STATE-OF-THE-ART OF EUROPEAN EARTHQUAKE LOSS ESTIMATION SOFTWARE

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ABSTRACT :

A review of the state-of the art of loss estimation methodology and software has been carried out as part of subproject JRA3 of the NERIES (Network of Research Infrastructures for European Seismology) project currently being carried out in Europe. This subproject is more specifically concerned with the development of a pan-European loss estimation tool for rapid post-earthquake response in urban environments. Following a literature review of the most recent developments in urban earthquake loss estimation methodology, information about existing software tools for earthquake loss estimation has been gathered and critically reviewed. In particular, the software packages have been examined in terms of their suitability for application in a pan-European context, and for use in a rapid post-earthquake response situation. To assess the capabilities of existing European loss estimation tools, a damage estimation exercise has been carried out using the building stock inventory and population database of the Istanbul Metropolitan Municipality and selected European earthquake loss estimation packages: KOERILOSS, SELENA, ESCENARIS, SIGE and DBELA. The input ground-motions, common to all models, correspond to a "credible worst-case scenario" involving the rupture of the four segments of the Main Marmara Fault closest to Istanbul in a M_w 7.5 earthquake. The results in terms of predicted building damage and social losses are critically compared amongst each other, as well as with the results of previous scenario-based earthquake loss assessments carried out for the study area. The key methodological aspects and data needs for European rapid post-earthquake loss estimation in urban centres are thus identified.

KEYWORDS: Loss Estimation, Damage Assessment, Earthquake Risk, Istanbul, Europe

1. INTRODUCTION

As illustrated by the 1994 Northridge, 1995 Kobe and 1999 Kocaeli and Düzce events, earthquakes striking densely populated urban centres can result in substantial social and economic losses even in countries in which extensive earthquake risk mitigation programmes have been implemented. An efficient management of emergency response in the immediate aftermath of the earthquake is an essential element of earthquake risk reduction, past examples having shown that poor emergency response or a follow-on disaster can multiply the death toll of an earthquake by factors up to 10 (Coburn and Spence, 2002, p.92). As a result, the field of Earthquake Loss Estimation (ELE) is burgeoning with a very large amount of active research currently being undertaken on various aspects of the methodology. In addition, the growing scope and comprehensiveness of modern loss estimation procedures means that the field is becoming more and more interdisciplinary, drawing on research from almost every earthquake-related discipline.

To assist decision-makers and planners, Earthquake Loss Estimation software tools have been developed over the past few decades. These tools often make use of Geographic Information Systems (GIS) to display spatially referenced data. This research has been pioneered by projects in the United States and Japan, with notably the development of the HAZUS multi-hazard software (*e.g.*, FEMA, 2006) by the United States Federal Emergency Management Agency (FEMA). Due to the larger political and administrative fragmentation of the

Euro-Mediterranean region, there is no institution equivalent to FEMA in charge of coordinating the emergency response at a pan-European level. Instead, the post-earthquake response is coordinated at national level by the individual civil protection agencies. As a result, separate ELE tools have been developed in various European countries. In line with previous and ongoing projects to ensure coordination of research efforts in the field of ELE across the Euro-Mediterranean region (e.g., RISK-UE, SAFER, LESSLOSS), work-package JRA3 of the NERIES (Network of Research Infrastructures for European Seismology) project funded by the European Commission under the 6th Framework Programme addresses the issue of developing a rapid loss estimation tool to be used by European agencies such as the European Mediterranean Seismological Center (EMSC) for computing and broadcasting near-real-time earthquake loss estimates to the relevant emergency response institutions. More details about the objectives of NERIES-JRA3 can be found in Çağnan *et al.* (2008).

2. EARTHQUAKE LOSS ESTIMATION IN EUROPE

As a preliminary step towards the development of a new pan-European tool, the state-of-the art of earthquake loss estimation methodology has been assessed (Stafford *et al.*, 2007), which included a review of currently available non-commercial ELE software packages developed world-wide over the past decade. A total of 18 packages have been identified, which have been assessed in terms of their suitability to rapid post-earthquake response applications in European urban centres.

