Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 1554

DEVELOPMENT OF EARTHQUAKE LOSS SCENARIOS FOR TWO MEDITERRANEAN CITIES

A. J. Kappos[1], G. K. Panagopoulos[2], A. G. Sextos[3], V. K. Papanikolaou[4],
K. C. Stylianidis[5], L. A. Kouris[6], C. G. Panagiotopoulos[7], E. D. Goutzika[8]

ABSTRACT

The paper presents the methodology and software for developing seismic scenarios in two Mediterranean cities, Grevena (Greece) and Düzce (Turkey) that were heavily hit by strong earthquakes during the last decade. After compiling the building inventory in each city, fragility curves were derived using the hybrid approach developed the authors, and a series of seismic scenarios were developed based on city-specific microzonation studies. Both the methodology and the results obtained in terms of loss estimates, required restoration times and the associated costs are presented in a GIS environment. The results obtained, but, more so, the methodology and tools developed, contribute towards the enhancement of seismic safety in the Mediterranean area, while they are also useful for other earthquake-prone areas.

Introduction

During the last decade, a growing interest is observed for seismic risk studies in a number of European cities, particularly those located in its southern part, where the earthquake activity and its consequences are significantly higher (Bard et al. 1995, Barbat et al. 1996, D'Ayala et al. 1996, Faccioli et al. 1999, Kappos et al. 2002, Erdik et al. 2003, Dolce et al. 2006). 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 setting priorities regarding the pre-earthquake strengthening of the built environment.

Within this context, a research effort was recently made to develop such scenarios for two

---

[1] Professor, Dept. of Civil Engineering, Aristotle University of Thessaloniki, 54124, Greece
[2] PhD Candidate, Dept. of Civil Engineering, Aristotle University of Thessaloniki, 54124, Greece
[3] Assistant Professor, Dept. of Civil Engineering, Aristotle University of Thessaloniki, 54124, Greece
[4] Postdoctoral Researcher, Dept. of Civil Engineering, Aristotle University of Thessaloniki, 54124, Greece
[5] Professor, Dept. of Civil Engineering, Aristotle University of Thessaloniki, 54124, Greece
[6] PhD Candidate, Dept. of Civil Engineering, Aristotle University of Thessaloniki, 54124, Greece
[7] Postdoctoral Researcher, Dept. of Civil Engineering, Aristotle University of Thessaloniki, 54124, Greece
[8] Graduate Student, Dept. of Civil Engineering, Aristotle University of Thessaloniki, 54124, Greece

Mediterranean cities, Grevena in Greece and Düzce in Turkey, within the framework of a European research project entitled 'SRM-DGC' (INTERREG III-ARCHIMED programme). The Grevena and Düzce projects were carried out by the Laboratories of Reinforced Concrete and Masonry Structures, and of Geotechnical and Foundation Engineering of the Aristotle University Thessaloniki (AUTh), with the co-operation of the local authorities and engineers. A comprehensive risk assessment methodology and a set of subsequent computational tools were developed, tailored to the needs of each case-study, and finally applied (Kappos et al., 2009a, b). A summary of this work focusing on the structural and economic aspects of both the methodology and the derived results is presented in the following.

Inventories of the building stock

The first and usually the most time-demanding step required for the development of seismic risk scenarios is related to the collection of reliable data for the building stock, which is required for the vulnerability and loss assessment. Different approaches for compiling the building inventories were used in each of the two cities studied, due to the different conditions in terms of human resources and data already available locally. In the case of the city of Grevena, the primary source of information was the archives of the Urban Planning Office, supplemented by data on basic building characteristics gathered during the 2001 national census and a number of additional data gathered through targeted in-situ inspections of building blocks. It is noted that the building stock of Grevena is mainly characterized by old buildings designed either to the 1959 seismic code or with no code at all; the percentage of low seismic design level reinforced concrete (R/C) and unreinforced masonry (URM, mainly brick) buildings was found to be about 70%. On the other hand, newly constructed R/C buildings, although fewer in number, were found to be more important in terms of built area since they are typically larger in plan and/or elevation (Fig. 1). 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). The map had to be updated in order to include the newly constructed buildings, to reflect specific modifications of the existing block boundaries, and remove recently demolished buildings. The same GIS platform was also used for the visualization of the resulting seismic vulnerability and loss assessment scenarios.

