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S.I. : SEISMIC RISK ASSESSMENT IN ITALY

Seismic risk assessment of residential buildings in Italy

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Abstract

The last National Risk Assessment NRA for Italy was developed at the end of 2018 by the Department of Civil Protection (DPC) in response to the specific requirement of the Sendai Framework for Disaster Risk Reduction 2015–2030 to periodically adjourn the assessment of disaster risk. The methodology adopted to perform seismic risk assessment and build national seismic risk maps was specifically developed to comply with the recent Code for Civil Protection, issuing that, in addition to a solid scientific base, risk assessment should be characterized by a wide consensus of the scientific community. As a result, six research units belonging to two Centers of Competence of the DPC, namely ReLUIS (Network of university laboratories for seismic engineering) and EUCENTRE (European Centre for Training and Research in Earthquake Engineering), collaborated under the guidance and coordination of DPC to produce the recent updating of national seismic risk maps for the residential building stock. This paper describes the methodology adopted to develop the consensus-based national seismic risk assessment and presents the main results in terms of expected damage and impact measures (unusable buildings, homeless, casualties, direct economic losses).

Keywords Residential buildings · Vulnerability · Inventory · Economic losses · Casualties · Homeless

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1 Introduction

The first out of four priority actions of the Sendai Framework for Disaster Risk Reduction 2015–2030 (United Nations 2015) is "*Understanding Disaster Risk* in all its dimensions of vulnerability, capacity, exposure of persons and assets, hazard characteristics and the environment." Such knowledge can be used for risk assessment and is at the base for the consequent actions of prevention, mitigation, preparedness and response.

In Italy, thanks also to the action of the national Department of Civil Protection (DPC), the fundamental role of the "knowledge of risk scenarios" has already been acknowledged for quite some time. Indeed, the first national risk maps date back to 1996 (GNDT-ING-SSN 1996). Since then, scientific enhancements allowed for progressive updating of the national maps (2001, 2008). In 2010, a seismic risk assessment at national scale was used to support the actions of the Italian National Seismic Prevention Program, financed by the Italian Parliament following the destructive 2009 Abruzzi earthquake. In that case, the distribution of the economic resources among Italian regions was concentrated on territories where the risk of building collapse was higher, according to regional seismic risk indices assessed through risk studies available at that time and carried out by DPC itself and its competence centers ReLUIS and EUCENTRE (Dolce 2012, 2019a, b, c).

The strong role of the "knowledge" towards effective protection is explicitly recognized in the recent Code for Civil Protection (Decree Law n.1 of 2/1/2018), which defines the knowledge of risk scenarios as one of the pillars of prevision and one of the activities of the so-called "non-structural prevention". Furthermore, the same Code underlines the important role of the scientific community, who effectively participates to the National Service of civil protection by turning knowledge and scientific products deriving from research work into prevention activities.

The National Risk Assessment (NRA) 2018 for Italy (ICPD 2018) was developed by DPC in agreement with EU decision 1313/2013 and in response to the specific requirement of the Sendai Framework to periodically adjourn the assessment of disaster risk. The document deals with all the 8 natural risks considered by the civil protection Code, namely seismic, volcanic, tsunami, hydraulic, hydro-geological, adverse meteorological events, droughts and forest fires.

Besides, the development of new seismic risk maps had to comply with the requirements of the new civil protection Code, issuing that, in addition to a solid scientific base, risk assessment requires a wide consensus of the scientific community. To this end, a new methodology for the assessment of seismic risk of the whole residential building stock in Italy was developed to foster the active involvement of the scientific community in the calculation of the new risk maps. In particular, 6 research units, belonging to two Centers of Competence of DPC, were involved in the research work: namely 1 research unit from EUCENTRE (European Centre for Training and Research in Earthquake Engineering) and 5 from ReLUIS (Network of university laboratories for seismic engineering). The effective collaboration among such research units, under the guidance and coordination of DPC, made it possible to produce the new national seismic risk maps for the residential building stock included in the NRA 2018 (ICPD 2018).

2 Methodology

Seismic risk, referring to specified asset types (e.g. residential buildings, public buildings, infrastructures, critical facilities etc.), is a probabilistic measure of the damage expected in a given time interval, in a region of interest. As discussed in (Silva 2018), the risk can be calculated using a probabilistic event-based risk methodology or following a classical probabilistic seismic hazard assessment PSHA-based risk approach. Risk depends on seismic hazard, on the vulnerability of the considered assets at risk and on their exposure (see Fig. 1). The previous definition does not take into account qualitative parameters such as the capacity, envisaged by UNSDR in a more comprehensive definition of risk (United Nations 2015).

Seismic hazard, expressing the probability of exceedance of levels of ground motion in a certain interval of time at a site, is obtained by Probabilistic Seismic Hazard Analysis, or PSHA; the latter mathematically combines models for the location and size of potential future earthquakes with predictions of the potential shaking intensity caused by them (Baker 2015). PSHA at a site may be represented by the hazard curve, linking the generic intensity measure IM to the mean annual frequency of exceedance of such intensity λ_{IM}, see e.g. central left panel in Fig. 1. On the other hand, the usual representation of this parameter at territorial scale is through hazard maps, showing the spatial distribution of expected intensity at an assigned return period, or having a given probability of exceedance in an assigned interval of time.

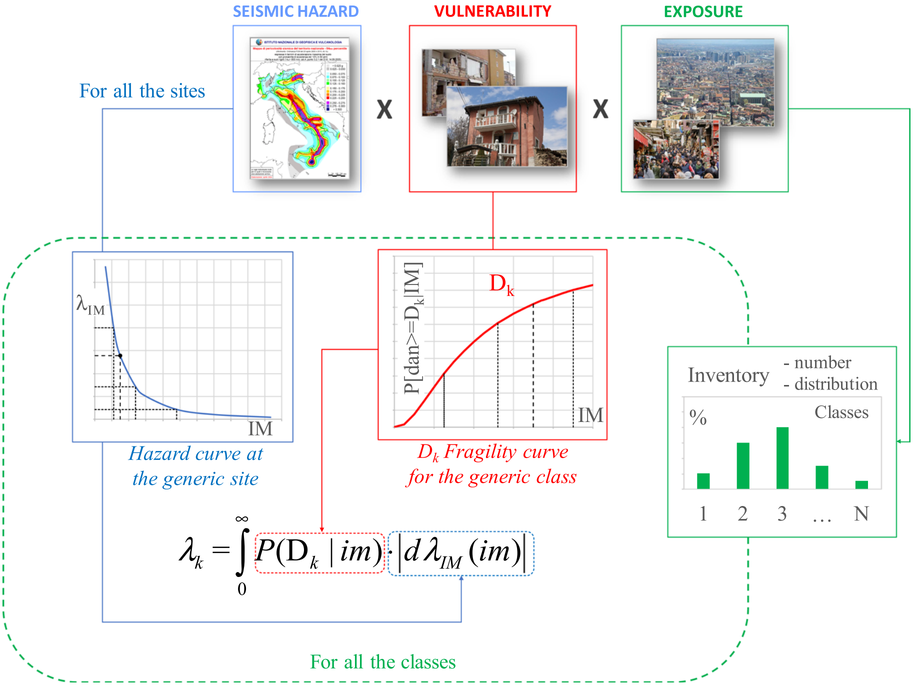


Fig. 1 Main elements contributing to seismic risk and mathematical formulation

Seismic vulnerability for assets at risk (e.g. building classes) is their susceptibility to be damaged by earthquakes, as a function of the seismic intensity. Typically, the vulnerability is described through fragility curves, expressing the probability of attaining different levels of damage by varying the seismic intensity. Further common representations of such risk factor are damage probability matrices (DPM), representing the conditional probability of obtaining different damage levels given the earthquake intensity, and vulnerability curves, that represent the variation of a mean value of damage with the earthquake intensity.

Finally, exposure describes, through building inventory, the quality and quantity of the assets at risk in the region of interest (number of buildings and percental distribution in the different vulnerability classes). This inventory is linked to the vulnerability model so that the assets at risk, based on their typological characteristics, are clustered in a certain number of vulnerability "classes" to which a specific vulnerability model is associated.

Mathematically, the calculation of seismic risk entails the convolution of the seismic hazard with vulnerability and exposure of the assets at risk. For large-scale assessment, the buildings, or similarly infrastructures, are clustered in relevant "classes" that are expected to behave similarly during a seismic event and whose different attitude to sustain seismic damage is expressed by suitable fragility (or vulnerability) curves. A typical example of building classification is the European macro-seismic scale EMS 98 (Grünthal 1998), that categorizes buildings in 6 classes (from A to F), based on the construction material and code design level, if relevant. The vulnerability classification introduced by EMS 98, although empirical and tentatively indicative of what it might be the real ranking among building types, considers in some way the broad uncertainties associated to the building classification process, so that the construction material is associated to a range of possible classes with a most probable one.

For each generic building class considered in the vulnerability model, the mean annual rate λ_k of attaining damage state D_k may be expressed as in Eq. (1):

$$\lambda_k = \int_0^\infty P\left(D_k \middle| im\right) \cdot \left|d\lambda_{IM}(im)\right| \tag{1}$$

with $P(D_k|im)$ representing the fragility of the building class for damage state D_k, i.e. the probability that the buildings belonging to the same class will attain damage states greater or equal to D_k when subjected to an earthquake with ground motion intensity level im and λ_{IM} the seismic hazard at the site, i.e. the mean annual frequency of exceedance of the ground motion intensity im. The calculation should be repeated for each vulnerability class of the building inventory (according to the exposure model) and then the results should be combined considering the proportion of each class in the considered asset (see Fig. 1).

For smallvalues of λ_k the mean annual rate approximates the probability p_k of attaining damage state D_k in 1 year $p_k \approx \lambda_k$ (Eads et al. 2013) and therefore Eq. (1) may be considered as a quantitative measure of seismic risk. More generally, the λ_k can be used to compute the probability p_k of attaining damage state D_k in t years assuming that the occurrence of earthquakes follows a Poisson process:

$$p_k(\text{in t year}) = 1 - e^{-\lambda_k t} \tag{2}$$

Equation (2) represents the unconditional seismic risk in t years referred to damage state D_k.

The estimation of seismic risk in terms of expected damage is the starting point for the impact calculation. Indeed, once the mean annual probability of attaining the different damage levels for all the buildings of the asset is calculated, it can be turned into consequence evaluations in terms of economic, human and societal losses. In a broader sense, seismic risk represents the probability of losses in a given time span, which is commonly assumed 1 year. For this reason, the seismic risk assessment is a fundamental tool for estimating the consequences of earthquakes in a region and it is a fundamental tool for planning and calibrating long-term risk reduction policies.

2.1 Evolution of national seismic risk maps in Italy

A comprehensive review of the national seismic risk maps developed in Italy until 2009 was previously presented in (Crowley et al. 2009). The paper reviews and compares several nation-wide risk studies, including the risk maps from the Italian Seismic Service (Lucantoni et al. 2001) and their updated version presented in (Bramerini and Di Pasquale 2008), the SAVE project (Zuccaro 2004), and the risk maps produced employing two different analytical vulnerability models for the built environment: DBELA (Crowley et al. 2004) and SPBELA (Borzi et al. 2008a, b).