Most of the ELE software packages reviewed can be run on a Windows-based PC with average technical specifications. For post-earthquake response applications, an essential requirement is that the ELE software packages can be run in deterministic forecasting (scenario) mode. The use of commercial GIS and database query programs might enhance the performance in terms of computing time and data display capabilities, but is generally costly in terms of licensing, and might affect the sustainability of the ELE software. A pragmatic compromise is to develop GIS-compatible ELE tools, *i.e.*, software packages that do not require GIS tools to run, but for which compatibility with the most widely-used commercial GIS tools in terms of input and output file formats has been considered.

The extensive research that is being conducted in all aspects of loss estimation ensures that components of the methodology will become redundant in time. For the sake of sustainability, it is therefore vital that ELE software applications are developed as part of a modular and updateable framework. This type of framework has the further advantage of allowing easy calibration to conditions other than those originally intended. The calibration to multiple types of data is likely to be an issue in Europe, where standardised databases such as those collected at a federal level in the United States do not currently exist, and are not expected to become available in the near future. It is also desirable to incorporate mechanisms that allow calibration and updating of the initial estimates calculated by the software with observed data, using for instance a Bayesian updating framework.

Techniques used for the characterisation of the spatial distribution of ground motions in the ELE software packages have been reviewed. In general, ground motions are estimated for a given scenario earthquake using empirical GMPE. Alternatively, some ELE applications allow skipping the ground-motion estimation step and directly inputting the ground-motion distribution. An application of particular interest to rapid post-earthquake response applications is the automated input of ground motions broadcast in near-real-time, such as the ShakeMap application developed by the U.S. Geological Survey (Wald *et al.*, 2006). Due to the unavailability of near-real-time strong-motion networks in vast parts of Europe, the ground-motion estimation step remains an essential component of ELE methodology. In order to ensure the sustainability and versatility of the ELE software, the ground-motion estimation module needs to be reasonably self-contained, so as to allow easy modifications in the event of updating or applying the methodology to another geographic area.

Although there is a trend towards spectrum-based methods, a number of ELE software packages still consider damage calculations based on macroseismic intensity. The choice between intensity-based and spectrum-based approaches will be mainly governed by the availability of appropriate ground-motion and vulnerability data. The definition of vulnerability classes, damage and loss calculation models for a selection of European ELE software packages have been investigated as part of a comparative damage estimation exercise described in the next Section. Additionally, surface deposits are expected to significantly affect the spatial distribution of ground motions, and their effects should be included provided site information is available. Site modification factors should ideally be frequency-dependent to accurately model the underlying physical process. This condition is currently satisfied only by spectrum-based methods.

3. ISTANBUL DAMAGE ESTIMATION EXERCISE

A collaborative exercise involving 6 European institutions has been performed, whose aim was to compare results from 5 selected European ELE software packages, using Istanbul as a testbed. Since all packages consider common inputs in terms of ground motions, building inventory and population, this exercise allows the evaluation of the influence of vulnerability functions and modelling assumptions on loss estimates.

3.1. Selected software packages

The five European ELE methodologies selected for the damage estimation exercise were KOERILOSS, SELENA, ESCENARIS, SIGE-DPC and DBELA. Table 1 summarises the models used by each of the selected software packages for representing the spatial distribution of the ground motions, and the vulnerability of the buildings.

Table 1 Ground-motion parameters and vulnerability functions considered in the selected ELE packages

SOFTWARE	**GROUND-MOTION MODEL**		**VULNERABILITY MODEL**
	Intensity	**Response Spectrum**	
KOERILOSS	EMS98	Standard response spectral shape constructed based on PGA and SA at 0.2s and 1.0s	Intensity-based approach: empirical mean damage ratios characteristic of Turkish building stock compiled from the literature Spectrum-based approach: modified HAZUS fragility curves calibrated to Turkish building stock
SIGE-DPC	MCS	-	Empirical fragility curves (Sabetta *et al.*, 1998)
ESCENARIS	EMS98	-	Level 0 : Empirical damage probability matrices (Roca *et al.*, 2006). Level 1 : Vulnerability functions and indices defined in the RISK-UE project (Giovinazzi, 2005; Mouroux and Le Brun, 2006)
SELENA	-	Standard response spectral shape constructed based on PGA and SA at 0.3s and 1.0s; guidelines to infer spectral shape when only PGA values available.	HAZUS fragility curves; alternatively, user-defined fragility curves can be used.
DBELA	-	Full specification of displacement response spectra, at user-specified periods.	Vulnerability functions in terms of displacement calculated from structural parameters using the DBELA approach (Crowley *et al.*, 2004). See Bal *et al.* (2007b) for details.

