological features of the buildings. They are therefore apt to the evaluation, at a territorial level, of the seismic vulnerability of the existing building as they are both representative of the effects of the May 1976 earthquake and carefully described from the point of view of the structural typology of damaged buildings.

7. The definition of typological classes

The scheme of the process used to define vulnerability classes and produce a vulnerability map is shown in Fig. 3. Typological characteristics taken from the DAF's and used to define building classes are summarised as follows:

- MAT building materials of vertical structures;
- AGE age of the building;
- FLOOR number of floors;
- FC number of fronts in common;
- BAS presence of basement.

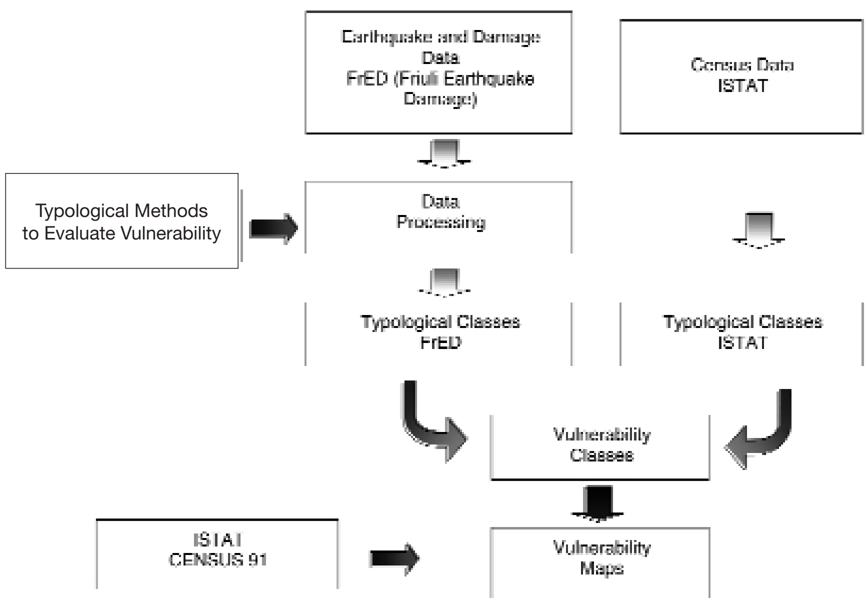

Fig. 3 - A flow-chart of the process carried out in order to produce a vulnerability map for the Friuli-Venezia Giulia region.

The three damage levels involved are $D_1 = RT\text{-}NS$, $D_2 = RT\text{-}ST$, $D_3 = RP$. Using the data of a Significant Municipality, the most representative building typologies $T_{1\,ref}$, $T_{2\,ref}$, $T_{3\,ref}$ are identified for each damage level. For each of these, of course, there are damage in the other levels as well. Therefore, the relative frequency of the 3 damage levels is considered for $T_{1\,ref}$, $T_{2\,ref}$, $T_{3\,ref}$. The resulting 3 triples define the reference distributions that constitute, considerating the correspondence between damage and vulnerability, the vulnerability classes V_j:

$$T_{1\,ref} \rightarrow (\%D_{11\,ref}, \%D_{21\,ref}, \%D_{31\,ref}) \rightarrow V_1$$
$$T_{2\,ref} \rightarrow (\%D_{12\,ref}, \%D_{22\,ref}, \%D_{32\,ref}) \rightarrow V_2$$
$$T_{3\,ref} \rightarrow (\%D_{13\,ref}, \%D_{23\,ref}, \%D_{33\,ref}) \rightarrow V_3$$

where $\%D_{ij\,ref}$ is the relative frequency of damage i for reference vulnerability class V_j.

Now, if $\%D_i$ is the relative frequency of damage level i for any building typology, we can classify it, i.e. assign it to one of the reference vulnerability classes just defined, according to the following steps:

- identify significant building typologies, i.e with a minimum number N of buildings;
- for each significant typology T_i determine the real distribution of damage $T_i(\%D_1,\%D_2,\%D_3)$;
- assign each significant typology T_i to a vulnerability class V_j.

