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Studying the uncertainties in the seismic risk assessment at urban scale applying the Capacity Spectrum Method: The case of Thessaloniki

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A B S T R A C T

Seismic risk assessment and loss estimation are of major importance for decision-making with respect to the reduction of earthquake-induced losses in large urban areas. However, the methodological chain of seismic risk assessment, from seismic hazard assessment to evaluation of potential losses, encompasses numerous uncertainties, both aleatory and epistemic, associated with different sources. The present study is a comprehensive application of the Capacity Spectrum Method to the seismic risk assessment of the city of Thessaloniki, aiming to give an insight into epistemic uncertainties involved in the above methodology, owing to hazard modelling, structural capacity, fragility and damping, as well as shaking duration. To quantify and discuss the uncertainties, a logic tree approach is used. A sensitivity analysis of the computed seismic risk results is performed to determine the input parameters having the greatest impact. The analyses were carried out for the building stock of the city of Thessaloniki, Greece, for which detailed building inventory and very good knowledge of the soil conditions are available. Only physical losses due to the structural damage of the building stock were considered. Considerable scatter in the risk estimates was observed due to epistemic uncertainties. The sensitivity analyses demonstrated that the most influencing parameters when applying the Capacity Spectrum Method are the selection of the fragility curves for the buildings and the seismic hazard model adopted in the analysis. The decision-making process with respect to seismic risk assessment should therefore carefully account for uncertainties and pay attention to the most influencing parameters regardless of the methodology used.

1. Introduction

Seismic risk assessment and loss estimation are of major importance for decision-making with respect to the reduction of earthquake-induced losses in large urban areas. Knowing the seismic risk and potential losses allows for proper budgetary planning, raising public awareness, assessment and allocation of the necessary manpower for mitigation and disaster management operations, educating the public and professionals on preparedness and mitigation, and prioritization of retrofit applications [1]. To this end, seismic risk assessment studies have been conducted for several cities in Europe, such as Barcelona [2,3], Cologne [4], Vienna [5], Lisbon [6–8], Istanbul [9], Potenza [10] and Thessaloniki [11], while several more are ongoing.

The methodological chain of seismic risk assessment, from seismic hazard assessment to evaluation of potential losses, however, encompasses both aleatory and epistemic uncertainties associated with different sources. Aleatory uncertainty is related to the intrinsic randomness of a phenomenon and reflects its stochastic nature, and thus cannot be reduced with the collection of additional data. Epistemic uncertainty on the other hand, related to the lack of proper knowledge about the system under consideration and to the necessity to use simplified models to simulate the complex nature or the response of the elements at risk, can theoretically be reduced by improving the inventory, the methods and generally the state of knowledge [4,12–14].

Treatment of epistemic uncertainty usually takes place in two complementary stages; quantification of uncertainty and sensitivity analysis. Quantification of epistemic uncertainty can be performed using methods such as Monte Carlo analyses (e.g. [15,16]), Bayesian methods (e.g. [17]), fuzzy logic methods (e.g. [18]), and logic trees (e.g. [19]). The logic tree approach, adopted in the present study, is based on the concept of applying alternative methods or models, each of which is assigned a weighting factor that is interpreted as the relative likelihood of that method being correct [20]. A logic tree consists of a series of nodes, where the different models are specified, and branches, representing the different models specified at each node. The sum of the probabilities of all branches originating from a given node must be equal to one. The logic tree approach has been widely implemented for the quantification of epistemic uncertainties related to individual

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components of the methodological chain of seismic risk assessment, especially in seismic hazard analysis studies [19,21–25] and site effect studies [26,27]. Recently, the logic tree approach has been applied in a holistic way in an attempt to propagate the uncertainties from the individual seismic risk components to the outcome result and to evaluate their relative contribution to the total uncertainty [4,28]. Sensitivity analyses, most commonly applied so far in seismic hazard assessment studies [13,23,29,30], are used as a complementary tool to identify the input parameters that have the greatest impact on the model output [31]. When a logic tree approach has been applied for the uncertainty analysis, the sensitivity analysis can identify the nodes of the logic tree which mostly affect the computed results.

The present study uses the logic tree approach for the quantification of uncertainties in seismic risk assessment within the context of urban environments when applying the Capacity Spectrum Method (CSM) [32,33]. For that the open-source software EarthQuake Risk Model (EQRM, [34]) has been used, taking into consideration different sources of uncertainties related with the different steps of the seismic risk assessment methodological framework, using the building stock of the city of Thessaloniki, Greece, as a case study. CSM is a performance-based seismic analysis method widely used for the seismic risk analysis of urban areas [3,28,34,35], in which the capacity of the structure (in the form of a pushover curve) is compared with the demands of the structure (in the form of response or demand spectra) and the response of the structure is approximated as the graphical intersection of the two curves, determining in that way a “performance point” [36]. Taking into consideration the most critical factors affecting the assessment of seismic risk when applying CSM, uncertainties in this study were classified into five groups according to what they represent, and a logic tree was constructed for each group. This means that the effect of each group of parameters was examined independently of the others, overlooking the propagation of uncertainties through the computational chain of seismic risk assessment. For the branches of each logic tree the expected physical losses were estimated in terms of percentages of damaged floor area for five different damage states, i.e. no damage, slight, moderate, extensive and complete damage. Average plus/minus one standard deviation values of the damage percentages were calculated for each damage state, with the range between the two values considered as indicative of the significance of the uncertainties related with this group of parameters. In order to further identify which nodes of each logic tree mostly affect the computed results, sensitivity analyses were performed using the range of the marginal means of each node as an indicator of the sensitivity of the specific node, as proposed by Rabinowitz et al. [23].