KOERILOSS is the ELE software developed by the Kandilli Observatory and Earthquake Research Institute (KOERI), Bogazici University, Istanbul. The vulnerability calculations can be based on empirical results (EMS intensity-based) or on a response-spectrum-based method similar to HAZUS. The outputs include direct economic and social losses due to building damage. This software package is still under development. The results from the runs carried out for the Red Cross study (BU-ARC, 2002) based on version 1.0 of the software have been used as the base case in the comparative analysis. No modifications were made to the results of the KOERI Red Cross study to reflect updates to the software that have been implemented since this study.

SIGE-ESPAS is the ELE software developed and used for emergency planning by the Italian Civil Protection (*Dipartamento di Protezione Civile*, DPC), Rome, Italy. Since 1995, SIGE includes a seismic scenario analysis module (Di Pasquale *et al.*, 2004). Developments are currently underway regarding the characterization of earthquake sources and the treatment of uncertainties. The loss estimation calculations are intensity-based, but make use of empirical fragility curves for PGA and spectral response ordinates derived by Sabetta et al. (1998), which were derived from damage surveys of about 50,000 buildings, carried out after past destructive Italian earthquakes. Losses are expressed in terms of the number of collapsed, uninhabitable and damaged dwellings together with an estimation of the direct monetary losses. Estimates of social losses (fatalities and injuries) are based on the population density from national census data. The software is integrated with the near-real-time earthquake parameter broadcasts of INGV. Runs calibrated to the Istanbul data have been carried out specifically for the purpose of this exercise by a DPC team composed of Antonio Lucantoni, Raquele Ferlito, Filomena Papa and Fabio Sabetta.

ESCENARIS is the ELE software developed by the Geologic Institute of Catalonia (*Institut Geològic de Catalunya*, IGC), Barcelona, Spain. As for SIGE-ESPAS, runs calibrated to the Istanbul data have been carried out by IGC specifically for the purpose of this exercise, by a team composed of Janira Irrizary and Xavier Goula, as well as Nùria Romeu from Geocat. This software has been used to develop a regional emergency plan for Catalonia (Susagna *et al.*, 2006) and is integrated with a rapid response system operating over the eastern Pyrenees (Dominique *et al.*, 2007). It also constitutes the basis for the SES 2002 (*Simulación de Escenarios Sísmicos*) software (Barranco and Izquierdo, 2002) used by the Spanish Civil Protection.

SELENA (SEimic Loss EstimatioN using a logic tree Approach) is a ELE software currently being developed at NORSAR in collaboration with the University of Alicante (*e.g.*, Molina and Lindholm, 2005). The software is still under development, and recent advances are summarised in Lang *et al.* (2008). SELENA is calibrated to Norwegian conditions in terms of ground-motions, and utilises the HAZUS capacity and vulnerability curves, which can however be overridden by user-specified data. In view of the open-source nature of the code, the SELENA simulations were calibrated and run at Imperial College London.

DBELA (Displacement-Based Earthquake Loss Assessment) is a ELE software currently being developed the ROSE School/EUCENTRE in Pavia (Crowley *et al.*, 2004, 2006). Runs were calibrated to the Istanbul data and run by a team composed of Ihsan Engin Bal (ROSE School), Helen Crowley and Rui Pinho (EUCENTRE). The procedure uses mechanically derived formulae to describe the displacement capacity of classes of buildings (grouped by structural type and failure mechanism) at different limit states. This allows the direct comparison of displacement demand and capacity at any period. Another innovation of DBELA is its comprehensive consideration of the uncertainties involved in the estimation of both demand and capacity. In view of the more advanced nature of the damage calculation procedure implemented in the software, the generic inventory data distributed to all participants would have been insufficient for calibration. Therefore, the members of this team also drew on their expertise regarding the geometric and material properties of the Marmara region building stock, which was acquired independently of the NERIES project (Bal *et al.*, 2007). The reader is referred to the paper by Bal *et al.* (2008) for a detailed description of the methodology applied to the present test case.

3.2. Exercise brief and input data

To simulate the conditions of a post-earthquake rapid-response situation, a scenario-based approach is adopted in which the spatial distribution of ground motions is provided by an external application, such as the ShakeMap package developed by the United States Geological Survey (*e.g.*, Wald *et al.*, 2006). The selected scenario is the deterministic scenario considered in the Red Cross study (BU-ARC, 2002). This scenario corresponds to a “credible worst case scenario” involving the rupture of the four segments of the Main Marmara Fault closest to Istanbul in a Mw 7.5 earthquake.