The criteria to assign each typology to a vulnerability class is based on the evaluation of the distance between the real distribution $(\%D_1,\%D_2,\%D_3)$ and the reference ones V_j; the typology Ti will be assigned to class V_j for which this distance is minimized. Such distance is obtained by an adaptation index A.I. with values in the range [0,1] defined as:

$$(\text{A.I.})_j = \frac{\sum_{i=1}^{3} \left| \%D_{ij,ref} - \%\, D_i \right|}{\Delta\,\%\,D_{max}}$$

where $\Delta\%D_{max}$ is a normalization constant, i.e. the maximum spread between a class V_j and a distribution of damage level.

A value A.I. = 0 indicates that the real distribution coincides exactly with one of the reference distributions while for a value A.I. = 1 there is the maximum distance.

8. A case study: Gemona del Friuli

Among all the Friuli Significant Municipalities, Gemona del Friuli represents the best choice for the classification of typological classes on the base of vulnerability. Its representativeness is high and there is a large absolute number of DAF's (more than 2000). When applied to Gemona, the procedure outlined above, furnishes the typological classes shown in Table 2, ordered from the most to the least vulnerable.

Table 2 - Results of the application of the typological classification procedure to Gemona del Friuli. The resulting typological classes are ordered from the most to the least vulnerable.

BUILDING TYPOLOGIES - PARAMETERS					Vulnerability Classes	Class Characteristics	
Material	Age	Floor	Common Fronts	Basement		Number of buildings	A. I.
PIE	before 1920	4	> 0	all	H-HH	83	0,30-0,32
PIE	1920-1950	4	> 0	all	H-HH	11	0,40-0,36
PIE	before 1920	3	0	all	H	22	0,26
PIE	before 1920	3	> 0	all	H	194	0,11
PIE	before 1920	2	> 0	all	H	41	0,19
PIE	1920-1950	3	> 0	all	H	93	0,10
PIE	1920-1950	2	> 0	all	H	19	0,06
PIE	after 1950	4	> 0	all	H	19	0,12
PLAT	before 1920	3	> 0	all	H	30	0,15
PLAT	1920-1950	3	0	all	H	25	0,19
PLAT	1920-1950	3	> 0	all	H	36	0,08
PLAT	after 1950	4	> 0	all	H	17	0,09
LAT	1920-1950	3	0	all	H	64	0,15
LAT	1920-1950	3	> 0	all	H	51	0,12
PIE	1920-1950	3	0	all	M-H	23	0,28-0,23
PIE	after 1950	3	0	all	M-H	38	0,16-0,24
PIE	after 1950	3	> 0	all	M-H	46	0,24-0,16
PLAT	after 1950	3	> 0	all	M-H	39	0,22-0,21
PIE	after 1950	2	> 0	all	M	14	0,14
PLAT	after 1950	3	0	all	M	47	0,13
PLAT	after 1950	2	0	all	M	29	0,16
LAT	after 1950	3	> 0	all	M	102	0,08
INT+CA	after 1950	3	0	all	M	17	0,09
LPIL+PPIL	after 1950	2	0	all	M	20	0,05
LAT	after 1950	3	0	all	M-L	282	0,11-0,16
LAT	after 1950	2	> 0	all	M-L	28	0,18-0,11
INT+CA	after 1950	2	0	all	M-L	25	0,10-0,15
LAT	after 1950	2	0	all	L	303	0,02
LAT	after 1950	1	0	all	L	77	0,07

In order to quantify the reliability of the Gemona typologies-vulnerability catalog, some tests have been performed analysing other Significant Municipalities and thus extending this classification to all municipalities of the Friuli-Venezia Giulia region.

