A Uniform Framework of Seismic Vulnerability Assessment and its Application in Seismic Risk Analysis of European Countries

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SUMMARY
To assess seismic vulnerability in regional loss estimation models, buildings are commonly classified in groups of similar behaviour based on construction materials, structural system, height, and sometimes year of construction. This approach works well when the seismic performance of buildings in the same class doesn't vary significantly, and temporal variation is consistent across the model domain. Such conditions are not met for buildings in Europe due to difference in construction practice and design standards. This study presents a uniform framework for vulnerability assessment which is independent of regions and classifies vulnerability by design base shear coefficient. Vulnerability of buildings constructed in any region and year is assessed according to region-specific seismic provisions. The framework flexibly allows adjustment to incorporate information from field observation and implicit seismic resistance from design to other loads (e.g. wind). This paper describes the methodology and illustrates its application to seismic risk analysis of some European countries.

Keywords: Loss estimation, risk analysis, vulnerability assessment,

1. INTRODUCTION

Estimation of possible losses due to future earthquakes is of prime importance for emergency planners, financial organization and (re)insurance companies. In making strategic decisions, these entities as well as government organizations rely significantly on regional risk analysis. To address the increasing demand for such analyses, several catastrophe loss estimation models have been developed and advanced in the past few decades. These models integrate earthquake hazard (seismic sources, ground motion prediction equations and soil effects), exposure distribution (elements at risk of earthquake damage) and seismic vulnerability in a probabilistic manner to provide a balanced view of risk in various regions of the world. Despite the relatively low to moderate seismic activity in Europe, devastating historical earthquakes together with large accumulation of vulnerable exposure render it a high risk area for aforementioned organizations. AIR Worldwide has developed an earthquake loss estimation model for Europe that assimilates a large building inventory database, hazard and vulnerability modules.

Vulnerability module, which is the subject of this study, translates the hazard at each exposure location to expected damage whereby the consequent monetary loss is estimated. In an ideal situation vulnerability assessment would entail sophisticated structural analysis of individual buildings; however, such analysis is not feasible in regional loss estimation applications due to size and resolution of the problem. In lieu of such sophisticated analyses, loss estimation models often resort into simplified methods such as the nonlinear static procedures (NSP). Accordingly, AIR model utilizes the well-known Capacity Spectrum Method (CSM) to determine the maximum roof displacement of a building using an equivalent single degree of freedom structure. Details of the CSM are not presented here for the sake of brevity but can be found elsewhere for example in ATC-40 (1996) and FEMA 440 (2005). The main components of CSM-based vulnerability module are the building capacity (determined from pushover analyses or code-based empirical approach) and damage functions. The latter correlates the expected damage to building roof drift ratio (RDR). To implement the module in regional loss estimation models buildings of different types should be classified in groups of similar seismic behaviour so that a typical capacity curve and damage function could appropriately represent each class. In classifying building groups, the primary characteristics are construction material, structural system and building height. Other factors such as age and construction quality are also considered often as secondary characteristics.

Vulnerability assessment based on building typology works well provided that seismic performance of buildings in the same class does not vary significantly; a condition that is not met for buildings in Europe due to difference in construction practice and standard of each country. A major challenge in seismic risk analysis of regions encompassing several countries is to systematically model the spatial and temporal variation of vulnerability in a manner that the relative vulnerability among the countries is also reflected. This is necessary because building vulnerability is influenced by the degree of scrutiny given to their design and construction which vary from country to country. Furthermore, seismic hazard maps and design requirements as well as construction standards in each country evolve over time as seismologists and engineers gain better understanding of local seismicity and building performance. However, the evolution does not occur consistently in all the countries of the region. It is, therefore, essential to develop a vulnerability assessment framework that is capable of capturing the salient aspects of seismic performance of structures while being implementable in the context of portfolio risk modelling. Although use of country specific models instead of regional models may appear as the first option to avert this problem, it is not the preferred solution as financial organization and decision makers often have interests which are spread over a region and require a consistent risk analysis. In this study a uniform vulnerability assessment framework, which is centred on classifying vulnerability by seismic resistance and connecting it to design codes and available past observation, is presented. Vulnerability, in this framework, is classified as “pre-code”, “low code”, “moderate code”, “high code” and “special code” with respect to stringency of design requirements. Buildings constructed in a certain region and time are given an appropriate “code level” based on an equivalent design base shear. By incorporating the evolution of seismic and wind design provisions and considering the degree of code enforcement and construction quality the scheme is capable of differentiating the vulnerability of buildings built in various regions and/or era.

