A comparison of seismic risk maps for Italy

Helen Crowley · Miriam Colombi · Barbara Borzi · Marta Faravelli · Mauro Onida · Manuel Lopez · Diego Polli · Fabrizio Meroni · Rui Pinho

Received: 2 May 2008 / Accepted: 22 November 2008

Abstract National seismic risk maps are an important risk mitigation tool as they can be used for the prioritization of regions within a country where retrofitting of the building stock or other risk mitigation measures should take place. The production of a seismic risk map involves the convolution of seismic hazard data, vulnerability predictions for the building stock and exposure data. The seismic risk maps produced in Italy over the past 10 years are compared in this paper with recent proposals for seismic risk maps based on state-of-the-art seismic hazard data and mechanics-based vulnerability assessment procedures. The aim of the paper is to open the discussion for the way in which future seismic risk maps could be produced, making use of the most up-to-date information in the fields of seismic hazard evaluation and vulnerability assessment.

Keywords Seismic risk · Vulnerability · Seismic hazard · Maps · Italy

1 Introduction

The evaluation of seismic risk to buildings involves many disciplines from data collection to vulnerability assessment to seismic hazard assessment to social and economic sciences. In simple terms, the seismic risk can be described as the probability of loss at a given site and is obtained through the convolution of three parameters: exposure, vulnerability and seismic hazard. A fourth parameter may then be added through which the seismic risk can be related to a social or economic loss; for example, the damage of buildings may be related to the

H. Crowley (✉) · M. Colombi · B. Borzi · M. Faravelli · M. Onida · M. Lopez · D. Polli
EUCENTRE, European Centre for Training and Research in Earthquake Engineering,
Via Ferrata 1, Pavia, Italy
e-mail: helen.crowley@eucentre.it

F. Meroni
Istituto Nazionale di Geofisica e Vulcanologia (INGV), Via Bassini 15, Milano, Italy

R. Pinho
Dipartimento di Meccanica Strutturale, Università degli Studi di Pavia, Via Ferrata 1, Pavia, Italy

direct economic loss for their repair or replacement, or the collapse of the buildings may be related to the number of casualties. When carrying out seismic risk assessment for a large region, or even a whole country, the exposure is generally obtained from a building census whilst the seismic hazard is described in terms of a ground-motion parameter which should be correlated to the damage of different classes of buildings or other exposed elements through a vulnerability function.

In mathematical terms, seismic risk can be described as the unconditional probability of failure (P_f) for a system with resistance R, under a seismic load S, using the following equation:

$$P_f = \int_0^{+\infty} f_S\,(S)\,F_R\,(S)\,d\,S \tag{1}$$

where f_S is the probability density function of the ground-motion parameter (which can be obtained through the derivation of the seismic hazard curve) and $F_R(S)$ is the probability that the resistance R is less than a given level of severity, S (often termed the vulnerability or fragility curve). Hence, the annual probability of collapse, for example, can be obtained by combining the probability of exceeding the resistance of the building to collapse for a given level of ground motion [$F_R\,(S)$], with the annual probability of obtaining that level of ground motion (f_S), and summing this product over all possible levels of ground motion. This would allow one to estimate the mean annual probability of collapse for a given typology of buildings; this calculation would need to be repeated for each typology present in the inventory of buildings (the exposure model) and then the results would be combined considering the proportion of each building typology. Once the mean annual probability of collapse for all buildings has been calculated it can be related to economic and social losses; e.g. the mean cost of reconstructing the collapsed buildings, multiplied by the annual probability of collapse, multiplied by the total number of buildings would lead to the mean annual loss due to collapse.

In this paper, various studies which have looked at the seismic risk to the building stock and population in Italy at a national level are presented. Many of the original seismic risk maps for Italy were based on single ground-motion parameters to define the seismic hazard such as peak ground acceleration or macroseismic intensity. The ground motion was then combined with damage probability matrices or vulnerability curves, based on observed damage data, to calculate the seismic risk. Seismic hazard maps for Italy have recently been developed in terms of spectral acceleration and displacement (INGV-DPC S1 2007a; INGV-DPC S5 2007b). It is well known that a good correlation exists between the spectral response of the building stock and damage due to the consideration of the frequency content of the ground motion and the period of vibration of the buildings. Analytical methods for predicting the capacity of the building stock in urban areas for a given level of seismic demand based on spectral acceleration and/or displacement are now rather common (as discussed in Calvi et al. 2006). Hence, the aim of this paper is to compare the seismic risk maps for Italy obtained with empirical vulnerability predictions and single ground motion parameters with more detailed analytical methods which use a mechanics basis to predict the probability of damage given a level of spectral displacement.

2 Existing seismic risk maps in Italy

Over the past 10 years in Italy, a significant amount of effort has been made towards the development of seismic risk maps at a national level. The first seismic risk maps for Italy were prepared in 1996 by a Working Group (*Gruppo di Lavoro*) set up specifically for this task by the Department of Civil Protection (DPC); these maps presented the average annual number of dwellings which would suffer damage in each municipality in Italy (of which there are currently 8101) and the average annual number of people who would be affected by collapsed buildings. These maps were never published but nevertheless served as a tool for the DPC through which the municipalities in Italy could be classified in terms of level of seismic risk to aid decisions regarding the prioritization for seismic intervention of the existing building stock.

As presented in Lucantoni et al. (2001), the aforementioned seismic risk maps were updated based on more recent seismic hazard studies and improved damage probability matrices (Di Pasquale et al. 2000) and fragility curves (Sabetta et al. 1998). Seismic hazard data in terms of both peak ground acceleration (PGA) and macroseismic intensity (on the Mercalli-Cancani-Sieberg, MCS, scale) were used in the production of the seismic risk maps. The coordinates of the centre of the main town in each municipality were used to model the location of the building stock and the seismic hazard was obtained at this point by interpolating the hazard data from the grid used for the whole country. The vulnerability of the residential building stock was modelled using 4 classes (A, B and C1 and C2) and the dwellings in Italy obtained from the 1991 ISTAT Census were assigned to each class using a procedure based on construction year and construction type as described in Di Pasquale and Orsini (1997). Population data obtained from the buildings assessed following the 1980 Irpinia and 1984 Lazio-Abruzzo earthquakes were also utilised. The results obtained in terms of the mean percentage of collapsed dwellings per municipality based on the seismic hazard maps in terms of macroseismic intensity are plotted in Fig. 1a.

The seismic risk map in Fig. 1a is compared with another study published in 2004 (Zuccaro 2004) under the SAVE Project (Fig. 1b). In this study, the macroseismic intensity seismic hazard data on the MCS scale, published in Lucantoni et al. (2001), was used whilst an extensive effort was made to improve the damage probability matrices used to define the vulnerability of the building stock and the classification of the building stock in terms of vulnerability classes. It is evident from Fig. 1 that the updated vulnerability functions and the new study assigning these functions to the building stock in Italy led to higher estimated levels of seismic risk in Italy, especially along the Apennines and in Calabria. An illustration of the influence of the seismic hazard data on the Italian seismic risk maps is presented in Fig. 1 where the mean percentage of collapsed dwellings per municipality using MCS intensity data (Fig. 1a) is compared with that obtained using peak ground acceleration seismic hazard data (Fig. 1c), both of which were derived by Lucantoni et al. (2001). When using peak ground acceleration, the empirical vulnerability functions by Sabetta et al. (1998) were used whilst the macroseismic intensity data was used with damage probability matrices proposed by Di Pasquale et al. (2000).

The results show that the spatial distribution of the risk follows the seismic hazard distributions (which are plotted in Fig. 2a, b, for MCS and PGA, respectively), and that a higher level of risk is observed in the south east of Sicily with the use of macroseismic intensity whilst the areas of Tuscany, Emilia Romagna and Friuli Venezia Giulia have a higher level of risk when the seismic hazard is modelled using peak ground acceleration. Lucantoni et al. (2001) mention that apart from the differences in the vulnerability functions used to produce the two risk maps, the spatial differences are more likely to be caused by the different ground-motion prediction equations used to produce the seismic hazard maps in terms of PGA and MCS. For the macroseismic intensity hazard map (Fig. 2a), different attenuation relationships were assigned to each source zone and the variability in

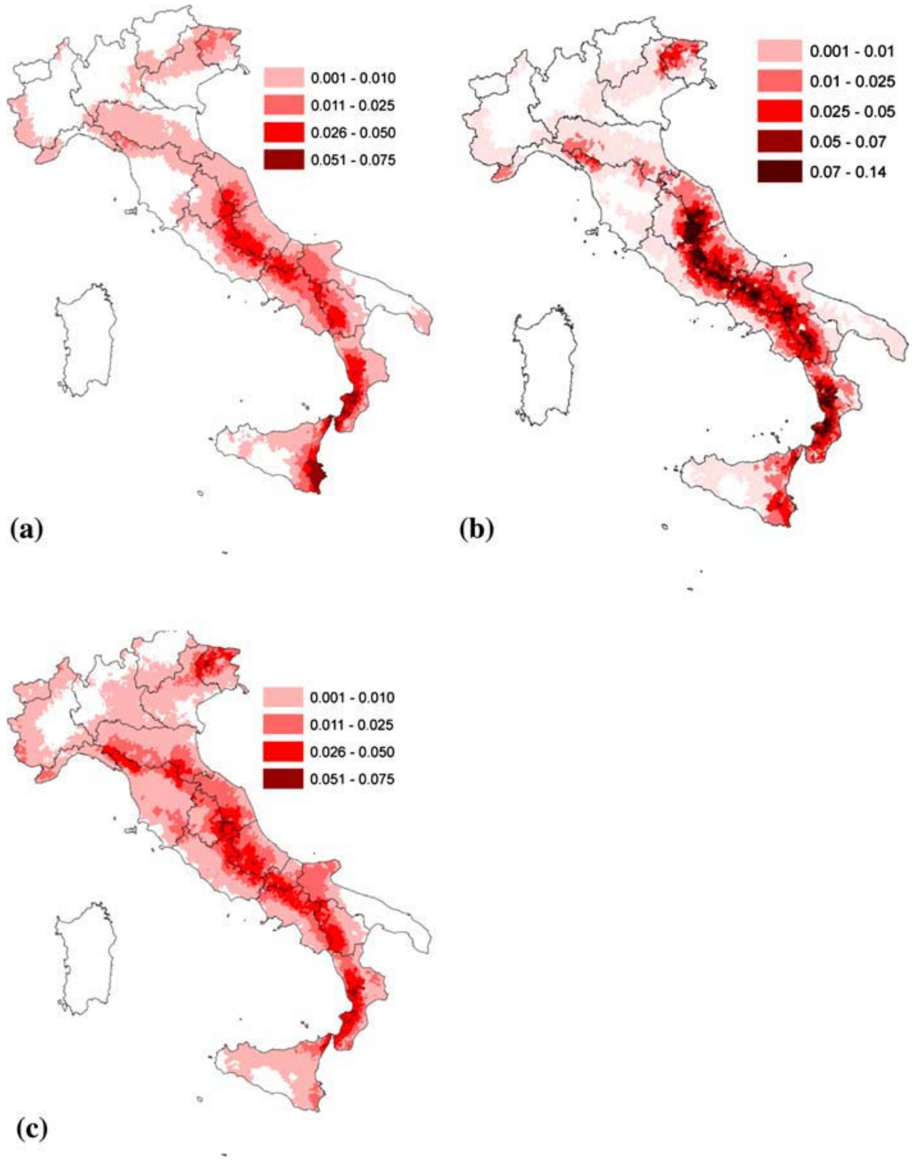


Fig. 1 Mean annual seismic risk in terms of the percentage of collapsed dwellings per municipality using seismic hazard estimates on the MCS scale **a** adapted from Lucantoni et al. (2001) and **b** the SAVE Project (Zuccaro 2004), and **c** using peak ground acceleration hazard data (adapted from Lucantoni et al. 2001)

these relationships was ignored, whilst for Fig. 2b the same relationship for the attenuation of PGA was applied to all source zones and the aleatory variability was accounted for.

The vulnerability map produced in the SAVE project is shown in Fig. 3a where a mean vulnerability class from A to E (A being the highest vulnerability) has been computed for each municipality based on building surveys and the 1991 census data. The map showing the

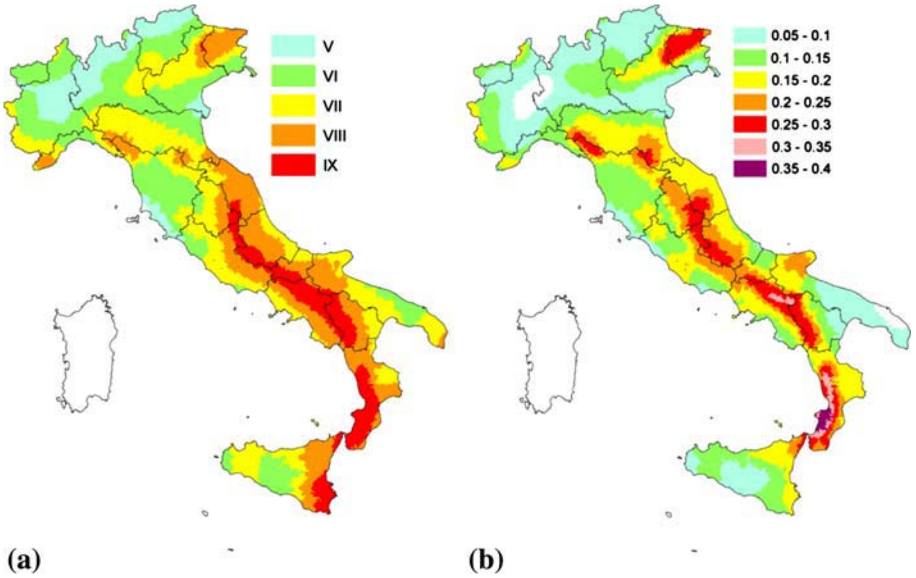


Fig. 2 Seismic hazard maps for a return period of 475 years in terms of **a** macroseismic intensity on the MCS scale, **b** peak ground acceleration (adapted from Lucantoni et al. 2001)

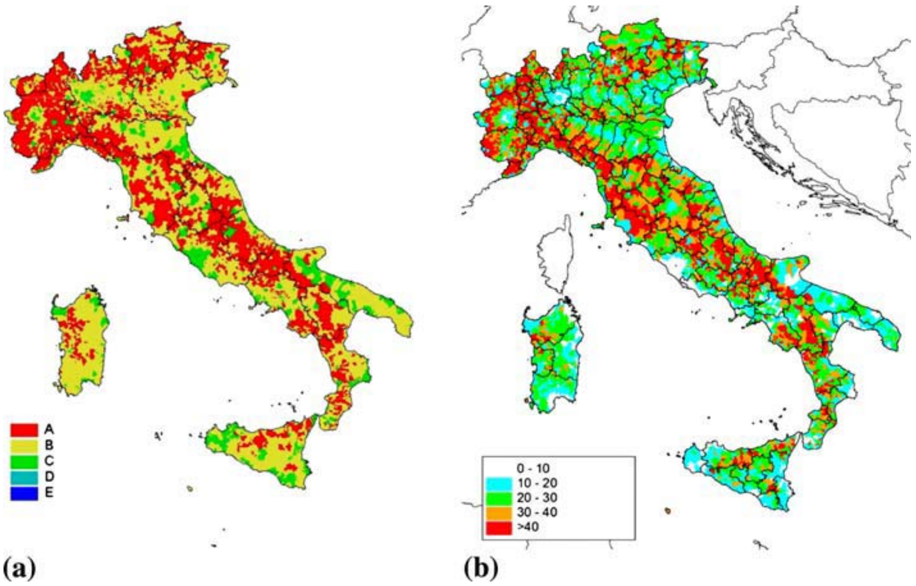


Fig. 3 Vulnerability maps produced in **a** the SAVE Project (Zuccaro 2004), and **b** Lucantoni et al. (2001)

percentage distribution of buildings belonging to vulnerability class A within each municipality utilised in the seismic risk calculations of Lucantoni et al. (2001) is shown Fig. 3b.