9. ISTAT typological classes

Table 3 shows the correspondence between the typological indicators contained in the ISTAT census data and the ones present in the DAF's. On the base of these correspondences, the typological classes have been identified in the FRED database as the ones that better approximate the ISTAT typological classes and their seismic vulnerability evaluated. Typological indicators used to build such classes are:

Table 3 - Correspondence between typological indicators contained in the ISTAT census data and the ones contained in the DAF's.

Typological Indicators	DAFs	ISTAT Census
MATERIAL	PPIL, LPIL, INT, CA	Reinforced Concrete
	PIE, PLAT, LAT	Masonry - Brick
AGE	Before 1920	Before 1919
	1920-1950	1919-1945
		1946-1960
	After 1950	1961-1971
		1972-1981
		After 1981
BASEMENT	No	—
	Partial	—
	Total	—
FLOOR	1	1
	2	2
	3, 4, 5	3-5
	6, 7, 8, 9, 10	6-10
	> 10	> 10
COMMON FRONT	0	Isolated
	1	Not Isolated
	2	
	>2	

- MATERIAL: almost all of the buildings collected in FRED belong to the ISTAT class Masonry-Brick;
- AGE: the values adopted are: Before 1920, 1920-1950 and After 1950;
- FLOOR: the values are grouped into the groups 1-2 and 3-5;
- COMMON FRONTS: only values isolated and non isolated are used.

With these parameters 12 typological classes are defined, as shown in Table 4.

Table 4 - The 12 typological classes resulting from the comparison of the ISTAT and DAF indicators.

BUILDING TYPOLOGIES	TYPOLOGICAL CHARACTERISTICS		
	AGE	COMMON FRONT	FLOOR
T 1	Before 1920	Isolated	1-2
T 2			3-5
T 3		Not Isolated	1-2
T 4			3-5
T 5	1920-1950	Isolated	1-2
T 6			3-5
T 7		Not Isolated	1-2
T 8			3-5
T 9	After 1950	Isolated	1-2
T10			3-5
T11		Not Isolated	1-2
T12			3-5

9.1. Vulnerability classes

The vulnerability curve $d = d\ (a)$ can be drawn in the (a,d) plane which relates the damage (d) to the seismic action (a). Unfortunately, the available data assume values which belong to a discrete, finite set of classes, and the determination of such a curve is therefore not straightforward. In order to determine it, we first transform the discrete quantities into continuous variables. We denote, with X, the variable linked to the seismic action a and with Y the variable connected to the damage d suffered by a given structural typology. The relationship between X and Y is assumed to be linear. In fact, in the literature there are still great uncertainties on the laws $d\ (a)$ to be used (Riuscetti et al., 1997), and the choice of more complex models is not advisable in this phase.

The buildings are first subdivided into classes associated to the 12 typologies found on the base of the ISTAT census parameters. After the linear regression is determined for each group of data, a comparison is performed in order to determine if the classes show a significantly different behaviour. In our work the number of samples is small (max 45) and we have to assume that random variables y_{1v} and y_{2v} (i.e. variable Y related to two different vulnerability classes) are independent with the same variance. When we compare the regression lines η_1 relative to two data groups, with models (i.e. regression lines) respectively given by $\eta_1 = \alpha_1 + \beta_1\ (x - \bar{x}_1)$ and $\eta_2 = \alpha_2 + \beta_2\ (x - \bar{x}_2)$, a first comparison may be carried out by verifying the parallelism hypothesis H_0 $(\beta_1 = \beta_2)$. If this is not rejected, the coincidence will be verified through the equal intercept hypothesis H_1 $(\alpha_1 = \alpha_2)$. The results of this procedure are shown in Table 5.

The T1, T2, T3 and T4 structural typologies, relative to buildings older than 1920, are practically indistinguishable both at a 5% and at a 1% significance level. Among the typologies of buildings built between 1920 and 1950 only the T5 typology (1-2 floors, isolated buildings)

Table 5 - Statistical comparison to determine significantly differences between typological classes.

