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Development of comprehensive earthquake loss scenarios for a Greek and a Turkish city - structural aspects

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Abstract. The paper presents a methodology for developing earthquake damage and loss scenarios for urban areas, as well as its application to two cities located in Mediterranean countries, Grevena (in Greece) and Düzce (in Turkey), that were struck by strong earthquakes in the recent past. After compiling the building inventory in each city, fragility curves were derived using a hybrid approach previously developed by the authors, and a series of seismic scenarios were derived based on microzonation studies that were specifically conducted for each city (see companion paper by Pitilakis *et al.*). The results obtained in terms of damage estimates, required restoration times and the associated costs are presented in a GIS environment. It is deemed that both the results obtained, and the overall methodology and tools developed, contribute towards the enhancement of seismic safety in the Mediterranean area (as well as other earthquake-prone regions), while they constitute a useful pre-earthquake decision-making tool for local authorities.

Keywords: earthquake damage scenarios; vulnerability; loss assessment; fragility curves; capacity curves; hybrid methodology; restoration time.

1. Introduction

During the last 15 years or so, a growing interest is observed for seismic risk studies (Bard *et al.* 1995, Barbat *et al.* 1996, D'Ayala *et al.* 1996, Faccioli *et al.* 1999, Kappos *et al.* 2002, 2008, Erdik *et al.* 2003, Dolce *et al.* 2006, Anagnostopoulos *et al.* 2008) in a number of European cities, particularly those located in its southern part, where the earthquake activity and its consequences are significantly higher. The reason is that it is now widely accepted that seismic risk scenarios and the estimation of the economic and human losses incurred by the earthquake, notwithstanding the inherent uncertainties and practical difficulties involved, are a useful tool for seismic risk management and for prioritizing the pre-earthquake strengthening of the built environment.

The writers have been developing over the last decade a methodology for vulnerability and loss assessment of the building stock based on a 'hybrid' approach, combining statistical data from actual earthquakes with the results of inelastic analyses of representative structures (Kappos *et al.* 1998, 2006, Kappos 2007). Successive versions of this methodology have been applied to develop damage and loss scenarios for the building stock of a number of cities in Greece (Kappos *et al.*

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2002, 2008, 2009a). The most recent version of the method (described in section 3.2) was recently applied to develop such scenarios for two cities located in Mediterranean countries, Grevena in Greece and Düzce in Turkey; these cities were heavily struck by strong earthquakes in 1995 ($M_w = 6.6$) and 1999 ($M_w = 7.2$), respectively. This research was conducted within the framework of a European research project (Kappos *et al.* 2009a, b) with the co-operation of the local authorities and engineers in both cities. The seismological and geotechnical aspects of this project are presented in a companion paper (Pitilakis *et al.* 2010).

The objectives of this paper are therefore to:

(a) present a comprehensive loss assessment methodology and a set of associated computational tools that were developed for both Grevena and Düzce,
(b) discuss the specific assumptions and adaptations that had to be made in order to tailor the existing methodology to the needs of each city under study, taking due account of the local conditions and peculiarities in each of them,
(c) comparatively assess the structural and economic aspects of seismic damage in each case, an effort that, to the best of the authors' knowledge, has not been done in the past for the Mediterranean region (although a number studies for specific Mediterranean cities have been carried out), and
(d) assess the applicability of the methodology and the potential to extrapolate the observations made to other areas worldwide with similar levels of seismic exposure, building stock, and demographic characteristics.

2. Compilation of building inventories

The first, and usually most time-demanding, task required for the development of seismic loss scenarios is related to the collection of reliable data for the building stock; this is a necessary step that is required for the vulnerability and loss assessment in any given area. Different approaches were used for compiling the building inventories in each of the two cities studied, due to the differences in terms of human resources and the number, quality, and nature of the data already available.

In the case of the city of Grevena, the primary source of information was the archives of the Urban Planning Office, supplemented by data of basic building characteristics gathered during the 2001 national census and a number of additional data gathered through specifically targeted in-situ inspections of selected building blocks (Fig. 1). It is noted that the building stock of Grevena is mainly characterized by old buildings designed either to the 1959 Greek seismic code (prescribing a uniform horizontal force profile along the height of the buildings, corresponding to a seismic coefficient of 4% of its total weight), or to no code at all. The percentage of these low seismic design level reinforced concrete (R/C) buildings, as well as of the unreinforced masonry (URM, mainly brick) buildings was found to be approximately 70%. On the other hand, newly constructed R/C buildings, although fewer in number, were found to have higher impact in terms of built area since they are typically larger in plan and/or elevation.

The data gathered and processed were visualized in space using the GIS platform ArcGIS (ESRI, 2006) and the digital map provided by the National Statistics Agency of Greece (ESYE), after appropriate update in order to include the newly constructed buildings, reflect specific modifications of the existing block boundaries, and remove the buildings demolished subsequent to the last

Fig. 1 Typical unreinforced masonry (top) and R/C (bottom) buildings in Grevena

Fig. 2 Typical buildings with various structural systems in Düzce

national Census. The same GIS platform was also used for the visualization of the resulting seismic vulnerability and loss assessment scenarios, as presented in section 4.

In contrast to the case of Grevena, in the city of Düzce a rather detailed database of buildings had already been developed by the authors (Sextos *et al*. 2008). This database which was intended for both pre-earthquake and post-earthquake assessment, was also connected to a GIS map, but through a different commercial platform (MapInfo Corporation 2001), used by the local authorities at the time the project started. Due to the extensive reconstruction of the damaged buildings subsequent to the 1999 earthquake and the development of new residential areas in the city (including exclusively new R/C buildings with dual systems of walls and frames), the building profile changed rapidly during the last decade.

Given the particular situation described previously, a number of structural characteristics were either missing from the database, or had to be verified on site, hence, numerous additional in-situ inspections were performed by teams of local engineers who, with the assistance of the authors, managed to inspect a reliable and fairly representative fraction of the building stock in the 'old' city

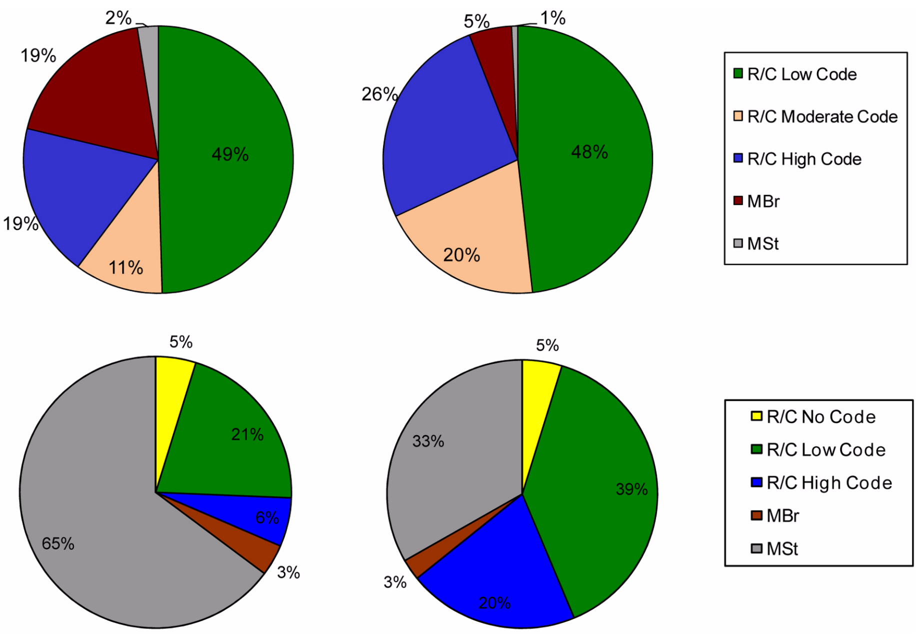

Fig. 3 Composition of the building stock in Grevena (top) and Düzce (bottom). Number of buildings (left) and built area in m^2 (right) per structural material and code design level

