Bulletin of Earthquake Engineering **1:** 115–140, 2003.

Earthquake Damage Scenarios of the Building Stock of Potenza (Southern Italy) Including Site Effects

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Received 10 September 2002; accepted 6 February 2003

Abstract. Damage scenarios relevant to the building stock of the town of Potenza, Southern Italy, are presented. A procedure for the preparation of scenarios has been purposely set up. In the first step, the inventory of the building stock has been made. Location and characteristics of buildings have been obtained from a survey carried out after the 1990 Potenza earthquake and further updated in 1999. In the second step, the absolute vulnerability of the buildings has been evaluated. A hybrid technique has been used, where typological analyses and expert judgement are combined together. Beyond the classes of vulnerability A, B and C of the MSK scale, the class D of EMS98 scale, for the less vulnerable buildings, has been considered. The third step has been the selection of the reference earthquakes by including also local amplification effects. Two events with 50 and 475 years return periods have been chosen as representative, respectively, of a damaging and of a destructive seismic event expected in Potenza. The sites that may exhibit important amplification effects have been identified using the first level method of the TC4 Manual. Damage scenarios of dwelling buildings have been prepared in the fourth step and reported in a GIS. They are relevant to the selected reference earthquakes, taking into account or not site effects. The generally low vulnerability of buildings results in a limited number of damaged buildings for the lower intensity earthquake, and of collapsed buildings, for the higher intensity earthquake. The influence of site effects on the damage distribution is significant.

Key words: building, damage probability matrix, damage scenario, earthquake engineering, seismic vulnerability, site effects

1. Introduction

Almost half of the world population presently lives in urban areas. Recent earthquakes (Northridge 1994, Kobe 1995, Turkey 1999, Taiwan 2001) showed that seismic areas with concentrated population, buildings and infrastructures are highly exposed to human and economical losses environments. The reduction of seismic risk of these areas, therefore, is of primary concern in a global policy of risk mitigation. Many questions, however, are to be faced, among others:

- setting up emergency plans for the immediate consequences of a seismic event;
- planning prevention policies for a medium-long term mitigation;
- setting up tools to forecast losses in a multi- disciplinary as well as practical way.

To this purpose, seismic scenarios can be a very powerful tool. Whereas in risk analysis the probability of losses over a specified period of time due to all the possible arriving earthquakes is calculated, in a seismic scenario the impact of a given earthquake is investigated and quantified. The former representation is very general but presents many drawbacks such as the difficulty of interpreting the results in practical terms and the difficulty of expressing and quantifying losses in highly dynamical systems, as the territorial systems. On the contrary, with the scenario approach, the behaviour of the built environment under study when subjected to an earthquake can be better studied and understood and effective countermeasures can be more easily identified (Dolce, 1996).

In the last years, many studies (e.g., Barbat *et al.*, 1996; D'Ayala *et al.*, 1997; Esteva, 1997; Fah *et al.*, 2001) as well as many research projects, both in national (e.g., in Italy, Catania project and Potenza project) and in international frameworks (e.g., RISK-UE project, ENSeRVES project, RADIUS project) have dealt with earthquake scenarios. Further, in the United States a software package named HAZUS was produced by FEMA (Federal Emergency Management Agency) and NIBS (National Institute of Building Standards) for the estimation of regional losses due to earthquake hazard, working in a Geographic Information System (GIS) environment (Whitman *et al.*, 1997).

Among the Italian projects, a particular prominence has the so-called Catania project (Faccioli *et al.*, 1999). It was funded by the Italy's Department of Civil Protection and performed by the Italian Group for the Defence against Earthquakes (GNDT). Main objective of this three-years project was to prepare damage scenarios for the city of Catania, located in Eastern Sicily (Southern Italy) with a population of 500,000 inhabitants. The main results of the project are provided in a GIS environment (see http://emidius.itim.mi.cnr.it/GNDT/home.html). Particularly remarkable are the predicted ground motion and building damage maps.

Aimed at adapting the software HAZUS to the characteristics of European seismic risk assessment (e.g. different building types), a project named RISK-UE (An advanced approach to earthquake risk scenarios with application to different European towns) has been financed by the European Commission and is presently in progress (see http://www.risk-ue.net). Many research centres of 7 European countries (France, Italy, Romania, Spain, Greece, FYROM, and Bulgaria) are involved in the project, whose main objective is to develop a general and modular methodology to create earthquake-risk scenarios specifically relevant to European towns. After an evaluation of the various European distinctive features, the methodology purposely developed in the project will be applied to seven European cities. Also involving emergency rescue, civil defence and other public authorities interested in risk reduction, a Risk Management Plan should be set up.

An international project named RADIUS (Risk Assessment Tools for Diagnosis of Urban Areas against Seismic Disasters) was launched by the secretariat of the International Decade for Natural Disaster Reduction (IDNDR, 1990–2000) in 1996, with financial and technical assistance of the Government of Japan. It aimed to promote worldwide activities for reduction of seismic disasters in urban areas, particularly in developing countries. Nine case-study cities all over the world were selected and studied to develop earthquake damage scenarios and action plans to reduce seismic risk, involving decision makers, local scientists, local government officers, representatives of the communities, and mass media. Based on the experiences of the case studies, practical tools for earthquake damage estimation were developed. A comparative study to understand urban seismic risk in the world was also conducted.

A network project, named ENSeRVES (European Network on Seismic Risk, Vulnerability and Earthquake Scenarios), was financed by the European Commission in 1997, within the INCO-Copernicus program and promoted by the European Association of Earthquake Engineering (Task Group 3 – Seismic Risk and Earthquake Scenarios). ENSeRVES gathered teams of scientists of different disciplines (Seismologists, Geologists, Engineers, Architects, ...) involving 11 prominent Institutions working on Earthquake Engineering and Seismology from 10 EU and CCE countries. The main objectives of the ENSeRVES Project were: (i) comparing seismic hazard, vulnerability and building damage assessment procedures used in various countries, (ii) improving and extending vulnerability assessment procedures for buildings through the integration of different approaches, (iii) reaching consensus on some unified approach to vulnerability assessment, (iv) comparing and developing methodological aspects of earthquake scenarios, (v) examine problems of earthquake protection at urban scale. More details on this Project can be found in (Dolce *et al.*, 2000a, 2002).

Earthquake scenarios can be referred to different kinds of damage and losses, such as damage to constructions (buildings, bridges, etc.), casualties, economic losses due to interruption of activities, social losses, etc. However the first step for any earthquake scenario is the evaluation of the damage to constructions, particularly to buildings. The preparation of a damage scenario of buildings requires pieces of information regarding (Dolce, 1996):

– inventory of the buildings of interest;
– absolute vulnerability of the buildings of interest;
– characteristics of ground shaking including possible site effects.

An inventory of buildings shall include information regarding position and geometrical-qualitative characteristics and/or mechanical-quantitative characteristics, according to the type of vulnerability evaluation to be carried out. It can be based on several sources of information, such as historical analysis, population census, aerial photogrammetry, field inspection, local expert interviews, and technical documentation.

Historical analysis can provide very useful information on age and structural characteristics of a building, on current practice at the time of construction and of transformations undergone during its lifetime, on seismic history. Population census gives geographical references, poor qualitative data (e.g., plan shape and size of each apartment, number of stories, age) and, possibly, some rough information on structural characteristics. Aerial photogrammetry also gives geographical references and poor qualitative data (e.g., plan shape and size, number of stories). If complemented with information drawn from historical analyses, field inspections or local expert interviews, information on age and structural characteristics of individual buildings can also be obtained. Field inspection gives geographical, geometrical-qualitative and, even, mechanical quantitative data. Local expert interviews provide qualitative information on age, structural characteristics, current construction practice and typical transformations (restoration, strengthening) (Dolce *et al.*, 1999). Finally, technical documentation provides geometrical-qualitative and, even, mechanical-quantitative data on structural materials and elements.