These maps show how the vulnerability of the building stock varies spatially over the country. Considering this spatial variation of vulnerability, it is perhaps strange to find that the seismic risk maps in Fig. 1 follow the spatial distribution of seismic hazard. Nevertheless,

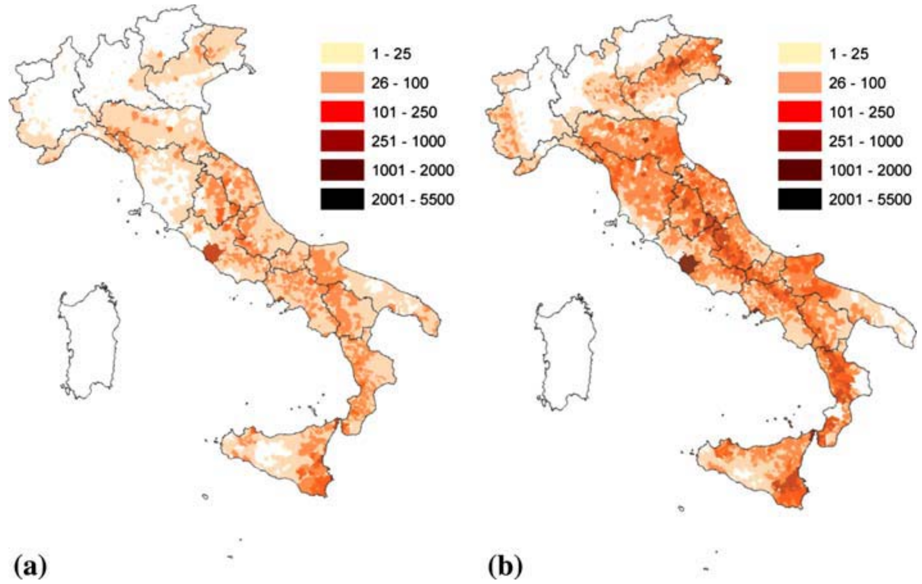


Fig. 4 Number of collapsed dwellings per municipality due to ground motions with a 10% probability of exceedance in 50 years from the SAVE Project using **a** macroseismic intensity data (Lucantoni et al. 2001) and **b** peak ground acceleration from the OPCM 3519 (OPCM 2006)

this suggests that, for the vulnerability functions and the range of intensity values considered in these studies, the damage increases at a higher rate when the hazard is increased than when the vulnerability is increased.

The influence of the seismic hazard data was also studied in the SAVE project whereby the number of buildings in each municipality predicted to collapse due to ground motions with a 10% probability of exceedance in 50 years were calculated using both the macroseismic intensity data and the peak ground acceleration data issued in 2006 in the Prime Minister Ordinance n.3519 (OPCM 2006), as described further in Sect. 3.2.1. The results based on the peak ground acceleration data, presented in Fig. 4b, are seen to be higher than those based on macroseismic intensity (Fig. 4a). In this case the peak ground acceleration data was transformed into MCS intensity (using the relationship by Margottini et al. 1987) in order to carry out the convolution of the data with the damage probability matrices. Considering that in both maps the vulnerability component is the same, the difference is certainly due to a higher hazard present in the PGA maps, but it should be considered that the same conclusion may not have been reached with the use of a different PGA-MCS Intensity relationship.

The seismic risk maps produced by Lucantoni et al. (2001) (Fig. 1a) were recently further updated using the 2001 Census data (Bramerini and Di Pasquale 2008). The influence of updating the census data is presented in Fig. 5 where the seismic risk maps for a time window of 100 years are presented; these maps are both based on the seismic hazard (in terms of PGA) and vulnerability data produced in the Lucantoni et al. (2001) study. It is noted that the use of the more updated exposure data does not have a significant effect on the spatial distribution of the percentage of collapsed dwellings and the difference in terms of the absolute number of dwellings at risk of collapse was found to be just a few buildings, even though the total number of buildings in Italy had increased by 9% from 1991 to 2001.

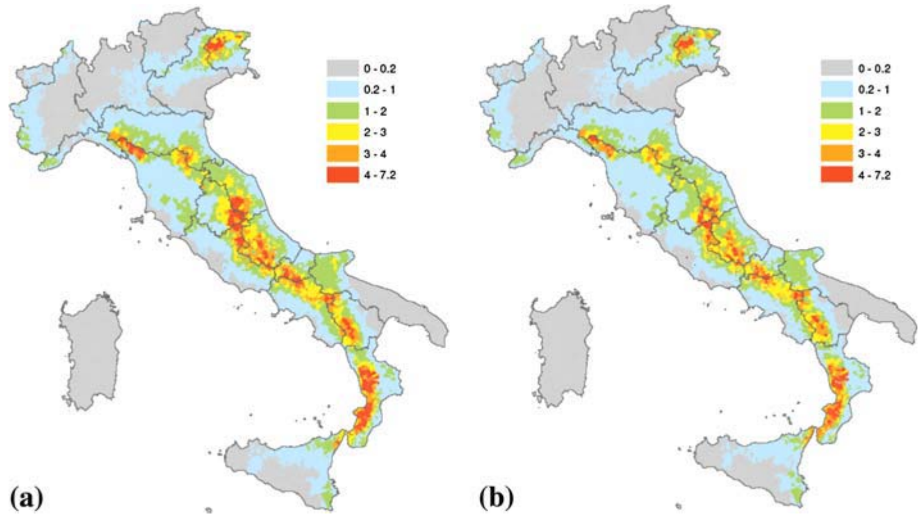


Fig. 5 Mean seismic risk in 100 years in terms of the percentage of collapsed dwellings per municipality using **a** ISTAT '91 data and **b** ISTAT 2001 data (Bramerini and Di Pasquale 2008)

3 Proposed method for the generation of seismic risk maps for Italy

All of the seismic risk maps presented in Sect. 2 have been derived considering empirical vulnerability functions based on the observed damage of buildings due to earthquakes in Italy. Many of the shortcomings of empirical vulnerability curves are related to the fact that the vibration characteristics of the buildings are not taken into account (for example, due to the use of peak ground acceleration or velocity) or that the macroseismic intensity is used to define the ground shaking, but this parameter is directly obtained from observed damage data and thus the damage and ground shaking intensity are not independent. A recent study was carried out by Colombi et al. (2008) to remove these shortcomings by dividing the damaged buildings into classes as a function of the number of storeys and estimating the displacement demand from a ground-motion prediction equation using an estimated mean period of vibration for each building type. Nevertheless, further disadvantages with the use of the observed damage database of Italian buildings for the generation of empirical curves were identified by Colombi et al. (2008). In particular, problems related to the inadequate compilation of the post-earthquake assessment forms meant that much of the data had to be removed from the database and so the proportion of damaged buildings in each damage band was very likely underestimated. Considering all of these shortcomings in the use of empirical vulnerability functions—and the additional disadvantage which is related to the fact that the advances in seismic hazard assessment can often not be availed of when using empirical functions—the use of analytical vulnerability functions appears to be a more promising option for the generation of future seismic risk maps.

The next sections describe two mechanics-based vulnerability assessment procedures which have been developed for the seismic risk assessment of urban areas and the application of these methodologies in the production of seismic risk maps for Italy using state-of-the-art seismic hazard data.

3.1 Vulnerability assessment

3.1.1 Analytical vulnerability assessment methodologies

Two mechanics-based methodologies, DBELA (Displacement-based Earthquake Loss Assessment) and SP-BELA (Simplified Pushover-Based Earthquake Loss Assessment), have recently been developed by the authors for the seismic risk and loss assessment of urban areas. Both methodologies predict the yield period of vibration (T_y) of a randomly generated building stock, the former through an empirical relationship between period and height and the latter through a simulated design procedure and subsequent simplified pushover analysis. An equivalent linearization approach is applied in both methods and hence for post-yield limit states, if an elastic-perfectly plastic behaviour is assumed, the buildings can be modelled using the secant period of vibration, based on the following formula:

$$T_{LS} = T_y \sqrt{\mu_{LS}} \tag{2}$$

where μ_{LS} is the ductility at the limit state in question.

The period of vibration of each random building is used to predict the displacement demand from an overdamped displacement response spectrum which is compared with the displacement capacity of single-degree-of-freedom (SDOF) representations of buildings at various limit states.

The displacement capacity of the buildings at different limit or damage states is predicted using structural mechanics principles which result in simple equations relating the displacement capacity to the material and geometrical properties. Three limit state conditions have currently been taken into account in both methods: slight damage, significant damage and collapse. The slight damage limit condition refers to the situation where the building can be used after the earthquake without the need for repair and/or strengthening. If a building deforms beyond the significant damage limit state it cannot be used after the earthquake without retrofitting. Furthermore, at this level of damage it might not be economically advantageous to repair the building. If the collapse limit condition is achieved, the building becomes unsafe for its occupants as it is no longer capable of sustaining any further lateral force nor the gravity loads for which it has been designed. The limit conditions are related to the rotation requirements imposed on the plastic hinges that lead to the formation of a mechanism. Figure 6 shows the possible response mechanisms of a reinforced concrete

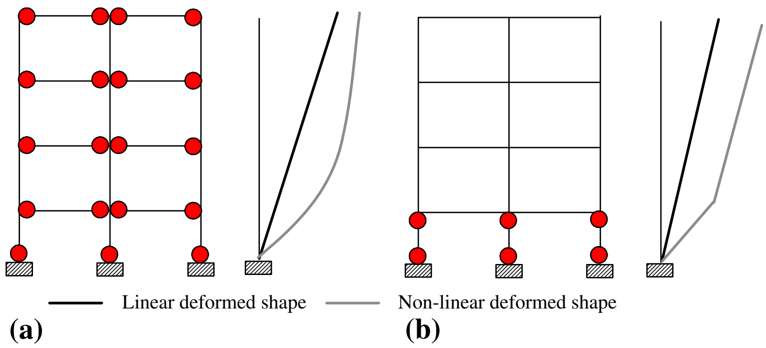


Fig. 6 Response mechanisms for a frame and associated deformed shapes. **a** Beam-sway mechanism. **b** Column-sway mechanism

frame: a beam-sway mechanism is caused by plastic hinges forming in all the beams above the first floor and in all of the columns at the base of the building whilst the column-sway mechanism forms when plastic hinges form at both ends of the columns in the ground floor. In the DBELA methodology, all buildings within a given building class are assumed to have either a beam- or column-sway mechanism whilst in SP-BELA the proportion of buildings with each mechanism is explicitly calculated and the possibility of a mixed mechanism with hinging in both the beams and columns is accounted for. Based on the shape of the displaced profile, the displacement capacity of the equivalent SDOF system can be calculated using the elastic displacement and the post-elastic displacement at the height of the SDOF system.

The reader is referred to Crowley et al. (2004) and Borzi et al. (2008a) for further information on the methodologies for reinforced concrete and to Crowley and Pinho (2008) and Borzi et al. (2008b) for details of the methods when applied to masonry buildings. Preliminary validations of the methods have also been carried out for reinforced concrete buildings by comparing the nonlinear static behaviour of buildings modelled in a detailed Finite Elements structural analysis program with the associated predictions from these simplified methodologies (Crowley et al. 2008) and for masonry buildings by comparing the vulnerability predictions with observed damage data (Colombi et al. 2008).

3.1.2 Italian building stock characteristics

These methodologies have been calibrated for the Italian building stock by considering relevant geometrical, material and limit state properties. For DBELA, the geometrical properties of reinforced concrete buildings which are required include the storey height, the column depth, the beam depth and the beam length; the statistics of these values have been obtained from a sample of reinforced concrete buildings processed by Marino (2005). In SP-BELA, the beam depth and the column depths are assigned during the simulated design procedure (along with the reinforcement details) and thus only the storey height and beam length statistics are required which have again been taken from Marino (2005).