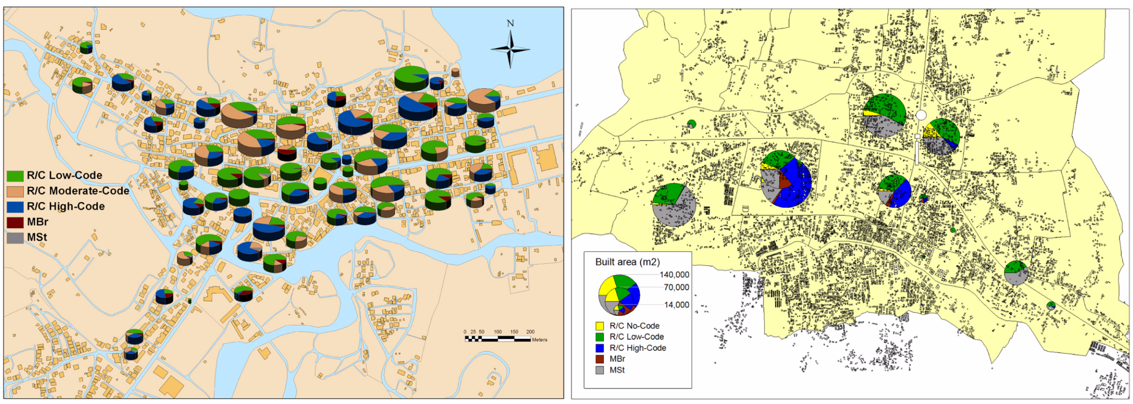

Fig. 4 Spatial distribution of the building stock of Grevena (left) and Düzce (right) in terms of built area for various combinations of construction material and seismic code used

(i.e., the city centre that was heavily hit by the 1999 earthquake). This sample consisted of 3025 buildings, which approximately correspond to 1/3 of the city centre stock (some typical buildings are shown in Fig. 2), which was the most vulnerable one. It is also notable that almost 65% of this stock consisted of stone masonry buildings in contrast to the situation observed in the city of Grevena where most of the buildings are R/C ones. Figs. 3 and 4 illustrate in a comparative way the composition of the building stock in terms of number of buildings, the built area for each construction material ('MBr' means brick masonry and 'MSt' stone masonry), and their spatial distribution on the respective GIS map.

3. Vulnerability assessment methodology

3.1 Building typologies and classification

In practical application (damage scenarios) it is not feasible to derive entirely new sets of functions for assessing the vulnerability of the buildings in a studied area. Hence, to establish a common basis for studying the two cities, the structural types adopted in each case were harmonized using an appropriate set of assumptions. More specifically, the building classification scheme proposed within the framework of the European project Risk-UE (Kappos *et al.* 2006, 2008, Lagomarsino and Giovinazzi 2006) was adopted, since it establishes a common basis for vulnerability studies in Europe, in a similar fashion that HAZUS (FEMA-NIBS 2003) classification is currently considered as a reference for North America. The structural types were broken down into a total of 72 R/C and 4 URM building typologies, according to which the R/C buildings were distinguished on the basis of the level of code design and detailing used (i.e., no code, low, moderate and high code), the height of the building (i.e., low-, medium-, or high-rise), the structural system (frame or dual) and the configuration of masonry infill walls (i.e., bare, regularly infilled and irregularly infilled). Unreinforced masonry (URM) buildings were distinguished according to their structural material (MSt for stone and MBr for brick structures), while a further distinction was made on the basis of their height (low- and medium-rise).

From the above 76 R/C and URM typologies resulting from the adopted scheme, only 30 were actually found in the building stock of Grevena, while only 12 of them constituted samples sufficient for statistical processing. It is also noted that in the Grevena building stock the 'No Code Design' class was grouped together with the 'Low Code' class, based on their observed similar seismic behaviour during past earthquakes in Greece (Penelis and Kappos 1997). Nevertheless, as noted earlier, for harmonization purposes, the same building typology matrix had to be used for both cities, therefore establishment of a reasonable correspondence between the seismic codes used in the two countries was necessary. Following detailed discussions with the local engineers in Düzce, 'Low Code Design' of R/C buildings was assumed to correspond to those designed according to the oldest seismic code in each country (Fig. 5), namely the 1959 Greek Code and the 1975 Turkish Code; both of these codes simply require design for a small amount of lateral force, without any provisions for ductility or capacity design. Similarly, 'High Code Design' was assumed for all modern R/C buildings designed according to the most recent Greek (1995 and 2000) and Turkish (1998 and 2006) seismic codes. An additional category ('Moderate Code'), including the buildings designed to the 1985 Greek seismic code was also used. Buildings in the Turkish city constructed prior to the introduction of seismic codes were assessed using fragility curves wherein

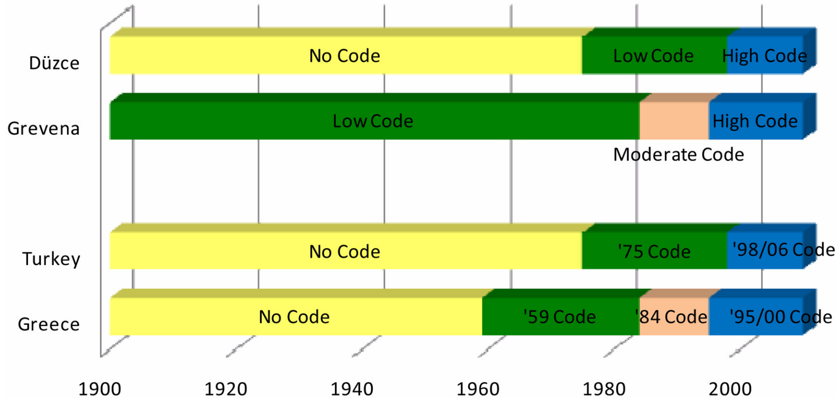

Fig. 5 Evolution of seismic code design in Greece and Turkey (bottom) and seismic code correspondence adopted for the present study (top)

median values were derived from the corresponding 'Low Code' classes, reduced using engineering judgement (see section 3.2). Furthermore, a special building typology, timber-framed masonry buildings, which were present in the city of Düzce, was also prescribed and the seismic performance of this class was explicitly studied using advanced finite element methods (Kappos and Kouris 2008).

Given the above considerations, the building stock in the city of Düzce was finally described using a total of 26 classes (among the 76 defined), 13 of which constituted adequate samples for statistical processing. The use of building classes initially intended to describe the building stock of Greece as the basis for the development of the seismic risk scenarios for Düzce is deemed to be adequate since the evolution of seismic codes (Fig. 5) as well as other construction practices were found to be sufficiently similar.

3.2 Fragility curves derived in terms of peak ground acceleration

Having established a unified building typology matrix for the two cities, building damage was assessed using a large set of fragility curves, originally developed for typical R/C and URM buildings that are common in Greece and the Southern Europe region, using the 'hybrid' approach developed by Kappos *et al*. (1998, 2006). This method combines results of inelastic analyses of typical structures for each class with actual damage statistics gathered after past earthquakes in Greece. The basic steps of the above methodology for R/C buildings, incorporating its latest enhancements (Kappos and Panagopoulos 2009), which include combination of available statistical data from multiple earthquakes and use of appropriate empirical weighting factors are presented in flow-chart form in Fig. 6. It is pointed out that two alternative procedures are shown in the chart, one leading to purely analytical fragility curves, and one to hybrid ones, wherein damage threshold values are adjusted by weighting analytically and empirically derived values as described in detail in Kappos and Panagopoulos (2009). The fragility curves resulting from the enhanced version of the hybrid procedure were used herein, for the first time in the framework of a seismic risk scenario development.