The seismic vulnerability of a building can be defined as its proneness to be damaged by an earthquake. Based on a quantitative assessment of seismic vulnerability, the probability of damage to given building types caused by earthquakes of various intensities can be predicted. This is a key step in the preparation of seismic scenarios, as economic losses (direct, repair costs, indirect, interruption of economical activities) and casualties are strongly correlated to structural types and their expected damage.

Seismic vulnerability can be assessed by making use of different techniques: Direct, Indirect and Conventional (Corsanego and Petrini, 1990; Dolce, 1996). The choice depends mainly on the level of information available and on the extension of the area under examination. Among others, direct typological and direct mechanical techniques are widely used in Italy.

Direct typological techniques are based on data collected during field inspection. After a seismic event, the site of a damaging earthquake can be thought as a full-scale laboratory model where remarkable discoveries may be made (Ambraseys, 1998). Particularly, the performances of engineered structures can be observed and analysed, so that the real behaviour can be compared with the theoretical one. However, survey data hardly ever can provide a complete set of data for vulnerability of buildings. This is mainly due to the limited number of damaging earthquakes and to the high number of structural types often present in a building stock (Dolce *et al.*, 1997). On the other hand, direct mechanical techniques, based on numerical simulations, are strongly conditional on the characteristics of the structures being examined and of the selected seismic input. Also, problems can arise in the evaluation of damage, as there is no clear connection between the mechanical damage parameters and the ‘real’ damage, both structural and economical. For these reasons, hybrid techniques that combine elements of the above said methods with expert judgement are also common.

In the evaluation of the characteristics of ground shaking, two aspects are of fundamental importance:

- selection of the reference earthquake (ground motion at bedrock);
- evaluation of possible site effects.

The ground motion at bedrock can be assessed on the basis of seismic regional features, by applying attenuation laws that consider the distance of the site from seismic sources. A maximum probable or maximum credible earthquake is considered with a best guess location, based on known geological faults or seismic source zones (Coburn and Spence, 1992), where the selection of the reference earthquake is usually made by geologists and seismologists, based on hazard analysis only. Lately, alternative methods for the selection of scenario earthquakes have been proposed based on the concept of perceptibility of seismic events (Burton, 1990; Goretti, 2000).

The observation of damage after a seismic event emphasises that the influence of the induced effects in the soil foundation, such as amplification, landslides and liquefaction must be considered (microzonation analysis), when preparing a damage scenario. The objective of a microzonation analysis is to define the areas characterised by a homogenous seismic response. Geologic, geomorphologic and seismo-stratigraphic conditions of the area under examination have to be examined, in order to evaluate if amplification phenomena of the seismic wave amplitude (with respect to the reference conditions of bedrock) or permanent deformations (due to landslides or liquefaction) may be induced. To this purpose, a great amount of data is requested, as well as different analyses and modelling, whose results are reported in a map of engineering use, at a scale which is a function of the demanded surveying accuracy level. The analyses of site effects permit to define the characteristics of the expected ground motion at a site, given the characteristics of ground motion at bedrock.

In this paper, the problems to be faced when preparing damage scenarios are discussed and solved, with reference to the town of Potenza in Southern Italy. Potenza is located in the Southern Apennines and has currently 70,000 inhabitants (2001 Italian Census). Its territory is considered to be a zone of moderate-high seismic activity. Presently, it is classified in medium seismic zone, according to the Italian Seismic Code (D.M. LL.PP., 1996), but recent studies and a new classification proposal (see Web site http://www.serviziosismico.it/PROG/1999/proposta_riclass) include Potenza in high seismic zone.

The seismic risk of Potenza has been studied within the so-called ‘Potenza Project’, funded by the Italian National Seismic Agency (SSN) and carried out jointly by the University of Basilicata and SSN. The final aim is to deal with different kinds of problems related to the prediction of the post-earthquake situation concerning costs of repair, casualties, lifelines serviceability, etc., but the attention was, first of all, concentrated on the prediction of damage to buildings, involving all the above mentioned steps. Due to the availability of a large amount of data regarding the building stock, Potenza has also been selected as a case-study within the frame of the ENSeRVES Project.

2. Procedure for the Preparation of the Damage Scenarios

Due to the peculiar characteristics of the data available and to the lack of some information, a specific procedure had to be set up. The main steps of the procedure are as follows:

- completion of the inventory of buildings;
- analysis of building types;
- derivation of Damage Probability Matrices;
- recognition of vulnerability classes;
- evaluation of local amplification effects;
- selection of scenario earthquakes;
- representation of damage scenarios.

The high costs and the long time needed by an inventory of buildings are the most conditioning factors in the preparation of a damage scenario. For this reason, the inventory is frequently based on census data or on rapid visual inspections. On the contrary, in the present study the damage scenario is based on a large inventory of buildings, obtained from a survey carried out after the 1990 earthquake that struck Potenza and its hinterland. The epicentre was located about 3 km North of Potenza and the local magnitude was $M_l = 5.2$ (Azzara *et al.*, 1993). The maximum intensity felt in nearby villages was VII MCS intensity. After that earthquake, a survey on buildings of 41 villages was carried out by local professionals, under the co-ordination of the Regione Basilicata, with the co-operation of the Civil Protection Department and the GNDT. 20 villages (between VI and VII MCS intensity) and the town of Potenza were completely surveyed. The surveyors used the 1^{st} level GNDT90 inspection form, for damage and vulnerability evaluation (GNDT, 1990). About 50,000 buildings were inspected, 12,000 of which were in Potenza. In 1999 that inventory was updated to include the new post-1990 R/C buildings. The updating was carried out by the authors, on the basis of the technical documentation provided by the Municipality of Potenza. In this case too, the data were collected using the 1^{st} level GNDT90 inspection form. About 300 buildings were surveyed, with about 1,500,000 m^3 total volume. The smallest R/C constructions, mainly located in rural zones, were not considered. The database obtained by merging the two surveys provides a complete description of the Potenza building stock.

The characteristics of the 1990 building stock have been analysed in a previous work (Dolce *et al.*, 1997). A large number of different building types were found. The analyses showed poor correlation between structural types and damage, mainly because of the low intensity and the low reliability of the damage assessment. This prevented from the use of a direct typological technique for vulnerability evaluation. For this reason, the vulnerability evaluation is made by using the Damage Probability Matrices (DPM's) set up by Braga, Dolce and Liberatore (Braga *et al.*, 1982). The DPM's of the most common building types were evaluated from the database obtained after the 1980 Southern Italy earthquake, when about 38,000 buildings were surveyed. Only one type of R/C building was considered, due to the lack of detailed data. This approach is currently named, in Italy, 1st level approach and can be considered an application of the Direct Typological Technique (Corsanego and Petrini, 1990). It has to be noted that Braga, Dolce and Liberatore considered and defined the DPM's of only three vulnerability classes, ranging from high (class A) to low vulnerability (class C), according to the characteristics of the buildings surveyed in 1980. In this paper, due to the features of several buildings in Potenza, a further class with lower vulnerability (class D) has been considered. The derivation of the DPM of the vulnerability class D is a critical point of the procedure, and will be described below.