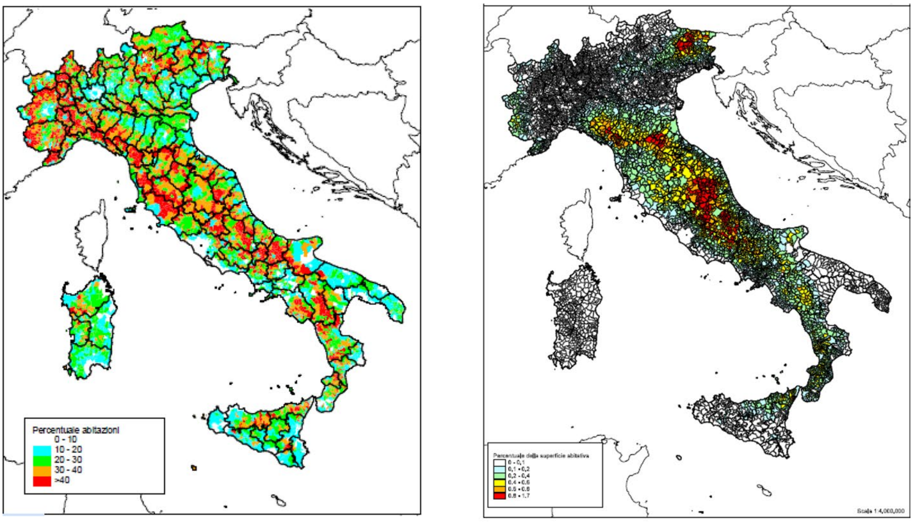
Over the last years, several other studies concerning the seismic risk assessment of the whole Italian territory were produced with different scopes, among whom it deserve to be mentioned the work carried out by Rota et al. (2011), who derived typological seismic risk for Italy, i.e. not considering the exposure, the one by Asprone et al. (2013), who performed a nation-wide risk assessment considering 5 building typologies with the aim to build a national insurance model, the one by Zanini et al. (2019) who developed risk maps considering suitable seismogenic model for each analyzed area with the goal of deriving risk targeted indicators at the municipal level. Finally, the Global Earthquake Model (GEM) foundation in 2019 produced a country profile with seismic risk assessment specific for Italy, as part of GEM's global seismic risk model (GEM 2019; Silva et al. 2020).

Despite the numerous studies existing on the topic, the biggest challenge for all of them is represented by the availability and reliability of tools of analysis as well as of suitable datasets for the entire peninsula. This issue is particularly remarkable for exposure datasets which play a central role in seismic risk convolution and that, especially for Italy, is subjected to significant differences over the country, especially in terms of building inventory.

The Italian Government has been dealing with this issue since the end of the 90's, when research Institutions, such as Italian Seismic Service (SSN), Earthquake Defense National Group (GNDT) and National Institute of Geophysics (ING), attempted former risk assessment analyses at national scale.

These national maps, formerly produced in 1996 by a workgroup purposely instituted (GNDT-ING-SSN 1996), were used to assign different rankings to all the Italian municipalities, with the scope to support the Government to take decisions towards seismic mitigation strategies. Although these maps were never published in scientific papers, they served as the base to suitably combine hazard and vulnerability models, as well as exposure data, in the framework of the probabilistic assessment of risk at the national scale. The innovation of the study was mainly in the definition of an exposure model at national scale based on the data on population and dwellings collected by the national census investigations (periodically updated by the National Institute of Statistics, ISTAT). The building inventory for the study in (GNDT- ING-SSN 1996) was based on 1991 census data (ISTAT 1991). This model did not change significantly in subsequent studies. As a matter of fact, the updated census dataset (ISTAT 2001, 2011), giving information on construction age, building material and number of storeys, are still used as the primary source for building vulnerability/exposure classification even in more recent studies, having the advantage of being homogeneous and complete for the whole national territory.

After this first study, the different models for seismic risk assessment were updated exploiting the progresses and scientific advancements in the computation of seismic hazard, as well as vulnerability characterization. The national risk maps were updated by the National Seismic Service in 2001 (Lucantoni et al. 2001), based on more recent seismic hazard studies (Albarello et al. 2000) and on new damage probability matrices (Di Pasquale et al. 2000) and fragility curves (Sabetta et al. 1998). The seismic hazard was described both in terms of macroseismic intensity (adopting the Mercalli-Cancani-Sieberg, MCS, scale) as well as in terms of peak ground acceleration PGA. The seismic vulnerability was defined by a typological-statistical approach according to which three vulnerability classes A, B, C introduced by the MSK scale (Medvedev 1977) and ranked from the most (A) to the less (C) vulnerable were distributed at municipality scale by using information like construction age and construction type as indicators for classification. Moreover, according to the proposal from Di Pasquale and Orsini (1997), class C was further subdivided in C1 (good quality masonry buildings) and C2 (reinforced concrete buildings), defining eventually 4 vulnerability classes (A, B, C1 and C2). The building inventory according to this vulnerability model was realized using the 1991 ISTAT census data on population and buildings for all the 8100 municipalities in Italy. Class assignment rules were suitably calibrated on the base of available damage and vulnerability data for approximately 80,000 buildings inspected after the Irpinia 1980 and 1984 Lazio-Abruzzo earthquakes, previously analyzed in Braga et al. (1982, 1983, 1986). As an example, Fig. 2a shows the percentage distribution over the national territory of dwellings with high vulnerability (class A). The seismic risk is presented in terms of average annual number (or percentage for each municipality) of dwellings which would suffer damage in each municipality in Italy and of the average annual number of people affected by building collapses. For instance, Fig. 2b



(a) (b)

Fig. 2 **a** Vulnerability map in terms of % dwellings in class A; **b** mean annual seismic risk, calculated using seismic hazard in terms of PGA, expressed by % collapsed dwellings (mean surface area) per municipality (Lucantoni et al. 2001) shows the mean annual seismic risk in terms of surface percentage of collapsed dwellings per municipality, calculated by using PGA as seismic hazard.

Since 2001, the scientific community has made several enhancements in the fields of hazard, vulnerability and exposure assessment.

Concerning seismic hazard, the scientific efforts focused on the development of a single hazard model at the national level. As a result, the new probabilistic seismic hazard assessment for Italy, known as MPS04 (Stucchi et al. 2004, 2011), was officially released in 2004 and appointed by the Prime Minister Ordinance (OPCM 2006) as official reference in the country for seismic hazard values, to be used in engineering applications, and explicitly used by national technical codes (NNT 2008, 2018). The hazard was evaluated in terms of PGA and elastic spectral acceleration Se(T) for 9 different probability of exceedance in 50 years (from 2 to 81 %), and mapped for 16,852 grid points spaced at 0.05° in latitude and longitude, covering nearly the whole national territory (excluding Sardinia and some minor islands).

In 2008 the risk maps were upgraded (Bramerini and Di Pasquale 2008) using more recent census data (ISTAT (National Institute of Statistics) 2001) towards building inventory, keeping hazard and vulnerability model unchanged. As shown in (Crowley et al. 2009) the use of updated building inventory, with an increase of 9 % in total number of buildings from 1991 to 2001, had just a slight effect on the spatial distribution of the percentage of collapsed dwellings, as well as in terms of the absolute number of dwellings at risk of collapse.

On the other hand, further vulnerability models were developed to estimate damage likelihood for ordinary building types, realized by masonry (M) or reinforced concrete (RC) structure. The literature on the topic shows that at least three different approaches are used to develop vulnerability models: (1) analytical approaches, where fragility is computed according to an analytical-based estimation of the buildings' response and damage estimation (2) empirical approaches where models are formulated on the basis of damage occurred in occasion of previous earthquakes and whose data are statistically processed (3) hybrid approaches that combine different evaluation systems, e.g. expert based or analytical based assessment with subsequent empirical calibration by observational data.

Concerning empirical fragility curves, consisting in an upgraded model of damage probability matrices early developed in Italy in the eighties (Braga et al. 1982, 1983, 1986, Dolce 1984), different models were proposed for M and RC building typologies in Italy, e.g. (Di Pasquale et al. 2005; Rota et al. 2008; Zuccaro et al. 2015; Del Gaudio et al. 2019, 2020) is an exemplifying list of some available proposals in the literature. Also, analytical methods were employed to derive analytical based fragility curves such as the ones for M (e.g., D'Ayala and Speranza 2003; Rota et al. 2010) and RC buildings (Polese et al. 2008; Del Gaudio et al. 2018). Finally, a hybrid fuzzy-random approach is used in (Lagomarsino and Giovinazzi 2006) to convert the linguistic assignments of the EMS 98 scale into typological fragility curves. A rich catalogue of existing physical vulnerability models for possible use in large scale applications worldwide is presented in (Yepes et al. 2016).

Concerning exposure, an exposure model for Europe was recently presented in (Crowley et al. 2020). Referring to Italy, significant efforts are being pursued to enrich the census inventory provided by ISTAT, by means of further data available for large scale assessments. To make an example, the image-processing based techniques allow to rapidly and automatically collect spatial features for the built environment over large regions (Polli et al. 2009). However, parameters that are more important for vulnerability assessment, such as, e.g., building age, construction materials and quality or state of preservation, just to mention some relevant vulnerability factors, cannot always be collected through

IT-based procedures or earth observation tools. The interview-based CARTIS form, aimed at the typological and structural characterization of urban settlements (Zuccaro et al. 2015b), was implemented in Italy by ReLUIS, under the coordination of the Italian Civil Protection Department, with the scope of improving the information quality relevant to exposure, as well as introducing territorial or regional modifiers. It allows relevant data on building typologies, which could enhance the relatively poor information available at census level, to be rapidly gathered. Polese et al. (2019, 2020) have shown that the use of building inventory based on census data upgraded by CARTIS information could lead to significant variation in the results and reliability of risk assessment. More refined typological characterization could lead to relevant differences in the risk assessment at regional scale, and this aspect should be properly considered in the next generation national risk assessments.

2.2 A multi-model approach

Theoretically, seismic risk maps can be obtained by adopting a single model for each of the three physical parameters describing seismic risk: hazard, vulnerability and exposure. Despite the enormous efforts provided by the research in this field, all the three factors show intrinsic and very wide uncertainties that can be ascribed to both aleatory and epistemic uncertainties. In addition, while seismic hazard, in Italy, is officially defined by a single model (Stucchi et al. 2004, 2011), the proposals for seismic vulnerability models are extremely varied and could not be adopted singularly. This is because most of them are applicable to specific sub-assets (Masonry or RC buildings) or even because they use very different fragility models and associated uncertainties, which would lead to biased final risk estimations, if each method were used singularly. For what concerns exposure, the reference database is still the one based on census returns (ISTAT 2001, 2011), hence with very large uncertainties regarding the structural characteristics of building stock to whom fragility models are related. Although the CARTIS approach is representing a promising tool to integrate, in the near future, the census inventory, in 2018 it had not yet been implemented exhaustively at national level and could not be employed for the national risk assessment.

Given the large uncertainties associated with risk assessment, the recent Civil Protection Code previously mentioned, requires that scientific products to be used for civil protection purpose enjoy the consensus of the scientific community. This was the reason why the Italian Civil Protection Department decided to perform the last NRA (ICPD 2018) through a multi-model methodology. This was agreed upon expert representatives of the scientific community belonging to the two Centers of Competence of the DPC operating in the seismic risk field: ReLUIS and EUCENTRE. In particular, 5 research units (RU) were involved for ReLUIS (namely: University of Naples, University of Padua, University of Pavia, University of Genoa and Plinivs studies centre) and 1 research unit for EUCENTRE, under the coordination of DPC, in the definition of a shared approach. Each research unit proposed a vulnerability/exposure model: 4 models were devoted to Masonry buildings and 2 to RC. All of them could be used for NRA.