Within the framework of the hybrid procedure described in Kappos *et al*. (2006), fragility curves were derived for URM buildings. It is noted that this procedure is different from the approach

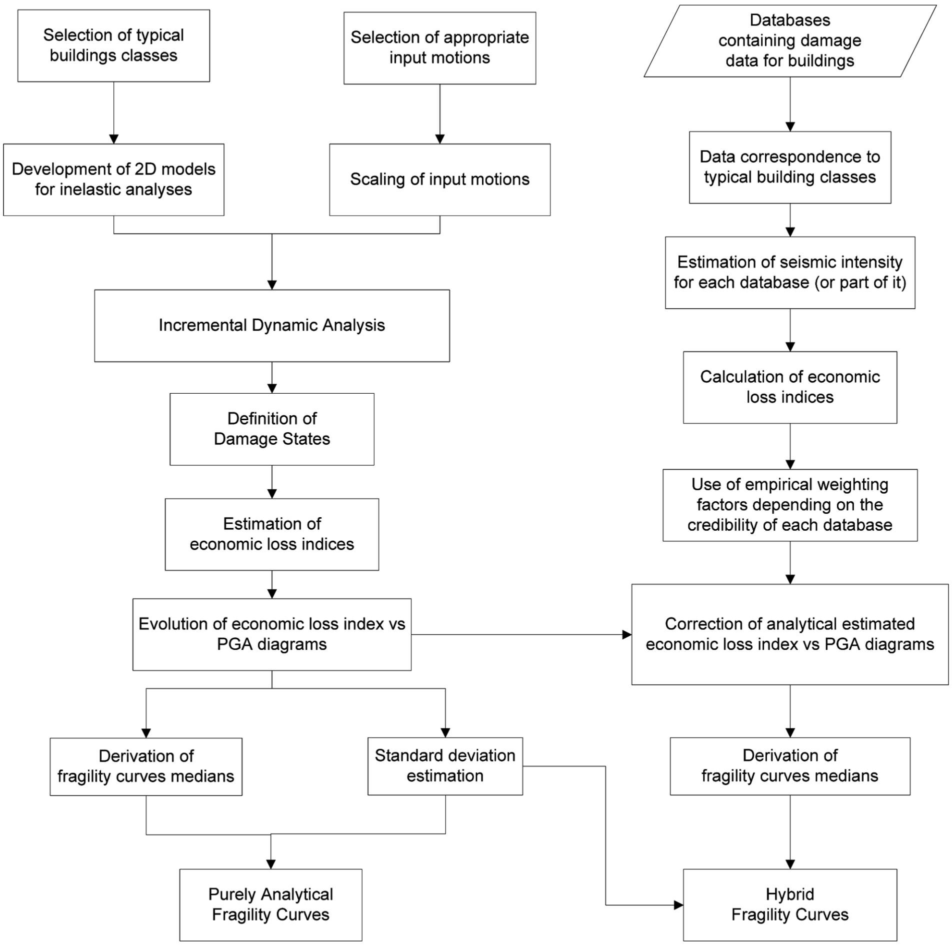

Fig. 6 Proposed methodology for the derivation of fragility curves in terms of PGA for R/C buildings

adopted for R/C buildings since it involves inelastic static, rather than inelastic dynamic response-history analyses. Furthermore, the experience from previous seismic events in Greece and elsewhere has clearly shown that URM buildings (which are usually old) are far more vulnerable than R/C ones. Using two different procedures for deriving fragility curves occasionally results in inconsistencies among the curves for URM and those for R/C buildings. In order to tackle this problem, it was decided to impose an additional constraint for the median PGA values of all URM buildings by adopting the following rule: if the median PGA value of a URM building class, for a specific damage state, was lower than the corresponding one for the most relevant R/C class, then the former value was neglected and the R/C class median value was used instead. For example if the median value of a damage state threshold for a low-rise URM building was found to be higher than the corresponding value for the 'Low-code' low-rise R/C building, the value for the R/C building was also used for the URM one. Typical fragility curves for R/C and URM buildings are presented in Fig. 7, it is worth noting that differences in the fragility of R/C and URM buildings are less than those implied from Fig. 7, in the case of frame structures.

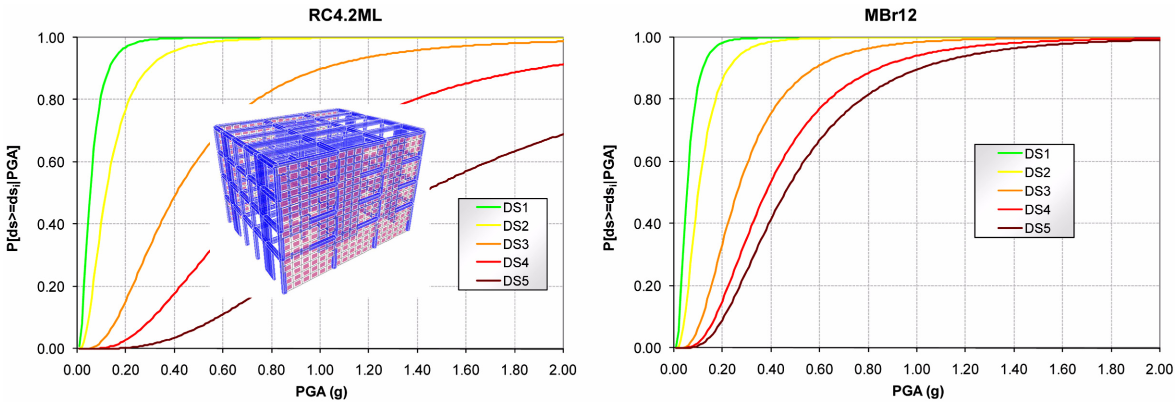

Fig. 7 Fragility curves in terms of PGA for low code, medium rise, regularly infilled R/C buildings with dual system, (left) and low rise, brick URM buildings (right)

3.3 Site-specific fragility curves utilizing spectral quantities

The starting point for the vulnerability analysis of the two cities was the set of fragility curves derived applying the above procedure (Fig. 6) and a total of 16 (8 recorded and 8 synthetic) accelerograms that were used for the response history analysis of R/C buildings (Kappos *et al.* 2006). Unlike the fragility curves of HAZUS, which are purely analytical and also independent of the ground motion characteristics since they are derived in terms of normalised displacement values (interstorey drifts), the curves derived in terms of PGA as shown in Fig. 6 are dependent on the spectral characteristics of the accelerograms used. Hence, a critical step in the present study was to make these curve area-specific, i.e., dependent on the characteristics of the representative ground motions in the cities studied (which were quite different, as described in detail in the companion paper by Pitilakis *et al.*). To this purpose, the simple procedure proposed by Kappos and Panagopoulos (2009) was implemented, wherein a further processing of the 'generic' fragility curves was carried out (see also section 4), by scaling their damage state thresholds to match the spectrum intensity of the representative pseudo-velocity spectrum in each city, as described in the following.