After the execution of an accurate typological analysis of the Potenza buildings stock, each building has been assigned one of the four considered classes of vulnerability, taking into account the following characteristics:

- vertical structural type;
- horizontal structural type;
- eventual retrofitting;
- age (before or after the seismic classification of the area, which occurred in 1981).

As far as the scenario earthquakes are concerned, two events have been selected, being representative of a damaging event and of a destructive event expected in Potenza.

To include site effects, a microzonation analysis has been carried out according to the specifications of the Manual for Zonation on Seismic Geotechnical Hazard (TC4-ISSMFE, 1999), where methods for assessing local ground amplification, soil instability and liquefaction are proposed. Three different levels of zonation, in relation to the extension of the area and to the type and the accuracy level of the data available are suggested in the Manual. Due to the characteristics of the available data in the whole Potenza territory, the first level method has been applied in the present paper.

Finally, data, results and cartographic maps have been organised in a GIS (Arc/Info Esri Inc.). Analysis, manipulation and restitution of geographical data can be carried out on a GIS, managing vectorial data, raster images (photographs, documents or images from satellite) and tables in a single integrated environment.

3. Classification of Building Types

The vulnerability evaluation has been preceded by a classification of the buildings types, mainly based on the field survey carried out after the 1990 earthquake. Beyond damage data, geometrical and qualitative characteristics were collected, such as height, plan and elevation configurations, age, type of vertical and horizontal structures, type of foundation and of roof, retrofitting, state of preservation, etc.

The property of buildings is mostly private (about 95%), as well as their use, as shown in Table 1, where the relevant distribution in terms of number of buildings

Table I. Distribution of buildings according to their use.

Use	**Distribution** [%]
Dwelling buildings	29.05 %
Production buildings	49.90 %
Mixed buildings	19.25 %
Public services	1.80 %

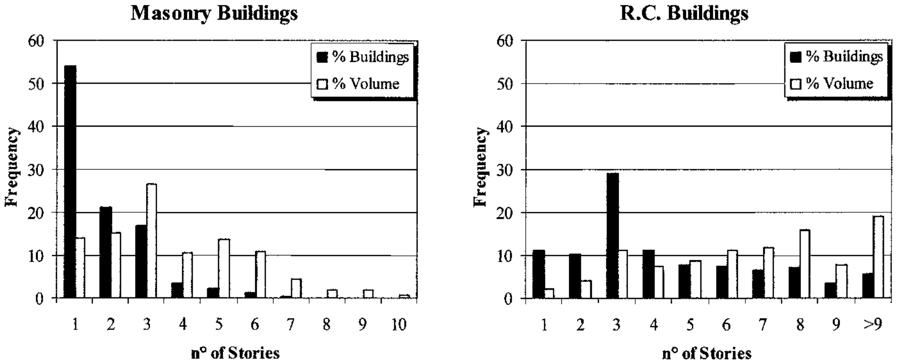

Figure 1. Number of stories: frequency distribution of masonry and R/C buildings.

is reported. It has to be noted the abnormal percentage of the buildings used for production activities. Actually, in many cases, these are very small constructions separated from the main building and used as agricultural warehouses or garages. More details on the characteristics of the building stock obtained from the 1990 survey can be found in (Dolce *et al.*, 1997).

Due to the small amount and to the peculiarities of the public buildings, only the private building stock will be considered. The composition of the private building stock is completely different if the number or the volume of the buildings is considered. In terms of number of buildings, the sample is mostly made of masonry (75%) rather than R/C structures (25%). On the contrary, in terms of volume there is a strong prevalence of R/C (70%) on masonry structures (30%).

The distribution of the number of stories for masonry and R/C buildings is shown in Figure 1, in terms of both number and volume of buildings. As expected, more than 95% of the masonry buildings have less than 3 stories.

The anomalous high frequency of the 1-story buildings confirms the large number of small masonry constructions (agricultural warehouses and garages). For R/C buildings, on the contrary, the number of buildings is almost uniformly distributed between 1 and 9 stories, with just a peak for the 3 storey category, which accounts for about 30% of the entire R/C group.

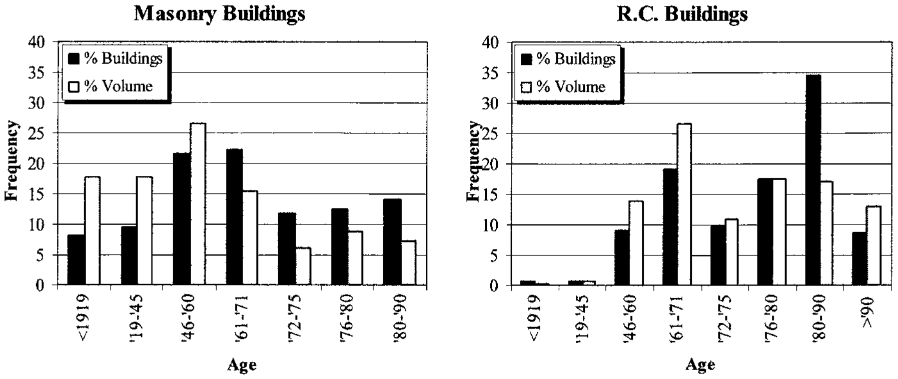

Figure 2. Age: frequency distribution of masonry and R/C buildings.

The distributions of both groups of buildings appear quite different if the volume is compared to the number of buildings. As expected, the consideration of the volume produces an increase of the frequency values for high-rise buildings and a decrease for low-rise buildings, with respect to the corresponding values related to the number of buildings.

Figure 2 shows the distribution of the age of masonry and R/C buildings. Obviously, old masonry buildings (pre ′60–′70s) prevail on new ones, while post-war R/C buildings account for almost hundred percent of the R/C population.

1980 was a key year for construction engineering in Potenza, as after the 1980 Irpinia earthquake the area of Potenza was classified as seismic zone for the first time. For this reason, two major periods have to be considered in the classification of buildings, i.e., pre-1980 and post-1980. In fact, all buildings (both R/C and masonry) designed after 1980 are seismic resistant, according to the Italian regulations. Another important consequence of the 1980 earthquake is the retrofit of a large number of constructions.

Some remarks can be made by considering separately masonry and R/C structures, and by categorising them according to the period of construction, the retrofit, if any, and the position of buildings in urban or rural zone.

In Tables 2 and 3 the results obtained with the aforementioned categorisation are reported.

Table 2 shows that a large number of masonry buildings (7,020 out of 8,925) are built in rural zones, whereas R/C buildings are more numerous in urban zones, with a significant presence also in the historical centre. This distribution of building types in the territory of Potenza is mainly due to politic decisions on the town-planning development taken after the II World War. In urban zones, new buildings, often public housing, were always constructed with R/C structure. Moreover, between 1945 and 1970, many old masonry buildings in the historical centre were demolished and replaced by new R/C buildings. On the contrary, in rural zones, masonry was widely used until the ′80s.

Table II. Distribution of number and volume of masonry buildings.

	Pre-1980 Buildings				Post-1980 Buildings		Total Buildings	
	Not retrofitted		Retrofitted					
	No. Build.	Volume	No. Build.	Volume	No. Build.	Volume	No. Build.	Volume (m^3)
Rural Zone	5,343	1,615,701	520	297,001	1,157	321,439	7,020	2,234,141
Urban Zone	1,393	1,644,075	392	943,697	120	42,689	1,905	2,630,461
Total	6,736	3,259,776	912	1,240,698	1,277	364,128	8,925	4,864,602

Table III. Distribution of number and volume of R/C buildings.

