Seismic Risk Analysis at Urban Scale in Italy

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Abstract. Seismic risk maps are a useful tool researchers use for representing to stakeholder and decision makers the adverse outcomes a seismic event can have over the territory. Generally, in those studies, urban areas, where the human activities are concentrated, focuses major attention. Main concerns are about the existing building stock, mostly composed by structures not compliant with modern seismic design criteria. The production of a seismic risk map is a complex task that involves the combination of data coming from different field of expertise. The aim of the study is to show how the already available information can be combined together in a Geographical Information System (GIS) tool. The results provide a reliable representation of the seismic risk at urban scale to be used when planning the mitigation measures to be undertaken in order to improve the level of preparedness in case of an earthquake. The analysis has been applied for demonstration purposes to the town of Cassino, Central Italy.

Keywords: Risk analysis · Reliability engineering · Earthquake engineering · Socio-Economic modeling · Seismic hazard · Seismic fragility functions

1 Introduction

The public awareness about the painful consequences that a moderate to strong earthquake [6],[17] can induce to a community in terms of loss of lives and damages is generally accompanied by the expectation that the modernstandards of living would be set in such a manner to prevent that harm. It is, however, a matter of fact that the knowledge about how the structures would be constructed in order to prevent collapses and reduce damages has evolved at a highly faster speed than the renovation rate of the building stock and sometimes the interventions needed to increase the structural safety of existing buildings, infrastructures, and critical facilities located in seismically prone areas are extremely expensive so that any decision about the mitigation measures to be undertaken is necessarily a trade-off between the cost-effectiveness of preparing for risks and that of coping with their consequences.

Seismic risk maps are usually employed in order to represent the expected loss an earthquake can produce over a territory taking into account the uncertainty that are involved into the forecast. It is worth noticing that during the risk evaluation some of the uncertainties are inherent (the randomness of the seismic phenomena is such that

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no one can say when, where and how intense will be the next earthquake), others uncertainties are epistemic and can theoretically be reduced, but equally practically persistent (the wider is the area object of the study, the looser will necessarily be the inventory of all the goods subject at risk considered in the analysis).

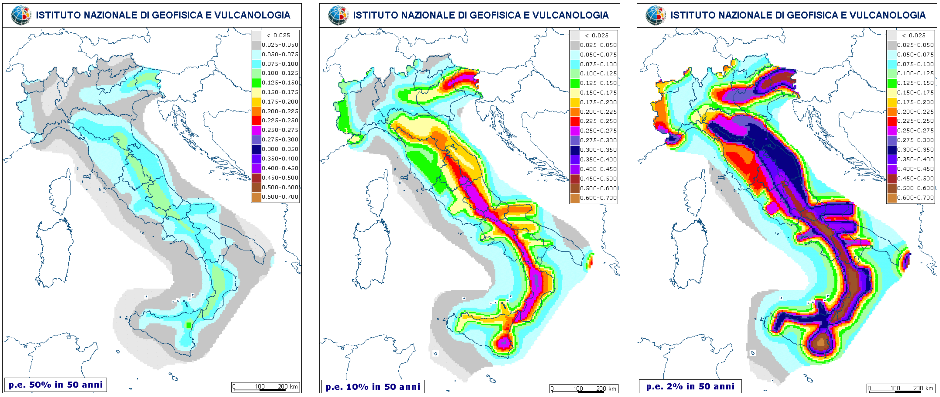
Usually the developing of such a map is a complex task that involves many disciplines including geophysics and geology (in order to take in account past seismicity, seismo-tectonic framework, wave propagation as well as soil effects), survey (in order to collect data about the building stock), structural analysis (in order to assess the building response under seismic loads) and social and economic sciences (in order to evaluate socio-economic consequences of an earthquake) [8],[9],[15],[16].

The standard definition of seismic risk is the probability or likelihood of a damage, due to an earthquake, and consequent loss to a specifiedclass of elements at risk over a specified period of time. In order to keep the problem of computing the risk tractable, it is tackled initially decomposing the task in specialized (simpler) components, conditionally independent and conventionally referred as hazard (pertaining to the likelihood of the seismic shaking on ground), vulnerability (pertaining to the susceptibility to damage of the built environment) and exposition (containing the socio-economic evaluation of the loss) and then recursively applying the total probability theorem in order to aggregate together the separate components. Hence the risk can be expressed by a convolution integral [5].