From 1939 until 1972 the design of reinforced concrete buildings in Italy was based on a single design code (*R.D.L. 16 novembre* 1939) which used an allowable stress design approach. The allowable stress in the concrete was 40–50kg/cm^2 whilst the allowable stress in the steel depended on the type of steel being used; in 1957 a ministerial memorandum was issued (*Circolare 23 maggio* 1957$n°$1472) which reported the allowable stress to the three most commonly used steel types at the time: Aq42 (1,400 kg/cm^2), Aq50 (1,600 kg/cm^2) and Aq60 (1,800 kg/cm^2). The 1939 design code remained in force for over 30 years until 1972 when a new code was issued (*D.M. 30 maggio* 1972$n°$); during the '70s and '80s a number of codes were issued but they did not differ greatly one from another (Stella 1999). In the 1972 design code, the allowable stresses in the concrete were defined using a formula based on the cubic characteristic resistance whilst the allowable stress in the steel was defined for the commonly used steel types of the period: FeB22k (1,200 kg/cm^2), FeB32k (1,600 kg/cm^2), FeB38k (2,200 kg/cm^2) and FeB44k (2,600 kg/cm^2), where the former two are smooth bars and the latter two are deformed bars. Hence, considering the change in material types and allowable stress values used in the design pre- and post-1970, the reinforced concrete buildings in Italy have often been divided into these two distinct classes (e.g. Vona and Masi 2004; Masi and Vona 2004).

The allowable stress values reported above have been used for the design of pre-1970 reinforced concrete buildings in SP-BELA, where a random selection of the three different types of reinforcing steel (Aq42, Aq50 and Aq60) was made. For the post-1970 reinforced concrete buildings, a random selection of two different types of FeB38k and FeB44k reinforcing steel was used and a randomly chosen cubic characteristic resistance of 25 MPa, 30 MPa or 35 MPa has been associated to the concrete for each building of the randomly generated dataset. In order to calculate the capacity of the buildings in both SP-BELA and DBELA, the mean resistance and standard deviation of the material properties are required. For the pre-1970 buildings, the mechanical properties of normal structural concrete and reinforcing bars used in Italy in the 1960s has been obtained from Verderame et al. (2001a,b). The mean compressive resistance of concrete from samples tested at the University of Naples from 1961–1970 has been found to be 29.33 MPa with a coefficient of variation of 30.96%. For the reinforcing bars, during the same decade, the mean yield strength of Aq42 bars has been found to be 325.4 MPa with a coefficient of variation of 7.1%; the mean yield strength of the Aq50 bars was 369.9 MPa with a coefficient of variation of 8% and the Aq60 bars were found to have a mean yield strength of 432.6 MPa with a coefficient of variation of 8.5%. For the post-1970 buildings, experimental data was not available upon which to calibrate the properties of the concrete and steel rebars and thus amplification factors of 1.1 and 1.5 for steel and concrete, respectively, were used to pass from the characteristic to the mean resistance (Priestley et al. 1996). In both cases a coefficient of variation of 10% was assumed. Once statistics of the mechanical properties of the concrete and steel used in Italy from 1970 onwards have been collected, they will allow the amplification factors defined above to be calibrated; it is expected that the coefficient of variation of the concrete compressive strength will be higher than 10%.

The two methodologies also require the limit state strains in the steel and concrete to be defined at the limit states to slight damage, significant damage and collapse; the choice of these limit state values depends on the level of confinement (see Borzi et al. 2008a). The 1939 and the 1972 design codes in Italy proposed similar levels of confinement spacing, both of which are deficient by today's standards and thus both classes can be considered to be poorly confined and the steel and concrete strains can be assigned accordingly.

An initial study of the pre-1970 and post-1970 reinforced concrete buildings using both DBELA and SP-BELA did not lead to a significant difference in the vulnerability characteristics of these two distinct classes. This is illustrated in Fig. 7 where vulnerability curves calculated with the SP-BELA method are presented in terms of the probability of exceeding the collapse limit state for given levels of peak ground acceleration (PGA) for both pre-1970 and post-1970 reinforced concrete buildings of 4 and 5 storeys. A description of the procedure used to produce the vulnerability curves in Fig. 7 is provided in Borzi et al. (2008a),whilst further comparisons of the DBELA and SP-BELA methodologies in terms of vulnerability curves may be found in Crowley et al. (2008).

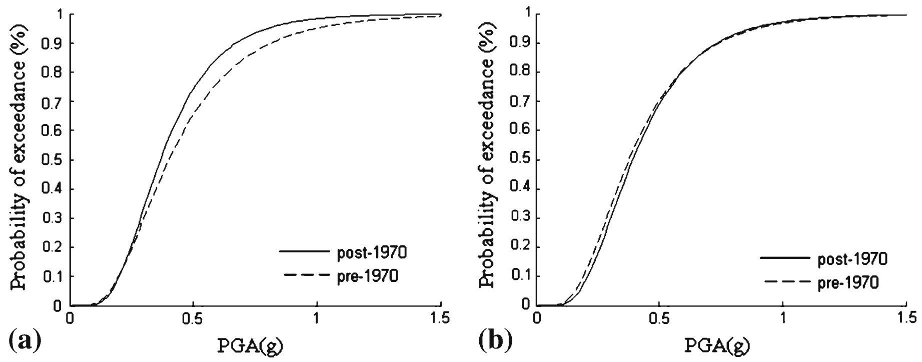


Fig. 7 Vulnerability curves for **a** 4 storey and **b** 5 storey non-seismically designed reinforced concrete buildings pre- and post-1970

The similarity in the vulnerability curves shown in Fig. 7 is due to the simplified nature of the methods used herein to predict the vulnerability. In reality the use of smooth bars in the pre-1970 buildings would be expected to lead to a larger amount of bar slip and a more pronounced strength and stiffness degrading behaviour of the structure and thus a higher level of vulnerability. Until these types of structural behaviour are included in the methods and also until further data is available upon which to calibrate the material properties of the post-1970 buildings, the difference in the vulnerability of reinforced concrete buildings pre- and post-1970 cannot be accounted for with the methods used herein. Hence, in the seismic risk maps presented herein only one type of reinforced concrete design has currently been considered, which is that related to the post-1970 buildings.

For masonry buildings, statistics related to the storey height, the pier height and the interstorey drift capacity at different limit states are required in DBELA, whilst in SP-BELA additional information on the areas of the walls, the shear resistance of the masonry and the specific weight of the masonry are required. All of these data have been collected from various sources including the GNDT 2nd level assessment forms which have been used to assess around 42,000 masonry buildings in Italy (Martinelli and Corazza 1999). The statistics used for masonry buildings in the current seismic risk maps are described in detail in Borzi et al. (2008b).

3.2 Seismic hazard assessment

3.2.1 Seismic input from the INGV-DPC S1 project

In 2004, a new probabilistic seismic hazard assessment for Italy, performed in terms of PGA was compiled and released, after review by an international board of experts, and became known as MPS04 (*Mappa di Pericolosità Sismica 04*: Seismic Hazard Map, in English). Following the issuing of the Prime Minister Ordinance n.3519 in 2006 (*Ordinanza del Presidente del Consiglio dei Ministri,* OPCM), MPS04 is now the official reference for seismic hazard values to be used in Italy in engineering applications. The seismic hazard has been assessed for 16,852 grid points spaced at 0.05° in latitude and longitude, covering the national territory with the exception of Sardinia and some minor islands for which ad hoc studies were necessary. The seismic hazard assessment underwent a process of peer review that involved national and foreign experts in the fields of seismology and engineering.

MPS04 was computed following a logic tree approach that accounted for various sources of epistemic uncertainties such as: (i) the earthquake catalogue completeness time intervals; (ii) the seismicity rates; (iii) and the ground-motion predictive relationships. The logic tree did not include alternatives to the seismogenic source model ZS9 ("*Zonazione Sismogenetica ZS9*", *Gruppo di Lavoro* MPS04, 2004) nor the earthquake catalogue CPTI04 ("*Catalogo Parametrico dei Terremoti Italiani* 2004", *Gruppo di Lavoro* CPTI04 2004) because these input elements were obtained from a review of the existing material, including the most updated studies, and a consensus amongst the experts was reached (Montaldo et al. 2007). The ground-motion prediction equations used in the logic tree for most sources were those proposed by Sabetta and Pugliese (1996) and Ambraseys et al. (1996), while in some areas (for example in the Alps) regional equations were used. The Sabetta and Pugliese (1996) equation is based mainly on analogue records from Italian earthquakes, whilst the Ambraseys et al. (1996) equation is based on European analogue records.

The seismic hazard in Italy in terms of spectral acceleration for different response periods has also been computed following the same methodology adopted to compute MPS04 within the INGV-DPC S1 Project (2007). The results have been computed for various annual

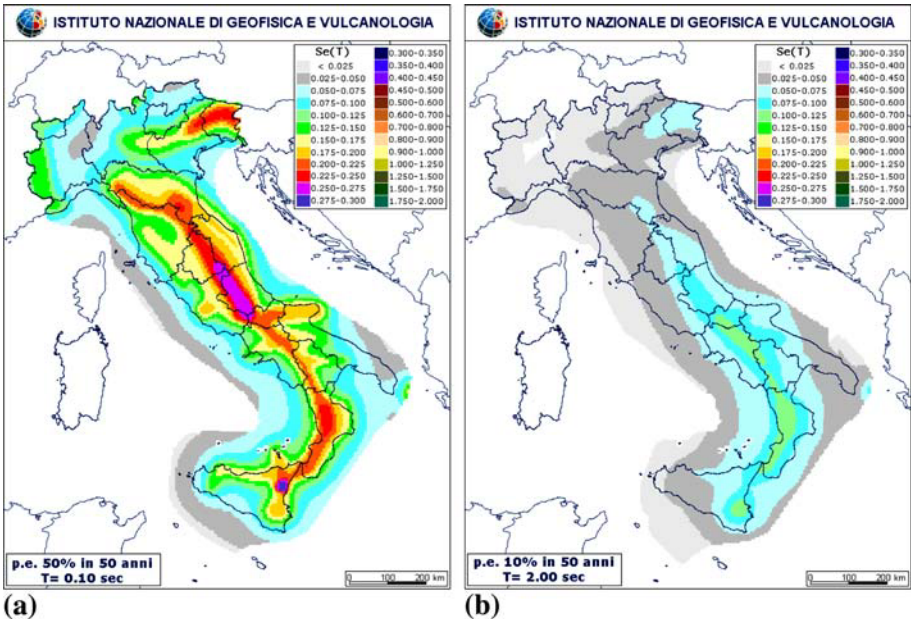


Fig. 8 Seismic hazard maps in terms of spectral acceleration ordinates. **a** Return period = 72 years, $T = 0.1$ s. **b** Return period = 475 years, $T = 2$ s (INGV-DPC 2007a)

frequencies of exceedance (the reciprocal of the return period) and the results are given as the percentiles of the distribution of all possible values resulting from the logic tree. In particular, the 16th, 50th and 84th percentile maps have been produced for the whole of Italy using the 0.05° grid presenting the spectral ordinates in acceleration for various response periods from 0.1 to 2 s and for return periods varying from 30 to 2500 years; 90 maps have been produced in total, two of which are plotted in Fig. 8.

In many cases, the logarithm of a ground-motion parameter and the logarithm of the corresponding annual frequency of exceedance can be assumed to be linearly-related, at least for return periods of engineering interest (see Fig. 9a). The negative gradient of the log–log

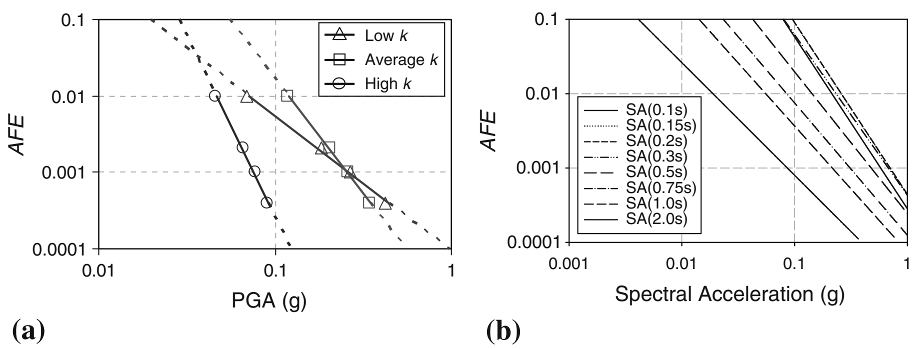


Fig. 9 **a** Relationship between frequency of exceedance and PGA on a log–log scale for three locations in Italy (taken from Grant et al. 2006). **b** Hazard curves on a log–log scale for each spectral ordinate Sa(T) for a single location in Italy

hazard curve is referred to as k in this paper, following the definition in Part 1 of Eurocode 8 (CEN 2004). Using this information, it has been possible to calculate the slope, k, in the log–log space of the hazard curve for each spectral ordinate $\mathrm{Sa}(T)$ in each municipality in Italy, where the seismic hazard data of each municipality has been obtained by interpolation of the grid using representative coordinates for each municipality. Using this slope and the spectral acceleration values at 475 years return period, the spectral acceleration at a given response period (T) at any annual frequency of exceedance can be calculated, as shown in the following workings:

$$\mathrm{AFE}\left[\mathrm{Sa}\left(T\right)\right] = 0.0021\left(\frac{\mathrm{Sa}\left(T\right)_{475\mathrm{yrs}}}{\mathrm{Sa}\left(T\right)}\right)^{k} \tag{3}$$

$$\mathrm{Sa}\left(T\right) = \mathrm{Sa}\left(T\right)_{475\mathrm{yrs}}\left(\frac{0.0021}{\mathrm{AFE}\left[\mathrm{Sa}\left(T\right)\right]}\right)^{1/k} \tag{4}$$

where AFE is the annual frequency of exceedance (which is equal to 0.0021 for a 475 year return period), $\mathrm{Sa}(T)$ is the spectral acceleration which is to be calculated for a given response period T at a given AFE, $\mathrm{Sa}(T)_{475\mathrm{yrs}}$ is the known spectral acceleration at a given response period T for a return period of 475 years and k is the slope of the hazard curve.