This paper lays out the framework of uniform seismic vulnerability assessment and demonstrates its application in a probabilistic seismic risk analysis of Europe. Tempo-spatial variation in vulnerability and relativity among the modelled European countries are presented. In addition, using artificial uniformly distributed exposures, risk maps that show the overall seismic risk in the region is also presented. The proposed framework can be easily refined and extended for application in other geographic region.

2. LITERATURE REVIEW

In all the studies that address seismic vulnerability at regional scales, buildings are classified into different types based on their expected behaviour; for instance, HAZUS (FEMA/NIBS, 1999), European Macroseismic Scale (EMS-98) and RISK-UE (2001) all provide their own building classification matrix. As mentioned previously, due to variation of design and construction quality among building of the same class, building classification matrix alone does not fully reflect the seismic vulnerability. In order to differentiate vulnerability of buildings of the same typology that are designed and constructed differently, some studies further introduce several classes of vulnerability.

Recognizing the impact of seismic design regulations could have on buildings performance, some studies classify vulnerability with respect to the year buildings were designed. In this approach the year that seismic design codes were effectively put in place or went through substantial upgrade are considered the milestones that define the change in building vulnerability. Accordingly, year built of buildings is taken as a proxy of the vulnerability class. For instance, considering that seismic design codes in Turkey were effectively developed after 1975, Erdik et al. (2003) introduced two levels of vulnerability for buildings built pre 1979 (included) and post 1980. Similarly, in developing vulnerability functions for different building types using observational damage data in Italy, Rota et al. (2008) divided the building stock in two vulnerability classes of "seismic design" and "no seismic design" with respect to the reference year of 1975 where the first applicable decree for seismic design of buildings went into place. By the same token, in a part of the Risk-UE study (Pitilikas et al., 2004), buildings in Thessaloniki, Greece where categorized in two categories of "old" and "new". The former is referred to buildings that were designed to pre 1984 design code and the latter is referred to those designed to post 1985 codes.

Another approach to vulnerability classification was implemented in the well-received EMS-98 study. In this study six vulnerability classes were introduced on the basis of the observed seismic performance of buildings in the past earthquakes. The six classes A to F in the order of decreasing vulnerability are defined regardless of building typology. Each building type depending on their characteristics and earthquake resistance design (ERD) is then assigned a probable range, a less probable range and the most likely vulnerability class. The methodology, despite being well developed, is not easily applicable to loss estimation models because of its qualitative nature. Giovinazzi and Lagomarsino (2004) presented the same methodology in a quantitative language using Fuzzy Set Theory. Nevertheless, the complexity of assessing vulnerability of each building types in a given region and year built in terms of aforementioned class A-F was not eliminated.

HAZUS, a widely used hazard analysis model developed for the USA, employs a design performance grading matrix to categorize building vulnerabilities. HAZUS methodology classifies buildings in five "code levels" based on the level of protection they may have against earthquakes. It considers buildings designed to UBC 1976 code and later versions to have benefited from modern design provisions while those built before 1941 are assumed to have no seismic consideration and, therefore, are tagged the most vulnerable class. With six seismic zones (based on UBC 1976) and three design eras (pre 1941, 1941-1975 and post 1975) HAZUS introduces a 6x3 building seismic performance grading in terms of "code levels" to represent the variation of seismic vulnerability.

As mentioned before, the challenge in vulnerability assessment methodologies in Europe is that the seismic design standards vary across the region and design code evolution does not happen consistently in all the countries. Therefore, it is not practical to classify building vulnerability in terms of year built for each of countries. In the next section a vulnerability assessment framework which leverages some of the above ideas to properly reflect tempo-spatial variation of vulnerability in Europe is presented.