2 Seismic Hazard

Seismic Hazard analysis is aimed at estimating a measure of the intensity of the ground motion at a site considering the characteristics of surrounding seismic sources. This kind of study is restricted to the shaking felt at the ground level and does not consider the action on the built environment. Therefore in hazard analysis the core aspects investigated are the source modeling (i.e. mechanism at the epicenter that produces the shaking), the wave attenuation (along the path between the source and the site of interest) and the local ground amplification (through the ground layers around the site). The probabilistic assessment of seismic hazard involves determining either the probability of exceeding a specified ground motion, or the ground motion that has a specified probability of being exceeded over a particular time period. Accordingly, output of the hazard analysis is either a curve showing the exceedance probabilities of various ground motions at a site, or a hazard map that shows the estimated magnitude distribution of ground motion that has a specific exceedance probability over a specified time period within a region.

Despite the fact that several studies on seismic hazard were undertaken in Italy before, only after 2004 this kind of analysis assumed official recognition in technical community, since the seismic classification was compulsory associated with the likelihood of reaching some levels of seismic accelerations at site.



(a) (b) (c)

Fig. 1. Seismic hazard maps in terms of PGA at different return period,Tr: (a) 72, (b) 475, (c) 1000 years

Therefore the probabilistic hazard analysis conducted by the INGV [14], has become the Italian national reference in engineering applications. The results have been mapped on national scale over a 0.05° grid for various annual frequencies of exceedance (the reciprocal of the return period: T_r, varying from 30 to 2500 years) presenting peak ground acceleration (PGA) and spectral ordinates in acceleration for various natural periods (T_n: varying from 0.1 to 2.0 sec.); in total 90 maps have been produced, three of which are presented in Figure 1.

3 Seismic Vulnerability

Seismic Vulnerability represents the susceptibility to damage of the object at study, givena measure of the seismic input. Methods applied in representing the vulnerability analysis vary greatly depending on the complexity of the approach and the available data about exposure (see next section). Generally when in a vulnerability analysis it is considered a single item (like a specific building) the study can reach a very fine level of detail, defying the modality of damage and/or the number and type of components damaged [10,11]; on the other hand when it is under scrutiny a bulk of items, like a building stock, the vulnerability may necessarily been defined in looser terms as the damage potential of a class of similar structures, using as classification a broad identification (as for example the same structural type, number of floors, age, technique of construction …). Vulnerability of structures to ground motion effects is often expressed in terms of fragility curves (or damage functions) that take into account the uncertainties in the seismic demand and capacity.

In the present study the fragility curves have been built according to the SP-BELA approach [2,3]. According to this methodology the displacement capacity of the buildings at different damage levels (limit states) is produced, relating the displacement capacity to the material and geometrical properties. Three limit state conditions have been taken into account: slight damage (LS1), significant damage (LS2) and collapse (LS3). 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 aforementioned limit states can be assumed equivalent to the definitions contained in Eurocode 8, as follows: LS1: Damage Limitation (DL), LS2: Significant Damage (SD) and LS3: Near Collapse (NC).

In order to fit fragility functions to exposure data, in the case of masonry buildings, four separate building classes have been defined as a function of the number of storeys (from 1 to 4), whilst for reinforced concrete the building classes have been defined considering the number of storeys (from 1 to 4) and the period of construction. The year of seismic classification of each municipality has then been used so 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.

4 Exposure

Exposure is a representation on the population of items object of the study and their relevant aspects in relation to the risk analysis (this kind of information has necessarily to interact with hazard and vulnerability components of the study). Depending on the extension of the scope of the analysis, exposure may include a single building with its occupants and contents, or may include the entire constructed environment in a specified area, inclusive of buildings and lifelines (infrastructural systems forming networks and delivering services and goods to a community). In order to facilitate information collection about the existing facilities in a region, a standardization of the inventory is deemed, providing a systematic classification of the structures according to their type, occupancy and function.

In Italy the general characteristics of the building stock are provided by the Census. The data utilized in the present study are obtained from the 14th General Census of the Population and Dwellings (ISTAT 2001) [12]. The Census data are collected and aggregated at different levels: the basic unit for data collection is the single household and dwelling, but each dwelling is classified as being located within a building, of a given construction type (RC, Masonry, Other), with a given number of storeys (1, 2, 3, 4+) and age of construction (≤1919, 1919/1945, 1946/1961, 1962/1971, 1972/1981, 1982/1991, ≥ 1991). In order to protect privacy, the collected data are disclosed only in aggregated format whose minimum territorial extension is the Census tract (a small, relatively permanent statistical subdivision of a geographical region, designed to be relatively homogeneous with respect to population characteristics, economic status and living conditions). In highly urbanized areas, like the Cassino town centre, a census tract has the dimensions of a building block. Further details about the elaboration of the exposure data are discussed in the next section.