In Düzce, a first database of buildings had already been developed by the authors during a previous European project (Sextos et al., 2008); however, the GIS map was available on another platform (i.e. MapInfo Corporation, 2001), in order to meet the local authorities requirements. Most importantly, a number of structural characteristics were either missing or had to be verified, hence, additional in-situ inspections were performed by teams of local engineers who, with the assistance of the authors, managed to record a fairly representative fraction of the building stock in the 'old' city (i.e. the part built before the 1999 earthquake), consisting of 3025 buildings, which is approximately 1/3 of this part of the city which is the most vulnerable one. It was also found that almost 65% of the stock examined consists of stone masonry buildings in contrast to the situation observed in the city of Grevena (Fig. 1).

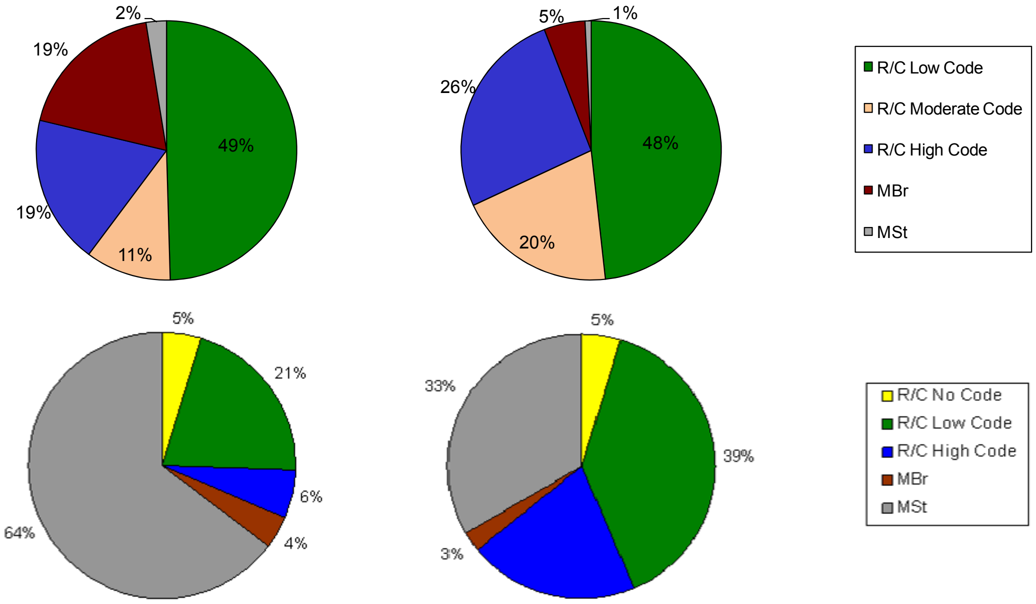

Figure 1. Composition of the building stock in Grevena (top) and Düzce (bottom). Number of buildings (left) and built area (m^2, right) per structural material and code design level.

Building typologies and classification

To establish a common basis for studying the two cities, the structural types adopted in each case were homogenized using an appropriate set of assumptions. In particular, the building classification proposed within the framework of the European project Risk-UE (Kappos et al., 2006, 2008) 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 in North America. The structural types were broken down into a total of 54 R/C and 4 URM general building typologies, according to which the R/C buildings were distinguished on the basis of the level of code design and detailing used, the height of the building (Low, Medium and High-Rise), the structural system (Frame or Dual) and the configuration of masonry infill walls (i.e. bare, regularly infilled and irregularly infilled). For the case of URM buildings, stone and brick masonry structures were considered with a further distinction concerning their height (Low and Medium-Rise). From the above 58 R/C and URM typologies, 30 were indeed detected in the building stock of Grevena, although it is only 12 of them that constitute a sample sufficient for statistical processing. Nevertheless, as already mentioned, for harmonization purposes, the same building classes were considered as representative of the building stock in typical Turkish cities as well, after appropriate adaptations. In particular, 'Low Code Design' of the R/C buildings was assumed to correspond to those designed according to the 1959 Greek or the 1975 Turkish Code, respectively, for the two cities. Similarly, 'High Code Design' was corresponded to modern R/C buildings designed according to current (2000) Greek and Turkish (1998) Seismic codes. It is noted that the 'No Code Design' classes were taken identical to the 'Low Code' class based on the observation that their seismic behaviour was found to be very similar (Penelis and Kappos, 1997). Moreover, a special building typology of timber-framed masonry buildings, typically present in the city of Düzce was also prescribed, the seismic performance of which was explicitly studied using advanced finite element methods by Kappos and Kouris (2008).Given the above correlation, the building stock in the city of Düzce was described using a total of 26 classes, 13 of which constituted adequate statistical samples.