	Pre-1980 Buildings				Post-1980 Buildings		Total Buildings	
	Not retrofitted		Retrofitted					
	No. Build.	Volume	No. Build.	Volume	No. Build.	Volume	No. Build.	Volume (m^3)
Rural Zone	434	833,964	68	69,889	803	940,263	1,305	1,844,115
Urban Zone	976	5,406,731	249	1,770,617	491	2,503,962	1,716	9,681,310
Total	1,410	6,240,694	317	1,840,506	1,294	3,444,225	3,021	11,525,425

As noted above, a strong difference between the distributions of number and volume of masonry and R/C buildings appears, by examining the last two columns of Tables 2 and 3. Actually, R/C buildings typically have a higher number of stories than masonry buildings, so that their average volume is larger (3,815 m^3 against 545 m^3). This is evident both in the urban zone (5,745 m^3 for R/C against 1,380 m^3 for masonry) and in the rural zones (1,415 m^3 for R/C against 318 m^3 for masonry). The very low average volume of masonry buildings in rural zones is due to a large number of very small constructions (typically having average area less than 25 m^2) used as agricultural warehouses or garages. These very small constructions are excluded in the following analyses so that the average volume of masonry buildings in rural zones rises to 732 m^3.

Tables 2 and 3 show also a limited presence of seismic resistant (retrofitted and post-1980) buildings. In terms of number, seismic resistant buildings are only 32% of the total (25% for masonry, 54% for R/C). However, it should be noted that the actual situation is somewhat better, as these data go back to 1990, whereas in the '90s many more buildings, mostly with masonry structure, have been retrofitted.

4. Derivation of Damage Probability Matrices

The definition of vulnerability classes has been made according to the Damage Probability Matrices (DPM's) set up after the 1980 strong earthquake (Braga *et al.*, 1982), based on the relevant damage data. They are shown in Tables 4a, b, c.

Three vulnerability classes (high A, medium B and low C), mostly relevant to buildings without any seismic provision, were considered. As said above, the structures built or retrofitted after 1980 should be considered as earthquake-resistant structures. Therefore, if from a historical and geographical point of view the data used by Braga *et al.* (1982) and then the derived DPM's, are consistent with the inventory under examination, a particular attention has to be devoted to the remarkable evolution of the building stock in the last 20 years. For this reason, a further class with smaller vulnerability (class D) relevant to earthquake-resistant or

Table IVa. Damage Probability Matrix for buildings of vulnerability class A.

	Damage grade					
Intensity	0	1	2	3	4	5
VI	0.188	0.373	0.296	0.117	0.023	0.002
VII	0.064	0.234	0.344	0.252	0.092	0.014
VIII	0.002	0.020	0.108	0.287	0.381	0.202
IX	0.000	0.001	0.017	0.111	0.372	0.498
X	0.000	0.000	0.002	0.030	0.234	0.734

Table IVb. Damage Probability Matrix for buildings of vulnerability class B.

Intensity	Damage grade					
	0	1	2	3	4	5
VI	0.360	0.408	0.185	0.042	0.005	0.000
VII	0.188	0.373	0.296	0.117	0.023	0.002
VIII	0.031	0.155	0.312	0.313	0.157	0.032
IX	0.002	0.022	0.114	0.293	0.376	0.193
X	0.000	0.001	0.017	0.111	0.372	0.498

Table IVc. Damage Probability Matrix for buildings of vulnerability class C.

Intensity	Damage grade					
	0	1	2	3	4	5
VI	0.715	0.248	0.035	0.002	0.000	0.000
VII	0.401	0.402	0.161	0.032	0.003	0.000
VIII	0.131	0.329	0.330	0.165	0.041	0.004
IX	0.050	0.206	0.337	0.276	0.113	0.018
X	0.005	0.049	0.181	0.336	0.312	0.116

retrofitted buildings, has been derived from the above mentioned DPM’s and from EMS98 scale (ESC, 1998), according to the criteria explained below.

To define the intensity degrees, EMS98 provides some quantities (Few, Many or Most) for the number of differently damaged buildings for different types of structures. From them, ‘linguistic’ damage matrices can be derived. Starting from such quantities, DPM’s can be estimated by assuming reasonable hypotheses on the continuity of damage distribution on less damaged and undamaged buildings (Bernardini, 1998). This procedure requires firstly a quantitative estimation of the ‘linguistic’ values given in EMS98. Applying the fuzzy sets theory (Bernardini, 1998), the following assumptions are made: Few $\approx$ All/12, Many $\approx 4 \times$ Few, Most $\approx 2 \times$ Many.

In Tables 5a and 5b the matrices relevant to vulnerability classes C and D, thus obtained, are reported. They show that, by scaling one intensity degree (from VI–IX to VII–X), the same damage distributions for the classes C and D are obtained. Based on this consideration and assuming a more continuous distribution for Intensity VI, the DPM of class D can be extrapolated from the already available DPM of class C, as shown in Table 6.

Table Va. Linguistic damage matrices for vulnerability class C buildings, according to EMS98 (values within brackets are not explicitly provided by EMS98).

Intensity	Damage grade					
	0	1	2	3	4	5
VI	(All-Few)	Few	(None)	(None)	(None)	(None)
VII	(Most-Few)	(Many)	Few	(None)	(None)	(None)
VIII	(Many)	(Many-Few)	Many	Few	(None)	(None)
IX	(Few)	(Few+Few)	(Many)	Many	Few	(None)
X	(Few)	(Few)	(Few)	(Many)	Many	Few

Table Vb. Linguistic damage matrices for vulnerability class D buildings, according to EMS98 (values within brackets are not explicitly provided by EMS98).

Intensity	Damage grade					
0	1	2	3	4	5	
VI	All	None	None	None	None	None
VII	(All-Few)	Few	(None)	(None)	(None)	(None)
VIII	(Most-Few)	(Many)	Few	(None)	(None)	(None)
IX	(Many)	(Many-Few)	Many	Few	(None)	(None)
X	(Few)	(Few+Few)	(Many)	Many	Few	(None)

In all the above considerations, reference has been made to a qualitative definition of damage, according to the specifications given in the MSK and EMS98 scales. They assume 5 grades of damage, beyond the null damage, as defined in Table 7. Consequently, also the damage scenarios are provided in terms of qualitative damage, according to the 5 damage grades of EMS.

5. Recognition of Vulnerability Classes

After setting up DPM's, the next step is the recognition of a structural type for each building. It is worth noting that the structural characteristics of masonry buildings often change from one story to another (e.g. vaults at the first story, wooden floors at the upper stories). Moreover, the survey form used in 1980 is different from the GNDT90 form. The number of vertical and horizontal structural types considered in this latter was very high, so that some simplifications were needed to make the information of the two forms comparable. Firstly the practical difficulty to distinguish from one type to another in a quick field inspection was considered. Secondly, the vertical and horizontal types exhibiting comparable seismic behaviour were grouped together. Thus doing, four vertical types have been obtained.

Table VI. Extrapolated Damage Probability Matrix for buildings of vulnerability class D.

Intensity	Damage grade					
	0	1	2	3	4	5
VI	0,900	0,090	0,010	0,000	0,000	0,000
VII	0,715	0,248	0,035	0,002	0,000	0,000
VIII	0,401	0,402	0,161	0,032	0,003	0,000
IX	0,131	0,329	0,330	0,165	0,041	0,004
X	0,050	0,206	0,337	0,276	0,113	0,018

In Table 8 the link between the various vertical structural types defined in the GNDT90 form and those defined in the DPM's is reported. The first three types, relevant to masonry, are defined with regard to the general quality of masonry, and are considered equivalent to the types defined in the original DPM's (respectively field stone masonry, hewn stone masonry and brick masonry).