3. UNIFORM VULNERABILITY ASSESSEMENT FRAMEWORK

The idea of a uniform vulnerability assessment is to establish a framework that is independent of the region and that could be equally applied to any country regardless of differences in construction practice and seismicity. It is widely accepted that seismic vulnerability of buildings is highly correlated with strictness of design codes and with the degree of enforcement of these codes. Damage surveys in recent earthquakes such as the 2008 Wenchuan, 2010 Haiti and Chile, 2010 and 2011 Christchurch and 2011 Tohoku earthquakes have once again confirmed this correlation. Needless to say, a higher seismic demand or a more stringent design requirement will lead to a better seismic resistance and lower vulnerability. In lieu of detailed structural analysis for regional loss estimation applications, it is deemed prudent to establish the vulnerability assessment scheme on the basis of stringency of seismic design codes. With improved understanding of regional seismicity and structural seismic performance over time, the design criteria, and consequently seismic vulnerability, vary spatially and temporally. Thus, the merit of using a vulnerability assessment framework based on seismic design codes is that it can reflect the change in vulnerability as the code undergoes enhancements. Taking Italy as an example, Fig.1 shows how the seismic zones vary over time following some landmark earthquakes; in the pre-1975 era seismic design was only required in the areas with history of large earthquakes.

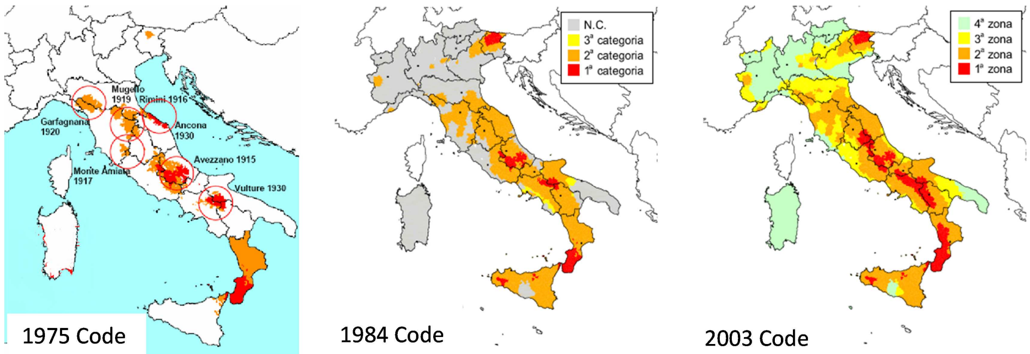

Figure 1. Evolution of seismic hazard zonation in Italian codes

As mentioned in section 2 most of the regional vulnerability studies in Europe (e.g. EMS-98 and RISK-UE) do not take into account the spatial and temporal variation of vulnerability concurrently. Temporal variation is typically approximated by introduction of age bands, but the spatial variation in different periods of time is often not properly considered. That is, the spatial variation in vulnerability, commonly defined according to the latest seismic zonation, is kept constant for all times. Decoupling spatial and temporal variation could lead to inaccurate assessments of vulnerability particularly in the regions where seismic zones changes drastically in code updates as a result of improved understanding of seismicity. The vulnerability assessment framework presented here, aims to effectively account for both concurrent spatial and temporal variation.

The proposed uniform vulnerability framework follows parts of HAZUS and EMS-98 in that it classifies vulnerability into general classes reflecting different levels of seismic performance. The main feature that makes this framework different from the aforementioned studies is that it utilizes a solid set of quantitative criteria, independent of a specific country, to define vulnerability classes. In this approach, design base shear coefficient is considered as the primary parameter in the classification and each vulnerability class is associated with a certain range of design base shear coefficient. Vulnerability class of structures built in any location and era (of any country) can then be evaluated by comparing the equivalent base shear defined by the applicable design codes with the range given by the classification criteria. The methodology permits adjustments when better information is available regarding actual building vulnerability, for example if a certain region is known to have construction defects or lack of rigorous code enforcement. Also, the implicit seismic resistance from design to other lateral loads such as wind loads could be explicitly considered in this methodology. It offers a simple and practical framework for regional loss estimation models.