Regression to Compare		**Level of Significance**	**Hypothesis to test**	
			$H_0 : \beta_1 = \beta_2$	$H_1 : \alpha_1 = \alpha_2$
T1	T2	0.05	Not Refused	Not Refused
		0.01	Not Refused	Not Refused
T1	T3	0.05	Not Refused	Not Refused
		0.01	Not Refused	Not Refused
T1	T4	0.05	Not Refused	Not Refused
		0.01	Not Refused	Not Refused
T2	T3	0.05	Not Refused	Not Refused
		0.01	Not Refused	Not Refused
T2	T4	0.05	Not Refused	Not Refused
		0.01	Not Refused	Not Refused
T3	T4	0.05	Not Refused	Not Refused
		0.01	Not Refused	Not Refused
T5	T6	0.05	Not Refused	Refused
		0.01	Not Refused	Not Refused
T5	T7	0.05	Not Refused	Refused
		0.01	Not Refused	Not Refused
T5	T8	0.05	Not Refused	Refused
		0.01	Not Refused	Refused
T6	T7	0.05	Not Refused	Not Refused
		0.01	Not Refused	Not Refused
T6	T8	0.05	Not Refused	Not Refused
		0.01	Not Refused	Not Refused
T7	T8	0.05	Not Refused	Not Refused
		0.01	Not Refused	Not Refused
T9	T10	0.05	Not Refused	Refused
		0.01	Not Refused	Refused
T9	T11	0.05	Not Refused	Refused
		0.01	Not Refused	Refused
T9	T12	0.05	Not Refused	Refused
		0.01	Not Refused	Refused
T10	T11	0.05	Not Refused	Refused
		0.01	Not Refused	Not Refused
T10	T12	0.05	Not Refused	Not Refused
		0.01	Not Refused	Not Refused
T11	T12	0.05	Not Refused	Refused
		0.01	Not Refused	Refused
T1	T8	0.05	Not Refused	Refused
		0.01	Not Refused	Refused
T8	T12	0.05	Not Refused	Refused
		0.01	Not Refused	Refused

can be distinguished from the others, T6, T7 and T8. Among the typologies of buildings built after 1950, the typologies T9 (1-2 floors, isolated buildings) and T11 (1-2 floors, non isolated buildings) are significantly different from the other two (T10 and T12, relative to 3-5 floors, isolated and non isolated buildings respectively). A general observation is that the typologies with different ages are significantly different; moreover, the typological distances in the same age class grow as the age decreases. The result is that the original 12 typologies can be grouped in the following broader typological classes:
typology A: it includes original typologies T1 - T2 - T3 - T4;
typology B: it includes original typologies T6 - T7 - T8;
typology C: it includes only original typology T5;
typology D: it includes original typologies T10 - T12;
typology E: it includes only original typology T11;
typology F: it includes only original typology T9.

For A, B and D typological classes, which group more than one of the original typologies, new regressions are computed on the complete set of data obtained merging the buildings belonging to all their typologies. We then proceed to a new series of significant difference tests among these new A-F classes to check if further merges can be carried out. While the H_0 hypothesis can never be rejected, the H_1 one is always rejected, thus confirming that we cannot