Also for the horizontal types unification was made. In Table 9 the link between the horizontal structural types considered in the GNDT90 form and those defined in the DPM's is shown.

According to the combination of the above defined vertical and horizontal structural types, each building is classified in one of the four vulnerability classes. When a variation of the structural characteristics along the height is observed, the most vulnerable vertical and horizontal types are considered. Information on age and eventual retrofitting are used to classify seismic resistant (after 1980) and retrofitted buildings (both R/C and masonry buildings) in vulnerability class D.

The final result of the vulnerability evaluation procedure is reported in Table 10, where the vulnerability class is specified for each building type. The statistical distributions of the vulnerability classes of all the private buildings of Potenza are shown in Figure 3.

Private buildings, whose total considered number is 10,670, exhibit globally a low vulnerability, as classes C and D account for about 65% in terms of number of buildings and about 90% in terms of volume.

6. Evaluation of Site Effects

Local relations were not available between seismic motion parameters and surface geology data. Consequently, reference has been made to the empirical relations reported in the technical literature. In particular, the Medvedev method (Medvedev, 1962) has been chosen, where the differences of local seismic site effects are attributed to the various soil rigidity in the first 10 m depth. The increments of

Table VII. Classification of damage according to EMS 98 (SD=Structural Dam., N-SD=Non-Struct. Dam.).

Damage grade	Definition	Notes	
		Masonry buildings	RC buildings
0	No damage	–	–
1	Negligible to slight damage (No SD, slight N-SD)	Hair-line cracks in very few walls, fall of small pieces of plaster only, fall of loose stones from upper parts of buildings in very few cases.	Fine cracks in plaster over frame members or in walls at the base, fine cracks in partition and infills.
2	Moderate damage (Slight SD, moderate N-SD)	Cracks in many walls, fall of fairly large pieces of plaster, partial collapse of chimneys.	Cracks in columns and beams of frames and in structural walls, cracks in partitions and infill walls, fall of brittle cladding and plaster, falling mortar from the joints of wall panels.
3	Substantial to heavy damage (Moderate SD, heavy N-SD)	Large and extensive cracks in many walls, roof tiles detach, chimneys fracture at the roof line, failure of individual non-structural elements (partitions, gable walls).	Cracks in columns and beam joints of frames at the base and at joints of coupled walls, spalling of concrete cover, buckling of reinforced rods, large cracks in partition and infill walls, failure of individual infill panels.
4	Very heavy damage (Heavy SD, very heavy N-SD)	Serious failure of walls, partial structural failure of roofs and floors.	Large cracks in structural elements with compression failure of concrete and fracture of rebars, bond failure of beam reinforced bars, tilting of columns, collapse of a few columns or of a single upper floor.
5	Destruction (Very heavy SD)	Total or near total collapse	Collapse of ground floors or parts of buildings.

Table VIII. Link between Vertical Types of GNDT90 survey form and of DPM's.

Vertical types (GNDT90 survey form)	Vertical type (DPM's)
Not squared stone Masonry, 'Sacco' Masonry, Rubble stone Masonry	Bad quality masonry
Not squared stone, 'Sacco' and Rubble stone Masonry with brick reinforcements	Medium quality masonry
Concrete block Masonry, 'Tufo' blocks Masonry, Brick Masonry	Good quality masonry
R/C Frames with and without infills, R/C walls	Reinforced concrete

Table IX. Link between Horizontal Types of GNDT90 survey form and of DPM's.

Horizontal types (GNDT90 survey form)	Horizontal type (DPM's)
Vaults with/without tie beams, mixed vaults-floors with/without tie-beams	Vaults
Wooden beams with/without tie-beams, pushing wooden, pushing mixed	Wooden floors
Steel beams with/without tie-beams, pushing steel beams	Steel floors
R/C floors and slabs	R/C floors

Table X. Definition of classes of vulnerability.

Horizontal structures	Vertical structures			
	Bad quality masonry	Medium qual. masonry	Good qual. masonry	R/C
Vault / mixed vault floors	A	A	A	
Wooden beam with/without tie beams	A	A	B	
Steel floors with/without tie-beams	B	B	C	
R/C floors and slabs	B	C	C	C
Seismic resistant & retrofitted buildings	D	D	D	D

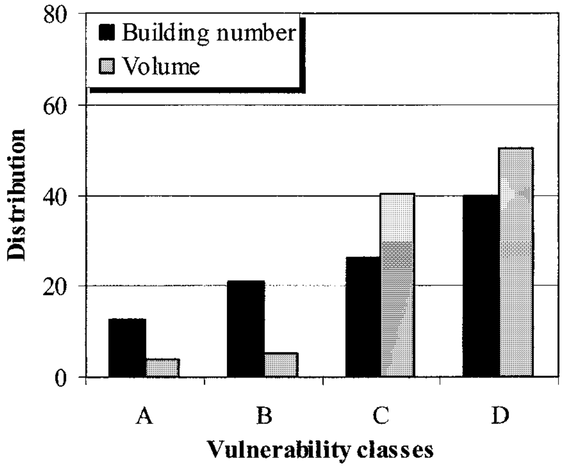

Figure 3. Distribution of classes of vulnerability of the private building stock of Potenza.

Table XI. Increments of macroseismic intensities according to Medvedev method.

Soil	ΔI (MSK scale)
Granite	0
Limestone, sandstone, shale	0.2 ÷ 1.3
Gypsum, marl	0.6 ÷ 1.4
Alluviums (gravels and stones)	1.0 ÷ 1.6
Sands	1.2 ÷ 1.8
Clay	1.2 ÷ 2.1
Uncontrolled fill	2.3 ÷ 3
Soil saturated (gravels, sands, clay)	1.7 ÷ 2.8
Uncontrolled fill and soil layers under ground water table	3.3 ÷ 3.9

macroseismic intensity are expressed in MSK scale and are inversely proportional to the soil rigidity (Table 11).

As shown in the geological map of the whole Potenza territory (Dolce *et al.*, 2000b), the geology of the municipal area of Potenza is made of a large number of units:

(1) *Cretaceous - Oligocene* (Cretaceous Unit): flysch galestrino, siliceous and calcareous marl, rey green clay and marl.

(2) *Oligocene - Miocene* (Tertiary Unit): unit of Paola Doce (clay, clay and marl), tufiti of tusa (clay,;rey green clay and marl, white marl), unit of Corleto Perticara (white marl, clay, grey green clay and marl), red flysch auctt.

Table XII. Increments of MSK intensities for Potenza soils according to Medvedev method.

Litotype	ΔI (MSK scale)
Flysch galestrino	1 average value for marls
Grey green clay and marl; Unit of Paola Doce; Tufiti of tusa, Unit of Corleto Perticara.	1.2 minimum value for clays
Red Flysch auctt, Altavilla unit	0.7 average value for limestones and sandstones
Ariano unit (concrete stones)	1.3 average value for sands
Ariano unit (sandy) Sand gravel alluviums, sand lime clay colluviums	1.5 average value for sands and clays
Sandy concrete stones	0.2 minimum value for sandstones and limestones
Sandy Lime debris	2.2 average value for saturated soils
Uncontrolled fill	3.0
Landslide debris	not considered

(3) *Pliocene Unit* (Tertiary Unit): Altavilla unit (limestone chalky sandstone, stratified sandstone, concrete stones), Ariano unit (sandy concrete stones).
(4) *Holocene* (Quaternary Unit): Sandy concrete stones, gravel alluviums, sand lime clay colluviums, landslide debris.