3.1. Vulnerability classification based on stringency of seismic design codes

Seismic performance of buildings depends on many parameters such as strength, stiffness, ductility and redundancy to name the most important ones. In vulnerability assessment of classes of buildings rather than an individual building, it is not easily possible to account for all of these parameters. In all modern seismic design codes, ductility is explicitly formulated; however, redundancy and structural detailing cannot be readily quantified in a manner appropriate for this study. The criteria for vulnerability classification, therefore, takes design base shear which in principle reflects stiffness and strength, as the primary index.

Vulnerability classes in HAZUS are determined in connection with the design provision of UBC 1976. The "special code" is assigned to buildings with "superior" performance level (maximum strength and ductility) in zone 4 of the UBC 1976. Buildings in the same zone with "ordinary" performance level (high strength and ductility) are assigned "high code". Those in seismic zone 2B with "ordinary" performance level are assigned "moderate code" and those in zone 1 with "ordinary" performance level are assigned "low code", those with "inferior" performance level (minimum strength and ductility) or those located in zone 0 are assigned "pre code" vulnerability class. EMS-98 also defines code levels for engineered buildings. In EMS-98 low, moderate and high code levels are assigned to buildings with a minimum, moderate and high level of earthquake resistant design respectively. EMS-98 assumes a base shear coefficient (with no mention of structure's type and height) of 2-4 %, 5-7% and 8-12% for low to high code classes respectively.

As one notices, vulnerability classification criteria in these studies is rather qualitative and requires a great deal of engineering judgment. To minimize the need for engineering judgement and to establish quantitative criteria that can be used in any region we determine the range of base shear coefficient for each vulnerability class from a global perspective. That is, retaining the existing terminology for vulnerability classes ("pre code", "low code", "moderate code", "high code" and "special code") we define the "special code" as buildings that are designed to the most stringent seismic provisions in the highest seismic hazard regions worldwide. To this end, making reference to definition of code levels in HAZUS and connecting it with a contemporary modern code (IBC-2009 the US) the range of base shear for each code is determined. Table 1 shows the HAZUS definitions (described in previous paragraph) and the corresponding hazard values pertaining to IBC-2009 base shear calculation.

Table 1. Relation between HAZUS vulnerability class and seismic zones and corresponding ground motion parameters for calculating base shear coefficient per IBC-2009

HAZUS Vulnerability Class	Associated Seismic Zone (UBC code)	IBC-2009 S_s (g)		IBC-2009 S_1 (g)	
		Min (>=)	Max (<)	Min (>=)	Max (<)
High Code	4	0.88	3	0.35	1
Moderate Code	3	0.48	0.88	0.21	0.35
Moderate Code	2B	0.26	0.48	0.1	0.21
Low Code	2A	0.19	0.26	0.06	0.1
Low Code	1	0.1	0.19	0.04	0.06
Pre Code	0	0	0.1	0	0.04

Taking a five story RC ordinary moment resisting frame building on an average soil (type D) the range of base shear coefficient for each vulnerability class can be determined as shown in Table 2. Sub levels are introduced to allow variation in different countries across Europe and to ensure a smooth transition between vulnerability classes.

Table 2. Vulnerability classification in the proposed framework (calculated for a five story RC frame)

Vulnerability Class	Sub-Level	Base Shear Coefficient	
		Min (>=)	Max (<)
Pre Code	I	0.000	0.035
Low Code	I	0.035	0.055
	II	0.055	0.090
Moderate Code	I	0.090	0.115
	II	0.115	0.130
	III	0.130	0.150
High Code	I	0.150	0.175
	II	0.175	0.200
	III	0.200	0.220
Special Code	I	0.220	0.300
	II	0.300	0.400
	III	0.400	0.500
	IV	0.500	-

Since base shear values depend on structure's natural period (represented by building height) the ranges corresponding to different code levels will vary by building types. It is important to note that base shear values shown in Table 2 do not intend to imply a fix set of numbers for all types of buildings; those values are relevant to the example 5 story RC frame mentioned above. However, the goal of vulnerability classification in the context of regional loss estimations is not to assign an exact vulnerability tag to each building; rather, the objective is to identify the vulnerability in a relative sense among different regions and at different periods of time. Thus, for the sake of assessing vulnerability of engineered buildings in a regional and temporal basis, one can take the same example building as the one used in generating the table, namely, the 5 story RC ordinary moment resisting frame and compare the design base shear with values in Table 2. For non-engineered buildings variation of vulnerability is much smaller since "special code" and "high code" levels do not apply to these types of buildings. Vulnerability of non-engineered buildings is independent of design codes but is influenced by regional construction practice and local experience from historical events. Fig. 2 shows the code levels in different regions of Italy based on the stringency of seismic design codes for engineered buildings in three different eras.