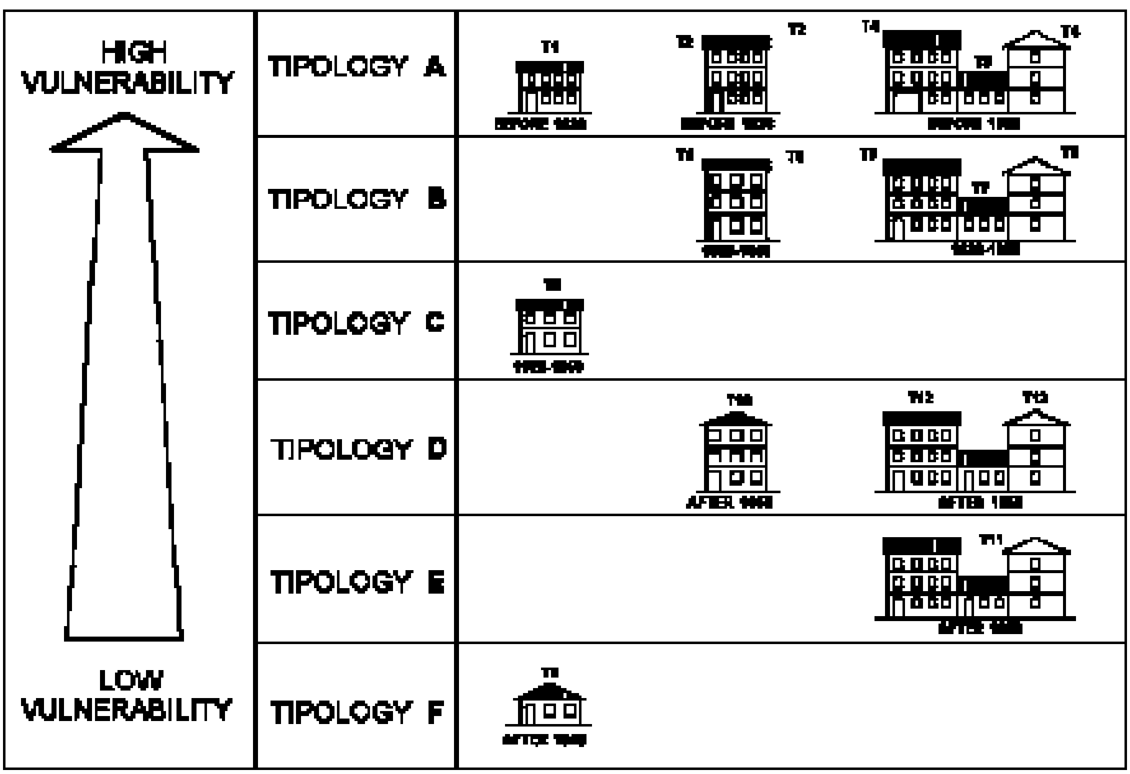

Fig. 4 - In the sketch we summarise the classification we derived from the ISTAT data, sorting out the typologies A - F on the base of decreasing vulnerability, and indicating for each the included typologies T_i with their relevant features and a schematic representation that helps a fast recognition in an urban area.

proceed with any further simplification without ignoring statistically significant differences in the typologies.

In Fig.4 we therefore show a schematical graphical representation of the final six significantly different typologies derived on the base of the ISTAT data. They represent structural typologies with different vulnerability, sorted from A (the most vulnerable) to F (the least vulnerable). In the sketch we also indicate the typologies T_i included in each class. The graphical schematic representation helps to recognize the typologies in an urban area quickly at a glance.

On the basis of the methodology described, it is possible to use the ISTAT census data to produce small scale vulnerability maps. As a concrete example, we present a seismic vulnerability map for masonry buildings, produced on the base of the data of the 13th General Census. Available data are grouped by a territorial unit named census area, which can be smaller than a municipality.

In every census area there are buildings characterised by different structures (masonry and framed-reinforced concrete) and different geometry; the 6 typological classes previously determined classify only masonry buildings, so that it is possible to evaluate the vulnerability only for these buildings. It is therefore necessary to assess the percentage of masonry buildings in each census area as shown in the first of the thematical maps (see Fig. 5). Unfortunately, some census areas have a very low number of masonry buildings or even buildings tout-court (e.g. mountain zones); it is therefore important to give little or no significance to the relative vulnerability estimation. In order to derive a global Vulnerability Index (VI) for each census area (Fig. 6) a linear combination was used. Different weights have been assigned to each typological class and the VI has been calculated as follows:

$$VI_i = \sum_{j=1}^{6} w_j \cdot p_{ij}$$

where w_j are the weights for class j and p_{ij} the percentages of buildings for class j and area i, respectively.