The ground-motion parameters provided are: macroseismic intensity (MSK), peak ground acceleration (PGA), and 5%-damped spectral accelerations at response periods of 0.2 s and 1.0s. The macroseismic intensity distribution was derived based on the intensity attenuation relation of Erdik *et al.* (1985). Site-specific intensities were obtained by applying intensity increments corresponding to the various geological units, following the method of Evernden and Thomson (1985). The PGA values were derived by taking the average of the values predicted by the relations of Boore et al. (1997), Campbell (1997) and Sadigh *et al.* (1997). The spectral acceleration values at 0.2s and 1.0s were derived by taking the average of the values predicted by the Boore *et al.* (1997) and Sadigh *et al.* (1997) relations at the NEHRP site class B/C boundary ($V_{S,30}$ = 760 m/s), and then applying site-specific amplification factors following the NEHRP (1997) provisions. The study area covers 39 districts (*ilce*) and 560 subdistricts (*mahalle*). In view of the large differences in size from one subdistrict to the next, the data have been resampled on a uniform grid of 0.005° x 0.005° cells (approximately 400m x 600m). This results in a database of 8,131 geocells.

Similarly, the building stock information is common to all participants in the exercise. The building stock inventory used is that derived in the Red Cross study based on the extensive data provided by the Turkish State Statistics Institute (SSI) and Istanbul Metropolitan Municipality (IBB). The building classification scheme considers 24 categories (B_{ijk}) based on construction type (i), building height (j), and construction year (k). Building stock data are available for 4,014 out of 8,131 geocells, the remaining 4,117 geocells corresponding to sparsely populated mountainous areas at the outskirts of Istanbul Metropolitan Municipality. The most common building type by far corresponds to reinforced concrete (RC) frame buildings, which represent 74% of the total number of buildings, with a predominance of low-rise (1-4 storeys, 60% of the RC building stock) and mid-rise (5-8 storeys, 34%) buildings. A large proportion of the RC building stock has been constructed in 1980 or later, following the introduction of earthquake-resistant design principles in the 1975 building code. Masonry buildings represent 25% of the total building stock, and are almost exclusively low-rise. Two thirds of the masonry building stock has been built prior to 1979; a similar proportion of the RC building stock was built after 1980, reflecting the rapid expansion of the Istanbul Metropolitan Area in recent years. Prefabricated and shear wall buildings only contribute marginally to the building stock (<1% of the total number of buildings).

3.3. Calibration of the vulnerability models

The ground-motion and building stock data used by all participants are identical. Therefore, observed differences in the loss results from the various software packages may only originate from differences in the modelling of the vulnerability functions. Since one of the aims of the exercise is the assessment of the portability of existing software applications across Europe, no modifications to the source code have been made in order to include additional, potentially more appropriate vulnerability functions. Thus, the key difficulty in calibrating the models is to establish an equivalence between the Istanbul building typologies as defined in the KOERI classification, and the local typologies that are considered in the other models. The weights assigned to each of the local building classes in order to obtain a typology equivalent to a given building class in the KOERI classification are generally based on expert judgment. For example, in the case of ESCENARIS, it has been considered that half of the RC frames have regularly infilled walls (RC3.1) and the other half have irregularly infilled walls (RC3.2). In the case of DBELA, the proportions of buildings corresponding to each KOERI class are determined using additional data regarding the Istanbul building stock (Bal *et al.*, 2007, 2008). A more comprehensive description of the calibration of the vulnerability models can be found in Strasser *et al.* (2008).

3.4. Damage estimation exercise results

The evaluation of the results of the damage estimation exercise focused in particular on the following points:

- Comparison of the total number of buildings in a given damage state, as defined in the European Macroseismic Scale (EMS98) or in the HAZUS99 approach (Figure 1);
- Assessment of the proportion of buildings in a given damage state for Istanbul overall and for selected districts (Figure 2);
- Consistency of the results at gridcell level;
- Implications in terms of social losses.