The mean acceleration spectrum of the aforementioned 16 records normalised to a PGA of 1.0 g, is illustrated in Fig. 8, together with the mean spectra derived from the Grevena and Düzce microzonation studies (Pitilakis *et al.* 2010) and the Greek and Turkish Code design spectra for soil types that are typical for the two cities. In this figure it is clear that the spectral accelerations predicted by the Grevena (microzonation-derived) mean spectrum are significantly lower than those corresponding to the mean spectrum that was used for the derivation of the fragility curves, for almost the entire period range (i.e., up to about 2.0 sec). This observation leads to the conclusion that the fragility curves derived using the aforementioned procedure provide a rather conservative estimate of the vulnerability of the Grevena building stock. The scaling was carried out by modifying the median values of the hybrid fragility curves using a uniform correction factor *c*, calculated from the ratio of the area enclosed under each pseudo-velocity spectrum (S_{pv}) for a period range from 0.1 to 2.0 sec as follows:

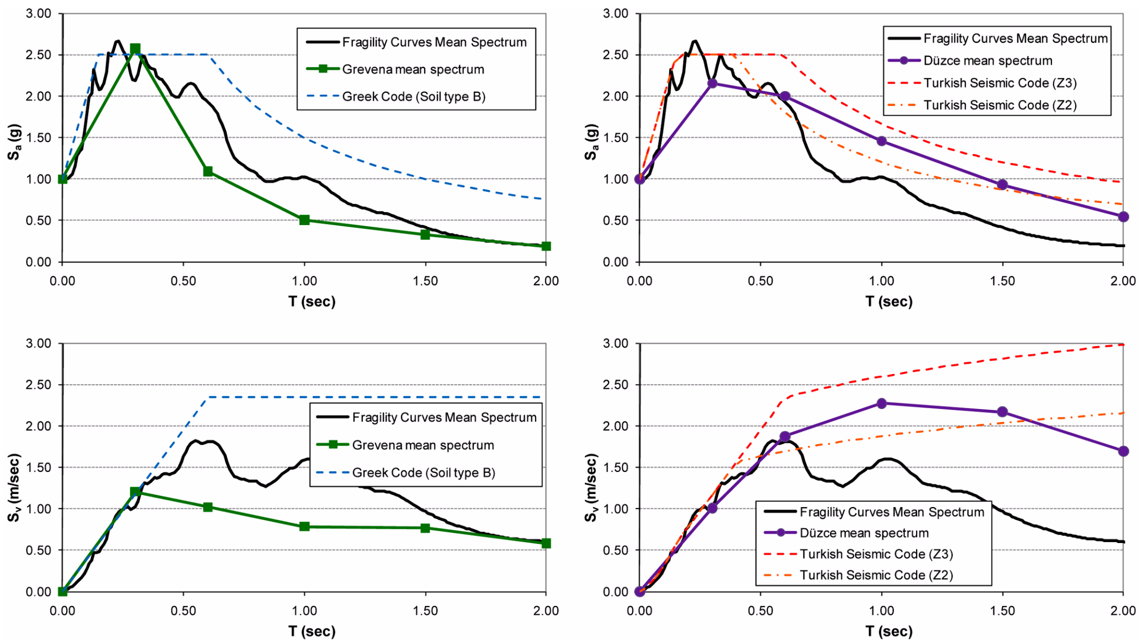

Fig. 8 Comparison of the Grevena (left) and Düzce (right) microzonation study mean spectra in terms of acceleration S_a (up) and velocity S_v (bottom) with the design spectra of the Greek and Turkish seismic codes and the mean spectrum of the records used for the derivation of fragility curves

$$c = E_{hfc} / E_{micr} \tag{1}$$

where E_{hfc} and E_{micr} denote the area under the mean pseudo-velocity spectrum of the records used for the derivation of the hybrid fragility curves and the microzonation study respectively (herein referring to the Grevena case). Using Eq. (1), a value of c equal to 1.38 was calculated and was then used for the correction of all damage state medians in the R/C fragility curves, regardless of the building class they referred to. This approach is quite general but very convenient for deriving site-specific analytical fragility curves for a building stock in a specific area (regardless of whether the appropriate 'target' spectrum is defined from a microzonation study or a seismic code). Alternatively, a more refined (and more complex) approach can be used involving structural type-dependent c factors which can be estimated within a period range close to the fundamental period T_0 of each typical building class. Using the constraint described in section 3.2, the site-specific spectral correction was implicitly applied to all the fragility curves derived for URM buildings.

Unlike the Grevena case, the mean spectrum of the microzonation study of Düzce (Fig. 8) lies very closely to the mean spectrum of the records used for the derivation of R/C buildings fragility curves, at least for the period range 0.1 to 0.7 sec, which is essentially the period range for practically the entire (low-rise) building stock of the old city. As a result, the value of the correction factor c defined in Eq. (1) was taken equal to unity.

3.4 Fragility curves derived in terms of spectral displacement S_d

As an alternative to the previous approach adopted for the generation of fragility curves, a second procedure was also adopted, involving the use of spectral displacement S_d as a measure of earthquake intensity. Capacity curves for all building typologies were derived using inelastic static (pushover) analyses of appropriate finite element models (Kappos *et al*. 2006). Two sets of fragility curves were then derived (Fig. 9, where DS0 means no damage, DS1 slight damage, DS2 moderate, DS3 substantial to heavy, DS4 very heavy damage, and DS5 collapse):

(a) one set derived through the transformation of the median values of the corresponding PGA-based fragility curves into S_d values, using the Capacity Demand-Diagram method and the mean spectrum of each microzonation study (i.e., leading to site-specific fragility curves) and,

(b) one directly from the capacity curves, after defining damage state thresholds based on appropriate fractions of the yield and ultimate points, as summarised in Table 1.

It should be noted herein that infilled R/C buildings should be treated with caution since all reduced spectra (either inelastic, or elastic derived for effective damping ratios higher than 5%) are computed based on bilinear skeleton curves. The idealised pushover curves for these buildings are usually closer to a quatrilinear, rather than a bilinear, approach, since the infill walls are typically the elements that fail first (with a corresponding drop in strength) but the structure is capable to undergo significantly larger displacements, approximating the behaviour of the corresponding 'bare'

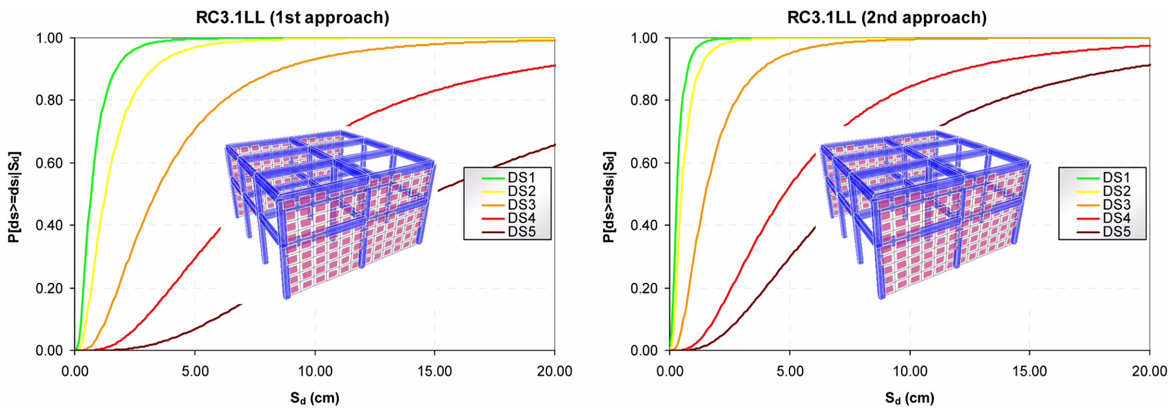

Fig. 9 Fragility curves in terms of spectral displacement S_d for low code, low rise, regularly infilled R/C buildings with frame system using the two alternative approaches

Table 1 Thresholds of spectral displacement for defining damage states.