Vulnerability assessment methodology

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. (1997, 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 capacity curves and the vulnerability (fragility) curves required in terms of peak ground acceleration and spectral displacement were then derived for all building typologies. The latest enhancements of the above methodology (Kappos and Panagopoulos, 2010), combining available statistical data from multiple earthquakes and appropriate empirical weighting factors were also implemented herein, for the first time in seismic risk scenario development.

Fragility curves derived in terms of peak ground acceleration

The 16 base accelerograms required for the time-history analyses, which for simplicity, were scaled to account for each seismic intensity level, correspond to 8 recorded and 8 synthetic input motions as described in Kappos & Papagopoulos (2009). The mean spectrum of the 16 records normalized to a level of PGA=1.0g, is illustrated in Fig. 2 together with the mean spectra of Grevena and Düzce microzonation studies, as well as the Greek and Turkish Code design spectra for soil types appropriate for the two cities. In this figure it is clear that the acceleration values 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 2.0sec). 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. To overcome this problem, it was decided to modify the median values of the hybrid fragility curves using a uniform correction factor *c* calculated from the ratio of the area under each pseudo-velocity spectrum (S_{pv}) for a period range from 0.1 to 2.0 sec as follows:

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

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 is calculated and is then used for the correction of all damage state medians in the R/C fragility curves, regardless of the building class they refer to. This convenient approach is quite general and can be used for deriving site-specific analytical fragility curves for the building stock in a specific area (for which the appropriate spectrum is defined, from a microzonation study or even from a seismic code). Alternatively, a more refined (and more complex) approach involving structural type-dependent *c* factors, estimated within a period range close to the fundamental period T_0 of each typical building, can be used.

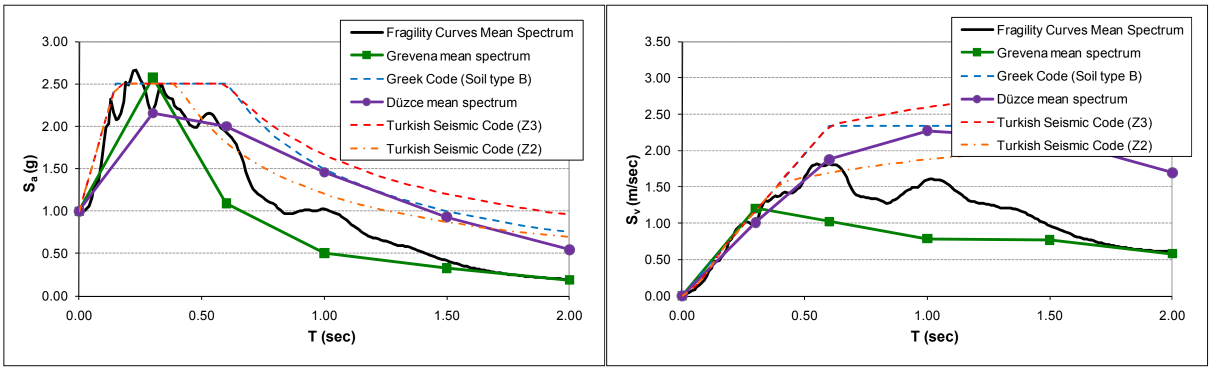

Figure 2. Comparison of the Grevena and Düzce microzonation study mean spectra (S_a and S_v) with the design spectra of the Greek and Turkish seismic codes and the mean spectrum of the records used for the derivation of fragility curves.

Unlike the Grevena case, the mean spectrum of the microzonation study of Düzce (Fig. 2) seems to lie very close to the mean spectrum of the records used for the derivation of R/C buildings fragility curves, for the period range 0.1 to 0.7sec, which is essentially the period range for practically the entire (low-rise) building stock of the city, as described previously. As a result, the value of the correction factor *c* defined in eq. 1 is close to 1.0.