The reason for calculating the slope of each spectral ordinate in each municipality is to allow the spectral ordinates for all response periods for a wide range of annual frequencies of exceedance to be predicted (see Fig. 9b). In this way, uniform hazard spectra can be produced for annual frequencies of exceedance (or return periods) which extend above and below the return periods for which the hazard data is available. These uniform hazard spectra will have different shapes depending on the seismicity of the region and the annual frequency of exceedance due to the influence of magnitude, and to a lesser extent distance, on the shape of the response spectra. As can be appreciated from Eq. 1, the seismic risk to a given building class must consider all possible ground motions that could cause the exceedance of the limit state and hence it is important that the hazard curves cover the ground motions which will take the building stock from a zero probability of exceedance of the limit state to a state where 100% of the building class exceeds the limit state. Hence, the uniform hazard acceleration spectra for all municipalities in Italy have been produced for a wide range of probabilities of exceedance for exposure periods of 1 year, 50 years and 100 years. The equation to relate annual frequency of exceedance (AFE) to probability of exceedance (PE) for a given exposure period (or time window), L, is given by the Poisson process:

$$\mathrm{PE} = 1 - \mathrm{e}^{-\mathrm{AFE}\times L} \tag{5}$$

As the vulnerability methods are displacement-based, they require the input in terms of displacement spectra and hence the uniform hazard spectra in terms of spectral acceleration have been transformed into displacement response spectra, $\mathrm{SD}(T)$, through the pseudo-spectral relationship:

$$\mathrm{SD}\left(T\right) = \mathrm{Sa}\left(T\right)\left(\frac{T}{2\pi}\right)^{2} \tag{6}$$

The spectral displacement at higher response periods has not been directly calculated; a plateau at 2 s has been assumed as this follows the guidance which is currently given in the design codes in Italy. It is noted that all spectra have been calculated for rock (with a shear wave velocity higher than 800 m/s) and site amplification factors have subsequently been added, as described in Sect. 3.2.3.

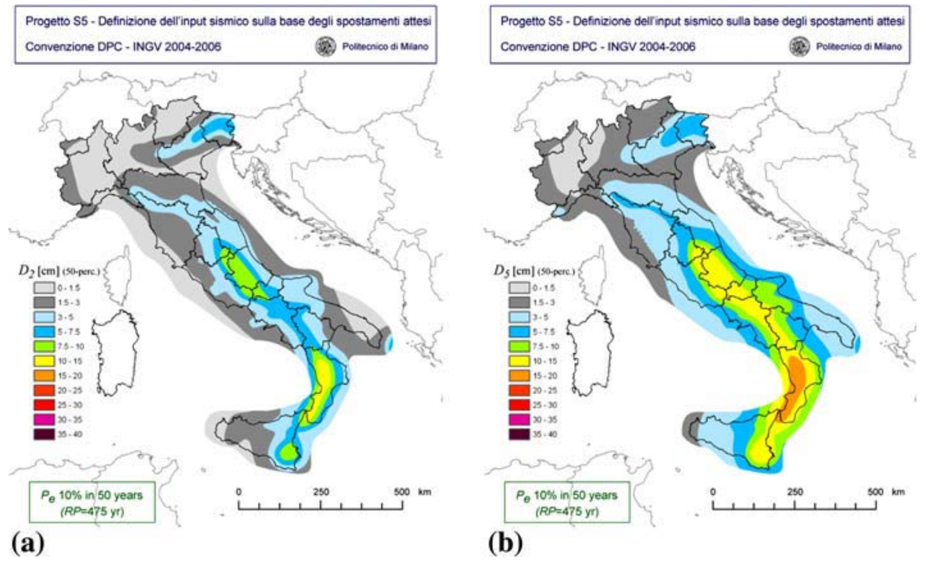


Fig. 10 Seismic hazard maps in terms of spectral displacement ordinates. **a** Return period = 475 years, $T = 2$ s. **b** Return period = 475 years, $T = 5$ s (INGV-DPC 2007b)

3.2.2 Seismic input from the INGV-DPC S5 project

A national research project (INGV-DPC S5) was initiated in Italy in mid-2005, aimed at providing: (a) a model of the seismic action in terms of arbitrarily damped displacement response spectra, extending to long periods and, (b) national hazard maps depicting the displacement response spectral values needed for design. A ground-motion prediction equation for displacement spectral ordinates was specifically derived as part of this project using digital records from around the world, as presented in Faccioli et al. (2007). Common seismic source models for the country were adopted (as mentioned in Sect. 3.2.1) and a similar framework based on logic trees and an external peer review was implemented. In this project, the seismic maps were plotted using the representative coordinates of the municipalities; some example maps are presented in Fig. 10.

Again, the slope of each seismic hazard curve in each municipality was obtained for the study herein, using in this case just the 72 year, 475 year and 2,475 year return period seismic hazard data. Uniform hazard displacement spectra covering periods of vibration from 0.1 to 10 s for all municipalities in Italy for a wide range of annual probabilities of exceedance were again derived using the procedure described in Sect. 3.2.1.

3.2.3 Site amplification

Amato and Selvaggi (2002) used a 1:500,000 scale geological map together with lithological criteria and age of the formations to assign site categories A, B or C, as defined in Eurocode 8 (CEN 2004), to the map of Italy as shown in Fig. 11a. Site A corresponds to rock or other rock-like geological formation with a shear wave velocity, V_{S30} greater than 800 m/s; Site B includes deposits of very dense sand, gravel or very stiff clay with shear wave velocities between 360 and 800 m/s; Site C covers deep deposits of dense or medium-dense sand gravel or stiff clay with shear wave velocities between 180 and 360 m/s. Four test areas were chosen

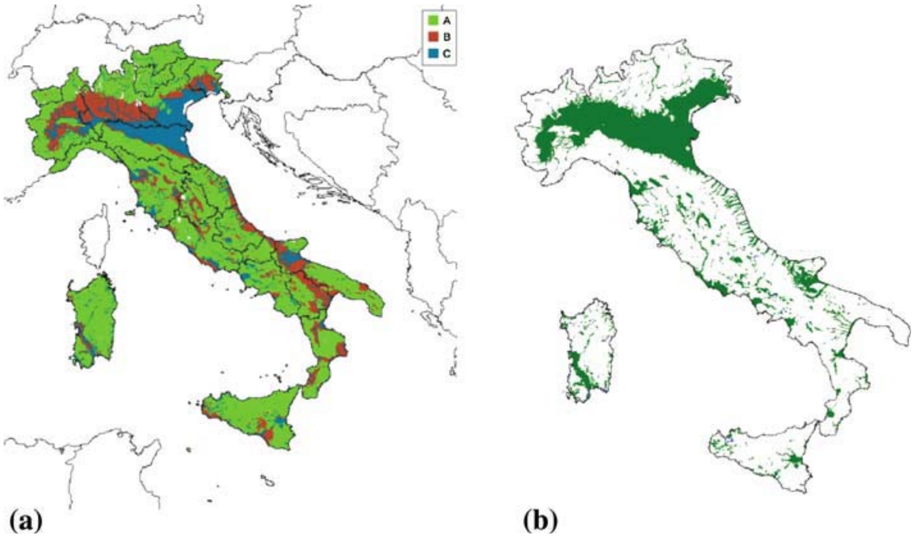


Fig. 11 **a** Site classification at a national scale in terms of three sites classes, A, B and C, as defined in Eurocode 8 (CEN 2004; Amato and Selvaggi 2002). **b** Map identifying the presence of basins or valleys where strong ground shaking may be amplified (Vanini et al. 2007)

by Luzi and Meroni (2007) and the site classes were compared with those obtained from a higher resolution geological map (1:100,000 scale); the results demonstrated that there were problems with the reliability of the site conditions with the use of the 1:500,000 scale map and so future developments are planned to reproduce the site condition map at a national scale at a higher resolution. Within the INGV-DC S5 project, GIS analyses have been performed using a DEM (Digital Elevation Model) and geological data to identify and classify the areas of the Italian Peninsula with potential "basin effects". Basins with a minimum dimension of approximately 500 m have been identified, as shown in Fig. 11b.

The basins and valleys identified in Fig. 11b have not been used in the seismic risk maps presented herein, but they serve to identify the areas where further geological investigations are necessary to better define the amplification of the response spectra.

Figure 11a has been used to identify the proportion of each site class A, B and C within each municipality in Italy. The site classes have then been used together with the acceleration response spectra for rock from S1 (Sect. 3.2.1) and the site amplification factors from the Italian seismic design code OPCM 3274 (2003). In OPCM 3274 (2003), for site classes B and C the code spectra for rock (site class A) are amplified by the same factors: 1.25 for the spectral accelerations at periods less than 0.5 s and 1.5625 for the spectral accelerations above 0.5 s. These factors have been used for the acceleration response spectra used herein, whilst the transition period, T_C, has been calculated separately for each spectra, based on the formula in the NEHRP guidelines (FEMA 2004):

$$T_C = \left(\frac{F\,(1)}{F\,(0.3)}\right)\left(\frac{\mathrm{Sa}\,(1)}{\mathrm{Sa}\,(0.3)}\right) = 1.25\left(\frac{\mathrm{Sa}\,(1)}{\mathrm{Sa}\,(0.3)}\right) \tag{7}$$

where $F(1)$ corresponds to the amplification factor at 1 s and $F(0.3)$ the amplification factor at 0.3 s, Sa(1) the spectral acceleration at 1 s and Sa(0.3) the spectral acceleration at 0.3 s. This transition period separates the constant acceleration from the constant velocity portion of the spectra; $F(0.3)$ is applied up to the transition period and $F(1)$ is applied after the transition period. The site amplification factors in OPCM 3274 (2003) do not account for non-linear effects (i.e. the fact that weaker ground shaking is amplified more than strong ground shaking); however, the decision to use these soil factors has been made as they have been specifically proposed for Italian soil conditions.

For the displacement spectra obtained from the INGV-DPC S5 seismic hazard study, the site amplification factors, $F(T; V_{S30})$, specifically derived within that project have been used, as described in the following equations:

$$\begin{aligned} T = 0\,\mathrm{s} \qquad & F(T; V_{S30}) = F_0 = 1.75 - 0.75\frac{V_{S30} - 360}{800 - 360}, \quad \text{site class B} \\ & F(T; V_{S30}) = F_0 = 1.75 - 0.75\frac{V_{S30} - 180}{360 - 180}, \quad \text{site class C} \end{aligned} \tag{8}$$

$$0 < T \le T_1 \qquad F(T; V_{S30}) = \left(\frac{F_p - F_0}{T_1}\right) T + F_0 \tag{9}$$

$$T_1 < T \le T_2 \qquad F(T; V_{S30}) = F_P = \left(\frac{800}{V_{S30}}\right)^{0.8} \tag{10}$$

$$T_2 < T \le T_3 \qquad F(T; V_{S30}) = F_P - \left(\frac{F_p - F_{LP}}{T_3 - T_2}\right)(T - T_2) \tag{11}$$

$$T_3 < T \qquad F(T; V_{S30}) = F_{LP} = \left(\frac{800}{V_{S30}}\right)^{0.375} \tag{12}$$

where T_1 is equal to 0.3 s, T_2 is 0.7 s and T_3 is 3 s for both site classes B and C. For site class B an average V_{S30} of 580 m/s has been assumed whilst a V_{S30} of 240 m/s has been assumed for site class C.

Once the response spectra for each site class have been obtained, a weighted average considering the proportion of each site class within the municipality has been calculated. This procedure assumes that the buildings are uniformly distributed throughout the municipality. This assumption will be verified through future studies based on the results of a questionnaire which was sent to 8101 municipalities between 2000 and 2002 as part of a project between the GNDT (National Group for Defence against Earthquakes) and INGV (National Institute of Geophysics and Volcanology). The aim of this questionnaire was to determine the distribution of buildings within the municipality in relation to the surface geology (in terms of the three soil classes presented in Fig. 11a). Although only 25% of the municipalities in Italy replied to the questionnaire, these municipalities were within the areas of highest seismic hazard.

3.3 Exposure data

The general characteristics of the Italian building stock have been obtained from the 13th General Census of the Population and Dwellings (ISTAT '91). The Census data in 1991 was collected in terms of dwellings; however, within the Census form, each dwelling was classified as being located within a building with a certain number of dwellings (from 1 to >30), of a given construction type (RC, RC with pilotis, Masonry, Other), and with a given number of storeys (1–2, 3–5, >5). Hence, based on the Census forms compiled for all dwellings within each census tract/municipality, Meroni et al. (2000) have estimated the number of buildings classified according to the period of construction, number of storeys and the vertical structural type within each municipality. The errors associated with the use of the 1991 Census data which is based on the number of dwellings to arrive at the number of buildings are recognised by the authors and have been identified and quantified in some areas of Italy (see e.g. Frassine and Giovinazzi 2004). However, without the presence of detailed exposure data it is necessary to make some sort of hypothesis in order to obtain the number of buildings of a given construction type and with a given number of storeys. The 2001 Census has not been used herein as although this Census was specifically carried out in terms of buildings, the disaggregated data, with a level of detail congruent with that described above for the '91 data, is not currently publicly available. The 1991 Census also includes the surface area and number of residents for each dwelling, from which the surface area and population of each building class (in terms of period of construction, number of storeys and vertical structural type) has been estimated in the same way as described above for the buildings. The volume of each building class has also been estimated by multiplying the surface area by an average storey height of 3 m.

For masonry buildings, five separate building classes have been defined as a function of the number of storeys (from 1 to 5), whilst for reinforced concrete the building classes have been defined considering the number of storeys (from 1 to 8), and the period of construction. The year of seismic classification of each municipality has then be used such that the non-seismically designed and seismically designed buildings could be separated. In this way, the evolution of seismic design in Italy and the ensuing changes to the lateral resistance and the response mechanism of the building stock could be considered in both DBELA and SP-BELA. In DBELA, it has currently been conservatively assumed that all reinforced concrete buildings with regular infill panels constructed before the year of seismic classification have a soft-storey mechanism at the ground floor, whilst all those constructed with seismic design have a beam-sway mechanism. All reinforced concrete buildings with pilotis are assumed to have a soft-storey mechanism at the ground floor. In SP-BELA, the buildings are designed considering only gravity-load design before seismic classification; following classification, depending on the seismic zone to which the municipality was assigned, a base shear coefficient has been used to design the buildings. For buildings assigned to zone 1, this coefficient has been taken as 10% of the weight, for buildings in zone 2 as 7% and for buildings in zone 3 as 4%. The influence of the infill panels on the lateral strength of the buildings is taken into consideration in SP-BELA and the buildings are separated into those with a regular infill panel distribution and those with an irregular infill panel distribution (i.e. with pilotis). In both methods, the buildings have been assumed to be inadequately confined without capacity design principles as these were only recently included into the seismic design of RC buildings in Italy. Table 1 reports the 29 vulnerability classes which have been defined for DBELA and the 69 classes for SP-BELA.