The shared approach is conceptually represented in Fig. 3. The core of the methodology is implemented into a WebGis platform where the data and tools can be uploaded, allowing the system to perform calculations and to display results. A number of vulnerability/exposure models (VEM) can be plugged into the platform, and damage and risk results can be displayed singularly for each model or by aggregating the results.

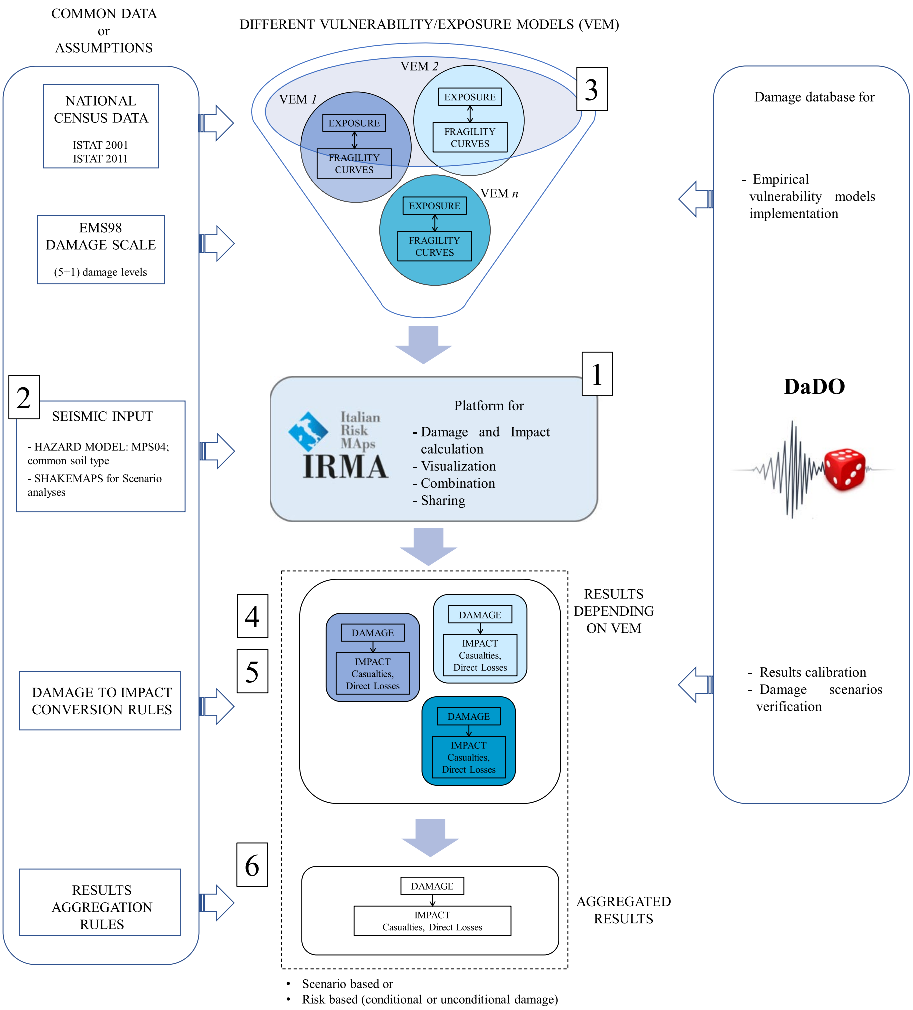


Fig. 3 Conceptual scheme for combination of data and models in the National Risk Assessment

More in detail, the national seismic risk assessment is characterized by the following features (see Fig. 3):

1. *Platform* the platform IRMA (Italian Risk Maps), specifically developed by EUCENTRE (Borzi et al. 2020) and employed to share data and models to evaluate the seismic risk of Italian residential buildings. The minimum calculation unit is represented by the municipality, so that hazard and exposure parameters are associated to its centroid for their mutual combination. The OpenQuake calculation engine (Pagani et al. 2014), developed as part of the Global Earthquake Model (GEM) (http://www.globalquakemodel.org), is employed to evaluate conditional or unconditional damage and risk maps based on hazard. Conditional risk refers to a selected return period, while unconditional risk is calculated with reference to an observation time window, e.g. t years as considered in

Eq. (2), according to the classical PSRA (Probabilistic Seismic Risk Approach). Damage scenarios depending on assigned shake-maps can also be calculated;

2. *Seismic hazard* the same hazard model, MPS04 (Stucchi et al. 2004, 2011), is employed with the six vulnerability/exposure models over all the national territory and is preloaded in IRMA. Moreover, to avoid arbitrary choices or large uncertainties in the selection of soil characteristics in specific sites, the same soil type is assumed over the whole Italian territory, namely soil type A, corresponding to rock or stiff soil category (NNT 2008). To allow for comparative analyses among the 6 models and with observed damage data in past earthquakes (Dolce et al. 2019a), calculation of damage scenarios for specific seismic events is also processed and the shake-maps of recent seismic events in Italy are also pre-loaded in IRMA;
3. *Vulnerability/exposure* Different models for vulnerability assessment and related exposure characterization are uploaded in IRMA and employed for risk calculation. Each model is previously tested, in order to check its reliability in reproducing realistic damage scenarios. Moreover, as a pre-requisite, the models are developed so as to be compatible with the IRMA platform, following established fragility and exposure description rules;
4. *Risk in terms of damage* the results for each model can be produced in terms of conditional damage (i.e., with selected return period) or unconditional damage (i.e., selecting an observation time window);
5. *Risk in terms of consequences* common damage-to-impact rules are established to evaluate the consequences in terms of direct economic losses, unusable buildings (in the short and long period) and casualties (injured, deaths); the impact can be calculated for each vulnerability model starting from the relevant estimated damage distribution;
6. *Aggregation* the results (in terms of damage or impact) can be combined by aggregating the outputs of two or more vulnerability and exposure models, under the condition that the total asset (regional or national) in terms of exposure must be processed and not exceeded. One example is two models depending on the material type (Masonry + RC), whose results can be simply joined. In case of more models relevant to the same asset type (e.g. Masonry buildings) specific weights can be customized.

As shown on the left side of Fig. 3, some of the data and assumptions in the risk calculation process are common in the shared approach. This is a specific feature of this multi-model approach, which has been pursued because quite often the results of different seismic risk assessment can be compared only on the final results, and not in the intermediate results, because of the many different assumptions made on the hazard, the exposure, the vulnerability metrics, the soil amplification modeling, the different damage-consequence converting relationships, as well as the calculation engine, which makes it impossible to ascertain the sources of the final differences of the risk assessment.

The exposure data are the same for all the models, as being provided by national census data (ISTAT 2001; 2011). In addition, the damage scale adopted for defining building vulnerability, the EMS 98 damage scale (Grünthal 1998), is the same for all the 6 vulnerability models. Furthermore, the seismic input used for the analyses (either for risk or scenario analysis) is pre-loaded. In terms of risk, the user can choose to perform unconditional or conditional risk assessment, i.e. choosing a single return period for the analysis: in both the cases the hazard model is always the same. In terms of scenario, analyses can be performed using the shake-maps that are available in IRMA. Similarly, common rules to evaluate impact starting from the calculated damage levels are adopted towards risk estimation.

Finally, the damage and risk maps can be aggregated to display the effect of combining two or more models in the risk assessment.

Concerning the vulnerability models, a unique opportunity for model calibration and results validation was provided by the availability of the recent tool DaDO (Observed Damage Database), a web-gis platform storing and sharing data from large post-earthquake damage surveys carried out in the aftermath of the most significant earthquakes occurred in Italy from 1976 to 2013 (Dolce et al. 2017, 2019). A thorough comparison of the different models is performed in (da Porto et al. 2020), where damage and impact scenarios calculated adopting the different models for two recent Italian seismic events, L'Aquila 2009 and Amatrice 2016, are evaluated and confronted, showing realistic results. Also, in (da Porto et al. 2020) it is found that, despite inevitable differences due to specific damage prediction trends between the models, the forecast of damage and impact by the various models is generally reasonably comparable. Therefore, for the NRA 2018 the multi-model risk assessment was performed giving the same weight to the vulnerability models.

3 The DaDO database

DaDO (Observed Damage Database) is a web-gis tool of the Civil Protection Department designed to collect, catalogue and compare data on the construction and structural characteristics, as well as on seismic damage, of ordinary buildings inspected during or following seismic crises of national importance, from 1976 onwards. In particular, the platform currently includes 10 databases on seismic events such as Friuli 1976, Irpinia 1980, Abruzzo 1984, Umbria-Marche 1997, Pollino 1998, Molise and Puglia 2002, Emilia 2003, L'Aquila 2009, Emilia 2012, and Garfagnana-Lunigiana 2013, the last one recently uploaded.

Realized with the support of the EUCENTRE, the tool is aimed to share post-earthquake damage data with the scientific community operating in the field of civil protection. The tool is addressed to Civil Protection users and members of the Scientific Community upon a registration process.

Although most of the survey form used in the past for damage data collection had their own peculiarities, each database contains information on the general and structural characteristics of detected buildings and the related damage. At present 322.728 buildings are recorded and georeferenced in DaDO, with information relevant to 9 Italian Regions.

These databases can be analyzed and downloaded either in the original or in a revised and decoded format, enabling the user to identify common information among the different datasets. The data homogenization has been carried out also for damage levels, which were different from one survey form to another, hindering mutual comparisons. A common metric, suitable for all the recorded datasets, was then formulated specifically for vertical structures (Dolce et al. 2017, 2019), coherent with the damage grades defined by EMS 98 scale (Grünthal 1998).

Besides, for each database, further information is provided in terms of event characteristics (geographic coordinates, magnitude, epicentral depth and so on) and in terms of casualties occurred (victims and injured people) together with resulting homeless.

The above data are extremely useful for seismic risk assessment and for damage scenarios calibration. As a matter of fact, the statistical elaborations of seismic damage and structural types of buildings when associated to an intensity measure of the shaking, such as the macroseismic intensity, of a given seismic event, can be used to derive damage prediction models for different building types, such as damage probability matrices, early developed for 1980 Irpinia earthquake (Braga et al. 1982, 1983), or empirical fragility curves. These predictive damage models are a fundamental tool for loss scenarios and risk analyses (Dolce et al. 2019a).

For the NRA the platform has been used by the 6 research units as a common resource providing observational data, useful for either formulating or calibrating fragility functions respectively for observational or mechanical approaches. To these aim, two datasets were particularly useful (Irpinia 1980 and L'Aquila 2009), as being featured by almost complete surveys over the entire building stock of the most affected municipalities. The total number of records of the two datasets amounts to 112.128 buildings, representing 34 % of the total records at present stored byDaDO.

The damage distribution of the two events, converted into 5+1 EMS 98 damage levels (from D_0, no damage, to D_5, collapse) together with relevant casualties occurred in both the events, worked as benchmark for comparing the damage scenarios independently produced by the 6 models as well as their associated damage distribution as a function of existing building types.

4 Vulnerability/exposure models

4.1 General criteria

Five research units from ReLUIS and one from EUCENTRE contributed to the definition of six vulnerability/exposure models, VEM, to be plugged into the IRMA platform to calculate seismic risk.