Damage state	Description of damage	S_d threshold		
		URM	R/C (bare)	R/C (infilled)
0	None	-		
1	Slight	$0.7 \cdot S_{dy}$		
2	Moderate	$0.7 \cdot S_{dy} + 0.05 \cdot \Delta S_d$		
3	Substantial to heavy	$0.7 \cdot S_{dy} + 0.2 \cdot \Delta S_d$	$0.7 \cdot S_{dy} + 0.3 \cdot \Delta S_d$	
4	Very heavy	$0.7 \cdot S_{dy} + 0.5 \cdot \Delta S_d$		S_{du}
5	Collapse	S_{du}	S_{du}	$S_{du,bare}$

*$\Delta S_d = 0.9 \cdot S_{du} - 0.7 \cdot S_{dy}$

typologies. However, it was deemed not feasible, at least at this stage, to introduce multi-linear pushover or capacity curves (i.e., including residual strength branches). Therefore, in order to tackle the above problem, the curves of the corresponding 'bare' typologies were used for displacements greater than the S_{du} value for the infilled ones, as discussed in Kappos and Panagopoulos (2009). Furthermore, note that for infilled typologies the threshold of spectral displacement for DS4 is taken equal to S_{du} while for the threshold of DS5 the value from the corresponding bare typology $S_{du,bare}$ is utilized, as shown in Table 1.

4. Earthquake loss scenarios

4.1 Overview of the developed loss scenarios for the two cities

The overall procedure for the development of loss scenarios is shown in flow-chart form in Fig. 10. The probabilistic approach adopted for the loss estimation of the building stock makes mandatory the use of a group of buildings, rather than individual buildings, as the unit for the development of each scenario. In the Grevena case, it was decided to use the building block as the

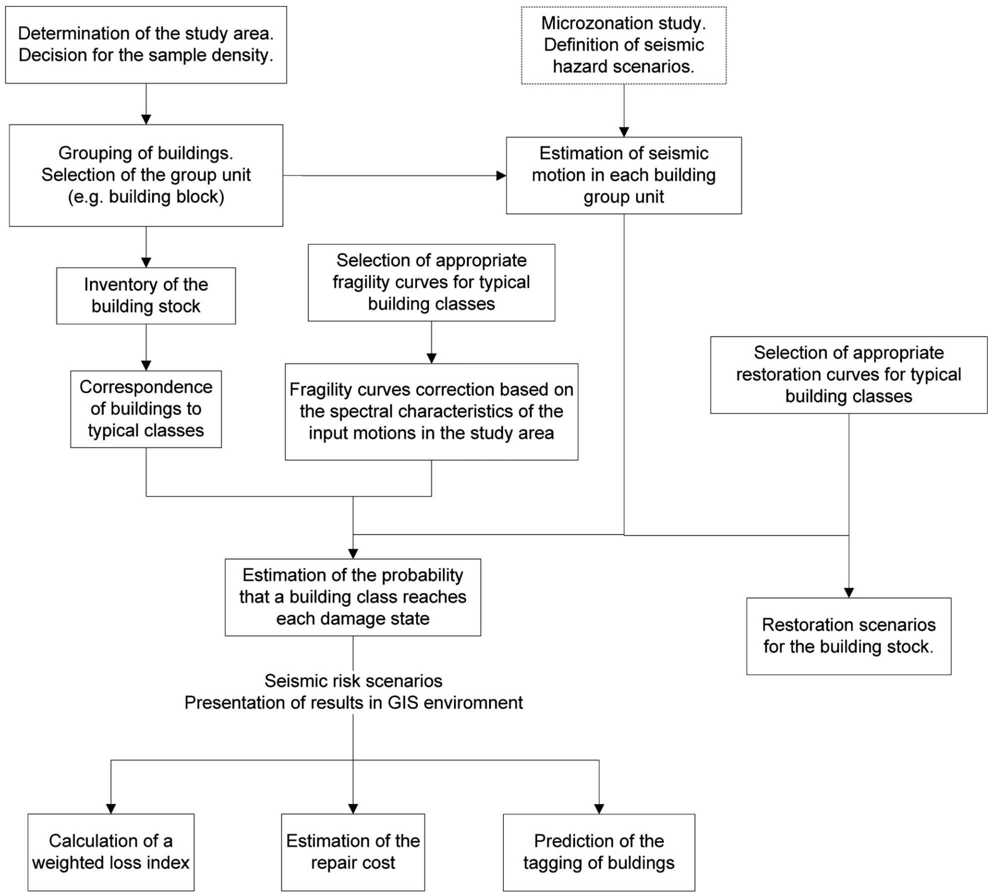

Fig. 10 Procedure for the development of seismic risk scenarios

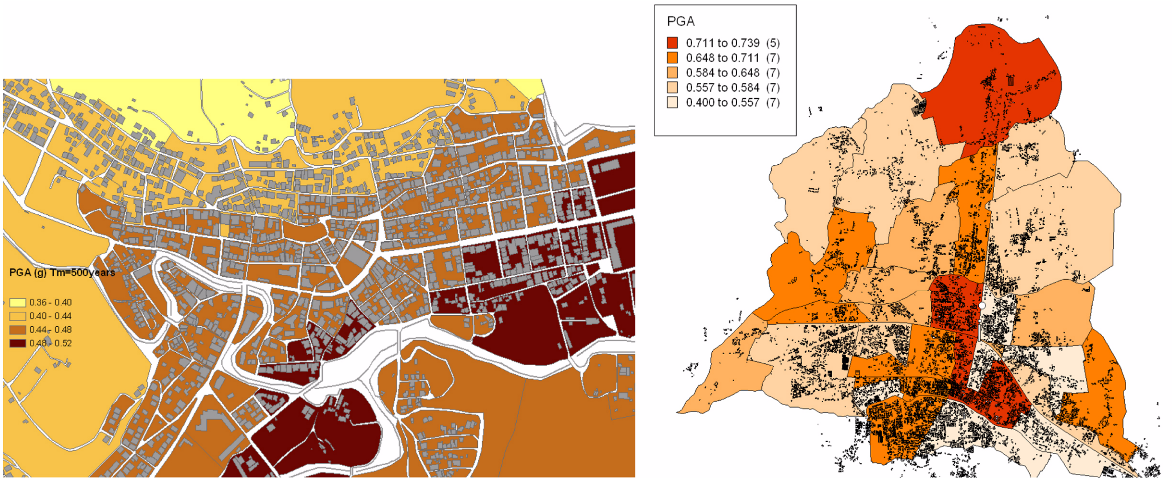

Fig. 11 Spatial distribution of input motion in Grevena (left) and Düzce (right) for the 500 year scenario ('design earthquake')

reference unit; however, such information was not available in the city of Düzce. As a result, it was decided to use a greater, and more commonly used in Turkey entity called "mahalle", that is "small neighbourhood" in Turkish. As such, the results presented herein, especially in the form of GIS maps, should be interpreted accordingly.

Regarding the level of seismic action, three basic seismic hazard scenarios were developed for the Grevena case, each one corresponding to earthquake events with return periods of 100, 500 and 1000 years, respectively (Pitilakis *et al.* 2010). Similarly, the basic seismic hazard scenario developed for the city of Düzce, was based on the probabilistic approach and was found to be in good correlation with available records from the 1999 major earthquake. Additional scenarios were also developed for both cities, using uniform PGA values for the entire city areas studied, taken equal to the design PGA specified in the corresponding national seismic codes (i.e., 0.16 g for Grevena and 0.40 g for Düzce). Based on the above, both PGA and spectral quantity values were assigned to each building block (in Grevena) or "mahalle" (in Düzce) using appropriate geostatistical interpolation techniques, the result of which is illustrated in Fig. 11. As anticipated, the difference in terms of seismic hazard between the two cities is substantial.

Furthermore, alternative sets of earthquake loss scenarios were developed for both cities using the aforementioned approaches involving the PGA-based and the S_d-based fragility curves. As a rule, only the results obtained using the first approach are presented herein, since they directly incorporate the hybrid approach and are in line with previous studies (Kappos *et al.* 2002, 2006). More results, also including those from the second approach, can be found in Kappos *et al.* (2009a, b).