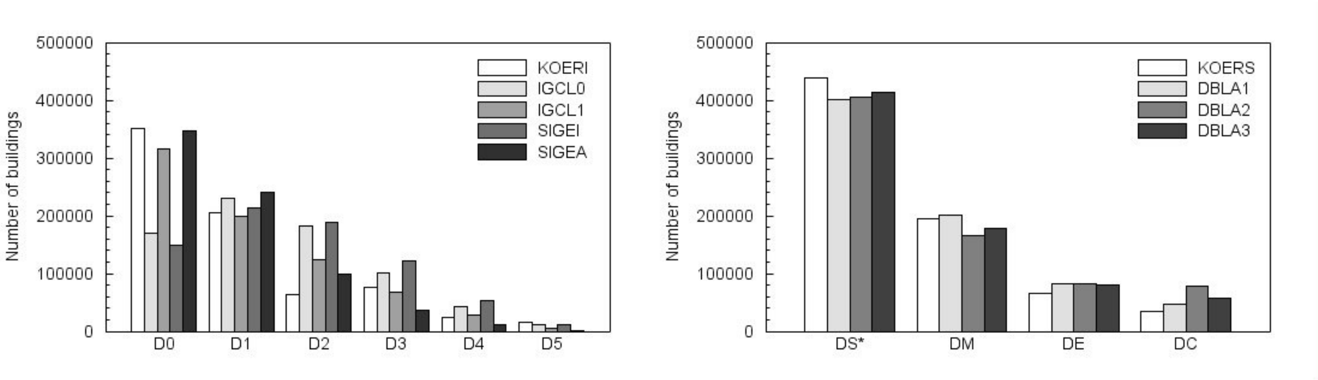

Figure 1 Total number of buildings in each EMS98 (*left*) and HAZUS99 damage state (*right*) damage state (DS*=slight or no damage; DM = moderate damage; DE = extensive damage; DC = complete damage), for several approaches considered in the exercise.

Figure 1 summarises the total number of buildings expected to be in each damage state, for several approaches considered in the exercise. Results are presented separately for intensity-based (EMS98 damage grades) and spectrum-based approaches (HAZUS99 damage states), in view of the difficulty of establishing an unambiguous correspondence between these two damage scales. Whilst the results from the DBELA runs show very good agreement with the KOERILOSS base case (*right panel*), the predictions from intensity-based methods are more variable (*left panel*). In particular, a very good agreement is found between the ESCENARIS Level 1 runs (IGCL1) and the intensity-based SIGE-DPC runs (SIGEI), whose inbuilt vulnerability functions are very similar, as they have been derived from common data. The results from the different approaches are compared both for the whole of the study area, and for selected districts of Istanbul Metropolitan Municipality, in order to investigate the impact of differences in the building stock characteristics.

The results exhibit a reasonable level of agreement in terms of the total number of damaged buildings. The spatial distribution of damage is also fairly consistent. Pockets of higher levels of damage tend to be concentrated on the European side of the city, in the districts of the historical centre (Zeytinburnu, Eminönü), as well as in areas where the level of ground motion is enhanced by the presence of soft soil deposits (*e.g.*, Avcilar). Figure 2 shows that variations in local site conditions and differences in building stock characteristics also have an influence on the level of agreement amongst predictions. In most cases, the influence of these factors is found to be stronger than differences between the individual modelling approaches.

The overall estimates of building damage fall within the range of values predicted in previous studies assessing the seismic risk in Istanbul, as recently summarised in Erdik (2007). However, whereas the level of agreement across the entirety of Istanbul Metropolitan Municipality, and for selected districts, is found to be reasonable, the results often differ by a factor of 3 or more at gridcell level. This highlights the fact that spatial resolution is likely to be an issue in the calibration of a future pan-European ELE tool.