5 Application Results

The case analyzed in this paper is represented by Cassino, a small sized town (35'000 inhabitants) located in southern Lazio, in a seismic prone area classified as at medium hazard level.

Local seismicity is characterized by active faults surrounding the town (even at a very close distance). The historic events that have hit Cassino are shown in Figure 2, where for each earthquakeyear and local seismic intensity are reported. Intensityis the classification of the strength of the earthquake shaking based on the observed effects (e.g. building damage) and in the graph it is measured according to the Mercalli-Cancani-Sieberg (MCS) scale, spanning from I=1 not felt, to XII=12 total destruction.

The main feature of the built environment of Cassino, that differentiates this town from similar Italian municipalities, is the fact that the town was almost completely destroyed at the end of World War II during the so called 'Battles of Monte Cassino' (January-May 1944) [21, 22] and then rebuilt, at the end of the war, in a relatively short time [23, 24, 25, 26].

In Figure 3 it is shown the evolution of the building activity at Cassino over time, together with the more relevant legislative measures that can be of interest in a seismic risk analysis. It is, indeed, of great interest for the aims of this study that the building stock of Cassino is relatively younger than the Italian average and that reconstruction began when the municipality was already classified in seismic zone after the Avezzano earthquake (January 13, 1915, M_w=7.0) [24], so that the first structures built during the reconstruction are supposed to be designed according with the seismic principles commonly applied at the time (elastic design relying over the allowable stress principle and using horizontal forces about 7% of the weight). Cassino was subsequently declassified in the 20 years span period since 1962 until 1982, when the economic boom was associated with the maximum rate of the building activity. It was, indeed, felt that the enforcement of seismic rules was an impediment to economic activities and urban development and therefore it was not so uncommon that municipalities, after some time since the last seismic event that justified their insertion in the seismic zone list, petitioned to be removed. In the case of Cassino, the cancellation was 'de facto', since it was sufficient not to be included in the new list prepared in 1962, while in the case of the nearby Pontecorvo town an 'at hoc' decree was issued in 1959 to selectively declassify the periphery (awaiting to be urbanized) whilst the already constructed urban centre was kept seismic. Cassino was then re-classified in 1983, after the Irpinia earthquake (November 23, 1980, M_w=6.9). Only after the Molise earthquake (October 31/November 2, 2002, M_w=6.0), a fundamental revision of the seismic classification as well as of the seismic design rules was undergone, redefining the seismic classification on the basis of a probabilistic hazard analysis rather than on an historical basis and incorporating in the new recommendations the limit state approach, with load and resistance safety factors and capacity design principles.

