Urban seismic risk model for resilient cities. The case of Thessaloniki

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Abstract. Seismic risk assessment and loss estimation are of major importance for decision-making with respect to the reduction of earthquake-induced losses at local, urban, national and even continental scale. In this study, we present a preliminary model for the probabilistic seismic risk assessment at urban scale. The studied model will be applied to the residential building stock of Thessaloniki, Greece, for which detailed building inventory and very good knowledge of the soil conditions are available. The applied model comprises three main components, i.e., seismic hazard, building exposure model, and physical and socioeconomic vulnerability models. Seismic hazard for rock site conditions is properly amplified to account for site effects of Thessaloniki city, considering the available detailed data of the soil conditions. Exposure model for residential buildings of Thessaloniki is developed based on the results from the 2011 Population and Housing Census. Both physical and socioeconomic losses were considered. For the assessment of the physical and socioeconomic losses, we applied the fragility and vulnerability models developed for Greece by GEM. The work has been conducted in the framework of SERA European project (http://www.sera-eu.org/en/home/), which aims at developing a pan-European seismic risk model, applicable at both urban and national risk assessment. The model developed in this work will contribute to the efforts towards increasing the resilience of cities.

1. Introduction

Seismic risk assessment and loss estimation are of major importance for decision-making with respect to the reduction of earthquake-induced losses at local, national and even continental scale. Particularly at urban scale, seismic risk assessment is crucial for the assessment of socio-economic impact of future earthquakes on a densely populated area, of potential interest for insurance and reinsurance industries, for the planning of effective actions for seismic risk mitigation and preparedness, for the improvement of decision making in support to emergency response and disaster management; and eventually for the optimization of retrofitting strategies [1].

In the framework of SERA European project (http://www.sera-eu.org/en/home/), an effort is being made to develop an open, transparent, and publicly accessible earthquake risk model at a European scale [2]. Within this context, we have developed a preliminary model for the seismic risk assessment of the residential building stock of Thessaloniki, Greece, for which detailed building inventory and very good knowledge of the soil conditions are available. The model comprises three main components, i.e., building exposure model, seismic hazard, and physical and economic vulnerability models. The exposure model for the residential buildings is developed based on the results from the 2011 Population and Housing Census held by the Hellenic Statistical Authority. The taxonomy scheme of the Global
Earthquake Model (GEM) initiative is applied [3], which allows buildings to be classified according to a number of structural attributes, i.e., main construction material, lateral load resisting system, number of storeys, age of construction and ductility level. The seismic hazard for rock site conditions developed within the SHARE European project (Giardini et al., 2013) is properly amplified to account for site effects using the soil amplification factors of EC8 [4] and Pitilakis et al., 2018 [5]. For the assessment of the physical and economic losses we applied the fragility and vulnerability models developed for Greece by GEM [6]. These models were selected over other models developed specifically for Greece [7], so as to achieve conformity across Europe within the SERA project. The model developed in this work will be able to provide estimates of critical risk metrics, such as physical and economic losses, useful for the development of seismic risk mitigation planning, and in this way it will be a valuable contribution to the efforts towards increasing the resilience of cities, i.e., increasing their ability to absorb, recover and prepare for future shocks.

2. Exposure model

The exposure model developed in this study concerns the residential building stock of Thessaloniki, Greece and is based on the taxonomy scheme of the Global Earthquake Model (GEM) [3], which allows buildings to be classified according to a number of structural attributes, i.e., main construction material, lateral load resisting system, number of storeys and ductility level, which is herein assumed to be a function of the period of construction and respective seismic design code in force (see Table 1). By using a uniform classification scheme, it is possible to ensure that fragility/vulnerability models of all elements at risk are compatible with the exposure model (that provides the location and value of those elements at risk) that may be developed by different parts of the engineering community [8].

For the development of the exposure model for Thessaloniki we used the results from the 2011 Population - Housing and Buildings Census [9], which include detailed data on the construction material, number of storeys, period of construction, type of roof and type of use for each census sector or each municipality of Thessaloniki. This data was properly processed to classify all the residential buildings into different building classes following the GEM taxonomy scheme (Table 1). For the lateral-load resisting system attribute, for which there was no available information from the census, we made some assumptions based on the feedback from the SERA European Building Exposure Workshop questionnaire (https://sites.google.com/eucentre.it/sera-exposure-workshop/questionnaire). The exposure model for Thessaloniki consists of a total number of 74032 residential buildings. Figure 1 shows the studied area and the distribution of residential building to the various regions. Figure 2 illustrates the distribution of residential buildings in Thessaloniki based on (a) the construction material, (b) number of storeys and (c) period of construction.