The macroseismic increments evaluated by applying the Medvedev method are reported in Table 12.

The map of increments of macroseismic intensity is reported in Figure 4. It shows a vast area, which includes the urban development of the town, where the increment of intensity ranges from 1.2 to 1.5. In the historical centre of Potenza the increment of intensity is equal to 0.2. The intensity increment ranges from 1.5 and 3 in some specific areas, due to the presence of filling soil.

The map of Figure 4 was used to evaluate the intensity increment within each census tract to prepare the damage scenarios. It has to be said that first level methods, based only on surface geological, provide qualitative results. However, in (Dolce *et al.*, 2000b) a comparison with the results of a second level approach,

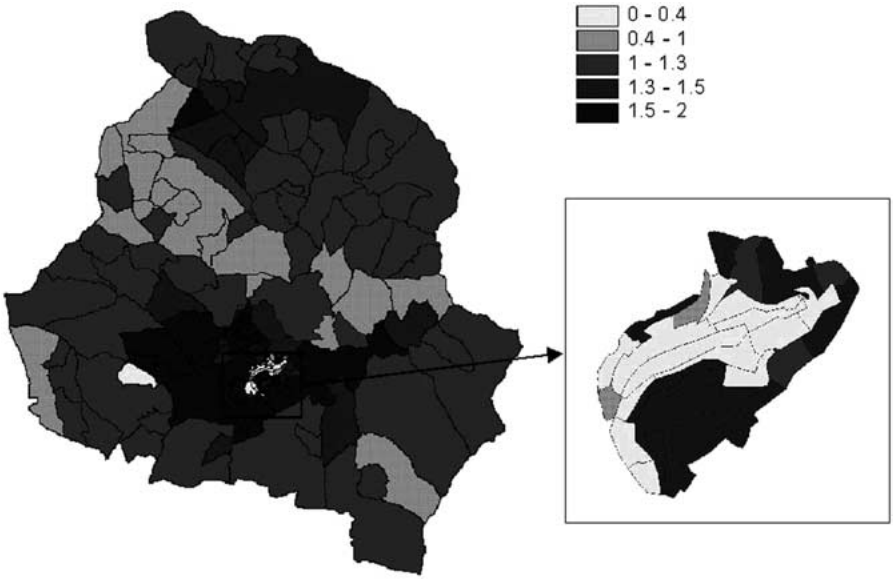

Figure 4. Map of increments of MSK intensities.

carried out on a limited area of Potenza, where more detailed data are available, has shown a quite good consistency.

7. Selection of Scenario Earthquakes

In this study two deterministic events have been selected with reference to 50 and 475 years return periods, respectively. The intensities of these earthquakes have been obtained from the 'New seismic hazard maps of the Italian territory' (Albarello *et al.*, 1998). They are the main result of a wide project of seismic hazard assessment of the Italian territory carried out by GNDT and SSN jointly. Three main tasks were tackled in that project (Slejko *et al.*, 1998): (i) compilation of an earthquake catalogue and a seismological database, (ii) preparation of the map of the Seismogenic Zones (SZ), (iii) assessment of hazard by probabilistic methodologies. A new earthquake catalogue GNDT-NT4.1 (Camassi and Stucchi, 1996), expressly designed for hazard purposes, was prepared. It contains 2421 earthquake records, relevant to the time period 1000–1980, having epicentral MCS intensity $I_0 \geq$ V–VI or surface wave magnitude $M_s \geq 4.0$. 80 seismogenic zones were identified, which represent the surface projection of one or more seismogenic structures showing similar kinematic behaviour and rupture mechanisms (Slejko *et al.*, 1998). Hazard maps were prepared with a probabilistic approach based on the Cornell's method (Cornell, 1968). Hazard maps in terms of both Peak Ground Acceleration (PGA) and MCS Intensity were constructed. The Ambraseys relation (Ambraseys, 1995) was used for PGA maps, while the Grandori relation (Grandori *et al.*, 1987) was used for MCS maps. Since DPM's are referred to MSK or EMS intensity, the following relationship between PGA and I_{MSK} has been used (Margottini *et al.*, 1994):

$$I_{MSK} = (1/0.258) * \log_{10}(PGA/2.279) \tag{1}$$

The intensities obtained for the selected reference earthquakes are $I_{MSK} = VI$ and $I_{MSK} = VII–VIII$, respectively, for the events having 50 and 475 years return period. They are assumed uniform values for stiff soil all over the territory of Potenza.

8. Damage Scenarios

The vulnerability, hazard and microzonation data have been geo-referenced and combined in a GIS system, using the ISTAT (Italian Central Statistics Institute) census tracts as elementary cells. For each census tract, a uniform value of the local amplification, ΔI_{MSK}, has been evaluated and considered. On the whole urban territory of Potenza, ΔI_{MSK} turns out to have 1.3 average value, with local values ranging from 0.2 to 2.2.

The comparison between the damage distributions caused by the reference earthquakes with and without soil amplification effects is shown in Figures 5 and 6. Due to the average low vulnerability of the building stock, a limited number of damaged buildings for the lower intensity, and of partially or totally collapsed building, for the higher intensity earthquake, can be generally observed. On the other hand, site effects show a remarkable influence on the damage distribution. For the seismic event with 50 years return period ($I_{MSK} = VI$) just a few percent of buildings, about 10%, have damage grade greater than 1, if site effects are neglected. This percentage increases up to 30%, when considering soil amplification. For the seismic event with 475 years return period ($I_{MSK} = VII–VIII$), the number of partially or totally collapsed buildings ($d \geq 4$) is less than 10%, if site effects are neglected, while it increases up to almost 30%, when considering soil amplification. It is worth noting that, as could be expected on the basis of the soil amplification values, the damage distribution due to the damaging event with site effects is comparable to that one caused by the destructive event without site effects.

To obtain a global evaluation of the damage due to a given intensity, a mean damage index (DI_{med}) is evaluated as follows:

$$DI_{med} = \sum_i (d_i \cdot f_i)/n \tag{2}$$

where d_i is a generic damage grade ($d_i = 1–5$) and f_i is the relevant frequency. The summation is calculated with regards to the $n = 5$ not null damage levels. DI_{med} varies betwen 0 and 1, where $DI_{med} = 0$ means total absence of damage and $DI_{med} = 1$ means total destruction.

For $I_{MSK} = VI$ (50 years return period) DI_{med} turns out to be equal to 0.08 and 0.21, when neglecting and considering soil amplification, respectively. For $I_{MSK} = VII$–VIII (475 years return period) DI_{med} is equal to 0.25 and 0.49 respectively.