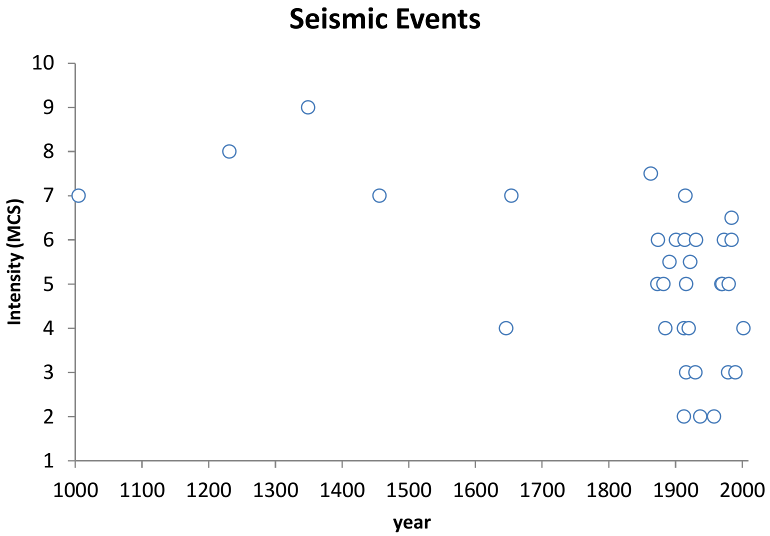


Fig. 2. Historic seismicity around Cassino

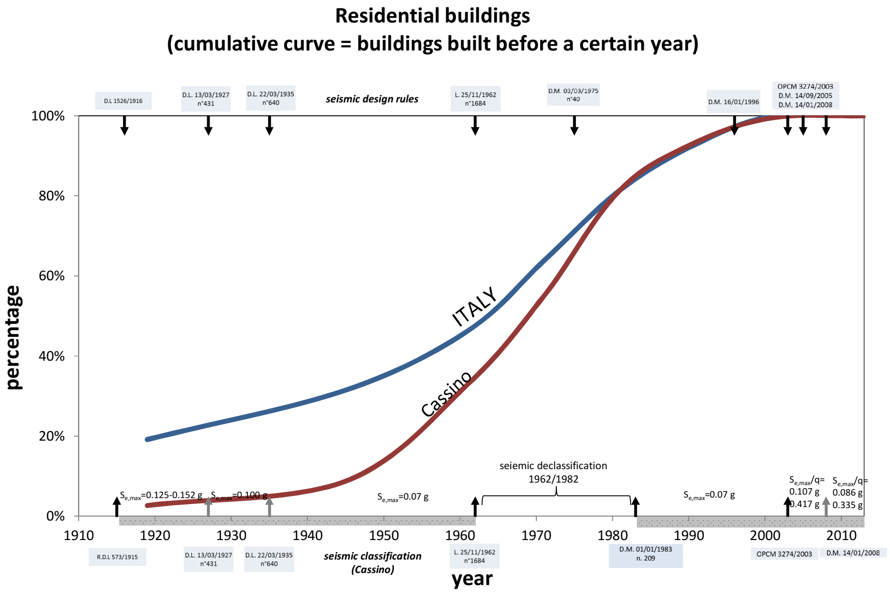


Fig. 3. Evolution of the Building Stock at Cassino

The information about the geotechnical setting has been obtained by a recent study on micro-zonation [18,19], from which emerges that the town of Cassino is settled in an alluvial plain, characterized by the presence of soft soils.

For privacy purposes the relevant data about buildings contained in census tracts (Cassino municipality is subdivided in 780 tracts) are made available through their marginal frequency, without disclosing the underlying joint distribution (this kind of data is available in aggregate format only for provinces and big cities). The problem of reconstruct the joint distribution from the marginal seven if it is known the correlation structure, it is not an easy task, since no unique solution exists. A possible approach is to consider a possible model representing the stochastic dependence structure among variables. In such a case Copula functions provide a useful tool to generate joint distributions by combining given marginal distributions.

The data made available by the Census have been surveyed in order to check the affordability and eventually introduce corrections. The following operations have been undertaken:

1. Extensive use of Google Earth all over the municipality to verify the correctness of the number of buildings and the story distribution within a single Census Tract;
2. Visual survey of the town centre in order to resolve dubious question left from point 1 above and to verify the construction technique (masonry, reinforced concrete, other).
3. Examination of some of the information available at the local office of the Civil Engineering Corps (Genio Civile). It is important to notice that since 1971 all the Reinforced Concrete structural projects (L.November 5, 1971, n. 1086) were subjected to be filed at Civil Engineering Corps before the construction started. The review of 15 complete structural projects (inclusive of technical drawings, relations and calculations) permitted to have an insight about the implementation into practice of design rules and construction standards;
4. Examination of the documentation available at the Technical Office of the Municipality of Cassino. On May 7, 1984 the Lazio-Abruzzo earthquake (Mw=5.9) hit the region, with epicenter located approximatively near San Donato-Val Comino, 27 km away from Cassino. In Cassino the damages to buildings (classifiable according to the EMS-98 scale as negligible to moderate, I=VI-VIII MCS) have to be reported to the Municipality by the property owners in order to accede to financial contributions for repairs. Each of the 86 requests examined were accompanied by a technical report signed by a local engineer, providing insight about the structures and the damages (usually the reports were accompanied by structural drawings, photographs and sketches of the crack patterns).

All the aforementioned components of the seismic risk have been handled within a Geographical Information System (GIS). A GIS represent the ideal environment for the management of spatial information, since it permits to archive, handle, compute, and display very large amount of data both in graphic or tabular format. The system, with its ability to be linked to external resources (like computational programs or high level database management systems) has also the feature to provide the required information interoperability, making possible to manage the great volume of data involved and the numerous processes needed in the calculations.

The seismic risk analysis has been carried initially performing the calculations over the 84 classes of buildings and then combining the results on tracts (in order to keep the output format consistent with the one provided by the Census) considering the effective composition of each tract through a weighted average. The results of the analysis are shown in Figures 3 and 4.