4.2 Loss estimation

Introducing a weighted loss index, defined as

$$MDF_w = \sum (MDF_i \cdot E_i)/E_{tot} \quad (2)$$

where the built area E_i of each building class i in a building block (or "mahalle" in the case of

Düzce) is used to weigh the Mean Damage Factor (MDF) for this class, numerous maps were produced, providing a good insight into the most vulnerable parts of each city (Fig. 12). Considering an average replacement cost of €800/m^2 and €500/m^2 for Grevena and Düzce, respectively, assumed as an average value for all building typologies, and by multiplying by the weighted loss index (Eq. (2)), the weighted cost per built area was then derived for each building block and seismic scenario. Fig. 13 illustrates such a cost for the 500 years scenario.

It has to be noted that for the city of Grevena, the average damage expected in each block was found to be moderate for an appreciable part of the city, even for the lower level (100 year) earthquake scenario. For the 500 year scenario (corresponding to the "design earthquake'), moderate damage is also expected to almost the entire city. Nevertheless, for the case of the 1000 year scenario there are only a few building blocks where severe damage is predicted, a fact that is attributed to both the moderate seismic exposure and the percentage of R/C buildings in the overall stock. On the contrary, for the old part of the city of Düzce, significantly more severe damage is anticipated, again as a result of both the higher earthquake level and the composition of the building

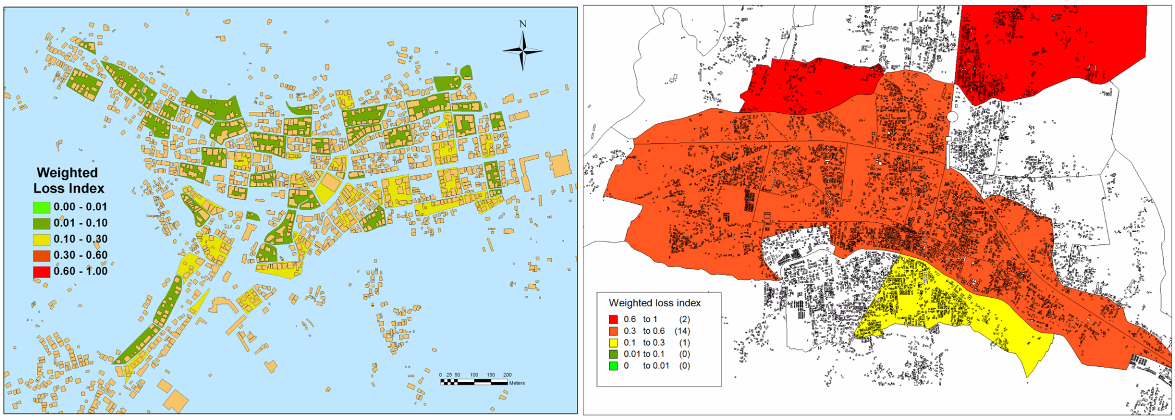

Fig. 12 Weighted loss index for the 100-year scenario in Grevena (left) and the microzonation study scenario in Düzce (right).

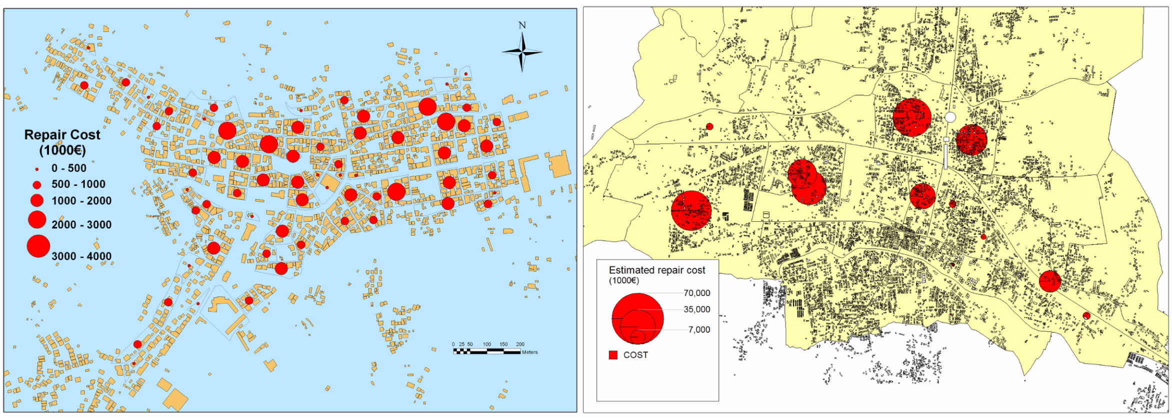

Fig. 13 Spatial distribution of repair cost for the 500-year scenario in Grevena (left) and the microzonation study scenario in Düzce (right)

stock, since the majority of buildings in the area examined are stone masonry or R/C structures designed to old seismic codes. The above observations are also reflected on the maps illustrating the predicted tagging of buildings, adopting the familiar Green-Yellow-Red tag approach, as presented in Fig. 14.

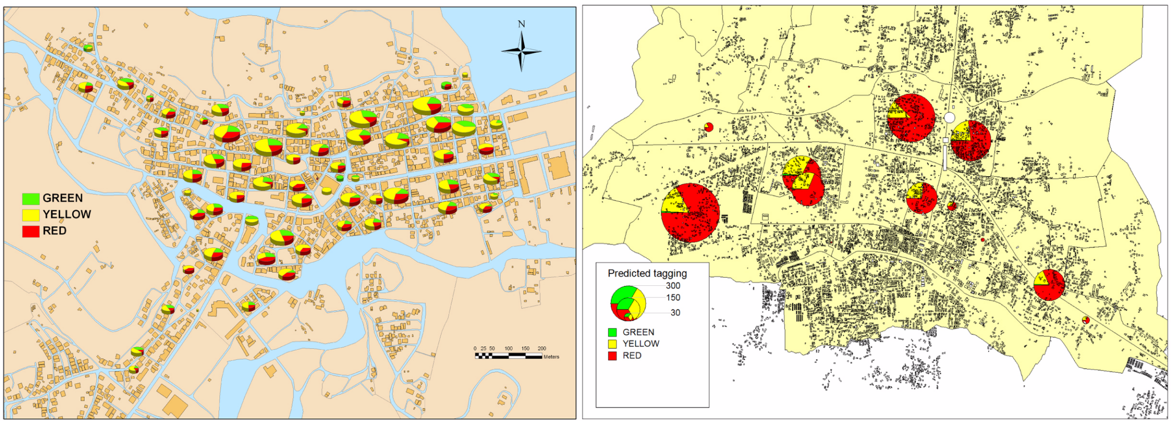

Fig. 14 Predicted tagging of buildings for the 500-year scenario in Grevena (left) and the microzonation study scenario in Düzce (right)