The total number of masonry, seismically designed reinforced concrete and non-seismically designed reinforced concrete buildings calculated within each municipality from the Census data are presented in Fig. 12.

As mentioned previously, the ISTAT data groups the number of storeys (1–2, 3–5, >5), whilst the DBELA and SP-BELA vulnerability classes are defined for each number of storeys separately. Hence, the vulnerability calculations for each number of storeys had to be aggregated to be consistent with the Census data; this was carried out based on statistics of the number of storeys of each construction type from a study of 12,503 masonry buildings and 6,494 reinforced concrete buildings in Catania (Faccioli and Pessina 2000), as reported in Fig. 13. These proportions were used to calculate a weighted average of the vulnerability for the exposure building class based on the vulnerability for each number of storeys separately.

Table 1 Vulnerability classes considered for the Italian building stock in DBELA and SP-BELA in terms of construction type, number of storeys and level of seismic design

Construction type	Number of storeys	
	DBELA	SP-BELA
Masonry		
Artificial brick	1–5	1–5
Reinforced concrete		
Non-seismically designed	1–8	1–8
Non-seismically designed with pilotis		1–8
Seismically designed	1–8	Zone 1: 1–8
		Zone 2: 1–8
		Zone 3: 1–8
Seismically designed with pilotis	1–8	Zone 1: 1–8
		Zone 2: 1–8
		Zone 3: 1–8

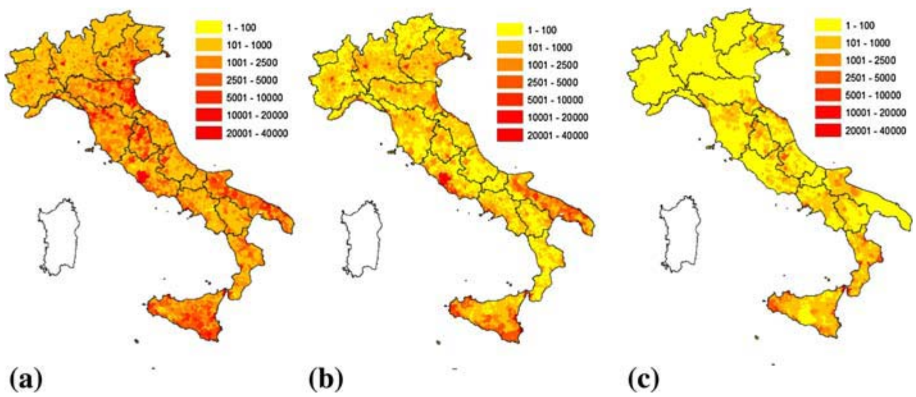


Fig. 12 Number of **a** Masonry. **b** Non-seismically designed reinforced concrete. **c** Seismically designed reinforced concrete buildings in each municipality

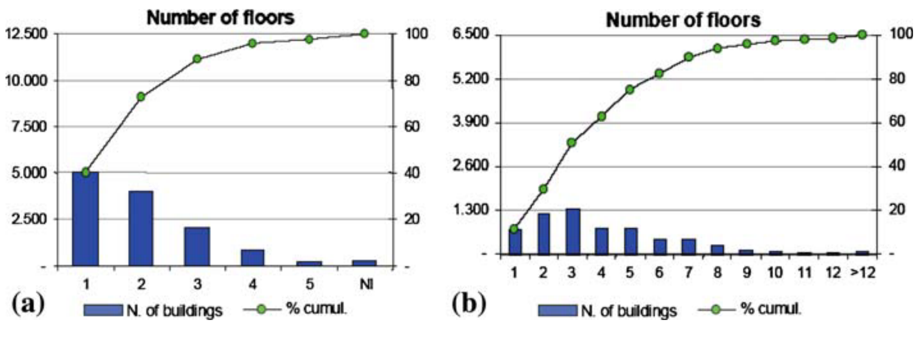


Fig. 13 Proportion of **a** Masonry and **b** Reinforced concrete buildings of each number of storeys obtained from a sample of buildings in Catania (Faccioli and Pessina 2000) (NI means the storey number was unknown)

3.4 Calculation of seismic risk

As mentioned in the Introduction, the seismic risk can be described as the unconditional probability of failure (or exceedance of a limit state) (P_f) for a system with resistance R, under a seismic load S, using Eq. 1. Hence, the calculation of seismic risk for each building class involves the convolution of the resistance and the hazard. This has been carried out in DBELA and SP-BELA using the seismic hazard from both the INGV-DPC S1 and S5 projects, as discussed in what follows.

Based on a database of structural characteristics for the given building stock, random populations of buildings can be generated for each building class (e.g. 2 storey masonry buildings) using Monte Carlo Simulation and the period of vibration and displacement capacity at the three different damage limit states can be calculated for each randomly generated building using both DBELA and SP-BELA, as discussed in Sect. 3.1.

The next step in calculating the seismic risk of the building stock involves the comparison of the structural capacity of the buildings with the ground motion from the uniform hazard spectra in each municipality for a number of annual probabilities of exceedance. Since DBELA and SP-BELA both rely on equivalent linearisation, each displacement response spectrum is overdamped using the damping correction equation presented in the 1994 version of EC8 (CEN 1994), following the recent recommendations given in Priestley et al. (2007):

$$\eta = \sqrt{\frac{7}{2 + \zeta_{eq}}} \tag{13}$$

where η is the correction factor and ζ_{eq} is the equivalent viscous damping, which for reinforced concrete frames has been obtained as a function of ductility, μ, using Eq. 14 (Priestley et al. 2007), whilst for masonry buildings the damping values suggested for each limit state in Restrepo-Velez and Magenes (2004) have been adopted.

$$\xi_{eq} = 0.05 + 0.565\left(\frac{\mu - 1}{\pi\mu}\right) \tag{14}$$

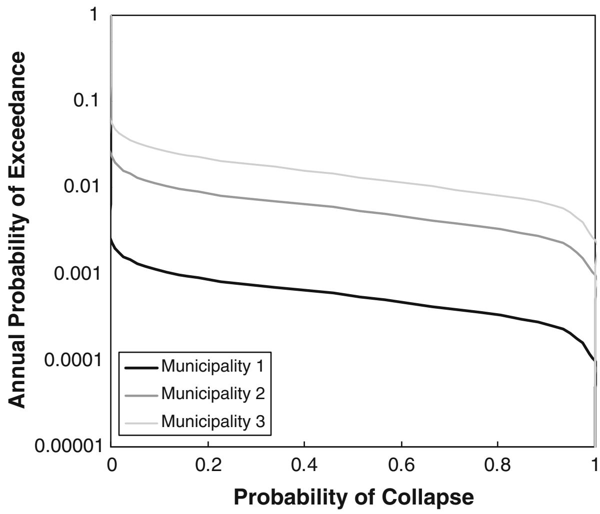
For a given displacement response spectrum, the displacement demand for the limit state period of vibration of a given building in the random population can be compared with its limit state displacement capacity; the sum of all buildings whose displacement capacity is lower than the displacement demand divided by the total number of buildings gives an estimation of the probability of exceeding a given limit state. The sample size is gradually reduced from one limit state to the next by removing the buildings which do not exceed the limit state.

The probability of exceedance of a given limit state (slight damage, significant damage or collapse) has been calculated for each building class for a number of annual probabilities of exceedance to produce curves for each municipality such as those presented in Fig. 14. This exceedance curve is analytically integrated to obtain the mean or expected annual seismic risk to the building class, which for the collapse limit state illustrated in Fig. 14 would be found as follows:

$$P_f = \sum_{i=0}^{+\infty}\left[\frac{APE_{2(i+1)} - APE_{2i}}{6}\right] \times \left[P_{collapse_{2i}} + 4P_{collapse_{2(i+0.5)}} + P_{collapse_{2(i+1)}}\right] \tag{15}$$

where APE is the annual probability of exceedance, $P_{collapse}$ is the probability of collapse and the integration has been carried out by applying Simpson's rule (see e.g. http://en.wikipedia.

Fig. 14 Illustration of damage state exceedance curves (for the collapse limit state) for a given building class for different municipalities



org/wiki/Simpson%27s_rule). The mean annual risk obtained in this manner is then multiplied by the number of buildings in each building class in each municipality, and the sum of this product for all building classes is calculated to give the absolute risk, which can then be divided by the total number of buildings to obtain the percentage risk.

The seismic risk obtained in this way might be termed a site-specific seismic risk as the calculations are based on site-specific probabilistic seismic hazard assessment at a municipality level. For an estimation of the aggregate risk or loss considering more than one site (or municipality, in this case), conventional site-specific probabilistic seismic hazard assessment should be replaced with a method that allows the joint probability of shaking at a number of locations to be predicted. This can be carried out by calculating the ground motion fields from a large number of scenario earthquakes from a stochastic catalogue (see e.g. Bommer and Crowley 2006; Crowley and Bommer 2006). In this way the intra-event (within-earthquake) component of the aleatory variability at different sites can be simultaneously generated considering a lognormal distribution for each event and the losses at each of these sites can be estimated and integrated to obtain the total loss.

Annual seismic risk maps in terms of the number of buildings exceeding different limit states within each municipality have been produced with both DBELA and SP-BELA using two different descriptions of seismic hazard, for the 50 percentile values in each case. The results of DBELA for the 50 percentile values of ground motion for the S1 and S5 descriptions of seismic hazard are presented in Fig. 15 for the probability of exceeding the slight damage state. The results in Fig. 16 show the map of mean annual percentage of buildings which exceed the collapse limit state in each municipality using both the S1 seismic hazard data and the S5 seismic hazard data (using the SP-BELA method). The spatial distribution of seismic risk is similar in both maps, which is not surprising considering that the same seismogenic models were used in the two seismic hazard studies. The influence of the spatial variation of vulnerability on the spatial distribution of seismic risk is minimal because the exposure in the majority of the municipalities in Italy is dominated by 1 and 2 storey masonry buildings. However, the mean annual percentage of buildings exceeding the collapse limit state is higher for much of the country when the S1 seismic hazard data is used. The difference between the spectral displacement at

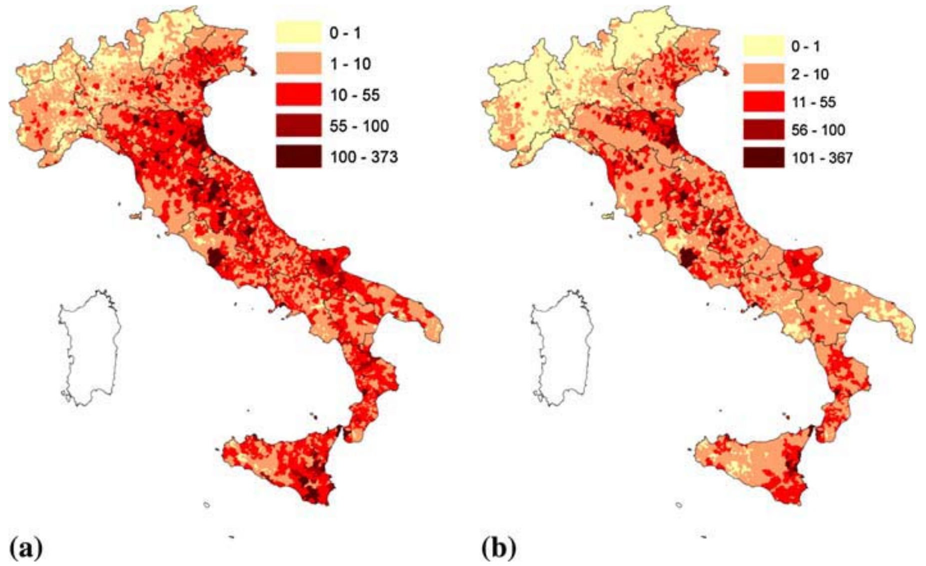


Fig. 15 Mean annual seismic risk maps in terms of the number of buildings which exceed the slight damage limit state per municipality using the DBELA vulnerability predictions. **a** S1 (acceleration-based). **b** S5 (displacement-based) hazard

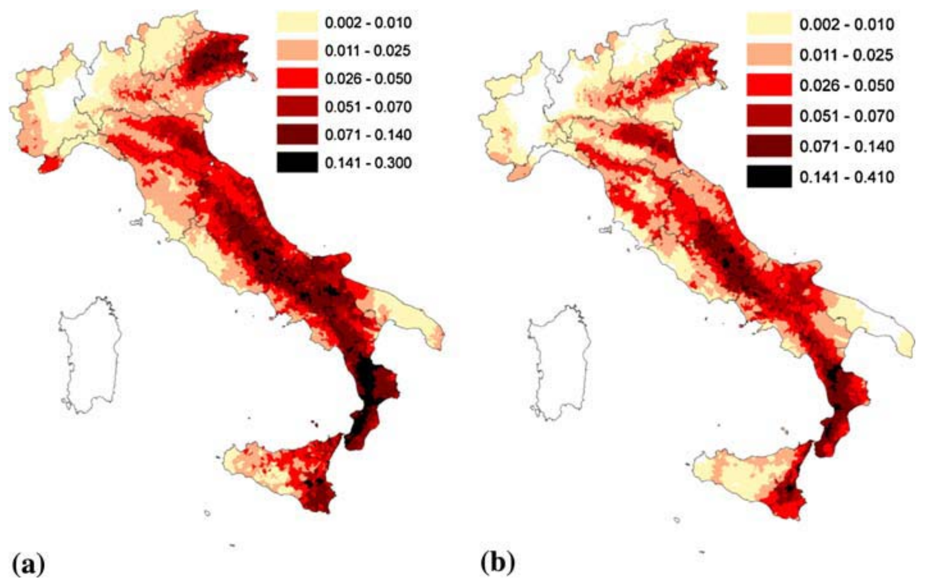


Fig. 16 Mean annual seismic risk maps in terms of the percentage of collapsed buildings per municipality using the SP-BELA vulnerability predictions. **a** S1. **b** S5 hazard