Four out of the six vulnerability models refer to masonry (M) and two of them to reinforced concrete (RC) buildings. Moreover, the approaches followed to derive these models are different. In three cases the vulnerability model relies on an empirical approach, (Rosti et al. 2020a,b; Zuccaro et al. 2020). Two models adopt an analytical approach to develop fragility curves (Faravelli et al. 2020; Donà et al. 2020). Finally, a hybrid heuristic approach is employed in the sixth model (Lagomarsino et al. 2020), as being based on the expert judgment implicitly encompassed in the EMS 98 scale (Grünthal 1998), but also calibrated on post earthquake damage data observed in Italy, available in DaDO platform.

Table 1 summarizes the main features of the six considered VEMs, indicating the research unit (RU) leading each model, the building typologies (M or RC) to which each model refers to, and the approach followed to derive the model. The models are all

Table 1 Vulnerability/exposure models implemented for NRA 2018 (ICPD, 2018) and plugged in IRMA platform

VEM	RU	Approach	Building material	References
VEM1	Plinivs (ReLUIS)	Empirical	M	Zuccaro et al. (2020)
VEM2	UNIGE (ReLUIS)	Hybrid (heuristic)	M	Lagomarsino et al. (2020)
VEM3	UNIPD (ReLUIS)	Analytical	M	Donà et al. (2020)
VEM4	UNIPV (ReLUIS)	Empirical	M	Rosti et al. (2020a)
VEM5	UNINA+UNIPV (ReLUIS)	Empirical	RC	Rosti et al. (2020b)
VEM6	EUCENTRE	Analytical	RC	Faravelli et al. (2020)

described in detail in the relevant papers in this issue (see Reference in Table 1), while in (da Porto et al. 2020) a comparative analysis is presented.

Despite the differences in the approaches followed to derive the VEMs, some common basic features were required to enable their implementation in the IRMA platform and their mutual comparison.

Each VEM was required to describe the behaviour of maximum 5 vulnerability classes, named A, B, C1, C2 and D, ranked according to increasing vulnerability level, coherently with EMS 98 scale. Such vulnerability classes are not uniquely defined, in the sense that each VEM has the possibility to associate them to different type of buildings and to describe them with different fragility curves, as will be explained in Sects. 4.2 and 4.3. However, within each VEM the trend is to assign the first classes to most vulnerable buildings and vice versa. As example, class A generally represents weak masonry constructions while class D generally refers to seismically designed M or RC buildings. The other classes, B, C1 and C2, describe intermediate behaviour that could be representative of both M buildings of decreasing vulnerability from B to C2 or RC buildings without seismic design. For each class in the generic VEM, the vulnerability is described in terms of lognormal fragility curves for 5 damage states from D_1 to D_5 of the EMS 98 scale (see Sect. 4.3).

The way according to which each class, and the relevant fragility curve, is associated to the existing building stock is rather different from one research unit (RU) to another, and each RU adopts specific criteria to assign building typologies of the census dataset to the relevant vulnerability classes. Such criteria are established through specific vulnerability/exposure models, customised by each RU and explained in the relative reference papers. The common rules to describe such assignment process are recalled in Sect. 4.2.

4.2 Exposure

Building typologies are defined on the base of the relevant parameters available in the national census database (ISTAT 2001), namely construction material (reinforced concrete, RC, Masonry, M, other construction types O), number of floors and construction age. Census information are available both in terms of buildings and dwellings, as there is a univocal correspondence between the two. As regards the construction material “O”, this is commonly related to steel or wooden buildings or, more often, to structures with a mixed typology, for example a masonry building with a superimposed reinforced concrete storey. However, in the Italian building stock these building types have significantly lower percentage incidence with respect to M and RC. Therefore, despite they are not analysed in terms of vulnerability models, they have necessarily to be considered in terms of exposure. Consequently, the number of O buildings (and associated dwellings) are subdivided between M and RC building types through a specific criterion illustrated in Table 2, depending on the age of construction and on the percentage incidence of M and RC buildings in each town.

In IRMA the census data are provided at the municipality level and are disaggregated, so that it is possible to derive the age-storey distribution for both M and RC buildings (and related surface areas) in each town.

The mutual match among the above-mentioned census parameters describes the residential asset at municipality level. In total 56 building types for M and 56 for RC are resulting from the parameters combination and to each of them the total number of buildings and associated dwellings is pre-recorded. Therefore, it is possible to derive for each municipality the number of buildings (and associated dwellings) and

Table 2 Criteria adopted for distributing O construction types between masonry M and reinforced concrete RC buildings

Storey number	Age		
≤ 5	≤ 1945	> 1945	
	M	*If not only O is present in town* proportionally to %M and %RC of the town	*If only O is present in town* 50 % M and 50 % RC
> 5	< 1919	≥ 1919	
	M	RC	

the distribution of building typologies defined in terms of material, construction age and storey number. For instance, Fig. 4 shows distributions of RC and M typologies, defined in terms of construction age and storey number starting from (ISTAT 2001) database, for the towns of Angri (a)-(b) and Portici (c)-(d) in Campania region, southern Italy. The number of M and RC buildings shown in Fig. 4 includes also the buildings classified as O in (ISTAT 2001), converted into M and RC according to the criterion illustrated in Table 2. As can be seen, the distribution of building typologies may be very different varying the town, even in the same region. For example, referring to RC buildings, the town of Portici is characterized by a relatively high percentage of medium-height buildings, having storey number≥ 5, built between 1962 and 1971, while in Angri most of the RC buildings are more recent (built mainly after 1972) and

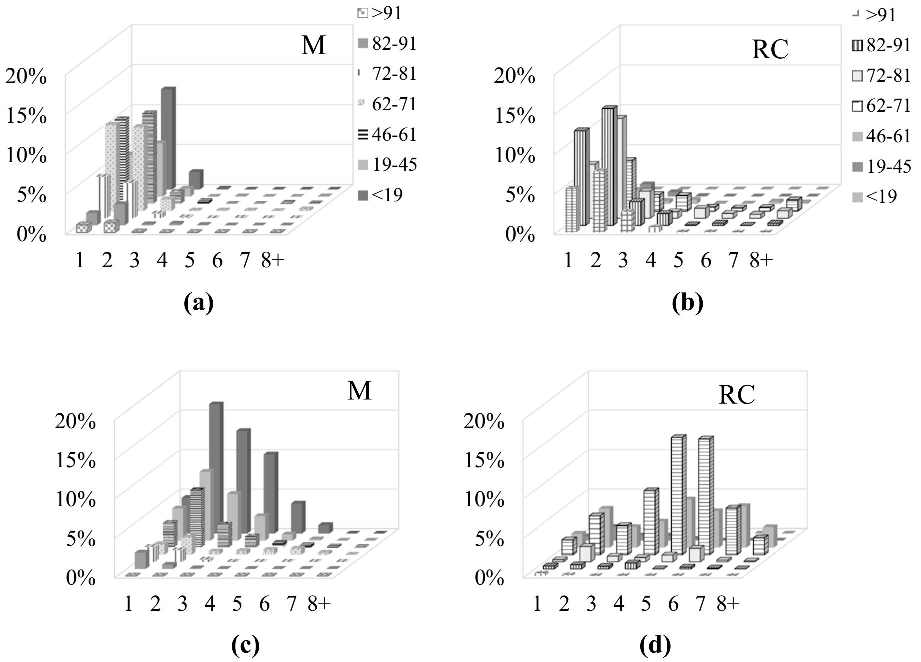


Fig. 4 Distribution of M and RC typologies, defined in terms of construction age and storey number, for the town of Angri (**a**–**b**), 3581 residential buildings, and Portici (**c**–**d**), 2070 residential buildings according to ISTAT (2001)

have lower number of storeys (mostly 1–2 storeys). On the other hand, large part of M buildings in Portici were built before 1919 and have less than 4 storeys, while for Angri a comparatively larger percentage of buildings, having mostly 1–2 storeys, were built between 1946 and the beginning of the 70's. Note that, even if in 2018 more recent census data were already available (ISTAT 2011), for the NRA 2018 it was decided to use the previous dataset (ISTAT 2001) because it is characterized by more detailed information on some building characteristics, such as number of storeys. Moreover, the small increase in exposure is due to buildings designed according to modern seismic codes, which have therefore low vulnerability and do not produce substantial increase of risk at local and national levels.

The above building typology distribution, at municipal level, is then described in terms of seismic vulnerability that, in IRMA, is defined through vulnerability classes (A, B, C1, C2 and D) and relevant fragility functions, whose association to the above building typologies requires a specific vulnerability-exposure model.

Therefore, given the building typology, it is necessary to establish for each VEM a general criterion for assigning each typology to one or more vulnerability classes. In other words, the exposure models in IRMA, developed for each of the considered VEMs, allow the building inventory to be processed in terms of relevant vulnerability classes starting from the census building typologies. Different approaches are used by the 6 RU to build the VEMs in IRMA, as also happened for past studies dealing with the same problem (e.g. Di Pasquale et al. (2005); Del Gaudio et al. (2019); Bernardini et al. (2008); Meroni et al. (2017)). Each exposure model is described with a suitably defined exposure matrix that defines the percental attribution of each typology to each vulnerability class.

The generic row of such matrix, defined for each VEM, refers to any of the 56 typologies; as an example, VEM2 subdivides the typology of the M buildings built between 1919 and 1945 and having 1–2 storeys into classes A (25 %) and B (75 %).

The same typology is subdivided differently in other VEMs; e.g., VEM4 subdivides it in A, B and C1 (45 %, 44 % and 11 %). The resulting building inventory, then, is different for each considered VEM. For instance, Fig. 5a, b show the percentage of buildings in class A for each municipality according to VEM2 and VEM4, respectively, and significant differences in the building inventory can be observed.

However, it shall be noted that, although the vulnerability is decreasing from class A to D, each vulnerability class in each vulnerability model is characterized by a specific fragility curve, which may be very different from one model to another. In other words, the vulnerability classes and associated fragility functions are assumed in IRMA in a broader way with respect to EMS 98 definitions: they envisage different seismic performances whose formulation is provided by specific fragility functions that are not comparable in a straightforward way. Consequently, the vulnerability associated to each building type can be subjected to sensible variations from one model to another, as illustrated in da Porto et al. (2020).