Figure 4 reports, both on the entire municipality and on a significant quadrant of the town centre, the probability of exceedance in a 50 years period of the three limit states considered (LS1: slight damage, LS2: significant damage and LS3: collapse). In order to have a term of comparison, the probability of exceedance calculated on the existing buildings, $P_{ex,50}(LS_i)$ (i=1,2,3), has been dividedby the probability of occurrence of the seismic action used in the design of the new residential buildings (and the assessment of the existing ones), $P_{new,50}(LS_i)$. According to Italian seismic rules NTC-08 [5] this probability is given for the three limit states as follows:

$$P_{new,50}(LS_1)=0.63 \qquad P_{new,50}(LS_2)=0.10 \qquad P_{new,50}(LS_3)=0.05.$$

Therefore the obtained index, $I_1=P_{ex,50}(LS_i)/P_{new,50}(LS_i)$, represents a comparative measure between the expected capacity (numerator) and the expected demand (denominator) in terms of probability of exceedance (the highest is the index, the less safe is the structure). Obviously the new structures, which have at least to comply with the indicated demand, are designedwith additional conservative measures (represented by load and resistance safety factors, capacity design rules, minimum design requirements), so that the few cases where the ratio is $I_1<1.0$, do not necessarily imply that an existing structure is safer than a new one.

As shown in figure 4, while the differential between capacity and demand is acceptable for LS1, it deepens as the level of damage increases (for LS2 or LS3). This kind of result was somehow expected, since the slight damage (LS1) is conditioned mostly by the quality of the details of non-structural components (whose design is controlled by architectural or climatic rather than seismic or structural considerations), while the occurrence of significant damage (LS2) and collapse (LS3) is conditioned by the presence in the design of seismic provisions and considerations about the expected mechanism of collapse under seismic actions.

The variability that can be observed, for each limit statethrough the entire municipality, is mostly due to the differences in structural type and age of construction of the buildings, since the soil conditions are constant for the whole town centre.

Finally figure 5 represent an index, $I_2=E(L)/R$, aimed at comparing the expected monetary lossesin 50 years due to an earthquake, E(L), and the cost for the retrofit of the structure, R.

The expected loss, E(L), has been defined considering for each limit state the associated costs for repairing or rebuilding (the more severe is the damage, the higher are the costs) and the probability of occurrence of the limit states.On the other hand, the retrofit cost, R, has been assumed as a deterministic value and independent of the existing structural conditions.

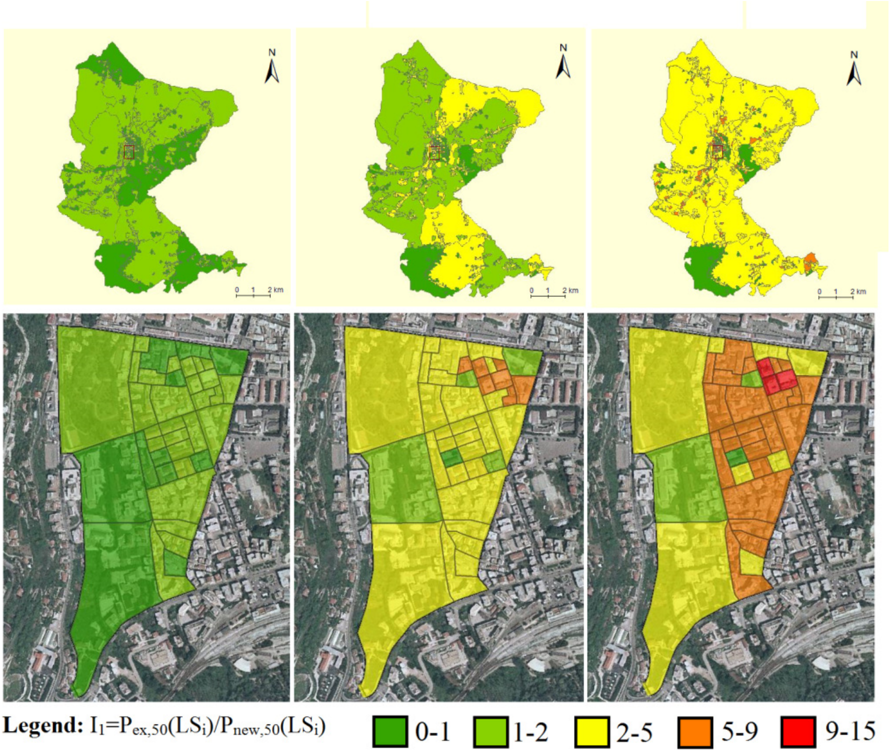


Fig. 4. Index of exceedance of the three Limit States, I_1; top: entire municipality, bottom: details of the South-West quadrant of the town centre; left: slight damage (LS_1), middle: significant damage (LS_2), right: collapse (LS_3)