0.5 s that has been predicted for the two seismic hazard studies is shown in Fig. 17 for two different return periods; negative values correspond to areas where the S5 spectral displacement is higher whilst the areas with positive values mean a higher seismic hazard in the S1 study. A comparison of the areas in Fig. 17 where the S5 seismic hazard is

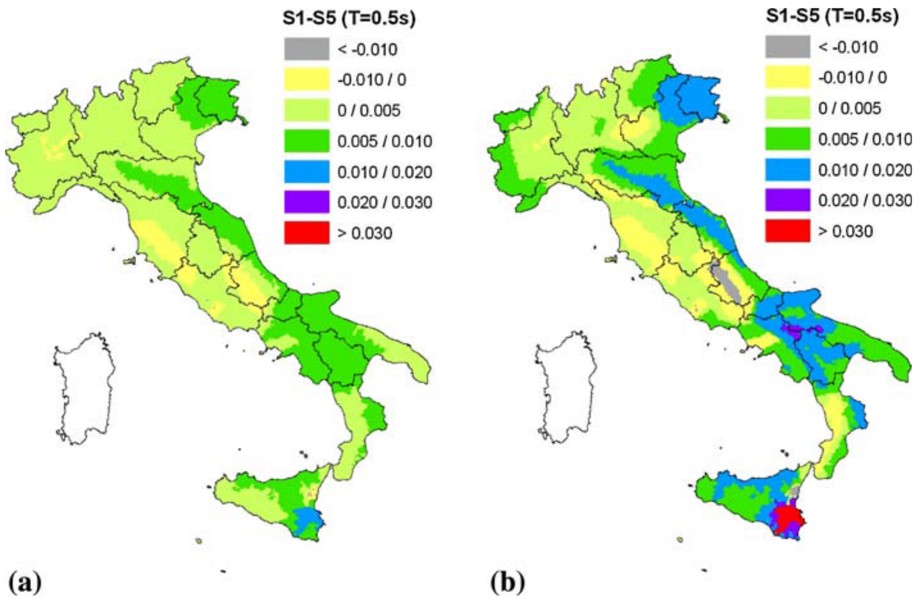


Fig. 17 Maps showing the difference in the spectral displacement on rock at 0.5 s between the S1 and S5 hazard assessments for a return period of **a** 475 years and **b** 2,475 years

higher (for example in Tuscany) with the seismic risk maps in Fig. 16 show that the seismic risk is in fact higher in these regions with the use of the S5 hazard. The opposite is true of the areas where the S1 hazard is higher, which although covers most of the country, is especially pronounced in southern Sicily and Friuli, in the northeast of Italy.

A comparison between the annual seismic risk for the significant damage limit state (as described in Sect. 3.1.1) obtained with the two vulnerability assessment methods (DBELA and SP-BELA) is shown in Fig. 18. It is apparent from this figure that similar spatial distributions of seismic risk are found with both methods, but the buildings are predicted to be more vulnerable in the DBELA methodology. This is not surprising as the DBELA methodology assumes a column-sway mechanism for all reinforced concrete buildings which are not seismically designed, which is known to be a conservative assumption. Furthermore, the masonry buildings are all assumed to have a ground floor storey sway mechanism, whilst in SP-BELA the mechanism and strength are both explicitly defined for each randomly generated building.

The annual seismic risk maps (in percentage terms) based on the SP-BELA method and the S5 (displacement-based) seismic hazard for the collapse limit state are presented in Fig. 19 for masonry buildings, non-seismically designed reinforced concrete buildings and seismically designed reinforced concrete buildings separately. These maps show the higher vulnerability of the masonry buildings compared to reinforced concrete buildings, and also the distribution of seismic design of reinforced concrete buildings in Italy. For example, all of the reinforced concrete buildings in Calabria are assumed to be seismically designed as this Region was certified as a seismic zone from 1909 and all of the reinforced concrete buildings were constructed after this date. Despite the inclusion of seismic design, the seismic risk to these buildings is still relatively high due to the significant levels of seismic hazard in this region of the country; it may appear that the seismically designed buildings are more vulnerable than the non-seismically designed buildings, but this is not the case. Higher levels of risk

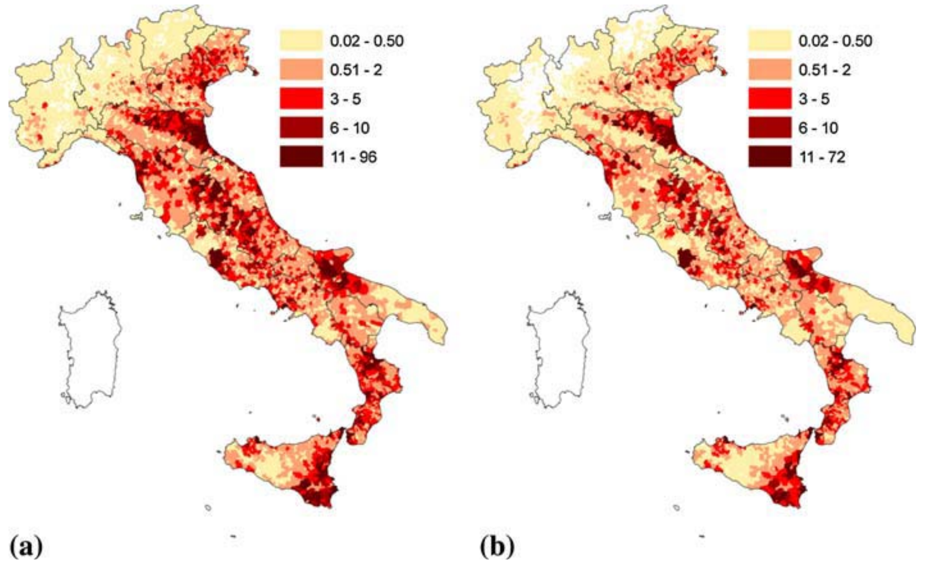


Fig. 18 Mean annual seismic risk maps in terms of the number of buildings which exceed the significant damage limit state per municipality using the S5 hazard and **a** DBELA and **b** SP-BELA vulnerability predictions

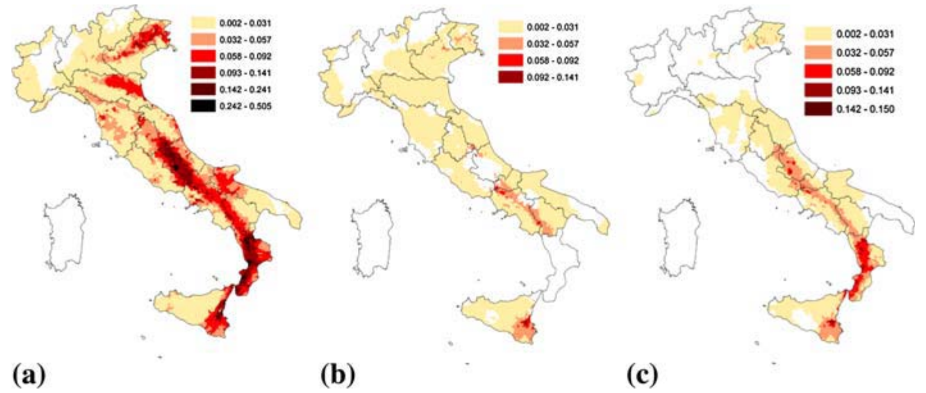


Fig. 19 Mean annual seismic risk maps in terms of the percentage of collapsed buildings per municipality using S5 hazard and the SP-BELA vulnerability predictions, for **a** Masonry, **b** Non-seismically designed reinforced concrete and **c** Seismically designed reinforced concrete buildings

may occur for the seismically designed buildings because the level of exposure of these types of buildings is much higher in the areas of high seismic hazard.

Figure 20 presents the annual seismic risk maps (in absolute terms) for the collapse limit state for all of the different types of exposure which were obtained from the 1991 Census data. These maps have been obtained with the S5 seismic hazard data and with the SP-BELA vulnerability methodology. The production of a seismic risk map in terms of dwellings (Fig. 20b) allows comparisons with the first seismic risk maps which were produced in Italy, as presented in Sect. 2. The consideration of volume and surface area (Fig. 20c, d) can be useful for the prediction of the costs required to repair the damage from earthquakes and the

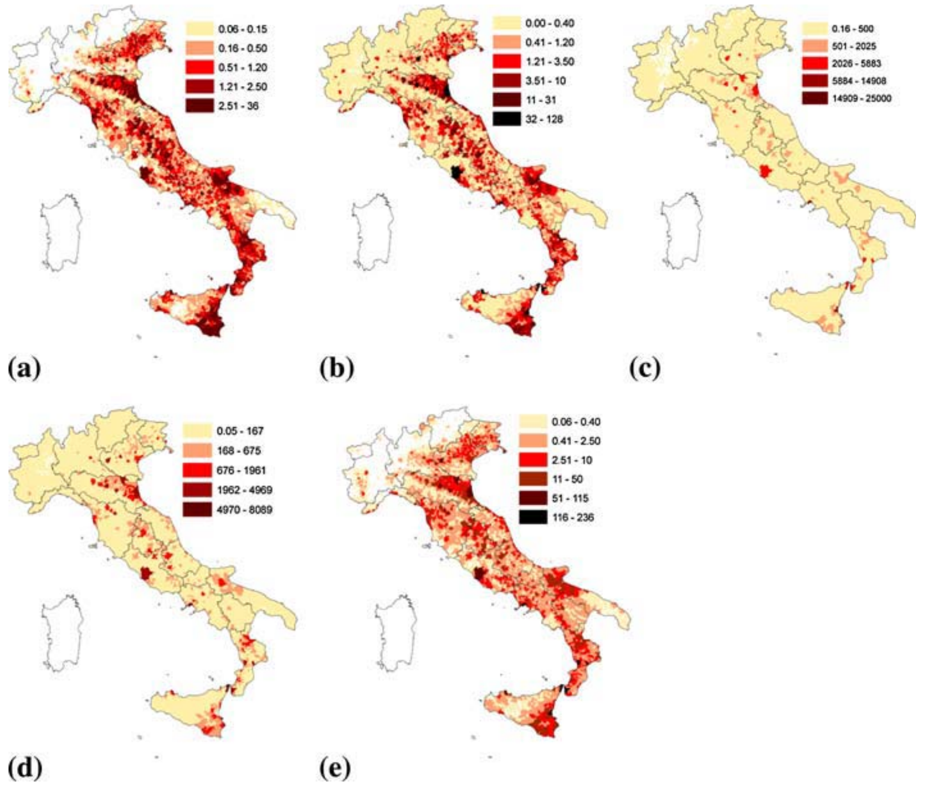


Fig. 20 Mean annual seismic risk maps using S5 hazard and the SP-BELA vulnerability predictions in terms of the number. **a** Collapsed buildings. **b** Dwellings in collapsed buildings. **c** Volume (m^3) of collapsed buildings. **d** Surface area (m^2) of collapsed buildings. **e** Residents living in collapsed buildings, per municipality

population living in the collapsed buildings (Fig. 20e) can be combined with empirical models to define the number of fatalities, injured people or people requiring shelter. It is important to note that the values of risk cannot be summed for the whole country in order to obtain annual risk at a national level, as the calculations have been carried out for each municipality independently. In order to consider annual aggregate losses at a national level, perhaps in terms of costs of damage and loss of life, it would be necessary to apply an event-based approach as described at the beginning of this Section. Nevertheless, all the results presented in Fig. 20 can be of use for the prioritization of municipalities for which risk mitigation initiatives should be applied.

When presenting seismic risk results to the public, the use of different exposure periods can help to convey the message of risk, especially in areas of low seismic hazard where the mean annual number of collapsed buildings may be less than 1. Figure 21 shows the seismic risk for three different time windows (or exposure periods) of 1 year, 50 years and 100 years.

Another difficulty with the presentation of seismic risk maps may arise when there is no indication of the boundaries of the areas within which the exposure is defined and the calculations are made. The calculations presented herein have been carried out at a municipality level, yet the boundaries of the municipalities have not been added to the seismic risk maps which have been presented thus far for the sake of clarity. However, if the reader is not

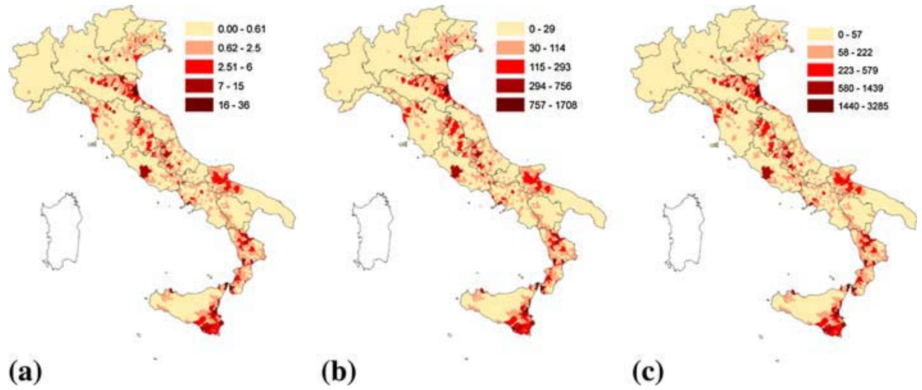


Fig. 21 Mean seismic risk maps in terms of the number of collapsed buildings using SP-BELA vulnerability and S5 hazard for different time windows. **a** 1 year. **b** 50 years and 100 years

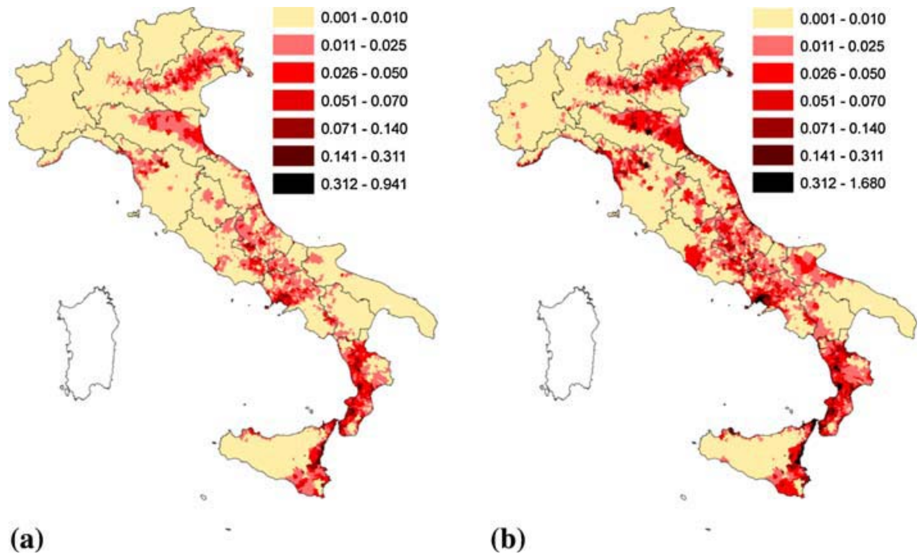


Fig. 22 Mean annual seismic risk maps in terms of the number of **a** buildings and **b** dwellings per km^2 which exceed the collapse limit state per municipality, using SP-BELA vulnerability and S5 hazard

familiar with the country, it may be unclear whether an area with a high level of risk refers to a number of municipalities each with a large mean number of collapsed buildings or if the results refer to a single municipality. One way in which this problem may be tackled is through the presentation of seismic risk maps where the number of buildings is normalized by the surface area of the municipality, as shown in the examples in Fig. 22. These results, which present the density of seismic risk, may also be of use for the prioritization of municipalities for seismic risk mitigation.