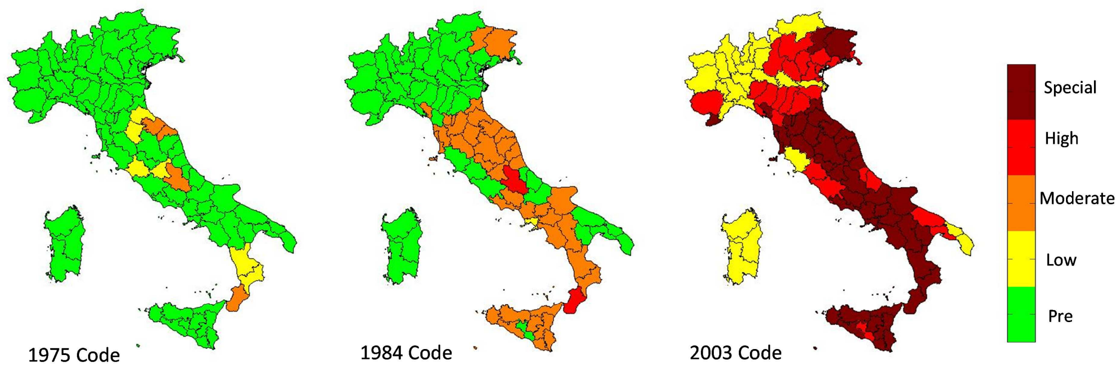

Figure 2. Code level designations based on stringency of seismic design codes in Italy

3.2. Inherent seismic resistance from design to other loads

In many regions where earthquake force is not considered a threat, codes may require buildings to be designed against other lateral loads such as wind loads. This is the case in some European countries such as United Kingdom, Ireland and Norway where codes do not mandate seismic design. Building design in these countries is often governed by wind loading. In assessing seismic vulnerability, the lateral load resistance inherent from design for wind loading should not be discounted. Therefore, in the vulnerability assessment framework presented here, design wind load is converted into equivalent seismic load, and building vulnerability class is then determined accordingly using the same criteria presented in the previous section.

If equivalent base shear from wind load was not taken into account, buildings in these countries would have been assigned the most vulnerable class (pre-code). However consideration of equivalent base shear from wind loading puts them at the boundary of pre and low codes. In light of high construction quality and standard in some of these countries the vulnerability class can be upgraded to low-code.

3.3. Code enforcement, construction quality and standard

Existence of seismic design codes per se does not promise that buildings in the region will perform as the code provisions intend. Discrepancy between the actual performance of buildings in a region and the performance objectives set out by the seismic design codes (effective at the time when buildings were designed) lies on the degree of code enforcement, workmanship, engineering experience and quality control standards. Limitations in the design code itself can also aggravate the discrepancy. It is clear that vulnerability assessment merely on the basis of stringency of seismic codes with no regards to actual building performance may lead to gross inaccuracies. In order to avert this potential inaccuracy and to ensure a reliable vulnerability assessment, information about code enforcement and construction quality in each region should be incorporated in vulnerability assessment methodologies.

In the proposed vulnerability assessment framework, impact of code enforcement is accounted for by adjusting the vulnerability class (code level). For example, Molise region in Italy was considered a medium seismicity zone in the 1986 version of the code, but due to an administrative delay the seismic provisions were not enacted until 2002 (Maffei and Bazzurro 2004). In vulnerability assessments, therefore, code level in this zone for the period of 1986-2003 was downgraded to that of the previous age band.