4.3 Fragility curves

The fragility curves in IRMA are defined for the five damage levels of the EMS 98 scale (Grünthal et al. 1998). Given the intensity measure, expressed in terms of PGA, the probability of reaching or exceeding a given damage state D_i as a function of PGA is expressed by a cumulative lognormal distribution:

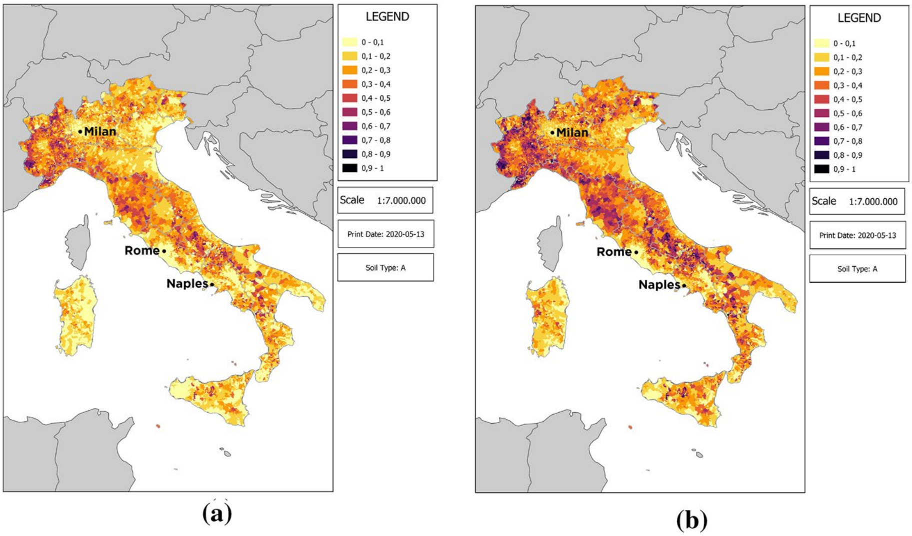


Fig. 5 Percentage of buildings in class A for each municipality for VEM2 (**a**) and VEM4 (**b**)

$$P\left(ds \geq D_i | PGA\right) = \Phi\left[\frac{\log(PGA/\theta_i)}{\beta_i}\right] \tag{3}$$

With Φ[·] the cumulative standard normal distribution, θ_i the median PGA value of the fragility curve associated with damage state D_i and β_i the corresponding logarithmic standard deviation.

As an example, Fig. 6 shows the fragility curves for D_1 to D_5 damage states referring to building class C1 and D, medium height, of the vulnerability model VEM5.

By considering that each building type vulnerability is defined through one or more vulnerability classes according to a percentage distribution, it is possible to obtain fragility functions specific of each building type from the analytical formulation of fragility curves above described. These can be obtained as a linear combination among fragility functions

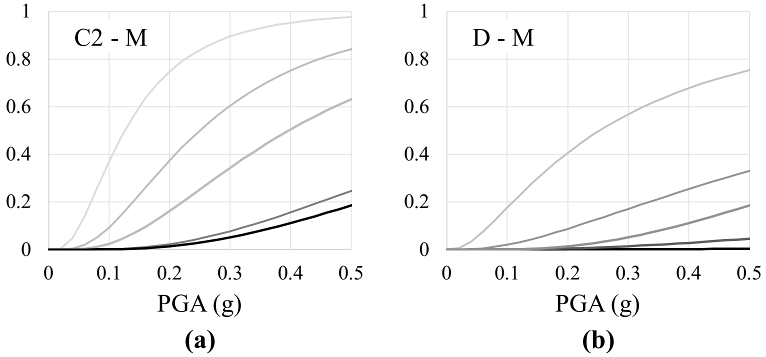


Fig. 6 Empirical fragility curves for vulnerability classes C2 and D and building height M (corresponding to 3–4 storeys) of VEM5

of vulnerability classes, according to the percentage distribution specific of each building type.

5 Seismic risk in terms of Damage level

As explained in Sect. 2, hazard, fragility and exposure are mutually combined for each model according to Eqs. 1 and 2 in order to evaluate the seismic risk in terms of expected damage levels. If the computation is performed with reference to the occurrence of an earthquake with a selected return period, or alternatively to an exceeding probability in 50 years, the results represent the conditional damage assessment. Conversely, when the probability of a ground shaking severity in a selected time window is taken into account, the results represent unconditional damage assessment. The latter is probably most useful for investigating the potential consequences of earthquakes in a region or country of interest. Indeed, the integral approach adopted to compute unconditional seismic risk allows earthquakes with different probability of occurrence, varying the intensity, to be taken into account. This favors a more objective comparison of results among different municipalities in the region under exam.

For the NRA purposes, two time windows were considered for the unconditional damage, namely one year and fifty years. In the former case the results of risk computation represent the annual probability of occurrence of the 5 damage levels or related consequences. The 50 years time window was chosen because deemed representative of the nominal life for ordinary buildings.

The seismic hazard, in terms of PGA on stiff soil, is represented by the MPS04 model (Stucchi et al. 2004,s 2011) and it is assumed the same soil type everywhere, namely the type A. Median values of the MPS04 model are employed to minimize variability of results due to hazard assumptions and to allow easier comparison of results.

Moreover, based on the expert opinion of the working group formed by the researchers developing the different VEMs, the minimum value of soil acceleration for which damage could be expected for any type of building type was set to 0.03 g. This choice was motivated, after several computations, by the need to avoid excessive incidence of high probability and very low consequence intensities in the computation of damage and related losses, which brought total resulting losses to raise indiscriminately.

The choice of a unique soil of type A might lead to unconservative results and estimated losses. However, while there exist some proposals to use VS30 values derived from topographic slope (Wald and Allen 2007) or geological maps (Wills and Clahan 2006; Forte et al. 2019) for rough consideration of soil effects at a site, in this study it was preferred to avoid introducing soil models which might have serious limitations and can produce some bias when comparing risk of areas where rapidly changing soil conditions occur, as it frequently happens in Italy. Indeed, in the near future more accurate micro-zonation studies, that are being produced throughout Italy, will be available and will be employed in the next risk assessment for a more reliable estimation of site effects.

The different VEMs introduced in Sect. 3 are employed to compute the risk, so that model-dependent results are obtained. For each VEM model the risk is calculated, through the IRMA platform, in terms of damage levels and associated consequences, for the two above mentioned time windows (1 year and 50 years).

In particular, given the uncertainties at stake, the NRA consequences produced by each model are not considered separately, but they are mutually combined in order to obtain a range of reliable figures. For the purposes of this study, the epistemic uncertainty was then roughly described by providing minimum, maximum and average values in the ensemble of approaches, while aleatory uncertainty in the vulnerability component was not considered and propagated.

Firstly, the results are combined separately for models relevant to Masonry M and RC buildings. The results obtained by the four VEMs for M buildings are averaged and maximum and minimum values among them are computed. Similarly, average, minimum and maximum results of the two VEMs for RC buildings were figured out. As ultimate stage, in order to get the overall estimated average, maximum and minimum values over the entire national residential asset, the results obtained for M and RC buildings are summed up. Figure 7 exemplifies the process of results aggregation with reference to the impact quantity "percentage of unusable dwellings for each town"; for the NRA 2018 equal weight was assigned to the different models relative to masonry and to RC buildings.

Tables 3 and 4, related to 1 and 50 years time frames respectively, show the resulting estimates in terms of dwellings affected by each considered damage level. Numbers in Tables 3

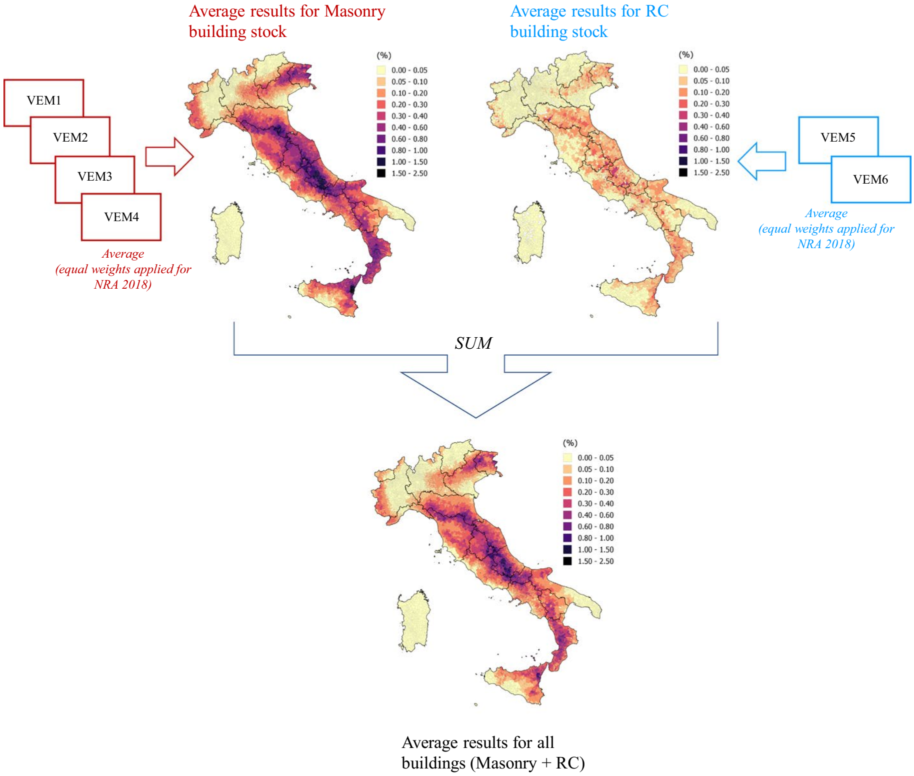


Fig. 7 The process of results aggregation: the output of models (average, maximum, minimum) for masonry (VEM1 to VEM4) and RC (VEM5 and VEM6) are weighted and then summed; for NRA 2018 equal weights are applied. The example if figure shows as impact quantity the average percentage of unusable dwellings for each town (unconditional risk in a time frame of 1 year)

Table 3 Unconditional risk in a time frame of 1 year

Damage level	D_1	D_2	D_3	D_4	D_5
Average	143.1	38.7	17.8	6.1	2.1
Maximum	203.1	65.1	13.4	8.1	3.3
Minimum	84.4	15.6	7.9	2.6	0.4

Average, maximum and minimum values of the expected number of dwellings affected by the considered five damage levels–thousands of dwellings

Table 4 Unconditional risk in a time frame of 50 years

Damage level	D_1	D_2	D_3	D_4	D_5
Average	4199.7	1436.0	783.0	290.9	103.6
Maximum	5738.4	2198.7	1348.0	382.2	161.9
Minimum	3154.4	631.2	372.2	130.6	19.5

Average, maximum and minimum values of the expected number of dwellings affected by the considered five damage levels–thousands of dwellings

and 4 represent thousands of dwellings. For the sake of completeness of description, in addition to dwellings, results are also calculated by IRMA in terms of number of buildings.

It worth to note that, since the number of dwellings in a building is highly variable, with typically more dwellings in a RC building with respect to a M building, the representation referred to dwellings seems to be more appropriate to provide a clearer picture of the actual risk distribution.

Looking at the average values, it can be noted that a high number of damaged dwellings is expected in one year and quite proportionally higher in 50 years. The number decreases by one order of magnitude from D_1 to D_3 and from D_3 to D_5. It is expected that about 2100 dwellings could collapse in one year (D_5), and about one hundred thousand in 50 years.

The scatter between maximum and minimum expected values depends on the different results from the adopted vulnerability models, and represents, at the same time, the assessment vulnerability/exposure model epistemic uncertainty. The high uncertainties would be even larger if the epistemic uncertainties due to hazard estimation, sub-soil amplification and possible co-seismic effects were considered in the calculation.

The maps in Fig. 8a–d show the maps for D_1, D_2, D_4 and D_5, respectively, as the ratio of the expected number of dwellings with damage level D_i in one year versus the total number of dwellings in each town. Analogously, Fig. 9 shows the geographic distribution of damage levels D_3. As a result of hazard, vulnerability and exposure convolution, the maps suitably take into account all the factors affecting seismic risk; however, being percentage maps, the damage distributions are coherent with the hazard map of MPS04 (Stucchi et al. 2004, 2011) adopted in the risk calculation.