Table 1. Values of attributes of the GEM Building Taxonomy [3] currently used to describe the residential building stock of Thessaloniki

| Attribute                        | Element code | Level 1 value          | Element code | Level 2 value                |
|----------------------------------|--------------|------------------------|--------------|------------------------------|
| MATERIAL OF LATERAL LOAD-        | CR           | Concrete, reinforced   | PC           | Precast concrete             |
| RESISTING SYSTEM                 | MUR          | Masonry, unreinforced  | CL           | Fired clay unit, unknown type|
| MR                               | Masonry, reinforced | ST          | Stone, unknown technology   |
| MCF                              | Masonry, confined | ADO       | Adobe blocks                |
| MATO                             | Material, other | CB         | Concrete blocks, unknown type|
3. Seismic hazard

The seismic hazard component that was selected to be used for the present exercise is based on the European seismic hazard model developed within the SHARE project [10] for rock site conditions, for a 5% and 10% probability of exceedance in 50 years, which corresponds to a mean return period of 975 and 475 years, respectively. Figure 3 illustrates the spatial distribution of the peak ground acceleration (PGA) obtained for rock site conditions for the selected return periods.

To account for local site conditions, the obtained seismic hazard data for rock was amplified using the site categorization schemes and respective site amplification factors of EC8 [4] and Pitilakis et al. (2018). The classification of the Thessaloniki territory based on EC8 and Pitilakis et al., 2018 [5] site categorization schemes is shown in Figure 4. Figures 5 and 6 illustrate the spatial distribution of the site-amplified PGA using the EC8 [4] and Pitilakis et al., 2018 [5] amplification factors, obtained from the 475-years and the 975-years PGA on rock respectively. It is observed that the use of the soil amplification factors by Pitilakis et al., 2018 [5], which are in general higher for soil classes B and C compared to EC8 factors, results in higher PGA values compared to the use of EC8 soil factors.
Figure 1. Thessaloniki city: (a) study area (b) distribution of residential buildings to the various regions.

Figure 2. Distribution of residential buildings in Thessaloniki according to (a) construction material, (b) number of storeys and (c) period of construction.
Figure 3. Spatial distribution of the Peak Ground Acceleration (PGA) values in Thessaloniki for (a) 475 years and (b) 975 years return period.

Figure 4. Site classification in Thessaloniki according to (a) Eurocode 8 (CEN, 2004) and (b) Pitilakis et al. (2018).
Figure 5. Spatial distribution of the site-amplified 475-year return period rock ground motions, using the amplification factors proposed by (a) Eurocode 8 and (b) Pitilakis et al. (2018).

Figure 6. Spatial distribution of the site-amplified 975-year return period rock ground motions, using the amplification factors proposed by (a) Eurocode 8 [4] and (b) Pitilakis et al., 2018 [5].

4. Fragility model
The fragility models adopted in the present study were developed for each building typology by Martins and Silva [6]. The same framework is also utilized by the GEM standard. The fragility models have been developed from the results of nonlinear dynamic analyses performed on equivalent SDOF systems.
representing each building class considered herein following a cloud analysis framework. Building-to-
building and record-to-record variability were included in the analyses by considering large sets of
capacity curves and ground motion records, respectively. For the generation of the fragility models the
main assumptions are the following: i) the capacity for each building class was assumed to follow a
multilinear model computed using the yield and ultimate displacements, ii) appropriate records were
selected from various ground motion databases, iii) nonlinear dynamic analyses were performed in
numerical models, iv) four distinct damage states ranging from slight damage to complete damage were
considered. The performance thresholds between damage states were estimated from the yield and
ultimate displacement capacity (see Table 2) of each SDOF system. Based on the damage thresholds
and taking into account the spatial distribution of seismic hazard, the probabilities of exceedance of each
damage state were developed. Figure 7 shows indicative fragility curves for two building typologies.

| Damage state       | Threshold                        |
|--------------------|----------------------------------|
| Slight damage (DS1)| 0.75Sdy                          |
| Moderate damage (DS2)| 0.50Sdy+0.33Sdu                  |
| Extensive damage (DS3)| 0.25Sdy+0.66Sdu                  |
| Complete damage (DS4)| Sdu                             |

Sdy - Spectral displacement at yield; Sdu - Spectral displacement at ultimate capacity

![Figure 7. Indicative fragility curves for two building typologies.](image)

Figures 8 and 9 illustrate the distribution of the most expected damage state of the residential buildings
of Thessaloniki for the site-amplified 475 and 975 year return period rock ground motions, using the
amplification factors by Eurocode 8 [4] and Pitilakis et al., 2018 [5]. It is obvious that damages are
generally increased when we apply the Pitilakis et al. [5] site amplification factors. In both approaches, however, the prevailing damage states are «No Damage» and «Slight Damage» for the greatest part of the study area.