Fragility curves for URM buildings were derived using the hybrid procedure described in Kappos et al. (2006), which is generally different from the approach adopted for R/C buildings (i.e. inelastic static, rather than dynamic time-history, analyses were performed). Furthermore, the experience from previous seismic events in Greece and elsewhere has clearly shown that URM (usually old) buildings are more vulnerable than R/C ones. Hence, 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, is lower than the corresponding one of the closer to it R/C class, then this value is neglected and the R/C class median value is used instead. In this way, the site-specific spectral correction is implicitly applied to all the fragility curves derived for URM buildings.

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 again derived using inelastic static (pushover) analyses of appropriate finite element models (Kappos et al. 2006). Two sets of fragility curves were then developed:

- one through the transformation of the median values of the corresponding PGA-based fragility curves into S_d terms, using the Capacity Demand-Diagram method and the mean spectrum of each microzonation study (i.e. leading to site-specific fragility curves) and,
- one directly from the capacity curves, after defining damage state thresholds based on appropriate fractions of the yield and ultimate points, as summarized in Table 1.

Table 1: Thresholds of spectral displacement for defining damage states.

Damage state	**Description**	**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}	$S_{du,bare}$

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

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. However, it is deemed not feasible, at least at this stage, to introduce multi-linear pushover or capacity curves (i.e. including residual strength branches), and what is suggested is to tackle the problem using the curves of the corresponding ‘bare’ typologies, as described in Kappos and Panagopoulos (2010).

Overview of the developed earthquake loss scenarios for the two cities.

The probabilistic approach adopted for the loss estimation of the building stock makes mandatory the use of a population of buildings, instead of a single building, as the unit for the development of each scenario. In the Grevena case, it was decided to make use of the building block as the reference unit; such information was not available in the city of Düzce, partly due to the different administrative framework. As a result, it was decided to use a greater entity called ‘mahalle’ (small neighbourhood, in Turkish), hence, the results presented (especially in the form of GIS maps) should be interpreted accordingly. Regarding the level of seismic action, three basic seismic hazard scenarios were developed by the Laboratory of Geotechnical and Foundation Engineering of the AUTh for the Grevena case, each one corresponding to earthquake events with return periods of 100, 500 and 1000 years, respectively. Similarly, for the city of Düzce, the basic seismic hazard scenario was developed based on the probabilistic approach and 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, set equal to the one prescribed in the corresponding national seismic code (i.e. 0.16g for Grevena and 0.40g for Düzce). Based on the above, both PGA and spectral quantity values were assigned to each building block or ‘mahalle’ using appropriate geostatistical interpolation techniques, the result of which is illustrated in Fig. 3. High resolution versions of the maps shown in Figures 3 to 7, plus some additional maps are available here. Furthermore, alternative sets of earthquake loss scenarios were developed for both cities using the aforementioned approaches that utilize the PGA-based or the S_d-based fragility curves. Results presented herein focus on the PGA-based scenarios, since they directly incorporate the hybrid approach and are in line with previous studies (Kappos et al., 2002; 2006).

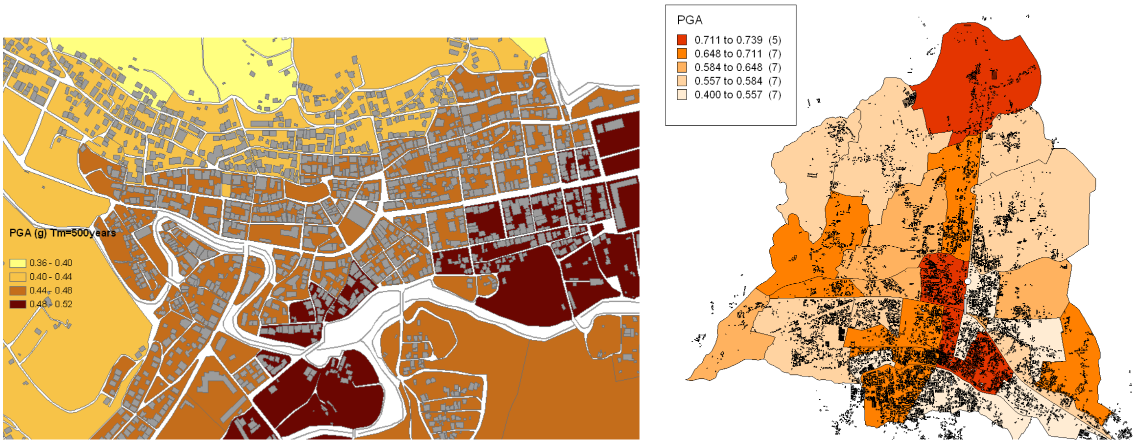

Figure 3. Spatial distribution of input motion in Grevena (left) and Düzce (right) for the 500 year scenario ('design earthquake').