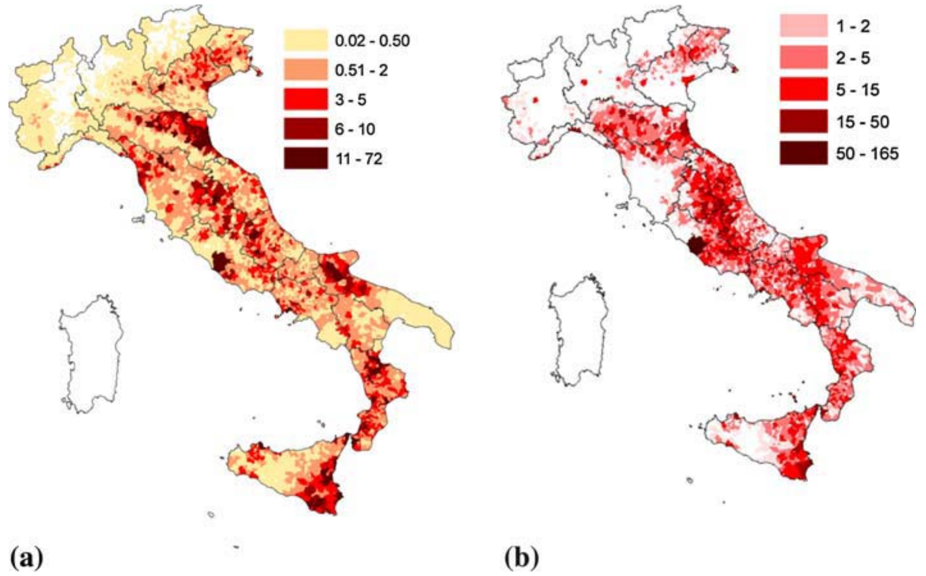


Fig. 23 Mean annual seismic risk in terms of the number of buildings which exceed the significant damage state per municipality from **a** SP-BELA, S5 hazard and **b** SAVE Project (Zuccaro 2004)

4 Comparison of existing and proposed seismic risk maps for Italy

The aim of this paper has been to propose a new mechanics-based method to calculate seismic risk maps for Italy which makes use of the most up-to-date seismic hazard data. Although the maps presented in the previous section are preliminary, it is still of interest to compare them with the existing maps to see how similar/diverse the results are. The method used herein is based on the seismic vulnerability of buildings, though as seen in the previous section the results can be extended to dwellings, volume, surface area and population as long as the number of each of these exposure measures can be classed in the same way as the buildings (i.e. in terms of year of construction, number of storeys and construction type). Many of the existing seismic risk maps in Italy presented in Sect. 2 are in terms of dwellings, though there have also been maps presented in terms of buildings, volume and population and thus a comparison with each of these exposed elements has been sought herein.

Figures 23 and 24 present a comparison of the mechanics-based seismic risk maps obtained with SP-BELA (using the S5 hazard data) with those from the SAVE project maps (Zuccaro 2004) in terms of the mean annual number of buildings predicted to exceed the significant damage and collapse limit states, respectively, in each municipality. In Fig. 23, the significant damage limit state of SP-BELA has been compared with the “unfit for use” limit state (meaning that the inhabitants cannot return to the building after the earthquake and it will most likely need to be retrofitted) used in the SAVE Project. The results in these figures show that a larger number of buildings are predicted to exceed the “unfit for use” limit state in the SAVE project, whilst the opposite is true for the collapse limit state. The reason for such differences could be manifold: differences in the level of seismic hazard and the vulnerability functions, the exposure data as well as the definition of the damage state. The collapse limit state is perhaps the most reasonable damage state upon which comparisons of different seismic risk maps should be made. However, the collapse limit state used in the mechanics-based

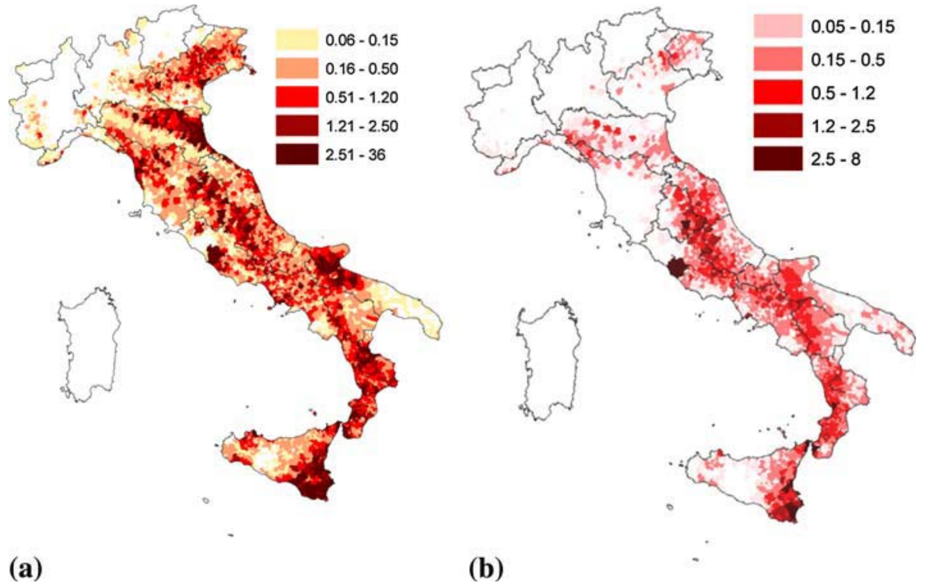


Fig. 24 Mean annual seismic risk in terms of the number of collapsed buildings per municipality from **a** SP-BELA, S5 hazard and **b** SAVE Project (Zuccaro 2004)

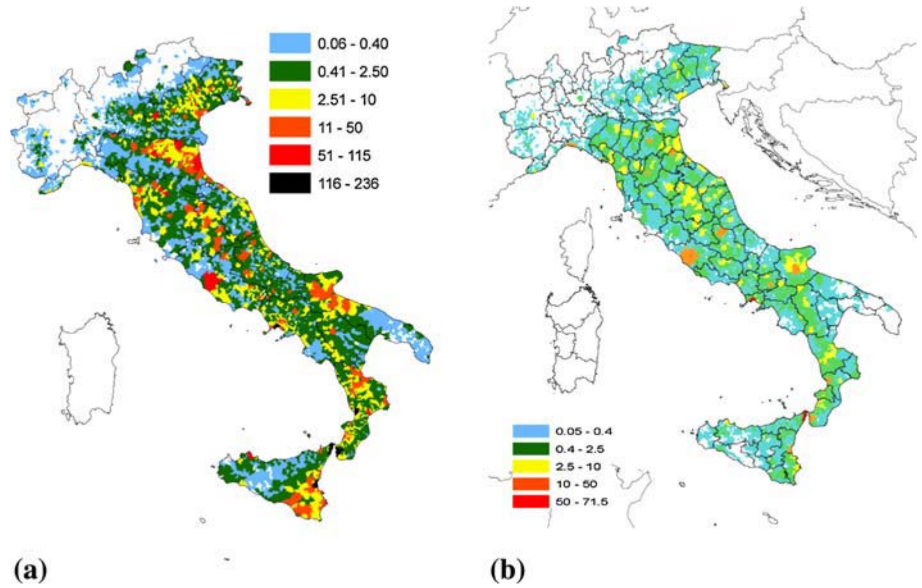


Fig. 25 Mean annual seismic risk in terms of the number of residents in collapsed buildings per municipality from **a** SP-BELA, S5 hazard and **b** Lucantoni et al. (2001) with PGA hazard

procedures follows the code-based definition of collapse which means that the building is either collapsed or no longer safe for the occupants (OPCM 2003) and as such this damage state might be closer to the unfit for use damage state of SAVE, or somewhere between the two.

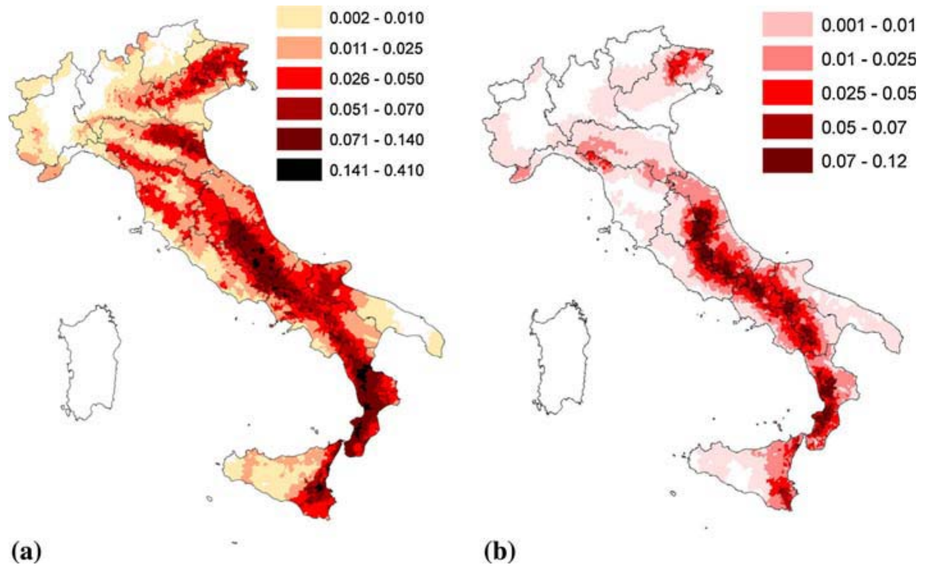


Fig. 26 Mean annual seismic risk in terms of the percentage of collapsed buildings per municipality from **a** SP-BELA, S5 hazard and **b** SAVE Project (Zuccaro 2004)

The differences in the limit states is also likely to be the reason for the higher mean annual number of residents predicted to be living in collapsed buildings shown in Fig. 25a, which is based on the mechanics-based method, as compared with Fig. 25b which has been taken from the Lucantoni et al. (2001) study. Nevertheless, despite the very different approaches used to predict the seismic hazard and vulnerability in the seismic hazard maps proposed herein and those previously derived for Italy, the differences can be seen to be less than one order of magnitude.

A comparison in terms of the spatial distribution of risk considering the seismic risk in terms of the percentage of buildings has also been carried out. Figure 26 shows the difference in the distribution of risk over the whole country between the method proposed herein and that applied in the SAVE Project (Zuccaro 2004); the reason for this spatial variation in seismic risk is due to the differences in the seismic hazard and is also probably due to the explicit inclusion of site conditions in the method applied herein. Figure 26a presents the map of mean annual percentage of buildings which exceed the collapse limit state in each municipality using SP-BELA (and the S5 hazard data) which, although weighted by the proportion of each building class, is not influenced by the absolute values of each building class; Fig. 26b presents the equivalent map from the SAVE project. A comparison of Fig. 26a with Fig. 2c, and 26b with Fig. 2a shows how the distribution of seismic risk closely follows the spatial distribution of seismic hazard used in each case. The areas of high risk which are not evident from the seismic hazard map, for example in the northeast of Reggio Emilia, are caused by the softer soil conditions which are considered in these areas (see Fig. 11a). These results highlight how changes to the list of municipalities which would be classified at a high level of risk should be made with the use of the up-to-date seismic hazard studies carried out in the past couple of years, together with the inclusion of site conditions. Similar differences in the spatial distribution of seismic risk are seen in the seismic risk maps in

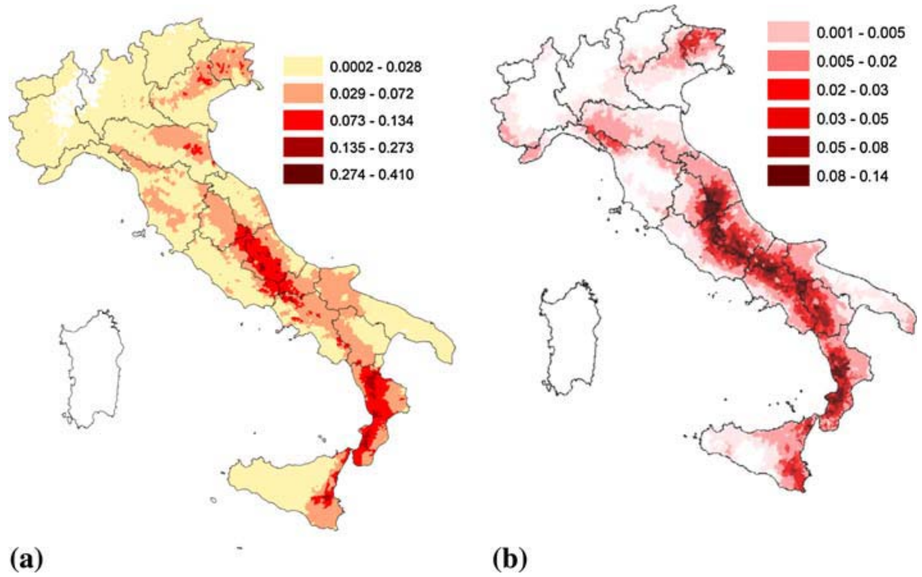


Fig. 27 Mean annual seismic risk in terms of the percentage of collapsed dwellings per municipality from **a** SP-BELA, S5 hazard and **b** Lucantoni et al. (2001) with PGA hazard

terms of dwellings, as presented in Fig. 27 where the mechanics-based seismic risk map is compared with the map from Lucantoni et al. (2001).