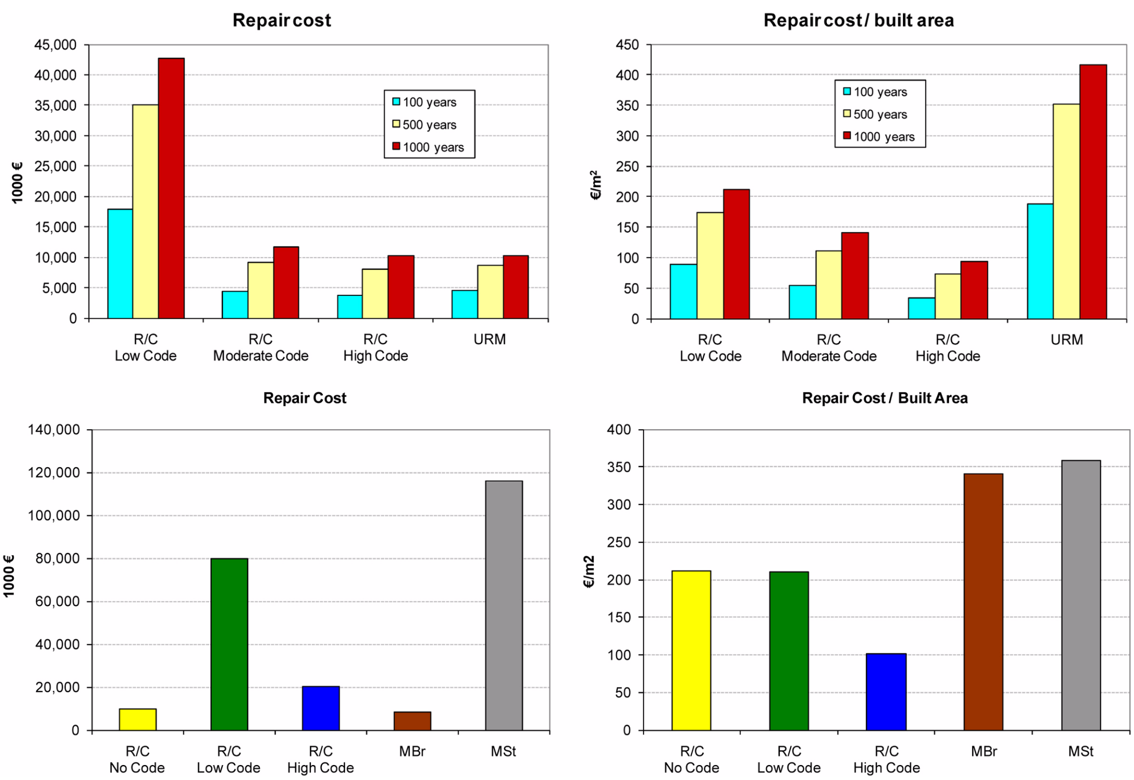

Fig. 15 Predicted repair cost for all PGA-based scenarios per structural material and code design for Grevena (top) and Düzce (bottom)

Table 2. Predicted repair cost for all Grevena scenarios (million €)

Seismic scenario	*PGA*-based fragility curves	S_d-based fragility curves 1st approach	S_d-based fragility curves 2nd approach
100 years	61.4	69.0	83.4
500 years	121.5	116.8	160.3
1000 years	149.4	142.4	197.7
Greek Code (PGA = 0.16 g)	104.2	-	-

Like the predicted tagging results, it is very interesting to see the difference in seismic behaviour, in terms of repair cost this time, due to the code design level and the structural material used (R/C or URM). Along these lines, Fig. 15 presents the estimated repair cost for the studied area, depending on the material and the level of seismic design in absolute monetary terms (left) or divided by the corresponding built area (right) for the three Grevena and the Düzce microzonation-based scenarios, using the PGA-based fragility curves. Note that the significant absolute cost that resulted for the R/C buildings designed to the old codes in the city of Grevena is attributed to the fact that this is the dominant building type in terms of built area. When the (normalised) repair cost is derived after dividing by the corresponding built area (Fig. 15, right), URM buildings appear to be related to much higher restoration cost. It is also noted that in the case of R/C buildings, their repair cost is reduced with the evolution of seismic codes, as expected.

The predicted repair cost for all Grevena scenarios is presented in Table 2. Despite the differences that existed for several buildings typologies, the *PGA*-based scenarios produced similar results with the first approach of the S_d-based scenarios, as anticipated since the S_d medians of the fragility curves were derived from the corresponding *PGA* medians. The second approach of the S_d-based scenarios resulted in more conservative estimates, especially for URM and Low-code R/C buildings since the high S_d demand values estimated by the seismic hazard scenarios were often greater than the corresponding available values (S_{du}) for these typologies. Likewise, a heavy cost of about 700-750 M€ is predicted for the old city of Düzce using the microzonation study input motions, again an indication of the severity of the estimated scenario earthquake. This cost is reduced to about 520M€ if a uniform PGA value of 0.40 g (according to the current Turkish code) is applied to the whole area.

4.3 Required restoration time

As the final stage of this study, several sets of restoration scenarios were developed, estimating the time required for the partial or the complete restoration of buildings that suffered a particular level of structural damage. Appropriate restoration curves were therefore developed using a combination of statistical data and expert judgement (Kappos *et al.* 2009). It is important to note that restoration time is computed under the assumption that a single technical unit will take over all restoration operations in a building, a situation that is not always realistic during the post-earthquake crisis period where the number of simultaneously operating teams is unknown and certainly depends on local conditions.

Given the above uncertainty, two alternative approaches were explored: (a) a "best-case" approach according to which a different technical unit will be made available for each damaged building and

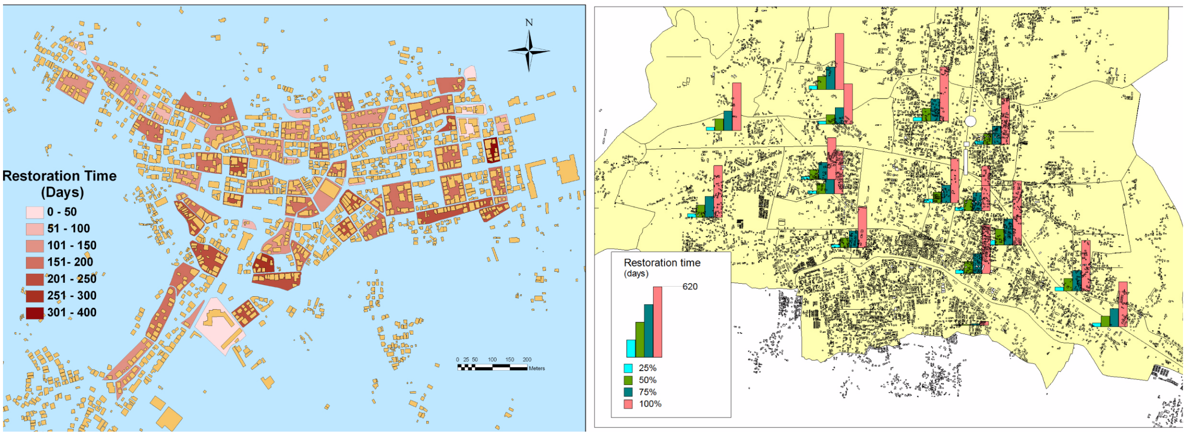

Fig. 16 Estimates of the required time for 100% restoration level for the 500-year scenario in Grevena (left) and the microzonation study scenario in Düzce (right)

the time needed in order to restore a building block will be approximately equal to the mean restoration time for the buildings contained in the block and (b) a "worst-case" approach wherein a single technical unit will be responsible for the restoration of an entire block; this was implemented only in the case of Grevena (where the unit used was the building block), since in the case that the unit is the mahalle it is not a realistic assumption. The authors believe that reality generally lies in-between these two extreme assumptions, and in all cases one should also take into account the size of the building stock used for the damage scenario. The results for the first approach and the two cities are depicted in Fig. 16 where it can be seen that the estimated required time for 100% restoration is close to one year for Grevena and about two years for Düzce. Note that this difference reflects the higher earthquake demand in Düzce, as well as the generally higher vulnerability of its building stock; however, it does not reflect potentially different conditions relating to the availability and/or experience of technical personnel working in the repairs, since the same assumptions were made for both cities regarding this factor.