Loss estimation

Assuming a weighted loss index defined as $\Sigma(MDF_i \cdot E_i)/E_{tot}$, where the built area E_i of each building class *i* in a building block (or 'mahalle') is used to weigh the mean damage factor MDF (central index, Kappos and Panagopoulos, 2010) for this type, maps like the ones presented in Fig. 4 were produced, providing a good insight into the most vulnerable parts of each city. Assuming an average replacement cost of €800/m^2 and 500/m^2 for Grevena and Düzce, respectively (uniform for all building typologies), multiplied by the weighted loss index, the weighted cost per built area was derived for each building block (Fig. 5). It is noted that for the city of Grevena, the average damage expected in each block is moderate for an appreciable part of the city, even for the lower (100 year) earthquake scenario. For the 500 year scenario (corresponding to the 'design earthquake') moderate damage is also expected to almost the entire city; however for the case of the 1000 year scenario there are only a few building blocks where severe damage should be expected. On the contrary, for the (old) city of Düzce, significantly more severe damage is anticipated, as a result of both the higher earthquake level and the composition of the building stock; it is recalled that the majority of buildings in the studied area is stone masonry or R/C 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. 6.

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. Nevertheless, there is significant uncertainty regarding the number of technical units that will, indeed, be available simultaneously.

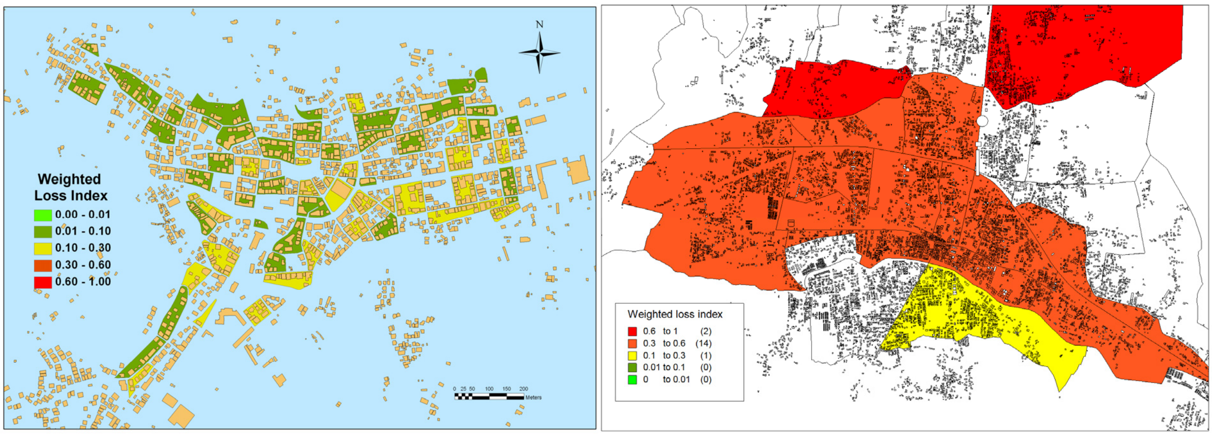

Figure 4. Weighted loss index for the 100-year scenario in Grevena (left) and the microzonation study scenario in Düzce (right)