Finally, a comparison with the conditional seismic risk map for a return period of 475 years presented in the SAVE Project is shown in Fig. 28. This comparison removes the differences which may arise due to a variation in the slopes of the seismic hazard curves used herein and those used in the SAVE Project as only a single return period (475 years) is considered. The comparison shows that the mechanics-based seismic risk maps predict a larger variation in the number of collapsed buildings from municipality to municipality. On the other hand, the SAVE Project maps show a more gradual variation of the number of collapsed buildings within the country. Such differences may again have an influence on the prioritisation of municipalities for seismic intervention.

5 Conclusions

The aim of this paper has been to compare the various seismic risk maps which have been proposed in Italy over the past 10 years. These maps have been updated over the years following the publication of more detailed seismic hazard and exposure data, and the updating of empirical vulnerability functions. The recent publication of updated seismic hazard maps in Italy has called for further seismic risk studies to be carried out using this state-of-the-art data. These seismic hazard maps are in terms of acceleration and displacement spectral ordinates and thus necessitate the use of more sophisticated models of the vulnerability such that the frequency content of the ground motion and the period of vibration of the building stock can be taken into account.

Analytical, or mechanics-based, vulnerability methods have been applied herein together with the seismic hazard data in terms of spectral ordinates to produce seismic risk maps. A

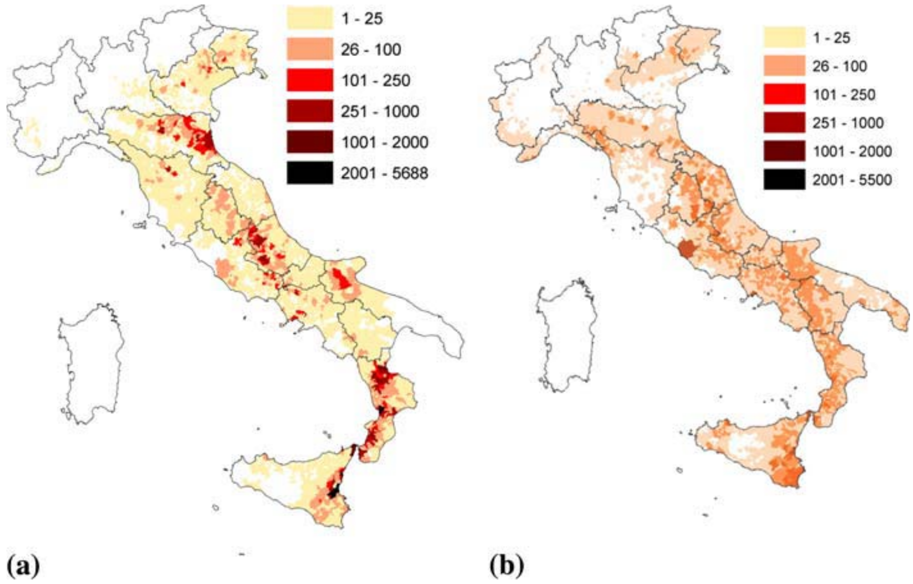


Fig. 28 Conditional seismic risk for a return period of 475 years in terms of the mean number of collapsed buildings. **a** SP-BELA, S5 hazard. **b** SAVE Project (Zuccaro 2004)

preliminary comparison of these maps with those previously derived for Italy has been carried out, though the aim is to further calibrate these mechanics-based methods to the Italian building stock characteristics before reliable comparisons in terms of absolute values can be made. In particular, the variation in material properties in the north, central and south of Italy is to be implemented to take into account the different construction standards throughout the country. Despite the need to further develop the mechanics-based methodologies, the main conclusion which can nevertheless be made from the results presented herein is that the spatial distribution of seismic risk is very different with the use of the new seismic hazard studies for Italy, with new areas now identified as being at a high level of seismic risk. These conclusions may have an influence on the way in which municipalities are prioritised for seismic retrofitting schemes.

Acknowledgements The authors would also like to acknowledge the support of the Italian Ministry of Research and Higher Education (MIUR—Ministero dell'Università e della Ricerca) through the financing of the project AIRPLANE (Advancing Interdisciplinary Research PLAtform on volcanoes aNd Earthquakes).

References

Amato A, Selvaggi G (2002) Probable earthquakes in Italy from 2000 to 2030: elements for the definition and prioritization of seismic risk mitigation measures. Gruppo Nazionale per la Difesa dai Terremoti (GNDT) (in Italian)

Ambraseys NN, Simpson KA, Bommer JJ (1996) Prediction of horizontal response spectra in Europe. Earthq Eng Struct Dyn 25(4):371–400

Bommer JJ, Crowley H (2006) The influence of ground motion variability in earthquake loss modelling. Bull Earthq Eng 4(3):231–248

Borzi B, Pinho R, Crowley H (2008a) Simplified pushover-based vulnerability analysis for large scale assessment of RC buildings. Eng Struct 30(3):804–820

Borzi B, Crowley H, Pinho R (2008b) Simplified pushover-based earthquake loss assessment (SP-BELA) for masonry buildings. Int J Archit Heritage 2(4):353–376

Bramerini F, Di Pasquale G (2008) Updated seismic risk maps for Italy. Ing Sismica XXV(2):5–23 (in Italian)

Calvi GM, Pinho R, Magenes G, Bommer JJ, Restrepo-Veléz LF, Crowley H (2006) The development of seismic vulnerability assessment methodologies for variable geographical scales over the past 30 years. ISET J Earthq Technol 43(3):75–104

CEN (1994) Eurocode 8: design provisions for earthquake resistance of structures—part 1: general rules, seismic actions and rules for buildings. ENV 1998-1-1:1994, Comité Européen de Normalisation, Brussels

CEN (2004) Eurocode 8: design of structures for earthquake resistance—part 1: general rules, seismic actions and rules for buildings. EN 1998-1:2004, Comité Européen de Normalisation, Brussels

Colombi M, Borzi B, Crowley H, Onida M, Meroni F, Pinho R (2008) Deriving vulnerability curves using Italian earthquake damage data. Bull Earthq Eng 6(3):485–504

Crowley H, Bommer JJ (2006) Modelling seismic hazard in earthquake loss models with spatially distributed exposure. Bull Earthq Eng 4(3):249–273

Crowley H, Pinho R (2008) Using basic principles of mechanics of materials to assess the seismic risk of entire countries. Environ Semeiot 1(1):1–19

Crowley H, Pinho R, Bommer JJ (2004) A probabilistic displacement-based vulnerability assessment procedure for earthquake loss estimation. Bull Earthq Eng 2(2):173–219

Crowley H, Borzi B, Pinho R, Colombi M, Onida M (2008) Comparison of two mechanics-based methods for simplified structural analysis in vulnerability assessment. Adv Civil Eng 2008, Article ID 438379, 19 pp

Di Pasquale G, Orsini G (1997) Proposal for the assessment of post-earthquake damage scenarios based on ISTAT data. In: Proceedings of the 8th national conference on earthquake engineering in Italy, vol 1, pp 477–486 (in Italian)

Di Pasquale G, Orsini G, Romeo R (2000) Sensitivity analysis in seismic risk assessment. In: Proceedings of the 6th international conference on seismic zonation, Palm Springs, CA

Faccioli E, Pessina V (eds) (2000) The Catania Project: earthquake damage scenarios for high risk areas of the Mediterranean. CNR—Gruppo Nazionale per la Difesa dai Terremoti, Rome p 225

Faccioli E, Cauzzi C, Paolucci R, Vanini M, Villani M, Finazzi D (2007) Long period strong motion and its use as input to displacement based design. In: Proceedings of the 4th international conference on earthquake geotechnical engineering, Thessaloniki, Greece

FEMA (2004) NEHRP recommended provisions for seismic regulations for new buildings and other structures, 2003 edn, part 1—provisions, part 2—commentary, FEMA-450 Report. Federal Emergency Management Agency, Washington, DC

Frassine L, Giovinazzi S (2004) Databases compared in the vulnerability assessment of residential buildings: an application to the city of Catania. In: Proceedings of the XI Congresso Nazionale “L’ingegneria Sismica in Italia”, Genova 25–29 January 2004 (in Italian)

Grant D, Bommer JJ, Pinho R, Calvi GM (2006) Defining priorities and timescales for seismic intervention in school buildings in Italy, Research Report ROSE-2006/03, IUSS Press, Pavia, Italy

Gruppo di Lavoro CPTI04 (2004) Parametric catalogue of Italian earthquakes version 2004 (CPTI04). INGV, Bologna. http://emidius.mi.ingv.it/CPTI/ (in Italian)

INGV-DPC S1 (2007a) Continued assistance to the DPC for the completion and management of seismic hazard maps foreseen in the Ordinance PCM 3274 and planning of future developments. http://esse1.mi.ingv.it (in Italian)

INGV-DPC S5 (2007b) Definition of seismic input in terms of expected displacements. http://www.ingv.it/progettiSV/Progetti/Sismologici/sismologici_con_frame.htm (in Italian)

Lucantoni A, Bosi V, Bramerini F, De Marco R, Lo Presti T, Naso G, Sabetta F (2001) Seismic risk in Italy. Ing Sismica XVII(1):5–36 (in Italian)

Luzi L, Meroni F (2007) Assessment of peak ground acceleration and response spectral ordinates amplified by local site conditions, Project INGV-DPC S1. http://esse1.mi.ingv.it/d6.html (in Italian)

Margottini C, Molin D, Narcisi B, Serva L (1987) Intensity vs. acceleration: Italian data. In: Proceedings of the workshop on historical seismicity of central-eastern Mediterranean region, Rome, 1987

Marino S (2005) Survey and statistical evaluation of the characteristics of existing reinforced concrete buildings for scenario damage assessment. Undergraduate Thesis, University of Pavia, Italy (in Italian)

Martinelli A, Corazza L (eds) (1999) Census of the vulnerability of public, critical and special buildings in the Regions of Abruzzo, Basilicata, Calabria, Campania, Molise, Puglia and Sicily, vols I, II, III, L’Aquila, Italy (in Italian)

Masi A, Vona M (2004) Seismic vulnerability of reinforced concrete buildings from the 1970s. In: Proceedings of the 11th national conference on “Earthquake Engineering in Italy”. Genoa, Italy (in Italian)

Meroni F, Petrini V, Zonno G (2000) "National distribution of vulnerability." Vulnerability of buildings: assessment of the seismic vulnerability of ordinary buildings at a national scale. In: Bernardini A (ed) CNR—Gruppo Nazionale per la Difesa dai Terremoti, Rome, 175 pp + CD-ROM (in Italian)

Montaldo V, Meletti C, Martinelli F, Stucchi M, Locati M (2007) On-line seismic hazard data for the new Italian building code. J Earthq Eng 11(Sp. Issue 1):119–132

Ordinanza del Presidente del Consiglio dei Ministri (OPCM) (2003) General criteria for the seismic classification of the national territory and technical standards for constructing in seismic zones. Ordinance no. 3274, G.U. n. 72 del 8-5-2003 (in Italian)

Ordinanza del Presidente del Consiglio dei Ministri (OPCM) (2006) Criteria for the identification of seismic zones for the production and updating of lists of the aforementioned zones. Ordinance no. 3519 of the 28th April 2006 (in Italian)

Priestley MJN, Seible F, Calvi GM (1996) Seismic design and retrofit of bridge structures. Wiley, New York

Priestley MJN, Calvi GM, Kowalsky MJ (2007) Displacement-based seismic design of structures. IUSS Press, Pavia, Italy

Restrepo-Velez L, Magenes G (2004) Simplified procedure for the seismic risk assessment of unreinforced masonry buildings. In: Proceedings of the 13th world conference on earthquake engineering, Vancouver, Canada, Paper no. 2561

Sabetta F, Pugliese A (1996) Estimation of response spectra and simulation of nonstationary earthquake ground motions. Bull Seismol Soc Am 86(2):337–352

Sabetta F, Goretti A, Lucantoni A (1998) Empirical fragility curves from damage surveys and estimated strong ground motion. In: Proceedings of the 11th European conference on earthquake engineering, Paris, France

Stella A (1999) The influence of the quality of steel on the seismic response of reinforced concrete frames designed for gravity loads. Undergraduate Thesis, University of Naples Federico II, Naples, Italy (in Italian)

Vanini M, Pessina V, Di Giulio G, Lenti L (2007) Influence of alluvium filled basins and edge effects on displacement response spectra. Deliverable 19, INGV-DPC S5 Project. http://www.ingv.it/progettiSV/Progetti/Sismologici/sismologici_con_frame.htm

Verderame GM, Manfredi G, Frunzio G (2001a) Mechanical properties of concrete used in reinforced concrete buildings in the 1960s. In: Proceedings of the 10th national conference on "Earthquake Engineering in Italy", Potenza-Matera, Italy (in Italian)

Verderame GM, Stella A, Cosenza E (2001b) Mechanical properties of steel used in reinforced concrete buildings in the 1960s. In: Proceedings of the 10th national conference on "Earthquake Engineering in Italy", Potenza-Matera, Italy (in Italian)

Vona M, Masi A (2004) Seismic resistance of reinforced concrete frames designed with R.D. 2229/39. In: Proceedings of the 11th national conference on "Earthquake Engineering in Italy", Genoa, Italy (in Italian)

Zuccaro G (2004) Inventory and vulnerability of the residential building stock at a national level, seismic risk and social/economic loss maps. CD-ROM, Naples, Italy (in Italian)