Knowledge about buildings performance in past earthquakes or from local vulnerability studies that reveal specific shortcoming in design and construction is also taken into account to adjust the code level designations. For instance, base shear calculated for the example 5 story RC building according to the 1963 Romanian building code would put the city of Bucharest in moderate code-I vulnerability class. However, local researchers suggested that buildings built between 1963 and 1977 in Bucharest were short of meeting the expected performance objectives and were better represented by low code level (RISK-UE, 2001). Therefore, vulnerability class has been adjusted to maintain consistency with these local studies.

In cases where no information about specific building vulnerability in a region is available, examination of possible similarity of construction practice and building characteristics to that of other regions with known vulnerability can provide some indirect information for vulnerability assessments. For example, since buildings in Bucharest built between 1963 and 1997 are considered low code, buildings constructed in the outskirt of Bucharest during the same period of time are deemed to be of equal or higher vulnerability.

The underlying assumptions in the vulnerability assessment framework and the subsequent adjustments in the vulnerability level designations warrant an extensive validation. This step is very crucial in developing loss estimation models. In the AIR model, vulnerability designation and the overall model performance is validated against damage and loss reports from historical earthquakes across the region. A major advantage of the uniform vulnerability assessment framework is that it makes it possible to establish relativities in vulnerability of modelled countries. Such relativities facilitate the validation processes in countries where historical data for validation is not available.

3.4. Spatial and temporal variation of vulnerability across the modelled countries

The general framework can be summarized in a simple flow chart shown in Fig. 3. As explained in previous sections, by connecting vulnerability to building codes and construction quality and by tracing the evolution of the seismic codes in each country, the uniform vulnerability assessment framework effectively echoes the change in vulnerability by region and time. A prominent aspect of the framework presented here is that it addresses the spatial and temporal variation concurrently.

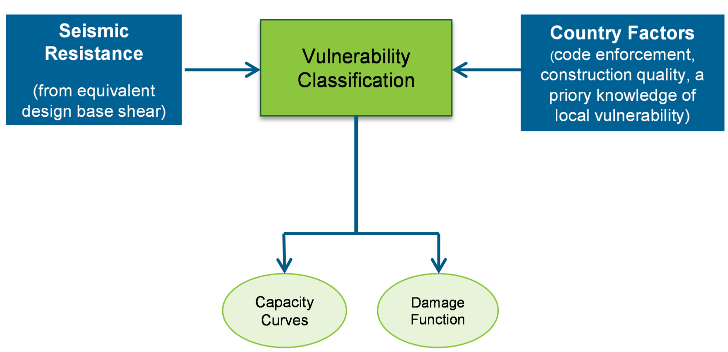

Figure 3. Simple flow chart of the uniform vulnerability assessment framework

The overall vulnerability level is a function of equivalent base shear (determined from seismic and wind design code in each country) and country factors that account for all other regional vulnerability information. Combining these pieces, one can determine the overall vulnerability level for each region of a country at a given year. A map showing the overall vulnerability level in each country provides a convenient means of comparing relative vulnerability among the modelled countries. Fig. 4 demonstrates these maps for engineered buildings constructed in four different years (1950, 1970, 1990 and 2010) in 30 European countries (those in grey are not modelled). It is evident from the figure that with improvements in design codes over time vulnerability decreases.