**Figure 8.** Distribution of the most expected damage state of residential buildings for the site-amplified 475-year return period rock ground motions, using the amplification factors by (a) Eurocode 8 [4] and (b) Pitilakis et al., 2018 [5].

**Figure 9.** Distribution of the most expected damage state of residential buildings for the site-amplified 975-year return period rock ground motions, using the amplification factors by (a) Eurocode 8 [4] and (b) Pitilakis et al., 2018 [5].
5. Seismic risk

The Total Repair Cost of each typology is derived as the product of Total Replacement Cost and the Mean Damage Ratio.

The Mean Damage Ratio (MDR) can be mathematically expressed as follows:

\[ MDR = (P=DS1) \times 0.05 + (P=DS2) \times 0.2 + (P=DS3) \times 0.6 + (P=DS4) \times 1 \]  
(1)

where \( P=DS1, P=DS2, P=DS3, P=DS4 \) are the discrete damage probabilities for slight, moderate, extensive and complete damage state respectively. The damage indices for each of the four damage states have been adopted from the GEM research team. MDR may be quantified in cost terms as the ratio of cost of repair to cost of replacement taking values from 0: no loss (cost of repair equals 0) to 1: complete loss (cost of repair equals the cost of replacement).

The total replacement cost (in Euros) is estimated for each region of Thessaloniki as a product of the replacement cost per area multiplied with the total number of buildings, the total number of dwellings per building and the area per dwelling. The replacement cost per area was considered as 800€/m\(^2\) for urban areas and 700€/m\(^2\) for the rural ones. As shown in Table 3, different assumptions were made for the total number of dwellings per building and the area per dwelling depending on the total height of the structure.

| Building height | Number of dwellings per building | Area per dwelling (m\(^2\)) |
|-----------------|---------------------------------|---------------------------|
| HEX:1           | 1                               | 90                        |
| HEX:2           | 1                               | 90                        |
| HEX:3,5         | 4                               | 85                        |
| HEX:6+          | 28                              | 80                        |

In Figures 10 and 11 the total repair cost is estimated according to Eurocode 8 [4] and Pitilakis et al., 2018 [5] for the site-amplified 475- and 975-year return period rock ground motions. It is shown that the total repair cost is generally increased when we apply the Pitilakis et al., 2018 [5] site amplification factors. In both approaches, however, the greater values of the total repair cost are expected around the port of Thessaloniki.
Figure 10. Total repair cost for the site-amplified 475 year return period rock ground motions, using the amplification factors by (a) Eurocode 8 [4] and (b) Pitilakis et al., 2018 [5].

Figure 11. Total repair cost for the site-amplified 975 year return period rock ground motions, using the amplification factors by (a) Eurocode 8 [4] and (b) Pitilakis et al., 2018 [5].

6. Conclusions
In this study we presented preliminary models for the residential building exposure, seismic hazard and physical and economic vulnerability for the residential building stock of Thessaloniki city. Using the site-amplified 475- and 975-year return period ground motions obtained from the PGA on rock, no,
slight or medium damages are expected for the majority of the residential buildings. The model developed in this work will be able to provide estimates of critical risk metrics, such as physical and economic losses, useful for the development of seismic risk mitigation planning, and in this way, it will be a valuable contribution to the efforts towards increasing the resilience of cities, i.e. increasing their ability to absorb, recover and prepare for future shocks. In the future, the event-based probabilistic risk assessment calculator of the OpenQuake-engine - the open-source software tool for seismic hazard and risk analysis developed by GEM [11, 12] will be used, to estimate the full probabilistic earthquake risk for the Greek territory.

7. References
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Acknowledgments
The authors are grateful to the GEM Foundation, Pavia, Italy, and more specifically to Venetia Despotaki for supporting this study. This work has been funded by the European Union’s Horizon 2020 research and innovation programme under grant agreement No.730900 (Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe, http://www.sera-eu.org/) and by the project “HELPOS - Hellenic Plate Observing System” (MIS 5002697) which is implemented under the Action “Reinforcement of the Research and Innovation Infrastructure”, funded by the Operational Programme "Competitiveness, Entrepreneurship and Innovation" (NSRF 2014-2020) and co-financed by Greece and the European Union (European Regional Development Fund).