6. Conclusions

In this paper, comprehensive seismic risk studies for the building stock in the city of Grevena in Greece and the city of Düzce in Turkey were presented. Fragility curves derived using the hybrid approach developed at AUTh were utilized for developing a series of earthquake scenarios based on the microzonation study of the two areas under study. Results were presented in a GIS environment, and include loss estimates as well as required restoration times for each scenario. To the authors' best knowledge, this is the first time that the same methodology was applied to a Turkish and a Greek city and results were assessed in a comparative way. As far as the methodology is concerned the most important in practical terms aspect was that the fragility curves used in each city were adjusted to the representative response spectra in each area, while the starting point was the same for both cities. Moreover, it was clear that, depending on locally available information and human resources, different types of loss scenario are feasible in each city (for instance, a larger unit for the building stock had to be used in the case of Düzce).

On the basis of the obtained distributions of damage and the associated repair cost presented in the paper, it is concluded that the performance of the building stock in Grevena seems to be superior due to both the lower level of the seismic action (corresponding to a given return period), as well as the relatively lower vulnerability of the buildings. This behaviour was also confirmed during the major earthquakes that struck the two cities in recent years. It is worth noting in this respect that the fact that the Turkish city is assigned to the highest seismicity zone (hence buildings are designed for a high design PGA of 0.4 g) according to the current Seismic Code, whereas the Greek city is assigned to the lowest one (design PGA = 0.16 g), is not really reflected in the vulnerability of the buildings in each case, since (in the area of Düzce studied) the building stock included a large fraction of pre-code construction.

Finally, it is deemed that the results obtained, but also the methodology and tools developed, can contribute towards the enhancement of seismic safety in the Mediterranean area, while they are also useful for other earthquake-prone areas in the world.

References

Anagnostopoulos, S., Providakis, C., Salvaneschi, P., Athanasopoulos, G. and Bonacina, G. (2008), "SEISMOCARE: An efficient GIS tool for scenario-type investigations of seismic risk of existing cities", *Soil Dyn. Earthq. Eng*., **28**(1), 73-84.

Barbat, A.H., Moya, F.Y. and Canas, J.A. (1996), "Damage scenarios simulation for seismic risk assessment in urban zones", *Earthq. Spectra*, **12**(3), 371-394.

Bard, P.Y., Bour, M., Duval, A.M., Godefroy, P., Martin, Ch., Meneroud, J.P., Mouroux, P., Terrier, M., Thibault, Ch., Velkov, P. and Vidal, S. (1995), "Seismic zonation methodology for the city of Nice", Progress report, *Proceedings 5th Intern. Conf. on Seismic Zonation*, Nice, France, 1749-1784.

D'Ayala, D.F., Spence, R.J.S., Oliveira, C.S. and Silva, P. (1996), "Vulnerability of buildings in historic town centres: a limit-state approach", *11th World Conference on Earthquake Engineering*, Acapulco, Mexico, Paper No. 864 [CD ROM Proceedings], Pergamon.

Dolce, M., Kappos, A., Masi, A., Penelis, Gr. and Vona, M. (2006), "Vulnerability assessment and earthquake damage scenarios of the building stock of Potenza (Southern Italy) using Italian and Greek methodologies", *Eng. Struct*., **28**(3), 357-371.

Erdik, M., Aydinoglu, N., Fahjan, Y., Sesetyan, K., Demircioglu, M., Siyahi, B., Durukal, E., Ozbey, C., Biro, Y., Akman, H. and Yuzugullu, O. (2003), "Earthquake risk assessment for Istanbul metropolitan area", *Earthq. Eng. Eng. Vib*., **2**(1), 1-23.

ESRI (2006), ARCGIS 9.2, 380 New York Street, Redlands, CA 92373-8100, USA.

Faccioli, E., Pessina, V., Calvi, G.M. and Borzi, B. (1999), "A study on damage scenarios for residential buildings in Catania city", *J. Seismology*, **3**(3), 327-343.

Federal Emergency Management Agency (FEMA) and National Institute of Building Sciences (NIBS) (2003), *Multi-hazard loss estimation methodology - earthquake model: HAZUS® MH technical manual*, Washington D.C.

Kappos, A.J., Stylianidis, K.C. and Pitilakis, K.D. (1998), "Development of seismic risk scenarios based on a hybrid method of vulnerability assessment", *Natural Hazards*, **17**(2), 177-192.

Kappos, A., Pitilakis, K., Morfidis, K. and Hatzinikolaou, N. (2002), "Vulnerability and risk study of Volos (Greece) metropolitan area", *12th European Conference on Earthquake Engineering*, London, UK, CD ROM Proceedings (Balkema), Paper 074.

Kappos, A.J., Panagopoulos, G., Panagiotopoulos, C. and Penelis, Gr. (2006), "A hybrid method for the vulnerability assessment of R/C and URM buildings", *Bull. Earthq. Eng*., **4**(4), 391-413.

Kappos, A.J. (2007), "Seismic vulnerability and risk assessment of urban habitat in Southern European cities, Keynote lecture", *Urban Habitat Constructions under Catastrophic Events Workshop (COST C26)*, Prague.

Kappos, A.J. and Kouris, L.A. (2008), "Modelling of traditional timber-framed masonry structures", *3rd National Conference of Earthquake Engineering*, Athens, Paper no. 2013. (in Greek)

Kappos, A.J., Panagopoulos, G. and Penelis, Gr.G. (2008), "Development of a seismic damage and loss scenario for contemporary and historical buildings in Thessaloniki, Greece", *Soil Dyn. Earthq. Eng.*, **28**(10-11), 836-850.

Kappos, A.J., Stylianidis, K.C., Sextos, A., Papanikolaou, V., Panagopoulos, G., Kouris, L., Goutzika, E. and Panagiotopoulos, Ch. (2009a), *SRM-DGC. Development and Proposition for Implementation of an Efficient Methodology and Appropriate Local Instruments for the Management, Prevention and Reduction of Seismic Risk in Düzce-Turkey, Grevena-Greece and Catania-Italy. D14: Vulnerability Analysis and Loss Estimation in Grevena*, AUTh, Greece.

Kappos, A.J., Stylianidis, K.C., Sextos, A., Papanikolaou, V., Panagopoulos, G., Kouris, L., Goutzika, E. and Panagiotopoulos, Ch. (2009b), *SRM-DGC. Development and Proposition for Implementation of an Efficient Methodology and Appropriate Local Instruments for the Management, Prevention and Reduction of Seismic Risk in Düzce-Turkey, Grevena-Greece and Catania-Italy. D16: Vulnerability Analysis and Loss Estimation in Düzce,* AUTh, Greece.

Kappos, A.J. and Panagopoulos, G. (2009), "Fragility curves for reinforced concrete buildings in Greece", *Struct. Infrastruct. Eng.*, **6**(1), 39-53.

Lagomarsino, S. and Giovinazzi, S. (2006), "Macroseismic and mechanical models for the vulnerability and damage assessment of current buildings", *Bull. Earthq. Eng.*, **4**(4), 415-443.

MapInfo Corporation (2001), MapInfo Professional User Guide v6.5, New York, USA.

Penelis, G.G. and Kappos, A.J. (1997), *Earthquake-resistant concrete structures*, E. and F. N. Spon, Chapman & Hall, London.

Pitilakis, K. et al. (2010), "Development of comprehensive earthquake loss scenarios for a Greek and a Turkish city - Seismic hazard, Geotechnical, and Lifeline Aspects", *Earthq. Struct. (submitted for publication)*

Sextos, A.G., Kappos, A.J. and Stylianidis, K.C. (2008), "Computer-aided pre- and post-earthquake assessment of buildings involving database compilation, GIS visualization, and mobile data transmission", *Comput. Aid. Civil Infrastruct. Eng.*, **23**, 59-73.

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