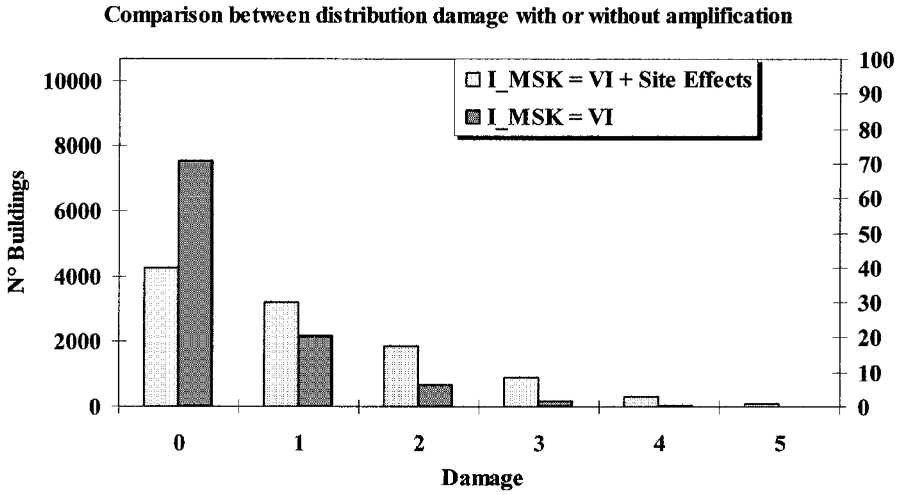

Figure 5. Building damage distribution relevant to the damaging seismic event (return period of 50 years).

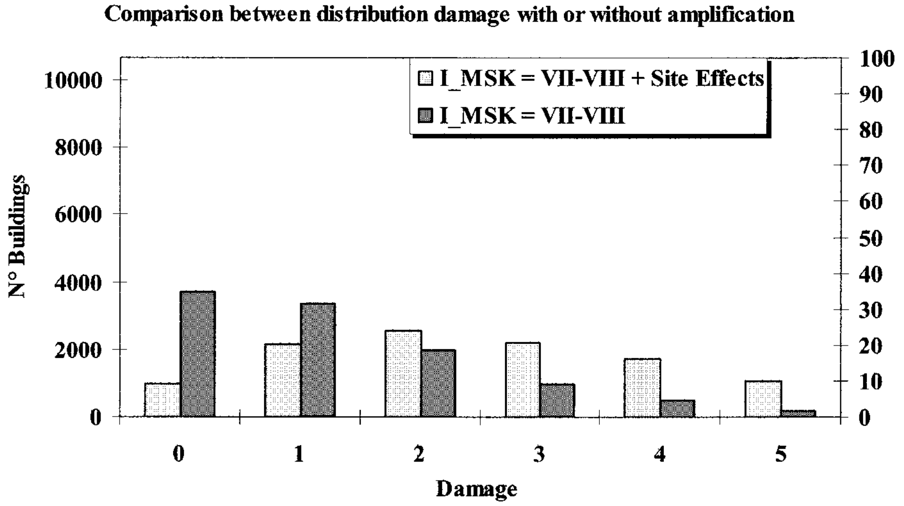

Figure 6. Building damage distribution relevant to the destructive seismic event (return period of 475 years).

To provide a global sight of the damage due to a given intensity, in Figures 7–10 the mean damage DI_{med} (0–1 scale) calculated in each census tract for the events with 50 and 475 years return period, neglecting and taking into account site effects, is shown.

When site effects are neglected, for the seismic event with $T_R = 50$ years (Figure 7), almost all the census tracts show null or low levels of mean damage ($DI_{med} = 0$–0.2), both for the whole Potenza territory and the historic centre. For the seismic event with $T_R = 475$ years (Figure 8), the most frequent value of the

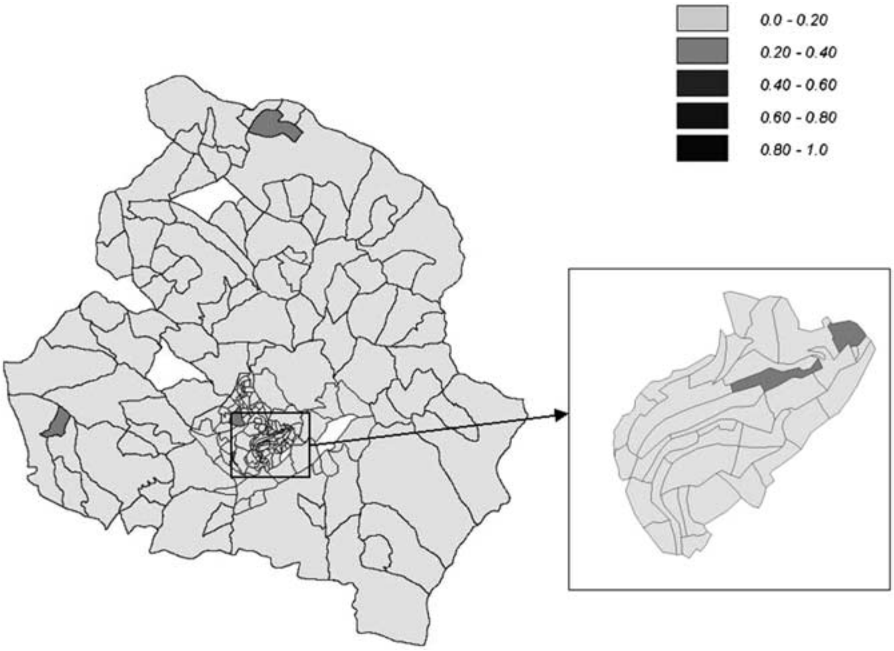

Figure 7. Map of the mean damage in each census tract of the whole Potenza territory and its historic centre (50 years return period, site effects not included).

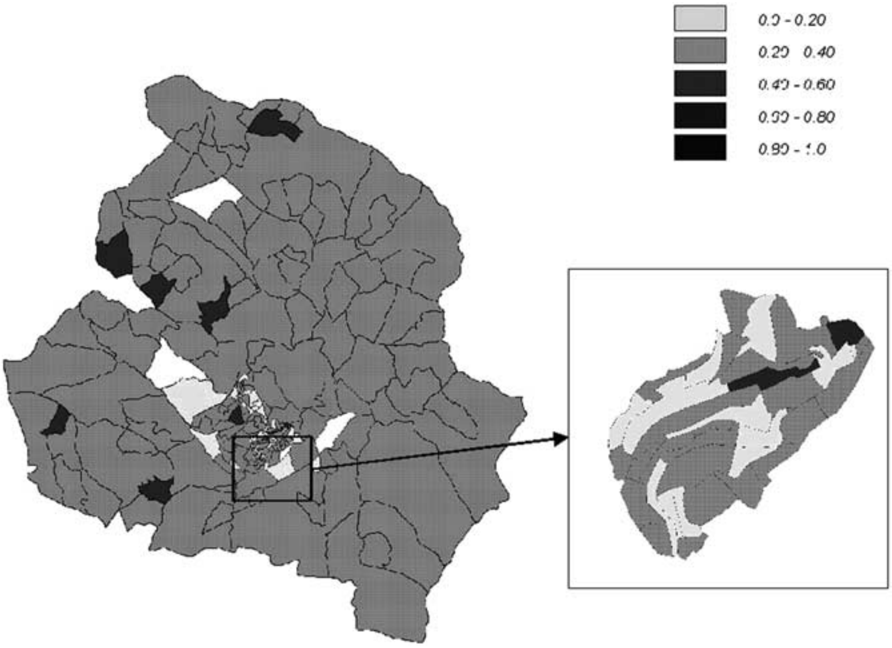

Figure 8. Map of the mean damage in each census tract of the whole Potenza territory and its historic centre (475 years return period, site effects not included).