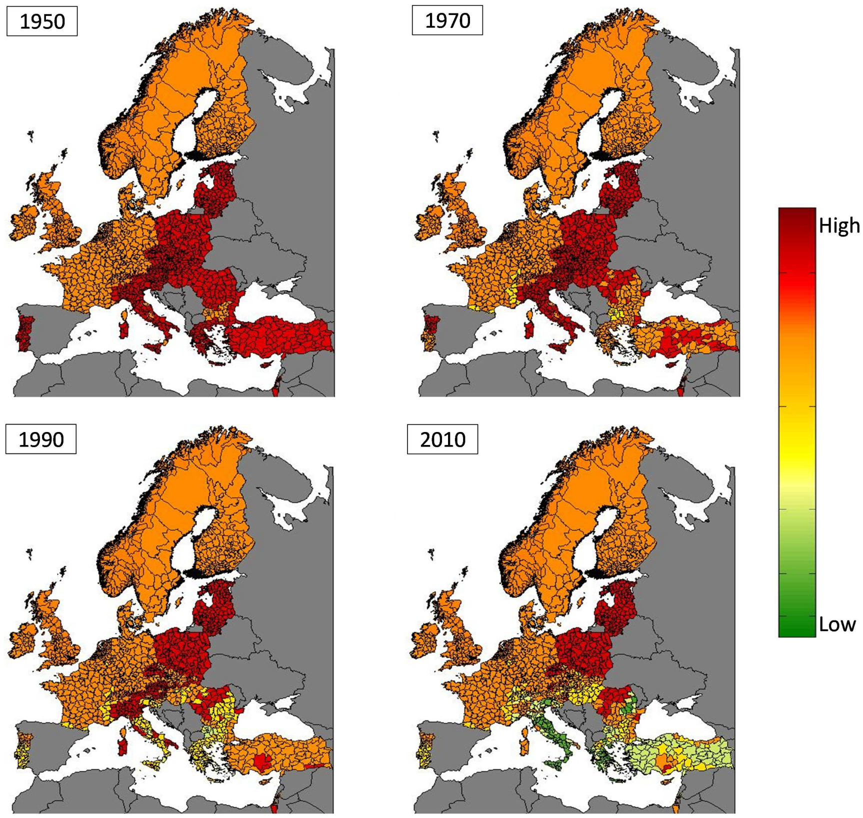

Figure 4. Maps of overall vulnerability level for engineered buildings constructed in four different years in 30 European countries

4. APPLICATION OF THE UNIFORM VULNERABILITY ASSESSMENT FRAMEWORK

The uniform vulnerability framework can be easily incorporated in loss estimation models for any region of interest. Regional loss estimation models perform probabilistic risk analyses by simulating a large number of events, and provide a range of losses with various probability of being exceeded in one year. A curve showing the range of losses, often referred to as EP curve (exceedance probability), is widely used in the (re)insurance industry. In addition to EP curves maps that show the average annual loss over a region, which is a collective reflection of hazard, exposure and their vulnerability, are frequently used in underwriting insurance policies and pricings.

4.1. Risk maps

A risk map is an illustration of annual average losses for an artificial exposure uniformly distributed over a region. The artificial exposure is a homogenous mix that consists buildings of the same construction type, height and year built distributed uniformly at a desired resolution. An individual risk map fundamentally reflects the variation of hazard in the region. However, by changing the exposure characteristics several risk maps can be created that when compared with one another allow visual comparison of the expected losses sustained by various types of buildings. A common use of risk maps in insurance industry is to perform simple relativity studies to understand risk associated with different types of buildings. Fig. 5 shows example risk maps generated for a highly seismic region in Europe encompassing Turkey, Greece, Bulgaria and Romania using 10,000 stochastic simulations. The exposure consists of a uniform 1km-grid of mid-rise RC frame buildings built in 1970 and in 2005. Red points on the map show the hot spots where the risk is particularly high. The spatial and temporal variation of vulnerability is evident by comparing the two maps; i.e., as one expects, the risk for buildings built in 2005 is smaller than that for the buildings built in 1970.