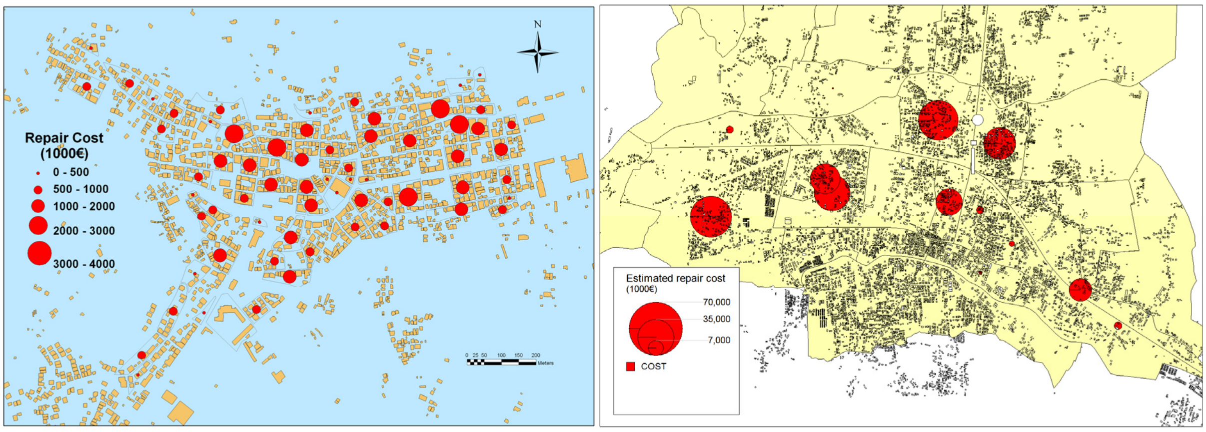

Figure 5. Spatial distribution of repair cost for the 500-year scenario in Grevena (left) and the microzonation study scenario in Düzce (right)

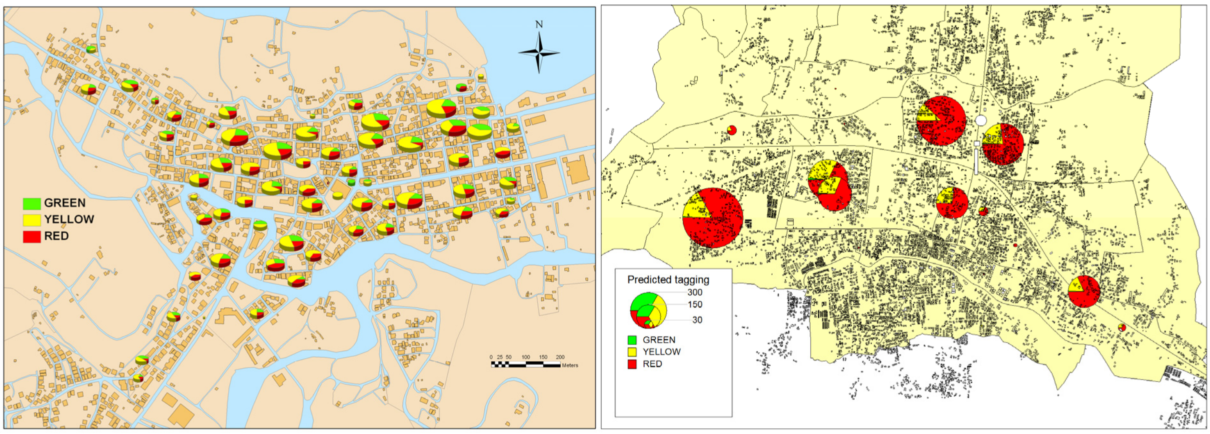

Figure 6. Predicted tagging of buildings for the 500-year scenario in Grevena (left) and the microzonation study scenario in Düzce (right)