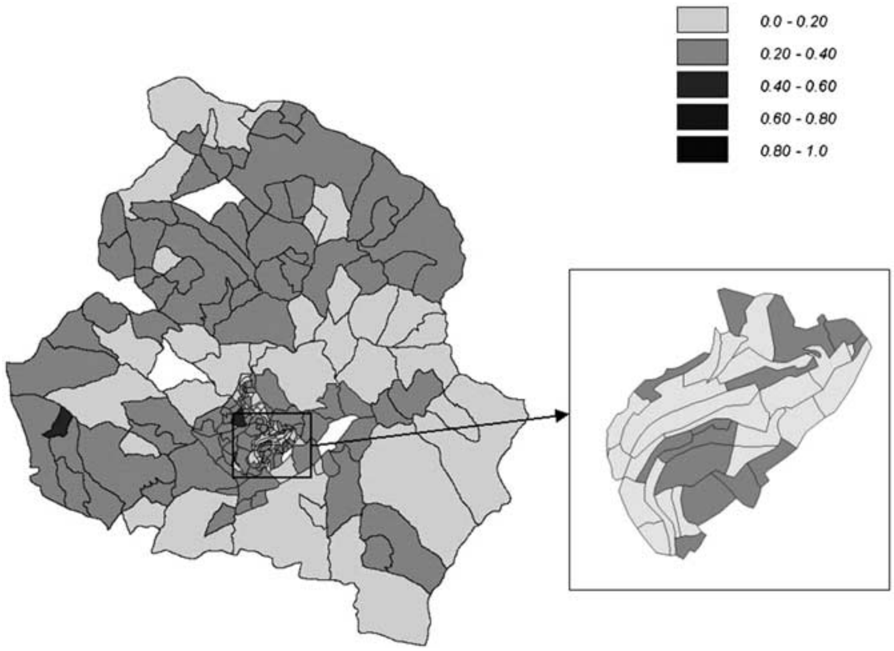

Figure 9. Map of the mean damage in each census tract of the whole Potenza territory and its historic centre (50 years return period, site effects included).

mean damage, both for the whole Potenza territory and the historic centre, is in the range $\mathrm{DI}_{\mathrm{med}} = 0.2$–$0.4$, even though in the historic centre some census tracts still have $\mathrm{DI}_{\mathrm{med}}$ values in the range 0–0.2.

Taking into account site effects, in the case of the seismic event with $T_R =$ 50 years (Figure 9), most of the census tracts show low ($\mathrm{DI}_{\mathrm{med}} = 0$–$0.2$) or medium ($\mathrm{DI}_{\mathrm{med}} = 0.2$–$0.4$) values of mean damage index, both for the whole Potenza territory and the historic centre. However, whereas in the whole territory an almost equal presence of undamaged ($d = 0$–1) and repairable ($d = 2$–3) buildings can be estimated, in the historic centre the percentage of undamaged buildings raises up to 60–80%. The maps relevant to the seismic event with $T_R = 475$ years, reported in Figure 10, show that the most frequent value of the mean damage in the whole Potenza territory is in the range $\mathrm{DI}_{\mathrm{med}} = 0.4$–$0.6$. High percentages (40–60%) of damaged buildings ($d = 2$–3) are present in most rural zones, where the most vulnerable buildings (class A and B) are mainly concentrated. Moreover, in some census tracts, always relevant to rural zones, there are many collapsed buildings ($d = 4$–5) with up to 20–40% percentages. Actually, since they often are masonry constructions with 1–2 stories, limited consequences in terms of human losses are expected. On the contrary, there is a wider presence of census tracts with $\mathrm{DI}_{\mathrm{med}} = 0.2$–$0.4$ in the historic centre, thus confirming that it would be damaged to a smaller extent than the other zones.

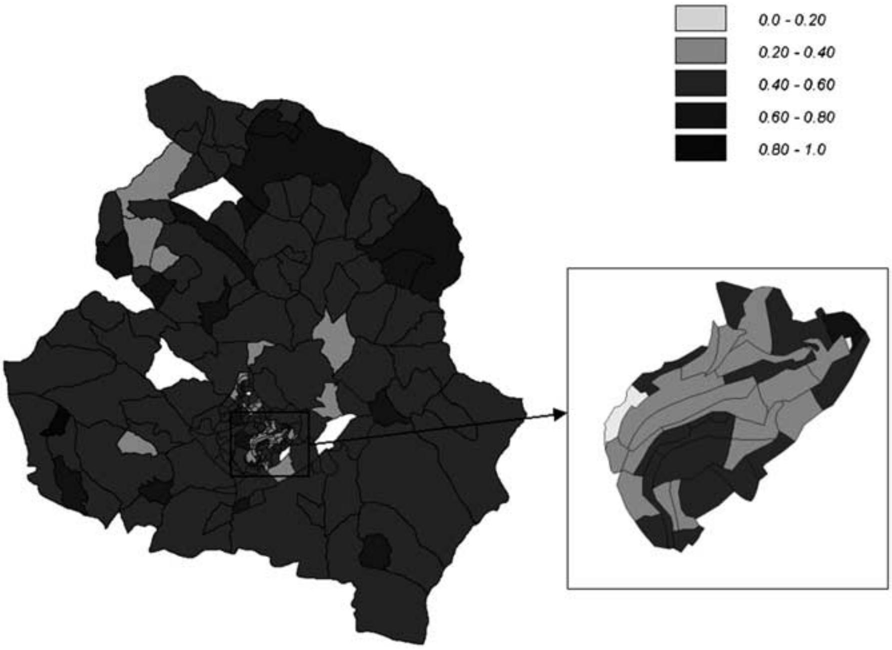

Figure 10. Map of the mean damage in each census tract of the whole Potenza territory and its historic centre (475 years return period, site effects included).

The lower vulnerability of the historic centre is a peculiar characteristic of the Potenza building stock, whereas in other Italian towns a higher vulnerability is typically found in the historic centre. As already said, this is mainly due to the widespread retrofit works made after the 1980 Irpinia earthquake, mostly relevant to buildings located in that zone. However, another peculiarity of the historical centre of Potenza is the presence side by side of retrofitted old masonry buildings and of high-rise R/C buildings without seismic design. In the present study they have been placed, respectively, in vulnerability classes D and C. A more accurate vulnerability evaluation for both the above said building types could change the scenarios to some extent.

9. Conclusion

The availability of a large set of data of its building stock, as well as the knowledge of the characteristics of soils, has given the possibility to make complete damage scenarios for the whole territory of Potenza town. Like in any scenario preparation, a specific procedure had to be set up and applied, because of the peculiar characteristics of the data available and of the lack of some information. Two damage scenarios of dwelling buildings have been prepared and reported in a Geographic Information System (GIS), related to the selected reference earthquakes and taking into account or neglecting site effects. They emphasise a generally low vulnerability and, then, a limited number of damaged buildings for the lower intensity, and of partially or totally collapsed building, for the higher intensity earthquake. The influence of site effects on the damage distribution is significant.

As far as the developments of this study are concerned, the following points need to be pursued:

- more accurate evaluation of the vulnerability for the retrofitted buildings, both masonry and R/C buildings, and for the various types of R/C buildings (e.g. bare, infilled and pilotis frames) with no seismic design;
- use of different methods for damage estimation;
- evaluation of secondary vulnerability to estimate induced damage and indirect losses (victims, buildings unusability, economic losses, etc.);
- evaluation of site effects in a more accurate way (second or third level microzonation);
- construction of building-by-building damage maps.

Acknowledgements

This work was partially supported by the European Commission within the framework of the ENSeRVES Project (Contract IC15 CT96-0203, INCO-Copernicus program, D.G. XII, 4th Framework) and by the Servizio Sismico Nazionale (Italian National Seismic Agency), within the Potenza Project contract.

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