6 Seismic risk in terms of consequences

The evaluation of seismic risk in terms of damage levels is the starting point for the assessment of additional impact indicators commonly used for civil protection purposes. Their computation and representation is aimed not only to set up and enforce response

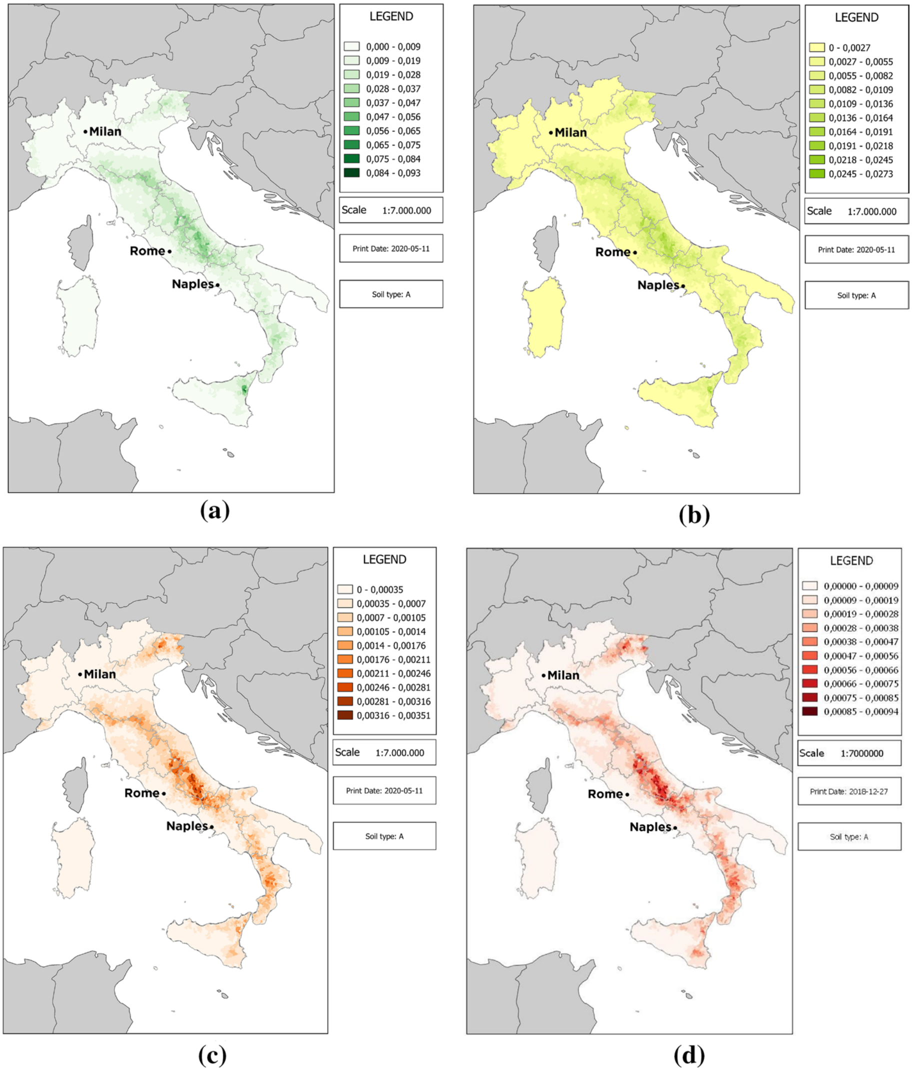


Fig. 8 Unconditional risk in a time frame of 1 year. Average expected percentage of municipal dwellings affected by Damage Level D_1 (**a**), D_2 (**b**), D_4 (**c**), D_5 (**d**). The D_5 map corresponds also to map of collapsed buildings in one year (see Sect. 6.1)

and mitigation strategies for reducing earthquake losses, but also to enhance preparedness measures and emergency planning.

For the NRA 2018, in particular, the following impact indicators are determined for each Italian municipality, coherently with EU international standards (JRC 2015):

- expected number of unusable buildings or dwellings in the short and long term;
- expected number of collapsed buildings or dwellings;
- expected number of homeless;

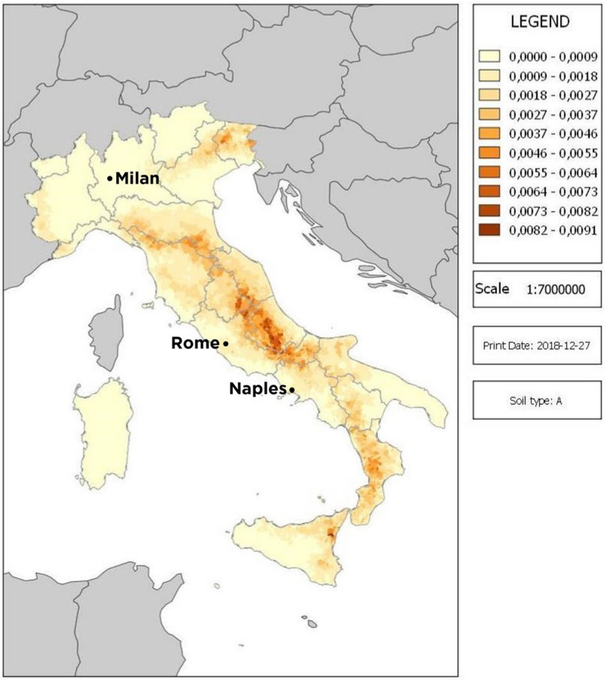


Fig. 9 Unconditional risk in a time frame of 1 year. Average expected percentage of municipal dwellings affected by Damage Level D_3

- Casualties in terms of expected number of victims and injured people;
- Direct economic losses;

The above indicators are determined by means of the expected numbers of buildings (or dwellings) affected by the different damage levels, whose calculation has been discussed in the previous paragraph. To this end, the same damage-to-impact conversion criteria, described in detail in the following paragraphs, are assumed in order to turn the damage results obtained by each of the VEMs introduced in Sect. 4, into consequences.

6.1 Unusable and collapsed buildings and homeless

A fundamental measure of earthquake impact is the number of unusable and collapsed buildings (or dwellings). Together with the number of homeless, these indicators allow indirect costs related to temporary shelters and other kinds of temporary arrangements for homeless to be estimated. In general, they constitute important factors affecting the social impact of earthquakes.

Several methodologies and tools for the estimation of unusable buildings and consequently evacuated population are available at international scale, e.g. Hazus-MH (FEMA 2003), Syner-G (Khazai et al. 2012), MCEER shelter model (Chang et al. 2008) among others. As observed in (Vecere et al. 2017), most of the existing methodologies to evaluate the unusable buildings and homeless primarily rely on the estimation of building damage.

The approach adopted in IRMA for the estimation of unusable buildings (or corresponding dwellings), derives from risk assessment methods previously carried out in Italy (Lucantoni et al. 2001; Bramerini and Di Pasquale 2008; Zuccaro and Cacace 2011). In general, unusable buildings account for the number of buildings (or dwellings), that are considered unsafe on the basis of the expected damage level derived from risk formulation analyses. The formulations adopted for the NRA are similar to the ones previously proposed in (Zuccaro and Cacace 2011) and further calibrated on expert judgement. While all the buildings having very slight damage (D_1) can be considered as usable buildings, the unusable ones can be distinguished in the two sub-categories, namely unusable buildings in the short term UB_{st} (due to light or moderate damage) and unusable buildings in the long term UB_{lt} (due to more severe damage). UB_{st} and UB_{lt} are determined by the following equations:

$$UB_{st} = \sum_{k=1}^{5} \left(N_{Mk} u_{stk} \right) + \sum_{k=1}^{5} \left(N_{RCk} u_{stk} \right) \tag{4}$$

$$UB_{lt} = \sum_{k=1}^{5} \left(N_{Mk} u_{ltk} \right) + \sum_{k=1}^{5} \left(N_{RCk} u_{stk} \right) \tag{5}$$

InEqs. (4) and (5), N_{Mk} and N_{RCk} are the number of M or RC buildings that experience structural damage level D_k and u_{stk} (u_{ltk}) are the percentage of unsafe buildings in the short (long) term for each structural damage level D_k. The same equations can be used to estimate the number of unusable dwellings, simply substituting the number of buildings in Eqs. (4) and (5) with the number of dwellings; in such a case, the results are indicated with UD_{st} and UD_{lt} respectively.

Percentages u_{stk} and u_{ltk} adopted in calculations for NRA are reported in Table 5. For the sake of simpleness it is assumed that percentages for RC and M buildings are the same, although different values could be adopted. To evaluate the expected number of collapsed buildings (or dwellings), the 100 % of the of buildings (or dwellings) in damage state D_5 are considered.

Once UB_{st},UB_{lt} are calculated, the number of homeless can be also estimated. This is obtained by the number of inhabitants in unusable buildings (in the short and long term) and next subtracting the estimated number of victims.

Equations (4) and (5) are applied to the damage level distributions calculated by each of the 6 VEMs, so as to obtain the results of the unconditional risks in terms of unusable buildings (in the short and long term), as well as in terms of homeless. Such results are then mutually combined by computing average, maximum and minimum values, as previously described for damage levels.

The main results in terms of unusable dwellings at national level in 1 year are summarized in the 1st and 2nd column of Table 6, while the number of homeless is indicated in the 3rd column.

One can note from Table 6 that in 1 year almost 36,000 unusable dwellings (in the short and long term) and 80,000 homeless are expected: these are impressively high numbers, bringing about a significant influence on the economic impact, also due to the indirect costs associated to temporary housing, as well as on the social impact of earthquakes, considering people displacement far from their home and work place and their community. The national maps showing the average percentage of unusable dwellings (in the short and long term period) and homeless expected in 1 year are shown in Fig. 11a, c. Percentages are calculated for each municipality with reference to the total number of items considered (dwellings/people). Figure 11b, d show the same results evaluated for a 50 year time frame. As it can be seen, approximately 1.5 % of unusable dwellings is expected each year in the areas of the country having higher risk; such percentage increases to more than 40 % in 50 years time frame. In the areas having lower risk level such percentages are sensibly lower, with less than 5 % unusable buildings in 50 years time-frame. Correspondingly, similar percentages of homeless are expected in the same areas.

6.2 Casualties

As proposed already in Coburn et al. (1992) the probability of injury or death of the building occupants can be computed as a function of the damage level of the building. In the monography "Human casualties in earthquakes" Spence et al. (2011) presented several interesting updates of the original idea from Coburn et al. (1992), considering the studies by various authors based on local context and considering observed data after significant earthquakes worldwide; for Italy the proposal from Zuccaro and Cacace (2011) was considered.