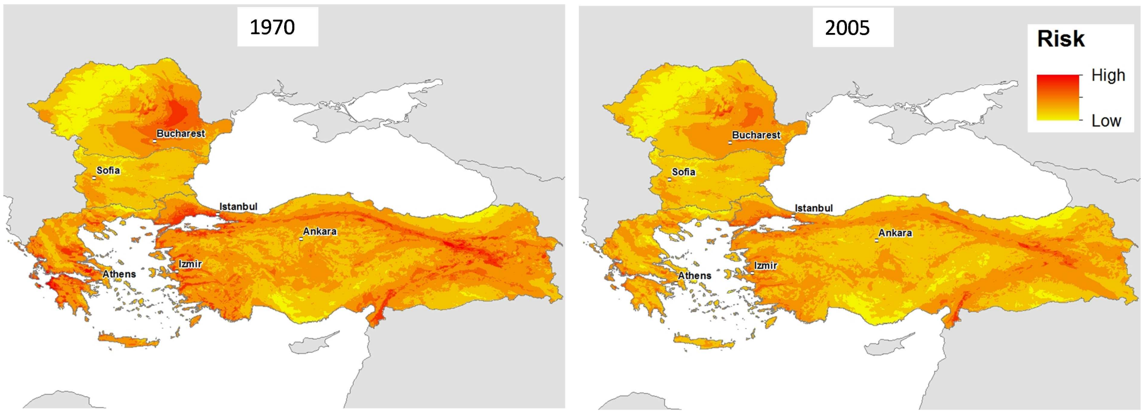

Figure 5. Risk maps generated for artificial uniform exposure consisting of mid-rise RC buildings constructed in 1970 and 2005

4.2. Loss-cost maps

A loss-cost map is conceptually the same as a risk map except that it uses the actual exposure instead of an artificial homogenous exposure. Combining hazard, actual exposure and their vulnerability, loss-cost maps portray a more realistic picture of varying risk across the region. Information presented in loss-cost maps is of substantial importance for insurance industry particularly in underwriting and pricings. Fig. 6 presents an example of a loss-cost map generated from 10,000 simulations for 30 countries in Europe.

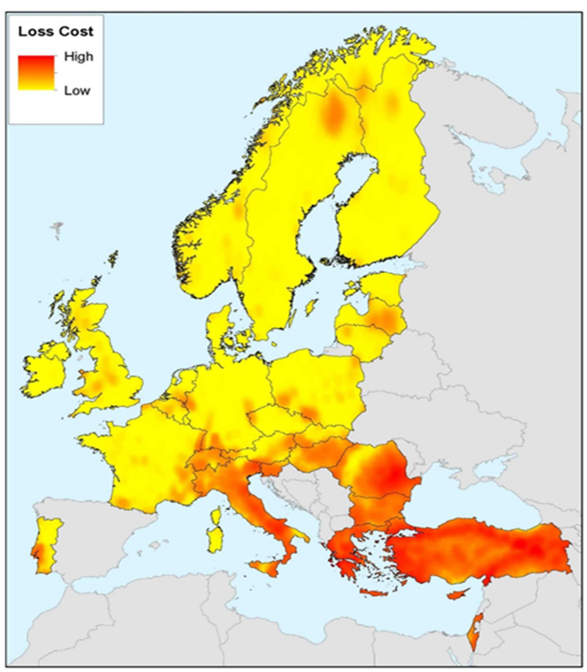

Figure 6. Loss-cost map for 30 countries in Europe using 10,000 stochastic simulations

Application of the uniform vulnerability assessment framework in the loss estimation model for Europe results in a consistent risk analysis across all the modelled countries. The consistency is manifested in the smoothness of loss-cost and risk maps at the country boundaries. It is worth noting that attaining this level of consistency in risk analysis is not easily possible when country- specific loss models are used instead of regional model.

5. CONCLUSIONS

Reliable regional risk assessment is challenging due to the inherent uncertainties in each of its major components. The key to achieve a promising model is to perform extensive validations (against historical observation if available) and to allow flexibility to absorb refinement and adjustments in the input. This paper presented a uniform vulnerability assessment framework for implementation in regional loss estimation models. The framework is developed on the premise that seismic performance of a building is highly correlated with the strictness of the codes to which a building is designed. In this framework vulnerability is categorized in five classes in terms of design base shear coefficient for engineered buildings. The main feature of the proposed framework is that it is independent of the region; i.e. the criteria for vulnerability classification are developed in a way that could be applied to any country. Furthermore, by tracing the evolution in seismic zonation and design provisions over time, the methodology captures the spatial and temporal variation in vulnerability concurrently. The framework is flexible and allows adjustments to account for the degree of code enforcement, construction quality and specific local vulnerability studies. Moreover, by establishing relativities in vulnerability of different countries in the region, the proposed framework facilitates validation processes in countries where historical observation are not available.

The proposed framework has been incorporated to a loss estimation model for 30 European countries. Maps showing the varying risk in these countries using artificial and actual exposures illustrated the application of the framework in the context of risk analysis for insurance industry. The simplicity and practicality of the procedure makes it possible for future modification and extension to any other region of interest.

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