2. Study area and exposure

The city of Thessaloniki is the second largest city in Greece and the financial centre of northern Greece. The study area considered in the present application (Fig. 1) covers the central municipality of Thessaloniki and is divided in 20 Sub-City Districts (SCD) as they are defined by Eurostat through the European Urban Audit (EUA) approach. The total population in this area is about 380,000 inhabitants, which is about one third of the population of the whole agglomeration of Thessaloniki. Soil conditions are very well known [37]. Figs. 2a and b illustrate a simplified large scale classification of the study area based on the soil classification schemes of EC8 [38] and the one proposed by Pitilakis et al. [27], respectively.

The building inventory is based on the inventory compiled during previous studies [11], with the improvements and additions that took place within SYNER-G FP7 European Collaborative Research Project (http://www.vce.at/SYNER-G, [39]). The reference unit of the inventory is the building block. The building inventory comprises 2893 building blocks with 27,738 buildings, the majority of which (25,639) are reinforced concrete (RC) buildings. The application presented herein was limited to the RC buildings of the building stock of the city, which however cover more than 90% of the buildings of the city.

The detailed building inventory for the city of Thessaloniki, which includes information about material, code level, number of storeys, structural type and volume for each building, allows a rigorous classification of the buildings in different typologies based on a Building Typologies Matrix (BTM) representing practically all common RC building types in Greece [40] (Table 1). The buildings are classified based on their structural system, height and level of seismic design. Regarding the structural system, both frames and frame-with-shear walls (dual systems) are included, with a further distinction based on the configuration of the infill walls. Regarding the height, three subclasses are considered (low-, medium- and high-rise). Finally, as far as the level of seismic design is concerned, four different levels are considered:

- No code (or pre-code): R/C buildings with very low level of seismic design or no seismic design at all, and poor quality of detailing of critical elements.
- Low code: R/C buildings with low level of seismic design (roughly corresponding to pre-1980 codes in southern Europe, e.g., the 1959 Code for Greece).
- Moderate code: R/C buildings with medium level of seismic design (roughly corresponding to post-1980 codes in southern Europe, e.g., the 1985 Supplementary Clauses of the Greek Seismic Codes) and reasonable seismic detailing of R/C members.
- High code: R/C buildings with enhanced level of seismic design and ductile seismic detailing of R/C members according to the new generation of seismic codes (similar to Eurocode 8).

The classification of the RC buildings of the study area based on the BTM of Table 1 is illustrated in Fig. 3. The majority of the RC buildings are either regularly or irregularly infilled dual systems (building types RC4.2 and RC4.3) and have been constructed prior to 1980, thus they have been designed with low seismic code level.

3. Methodology of seismic risk assessment

The seismic risk assessment of the RC building stock of Thessaloniki, i.e. the probability of the buildings of each specific typology to exceed a specific damage state, is carried out with the open-source software EarthQuake Risk Model (EQRM, [34]), which is based on the Capacity Spectrum Method (CSM) [32,33], as described in HAZUS [41] and properly modified so that it can be used for any region of the world [42].

The Capacity Spectrum Method (CSM) was first proposed by Freeman et al. [43] as a graphical procedure for rapid assessment of existing buildings. CSM leads after iterations to the evaluation of the structure's performance point (PP), using a graphical plot of the seismic demand with the structural capacity (in terms of pseudo-accelerations and displacements). The PP stems from the intersection of the two curves, and represents the performance of the structure to a specific earthquake record. CSM relies, therefore, on two main counterparts: the demand spectrum and the capacity curve. The elastic demand spectrum for rock-site conditions for a specific return period can be derived either from a specific site-dependent seismic hazard analysis or directly from a seismic code (e.g. Eurocode 8 [38]). Proper period-dependent soil amplification factors can be applied to account for site effects ([26,27]). Elastic demand spectra should then be appropriately modified in order to incorporate the inelastic energy dissipation. The capacity curve can be derived after conducting static nonlinear analysis or directly from literature (e.g. [40]).

In order to further assess the seismic risk for a building or a building class, i.e. the damage probability in each of the considered damage states, the displacement which corresponds to the performance point is overlaid with the corresponding fragility curves, which describe