For the 2018 NRA, based on previous risk assessments (Lucantoni et al. 2001, Bramerini and Di Pasquale 2008) it is assumed that the ratio of injured and victims with respect to occupant numbers is determined only by damage levels D_4 and D_5 (the most severe ones). The following equations are adopted to calculate the expected number of deaths N_d or injured N_i:

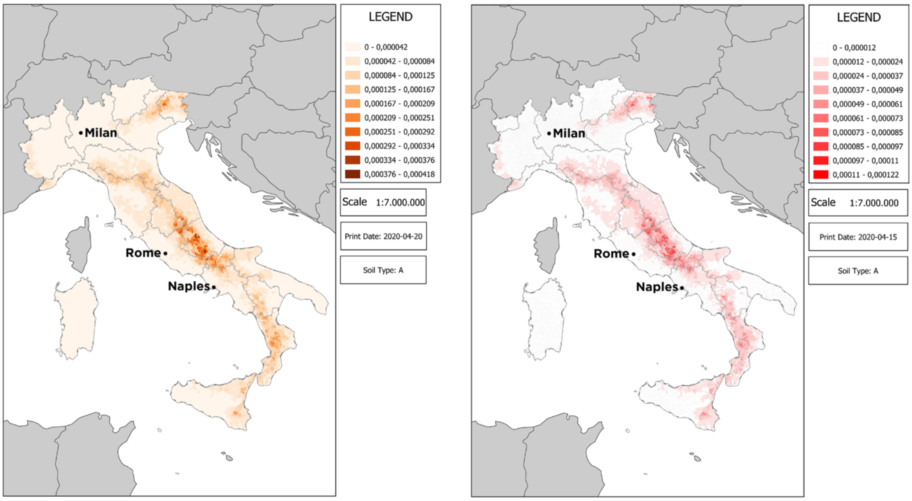
$$N_d = \sum_{j=1}^{n_M} \left[\left(O_{Mj,D4} \cdot p_{d,D4} + O_{Mj,D5} \cdot p_{d,D5} \right) \right] + \sum_{l=1}^{n_{RC}} \left[\left(O_{RCl,D4} \cdot p_{d,D4} + O_{RCl,D5} \cdot p_{d,D5} \right) \right] \tag{6}$$

$$N_i = \sum_{j=1}^{n_M} \left[\left(O_{Mj,D4} \cdot p_{i,D4} + O_{Mj,D5} \cdot p_{i,D5} \right) \right] + \sum_{l=1}^{n_{RC}} \left[\left(O_{RCl,D4} \cdot p_{i,D4} + O_{RCl,D5} \cdot p_{i,D5} \right) \right] \tag{7}$$

In Eqs. (6) and (7) n_M and n_{RC} are the number of M and RC building typologies respectively; $O_{Mj,D4/D5}$ ($O_{RCl,D4/D5}$) is the number of occupants in M (RC) buildings (whose structural type is identified by j (l)), which experienced a damage level D_4 or D_5; $p_{d,D4}$ and $p_{d,D5}$ ($p_{i,D4}$ and $p_{i,D5}$) are the percentage of deaths (injured) with respect to the occupants in buildings with damage levels D_4 and D_5. Note that the damage and collapse mechanisms in M and RC buildings are quite different and this may affect the expected number of deaths and injured people depending on the specific structural type. Indeed, some casualty models propose different percentages of deaths and injured depending on the construction material, see e.g. (Zuccaro and Cacace 2011). In IRMA the same percentage for fatalities and injured people for D_4 and for D_5 is assumed, independently of the building material, namely $p_{d,D4}$=1 %, $p_{d,D5}$=10 %, $p_{i,D4}$=5 % and $p_{i,D5}$=30 %.

Similarly to the process for accounting unusable buildings and homeless, the estimation of casualties was firstly performed for each VEM, and then relevant impact results combined among the 6 models according to the same approach, by calculating average, maximum and minimum values. The main results in terms of expected number of victims and injured people in 1 year are summarized in the 4th and 5th columns of Table 6.

One can note from Table 6, a high number of fatalities, more than 500 expected per year. This number might seem inconsistent with respect to the victims occurred in the last 50 years, amounting to about 5100. On the other hand, it should be considered that in 150 years from 1860 to 2010, more than 200,000 people died because of earthquakes (Dolce 2012) so that indicators in Table 6 could be even underestimated.



(a) (b)

Fig. 10 Unconditional risk in a time frame of 1 year. National maps relative to average expected: **a** percentages of injured people (**b**) and victims

Table 5 Default percentages adopted in IRMA for the estimation of short term and long term unsafe buildings (or dwellings)

% Unsafe buildings	D_1	D_2	D_3	D_4	D_5
u_{stk}	0	40	40	0	0
u_{ltk}	0	0	60	100	0

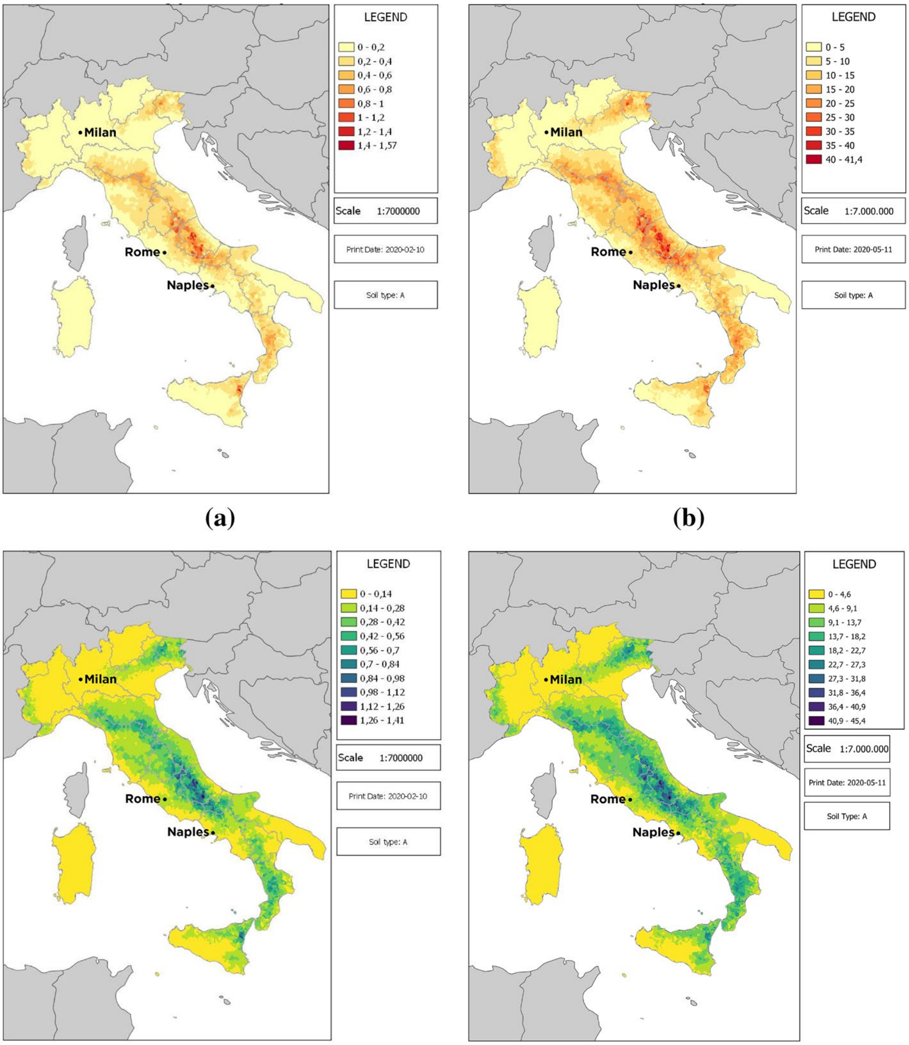
Table 6 Unconditional risk in a time frame of 1 year

	UD_{st} (1y)	UD_{lt} (1y)	Homeless (1y)	N_d (1y)	N_i (1y)	L (1y) Billion euro
Average	20.938	15.635	78.602	505	1.744	2.13
Maximum	31.847	22.024	131.952	763	2.588	3.27
Minimum	9.962	7.404	4.0381	123	469	1.27

Average, maximum and minimum values of the seismic risk in terms of consequences (impact indicators: unusable dwellings in the short and long term, homeless people, number of deaths, injured people and direct economic losses)

Table 7 CU and cost parameters c_k (%) used for computation of direct economic losses

CU (€/m^2)	D_1	D_2	D_3	D_4	D_5
1350	2	10	30	60	100



(a) **(b)**

(c) **(d)**

Fig. 11 Unconditional risk in time frames of 1 year (left) and 50 years (right).: **a**, **b** percentage of unusable dwellings (number of unusable dwellings-versus the total number of dwellings); **c**, **d** percentage of homeless (number of homeless versus number of inhabitants of each municipality

These significant differences could depend on the specific seismicity in the time window considered, but also on the large uncertainty that characterizes the casualty models. Indeed, the assessment of expected casualties after an earthquake is subjected to high uncertainty due to a series of factors that can affect the real impact. As a matter of fact, the potential injured and fatality number is not only influenced by damage and collapse mechanisms of the buildings (either partial or total) and by the effectiveness of rescue operations, but it is also affected by the number of people subjected to the earthquake effects (if the epicenter is closer or farther with respect to densely populated areas) and by the time of its occurrence (time of the day, day of the week, season).

The national maps representing the percentage of injured people and fatalities in 1 year (as average expected casualties versus the number of inhabitants per municipality), are shown in Fig. 10a–b.

6.3 Direct economic losses

As already proposed in several approaches [e.g. Hazus-MH (FEMA 2003), Maeviz (Karaman et al. 2008), SELENA (Molina et al. 2010) among other], the total direct economic losses L may be computed on the basis of loss parameters that are related to damage repair and to building inventory data:

$$L = CU\left(\sum_{j=1}^{n_M}\sum_{k=1}^{5} A_{Mj}p_{Mj,k}c_k + \sum_{l=1}^{n_{RC}}\sum_{k=1}^{5} A_{RCl}p_{RCl,k}c_k\right) \tag{8}$$

In Eq. (8), n_M and n_{RC} have the same meaning as in Eq. (6) and (7), CU is the Unit cost (Euro/m^2) of a building, including technical expenses and VAT, A_{Mj}, A_{RCl} are the built area of the jth M or lth RC building typology, respectively; $p_{Mj,k}$, $p_{RCl,k}$ are the probability, in the considered time frame t for risk estimation, for the jth M or lth RC building typology to experience structural damage state D_k; c_k is the percentage cost of repair or replacement (with respect to CU) for each structural damage state D_k. Obviously, in addition to the significant influence of damage distribution, that in turn is dependent on the vulnerability model adopted for the assessment, the expected losses are affected by the choice of CU and by the percentages assumed for c_k, as already pointed out in past studies that investigated on such relevant factors (e.g., Dolce et al. 2006; Dolce and Goretti 2015).

The cost parameters adopted to calculate direct economic losses with Eq. (8) in IRMA are calibrated on the basis of the actual repair costs that were monitored in the reconstruction process following recent Italian earthquakes (Di Ludovico et al. 2017a, b), as reported in percentage terms in Table 7 for damage levels from D1 to D5.

Similarly to previous indicators, the direct economic losses are first calculated for the single VEMs and then aggregated with the approach explained in Sect. 5.

The loss resulting at national level (average and maximum and minimum values obtained by the various models) are summarized in the last column of Table 6, that refers to risk estimation in 1 year time frame. It has to be noted that, having considered the same soil type everywhere, namely the type A, the obtained risk results are most likely on the low side of real ones.

Obviously, the evaluation of total expected losses in a region depends, in addition to seismic hazard and building vulnerability, on the effective exposure of the considered assets, i.e. on residential buildings inventory. As it can be seen from the results in Table 6, the average losses due to direct costs amount to about 2 billion euro; maximum and minimum expected losses due to the different VEMs adopted differ by approximately ± 50 % with respect to average, and this large scatter confirms the high uncertainty in this estimation.