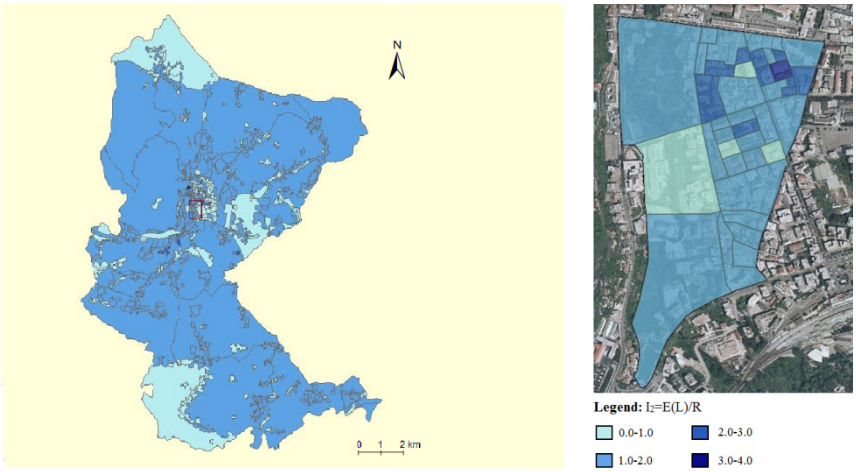


Fig. 5. Expected monetary loss and retrofitcost ratio, I_2. left: entire municipality, rigth: details of the South-West quadrant of the town centre

Obviously the reference economic values required for this kind of analysis depend highly upon many factor such as the method used for the cost estimation (this task can be performed either analytically considering typical standardized cases and analyzing the breakdown of the works deemed and then multiplying their quantity for their unit cost or historically considering how much was spent in the past in similar circumstances), the local conditions (construction costs have a significant regional variation), the quality of building finishes. In this analysis, the monetary values assumed have been selected consistently with international [13],[20] and national literature [1],[4].

Therefore the cost of construction of a new building has been assumed as 1'200 €/m^2 (1'280 €/m^{2}is the maximum contribution the State pays for reconstruction in L'Aquila after the 2009 earthquake [4]) whilst the one for retrofit using a traditional technique is around 500 €/m^2 (the State pays for the retrofit of public buildings a maximum of 150 €/m^3, that is 450 €/m^2 when considering a typical 3 m inter-story height, OPCM 3362/2004).

Obviously the index graphed in Figure 5 wants to represent the order of cost-effectiveness of undertaking measures of reduction of seismic risk even if it does not consider the possible utility associated with the market value of the real estate.

6 Conclusions

The work presented herein consisted in the assessment of theseismic risk map of the town of Cassino using the state-of-the-art evaluation procedure. The study, even if focused on a particular case for demonstration purposes, can be usefully extended to any other Italian urban agglomerate since the basic ingredients used in the analysis are already made available at national scale and the procedure can be easily standardized using modern computing tools like GIS. The study permitted to evaluate the level of affordability of the input ingredients and thus to evidence the aspects requiring a better refinement in a possible extension of the study at national scale.

It is important to point out that when tackling a small town, like Cassino, an extensive verification of the quality of the information utilized in the analysis was possible and reasonably not onerous. On the contrary, at national level, the availability of a very large amount of data, coming from different institutions and not necessarily collected for the scopes of a seismic risk analysis, poses the problem of harmonization of the pieces of information. The problem is quite arduous when considering the extreme variety of construction techniques (Italian building stock has a not indifferent percentage of vernacular and heritage architecture built following local traditions) and the different implementation of design rules and construction standards throughout the country. On the other hand the development of risk analysis through regional at hoc studies poses the problem of not-consistencies, especially when it comes to transform descriptive information about quality of construction and level of damage (usually expressed through verbal expressions) into measurable results (such as a quantification of the probability of occurrence or the monetary losses).

Coming to the specific aspects of the application, the results of the study have highlighted that, although a century has passed since the devastating 1915 Avezzano earthquake and although seismic design rules have been introduced after the event (but suspended during the construction boom), the seismic risk is still unacceptably high: a large number of buildings would suffer significant damage and collapse, causing loss of life, damages and business interruptions.

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