10. Conclusions

From the analysis of the DAF's filled in after the Friuli 1976 earthquake, typological parameters were derived in order to define the degree of vulnerability of a given building. To this purpose the original data have been reorganised, integrated and processed, in particular to assess the quality of the information contained, (see also Riuscetti et al., 1997) by comparing the measure of the earthquake intensity as computed on the base of the judgements in the forms with that derived from the published isoseismal maps for the event (Giorgetti, 1976). After having characterised the typologies present in the set of buildings examined and the vulnerability classes that can be associated with them by combining the information from

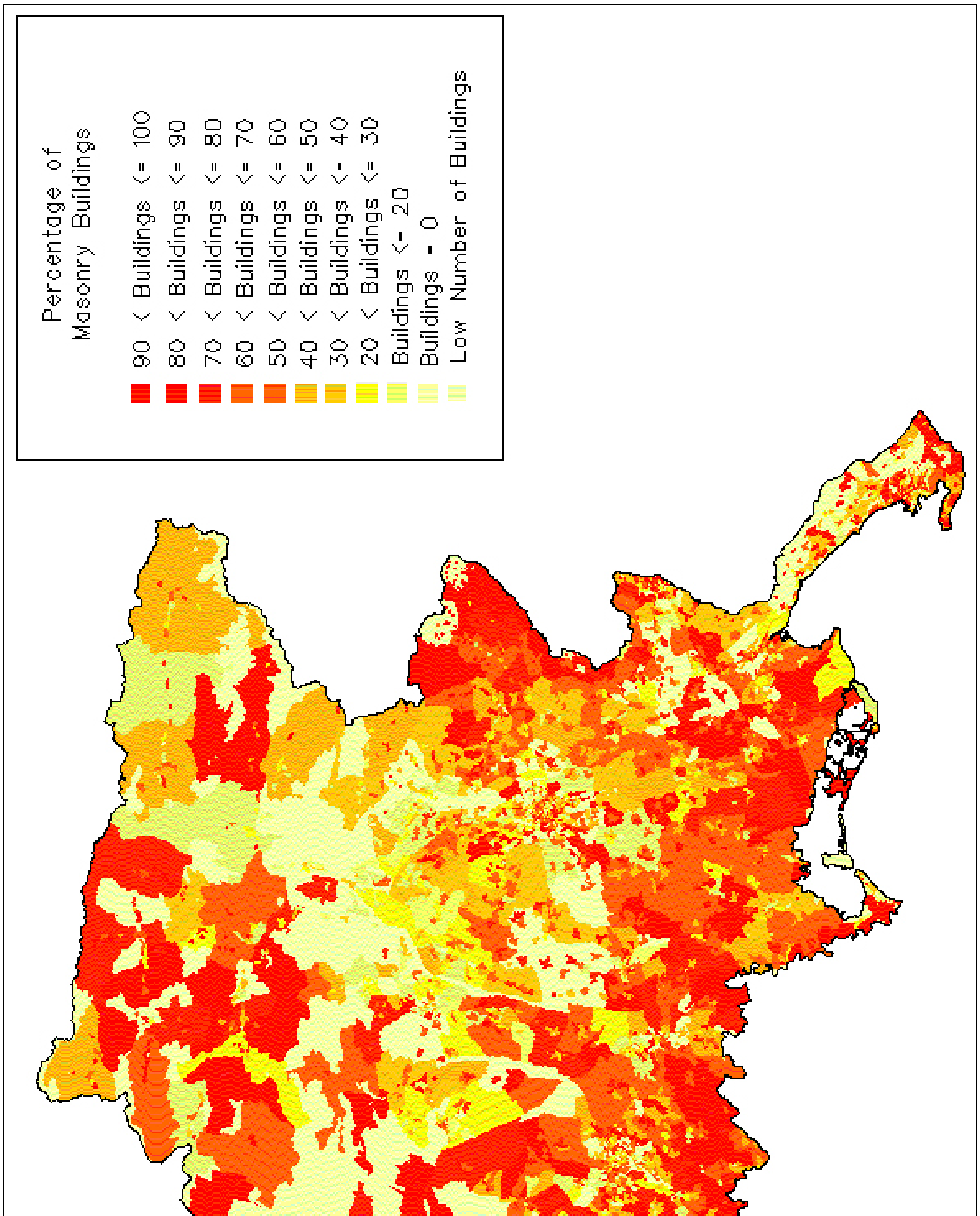

Fig. 5 - The distribution of the percentage of masonry buildings in the Friuli-Venezia Giulia region. A value is given for every census area.