In spite of the high variability of results, the average estimated value seems quite consistent with the total costs of earthquakes in the last 50 years. Indeed, the latter are in the order of about 211 billion of euros, thus leading to an expected total costs in the order of 4–4.5billion euro per year, that is approximately twice the average loss results reported in Table 6. While these loss values estimated with the procedure described in this section refer to the direct costs due to repair/reconstruction of residential buildings, the total costs of earthquake include also the costs associated to reconstruction or repairing of other assets, i.e. commercial and industrial buildings, public buildings, cultural heritage, infrastructures, as well as the costs for the management of the emergency phase (e.g. shelters, temporary housing, etc.). As observed in (Dolce and Di Bucci 2017), the total costs approximately double the costs due to direct losses to dwelling buildings; the application of this simple rule of thumb to the average loss results of Table 6 seems to confirm the possibility to perform a realistic estimation of total losses, even if affected by high uncertainty.

Another interesting comparison can be performed by considering the risk assessment for Italy (https://downloads.openquake.org/countryprofiles/ITA.pdf) developed by the Global Earthquake Model (GEM) Foundation (Silva et al. 2018, 2019). Such model uses the ESHM13 hazard from the SHARE project (incorporating the MPS04), and it considers site amplification and epistemic uncertainty in the hazard. The estimated annual loss due to the expected damage to residential buildings with GEM amounts to 1.67 billion dollars, that seems in good agreement with the 2.13 billion euro reported in Table 6, especially considering that GEM attributes a lower value to residential building assets with respect to the approach utilized here. The complying comparison is confirmed by the value of average annual loss ratio reported in the Italy profile produced by GEM, 0.68 ‰; the latter value is calculated as the ratio of expected annual loss versus the asset replacement cost. Considering that the total built area according to ISTAT (2001) data is approximately 2.5 billions m^2, and assuming a reconstruction cost of 1350€/m^2, the total asset replacement cost for Italy would be in the order of 3400 billion euro; this means that the expected annual loss corresponding to the average losses reported in Table 6 would be approximately 0.63 ‰ of the asset replacement cost, confirming the good agreement with the estimation from GEM.

Concerning the geographical distribution, Fig. 12a, b represent it in terms of expected economic losses per m^2 for each municipality in 1 and 50 years. The unitary losses in €/m^2 are obtained by dividing the average losses versus the total built area of each town.

As it can be seen, it is expected that nearly 9 €/m^2 could be lost yearly due to earthquakes in the areas at major risk; while in 50 years this indicator increases up to 275 €/m^2, corresponding to a direct loss of approximately 20 % of the value of the built environment in the areas at major risk.

This representation of normalized annual risk can be useful to help shaping suitable seismic risk mitigation policies, where higher investments are foreseen in areas of major risk; moreover, they could be used as benchmark evaluations facilitating the calibration of insurance premiums for buildings in different areas of the country. Total expected direct economic losses of Fig. 13a, b are shown, in one year frame, for each municipality and for each region respectively. The map in Fig. 13a reflects the higher exposure in bigger cities, hence resulting in higher losses where the larger exposed building stock is present. Similarly, Fig. 13b, showing the expected economic losses per region in 1 year, results in larger expected losses in Emilia Romagna (up to 300 Millions of Euro per year) that is a region having relatively high seismic hazard and significant amount of exposed assets, including residential buildings.

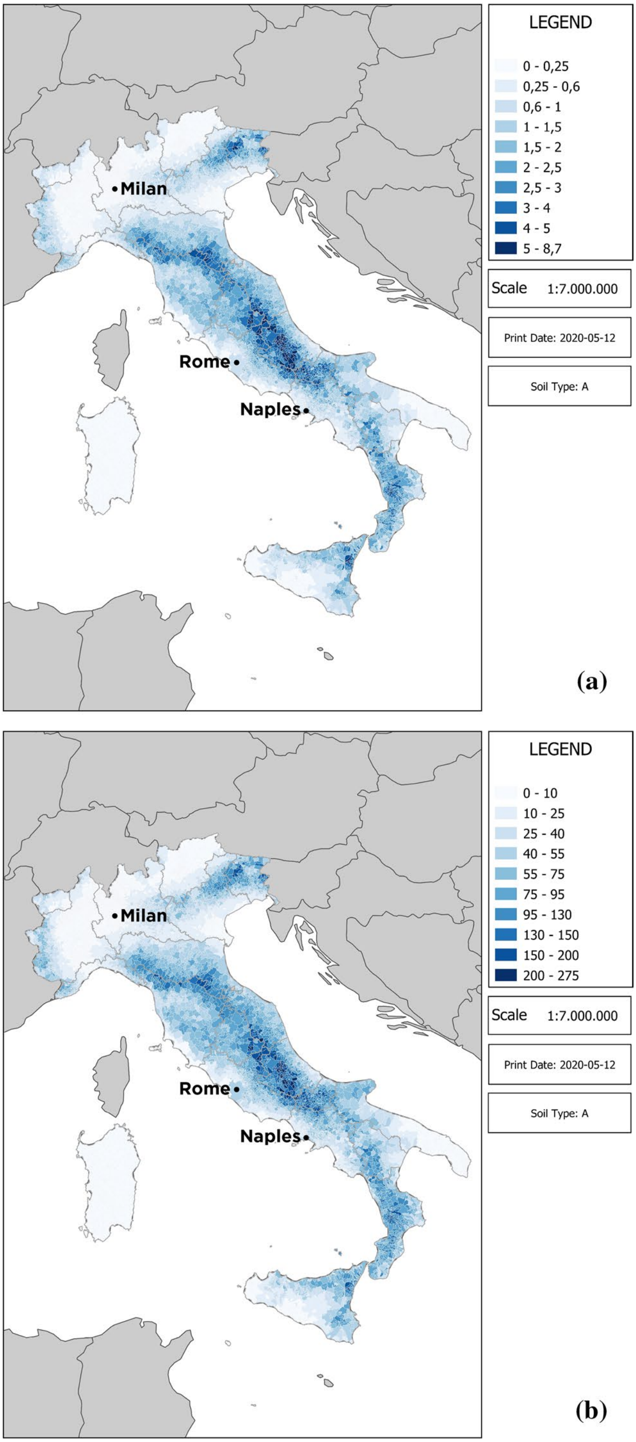


Fig. 12 Unconditional risk in time frames of 1 year (top) and 50 years (bottom): **a**, **b** direct economic losses per m^2 for each municipality

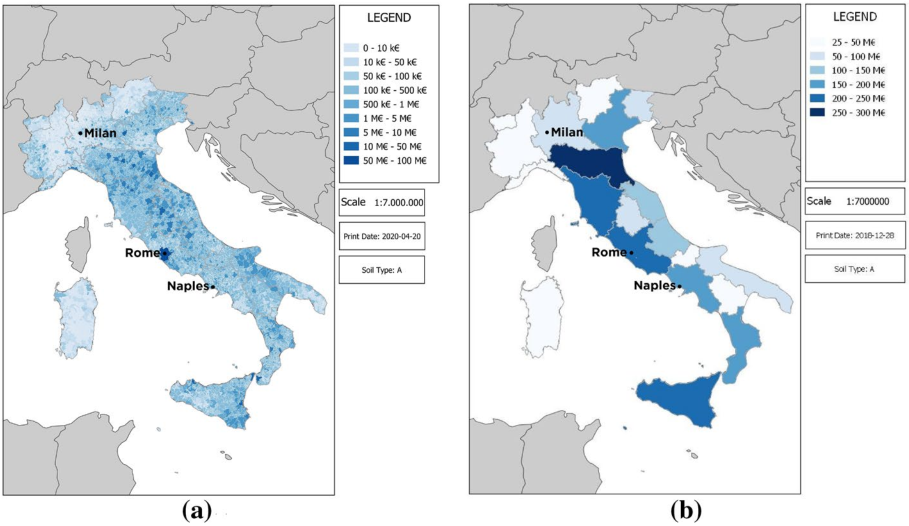


Fig. 13 Unconditional risk maps in a time frame of 1 year. Average expected economic losses for each town (**a**) and region (**b**)

7 Conclusions

The methodology specifically developed and employed for the evaluation of seismic risk in the last National Risk Assessment NRA in Italy has been presented. The methodology adopts a shared approach in the Italian scientific community operating in the seismic vulnerability and risk field; it is based on the consensus on procedures to compute the risk in terms of expected damage for the residential building stock and associated consequences (direct economic losses and impact quantities such as unusable buildings, homeless and casualties), although allowing for the maximum freedom in the definition of the vulnerability/exposure model. Moreover, to avoid inconsistencies in the analysis, the same input databases and calculation engine are used for all the vulnerability models used in the analysis. In particular, the same seismic hazard model is adopted and the same database based on census returns (ISTAT 2001) is employed as input for the exposure modeling of the residential building stock and population.

Six research units from the Centers of Competence of DPC ReLUIS and EUCENTRE collaborated under the guidance and coordination of DPC, to develop the shared methodology and to produce the recent updating of national seismic risk maps for the residential building stock. Each research unit developed a vulnerability/exposure model VEM so that 4 VEMs were developed for Masonry buildings and 2 for reinforced concrete RC ones. All of them were combined to produce the national seismic risk assessment.

The shared methodology was implemented adopting the IRMA platform to evaluate national seismic risk and maps for the last National Risk Assessment (NRA). Specific choices were made for this first application of the methodology. In particular, the same soil type was assumed everywhere, namely the type A corresponding to stiff soil category. This assumption could possibly be removed in future national risk assessment, adopting different soil types in different parts of the territory, as soon as the results of ongoing studies allowing for more specific geotechnical characterization for the entire national territory will be available.

The final results at national scale are obtained by combining the consequences calculated by each VEM.

The results obtained at national scale confirm the high seismic risk with reference to the ordinary residential building stock in Italy. The risk in terms of unconditional damage show also the significant scatter that can be obtained using different VEMs. Adopting suitable damage to impact conversion rules, the consequences in terms of expected number of unusable buildings, homeless, casualties and direct economic losses are also determined. As expected, the high uncertainty is shifted also to the consequences that are evaluated starting from damage derived by the use of the different VEMs. For example, referring to direct economic losses, the average value amount to about 2 billion euro, while maximum and minimum expected losses due to the different VEMs adopted differ by approximately ±50 % with respect toaverage. In spite of this significant uncertainty, the average results may be considered as an acceptable estimation of the seismic risk at the national level. Comparing, for example, the average annual loss ratio of 0.63 ‰ of the asset construction cost, computed with the proposed methodology, with the one of 0.68 ‰ estimated independently by the Global Earthquake Model GEM for Italy, a very good agreement of results is found.

The maps in terms of seismic risk and consequences produced for the last NRA will be a useful tool for planning seismic risk reduction strategies at the national level, allowing future risk targeted mitigation measures to be to effectively addressed.

Besides, the risk maps are already effectively used to enforce another pillar of the new Civil Protection Code, which is to enhance nonstructural prevention by increasing community's awareness in order to mitigate the impact of existing risk. Indeed, in the framework of an agreement between DPC and EUCENTRE, a specific web-tool SICURO+ https://www.sicuropiu.it was developed to allow citizens to view the newly developed seismic risk maps. SICURO+, adopts a suitable communication strategy to the public; in this way ordinary people can become aware of the seismic risk level of the municipality where they live, work or spend their holydays and take adequate prevention measures (Dolce et al. 2019a).

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