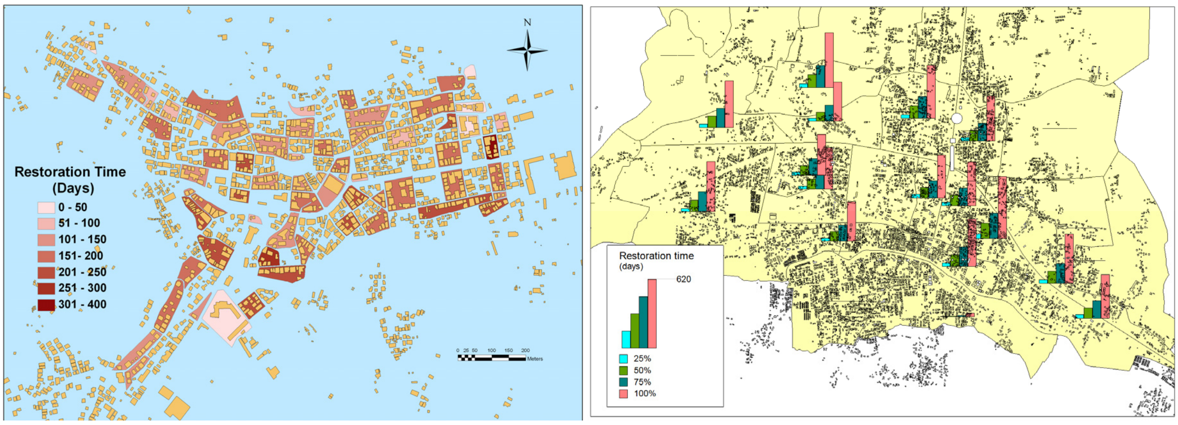

Figure 7 Estimates of the required time for 100% restoration level for the 500-year scenario in Grevena (left) and the microzonation study scenario in Düzce (right)

As a result, two scenarios were investigated: (a) an ‘optimistic’ approach according to which a different technical unit will be made available for each damaged building and that the time needed in order to restore a building block is the mean restoration time of the buildings contained in the block and (b) a ‘pessimistic’ scenario where a single technical unit will be responsible for the restoration of an entire block (the estimate of the authors is that reality lies in-between these two assumptions). The results for both cities using the optimistic approach are depicted in Fig. 7.

Conclusions

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 seismic 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 harmonized methodology was applied to a Turkish and a Greek city and results were assessed in a comparative way. 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, as well as their lower vulnerability. This behaviour was also confirmed during the major earthquakes that struck the two cities during the previous years. 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.

References

Barbat, A.H., Moya, F.Y. & Canas, J.A., 1996. Damage Scenarios Simulation for Seismic Risk Assessment in Urban Zones. *Earthquake 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. & Vidal S., 1995. Seismic zonation methodology for the city of Nice, Progress report. *Proceedings 5th Intern. Conf. on Seismic Zonation*, Nice, France, 1749–84

D'Ayala, D.F., Spence, R.J.S., Oliveira, C.S., & 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. & Vona, M., 2006. Vulnerability assessment and earthquake damage scenarios of the building stock of Potenza (Southern Italy) using Italian and Greek methodologies. *Engineering Structures,* 28 (3): 357-371.

Erdik, M., Aydinoglu, N., Fahjan, Y., Sesetyan, K., Demircioglu, M., Siyahi, B., et al., 2003. Earthquake risk assessment for Istanbul metropolitan area. *Earthquake Engineering and Engineering Vibration*, *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., & Borzi, B., 1999. A study on damage scenarios for residential buildings in Catania city. *Journal of 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 DC

Kappos, A. J., Stylianidis, K. C., & 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. & 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., & Penelis, G., 2006. A hybrid method for the vulnerability assessment of R/C and URM buildings. *Bulletin of Earthquake Engineering*, 4(4), 391-413.

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

Kappos, A.J. and Kouris, L.A., 2008. Modeling of Traditional Masonry Timber Framed Structures, *3rd National Conference of Earthquake Engineering*, Athens (in Greek).

Kappos, A. J., Panagopoulos, G., & Penelis, G. G., 2008. Development of a seismic damage and loss scenario for contemporary and historical buildings in Thessaloniki, Greece. *Soil Dynamics and Earthquake Engineering*, 28(10-11), 836-850.

Kappos, A.J., Stylianidis, K.C., Sextos, A., Papanikolaou, V., Panagopoulos, G., Kouris, L., Goutzika, E., Panagiotopoulos, Ch., 2009. 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 Grevena, Düzce, Greece.

Kappos, A.J., Stylianidis, K.C., Sextos, A., Papanikolaou, V., Panagopoulos, G., Kouris, L., Goutzika, E., Panagiotopoulos, Ch., 2009. 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., and Panagopoulos, G., 2010. Fragility curves for reinforced concrete buildings in Greece. *Structure and Infrastructure Engineering*, 6(1-2), 39-53.

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. & F. N. Spon, Chapman & Hall, London.

Sextos, A. G., Kappos, A. J., & Stylianidis, K. C., 2008. Computer-Aided Pre- and Post-Earthquake Assessment of Buildings Involving Database Compilation, GIS Visualization, and Mobile Data Transmission. *Computer-Aided Civil and Infrastructure Engineering*, 23, 59-73.