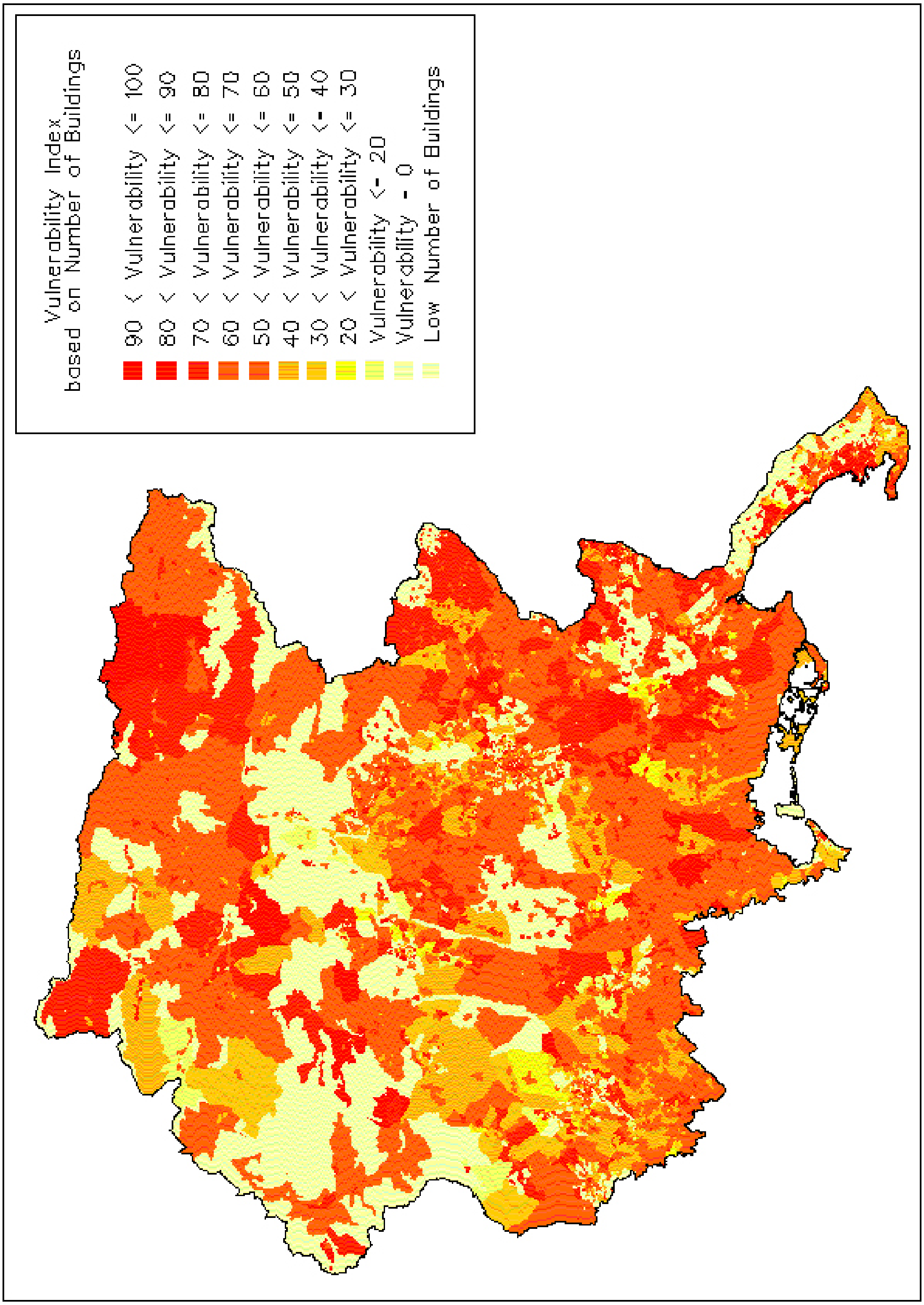

Fig. 6 - Vulnerability Index for masonry buildings in the Friuli-Venezia Giulia region. A value is given for every census area.

the DAF's and the one coming from the periodic ISTAT censuses, we proceeded to statistically evaluate the differences in their behaviour under seismic action. From these comparisons six statistically significantly different classes have been selected. Once mapped to vulnerability classes, they allow us to highlight the most vulnerable typologies. The next step in this direction will be the creation of a vulnerability map for the Friuli-Venezia Giulia region at different degrees of detail. At the most detailed level, vulnerability evaluation is based on the availability of information for each building or structural aggregate. At the other end, a less detailed vulnerability map can be furnished based only on statistical data that identify the structural behaviour for different building typologies, such as in Fig. 6. The application of GIS techniques allows the integration of these data with other information such as, for instance, administrative subdivisions, already available on numerical maps.

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References

Giorgetti F.; 1976: *Isoseismal map of the May 6, 1976 Friuli earthquake*. Boll. Geof. Teor. Appl., **19**, 707-714.

GNDT; 1993: *Rischio sismico di edifici pubblici. Parte I: Aspetti metodologici*. Gruppo Nazionale Difesa dai Terremoti, CNR, Roma.

Grandori G., Guagenti E. and Petrini V.; 1984: *On the use of renewal processes in sesimic hazard analysis*. In: Proceedings of 8th World Conference on Earthquake Engineering, San Francisco, 1, pp. 287-294.