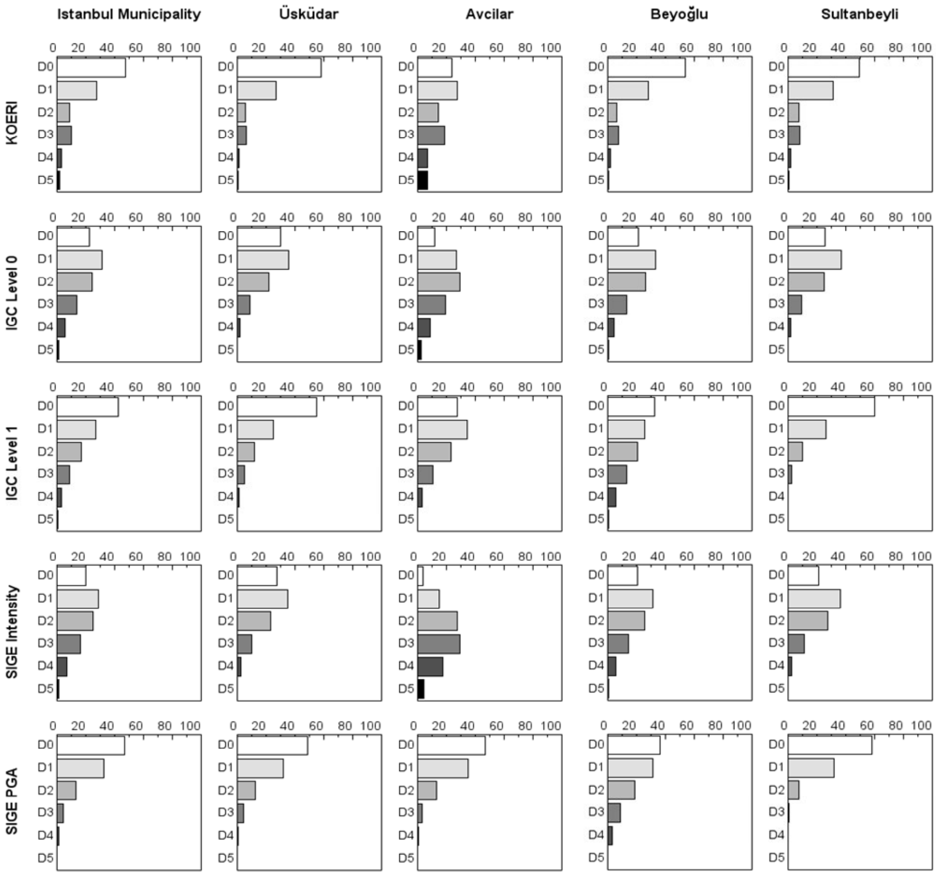

Figure 2 Proportions of buildings predicted to be in a given EMS98 damage state for Istanbul Metropolitan Municipality in its entirety (*first column*), and selected districts (*columns 2 to 5*).

In terms of social losses, the predictions from the various approaches show a large degree of scatter. For non-fatal injuries and shelter needs, a direct comparison is hampered by differences in the definitions of the parameters used. For cases where building damage predictions are similar, and casualty descriptors are directly comparable, the differences in estimated social losses are driven by differences in the casualty rates assumed, which are strongly dependent on local construction practices.

4. CONCLUSIONS

A review of the state-of-the-art of earthquake loss methodologies has been carried out, with a particular focus on applications suitable for rapid post-earthquake applications in European urban centres. Results from a comparative damage estimation exercise carried out for Istanbul are encouraging, since they provide a similar general picture. However, differences in the details of the predictions reveal several issues to be addressed in the development of a pan-European ELE tool. A modular approach incorporating all currently used models as alternatives is recommended.

A crucial component of the calibration of the vulnerability functions in such a modular approach is the determination of equivalences among the building typologies used by the various models considered. More research is required into the portability across Europe of vulnerability functions derived for one specific application, in addition to the collection of building stock inventory data. This could also provide guidance on how to adapt existing vulnerability models to regions where the vulnerabilities have not yet been assessed. The issue of correspondence between damage scales is likely to be an issue for the planned pan-European loss tool, as multiple levels of analysis may be required to cope with the regional disparities in data availability. For this reason, it is recommended that the nature and extent of damage corresponding to each damage grade are clearly described and if possible quantified. Similarly, the definitions of the social loss descriptors need clarification, as the use of a consistent terminology is essential for risk management purposes

This comparative study has examined the case of Istanbul, which is amongst the urban centres in the Euro-Mediterranean region with the highest level of seismic hazard. Istanbul also stands out as one of the most populous urban areas in this region, as well as being characterised by one of the fastest rates of urban expansion. All these factors would tend to indicate that the example studied here is a worst-case scenario both in terms of the loading conditions (high hazard) and in terms of capacity (high vulnerability of the building stock) and exposure (large population). On the other hand, the Istanbul case currently also represents a frontier in terms of data availability. Similarly detailed inventories throughout the Euro-Med region are a key data requirement for future European ELE applications, and in particular to determine whether observed discrepancies between existing ELE methodologies reflect regional differences (*calibration issue*) or uncertainty as to the “best” model to use (*validation issue*).

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