Grandori G., Garavaglia E. and Petrini V.; 1991: *Analysis of some of the uncertainties in the statistical elaboration of historical data for local seismic hazard evaluation*. In: Proceedings of 6th International Conference on Application of Statistics and Probability in Civil Engineering, Mexico City.

Hays W., Mohammadioun B. and Mohammadioun J. (eds); 1998: *Seismic zonation: a framework for linking earthquake risk assessment and earthquake risk management*. Ouest Editions, Paris, 160 pp.

Picco E.; 1997: *La tipologia edilizia come parametro significativo per la definizione della vulnerabilità sismica su scala territoriale: analisi del comportamento degli edifici danneggiati dal terremoto del 1976 in Friuli*. Tesi di Laurea, a.a. 1995/96, Facoltà di Ingegneria, Università degli Studi di Udine, 216 pp.

Riuscetti M., Carniel R. and Cecotti C.; 1997: *Seismic vulnerability assessment of masonry buildings in a region of moderate seismicity.* Annali di Geofisica, **40**, 1405-1413 .

Riuscetti M., Carniel R., Cecotti C., Chiarandini A., Grimaz S., Iacop F. and Petrini V.; 1999: *Convenzione con la Direzione Regionale della Protezione Civile per la realizzazione della Mappa del Rischio Sismico per la regione Friuli - Venezia Giulia*. Relazione scientifica di sintesi, Dipartimento di Georisorse e Territorio, Università di Udine, 2 vols, 171 + 215 pp.

Sandi H.; 1986: *Report of the Working Group "Vulnerability and risk analysis for individual structures and systems" of the European Association of Earthquake Engineering*. In: Proceedings of 8th European Conference on Earthquake Engineering, Lisbon.