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How much may the precision of site conditions modelling affect seismic risk assessment at large urban scale? The case of Thessaloniki, Greece.

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ABSTRACT

The accurate knowledge of the geological, geotechnical, geophysical and geometrical characteristics of soil conditions at urban area, usually obtained through microzonation studies, is generally important to the seismic hazard and risk assessment, and consequently for decision-making with respect to the reduction of earthquake-induced losses and insurances. However, the level of precision of the knowledge of soil conditions required for seismic risk assessment at urban scale, usually described with a single parameter (e.g. $V_{s,30}$) is still debated. The aim of the present study is to investigate whether a very detailed knowledge of site conditions in terms of $V_{s,30}$ may affect the seismic risk assessment compared to more simplified approaches, using as case study the city of Thessaloniki, Greece where we have a very good knowledge of the soil conditions. For this purpose, the European seismic risk model recently developed in the framework of the H2020 EU SERA project was applied to the residential building stock of Thessaloniki, Greece. We used different $V_{s,30}$ models of increasing accuracy, including a simplified one obtained via correlation to topographic slope and a rigorous one, obtained from measured V_s profiles. For the risk assessment we applied the taxonomy scheme and vulnerability models developed by the Global Earthquake Model. The results are presented in terms of average annual losses. For the specific case study and seismic hazard model, the estimated economic losses at urban scale are not significantly affected by the precision of $V_{s,30}$ model, although significant discrepancies may occur at local scale.

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. One of the main components affecting seismic risk assessment, especially at urban scale, is local site conditions, described by the geological, geotechnical, geophysical and geometrical characteristics of the soils underlying an urban area. Local site effects in seismic risk applications are represented by appropriate models of $V_{s,30}$ (time-averaged shear wave velocity to 30 meters depth), as $V_{s,30}$ is the most commonly soil amplification parameter adopted by ground motion prediction equations (GMPEs). For large scale applications, $V_{s,30}$ models covering the entire urban area can be derived from correlations with readily available topographic slope data (e.g. Wald and Allen, 2007) or from the combined use of topography and geology (e.g. Kwok et al., 2018).

In this work we investigate the role of local site conditions in seismic risk assessment at urban scale through the application of the open access European seismic risk model developed in the framework of the H2020 EU SERA project (http://www.sera-eu.org/en/home/) to the residential building stock of the city of Thessaloniki, Greece, which is very well documented in terms of local site conditions. To this end, we use different $V_{s,30}$ models of increasing accuracy, including a simplified one obtained via correlation to topographic slope and a very rigorous one, obtained from measured V_s profiles at the study area. For the seismic risk assessment we use the "Stochastic Event Based Probabilistic Seismic Risk Analysis Calculator" of the open-source seismic hazard and risk software OpenQuake-engine (Pagani et al., 2014; Silva et al., 2014) and we apply the taxonomy scheme by Brzev et al. (2013) and the vulnerability models developed by Martins and Silva (2020), both developed by the Global Earthquake Model (GEM). Estimated economic losses for the different $V_{s,30}$ models are compared in terms of average annual losses at both local and urban scale.

2 STUDY AREA

Thessaloniki is the second largest city in Greece and the financial center in Northern Greece. It is located in one of the most seismo-tectonically active zones in Europe. Its seismicity is mainly associated with the activity of the Mygdonia and the Anthemountas faults, which were responsible for severe destructive earthquakes with magnitudes up to M_w=7.0 (Papazachos and Papazachou, 1997). The latest major earthquake in Thessaloniki happened in June 1978 with an epicentre located at a distance of about 30km NE of the city and a magnitude of M_w 6.5, causing 47 fatalities, most of them in an eight-storey RC building which collapsed, 220 injuries and serious damages to about 4000 buildings (Penelis et al., 1988; Panou et al., 2014). The area studied herein (Figure 1) includes 16 municipalities and covers an area of 108 km^2.

2.1 Site conditions

For the study area we adopted three $V_{s,30}$ models of increasing accuracy (Figure 2). The first model (Figure 2a), which is the most simplified one, was extracted from the global slope-based $V_{s,30}$ model developed by the U.S. Geological Survey (USGS) (Wald and Allen, 2007). According to this $V_{s,30}$ model, most regions in Thessaloniki are classified as soil class B based on the Eurocode 8 (EC8) soil classification scheme (CEN, 2004) with $V_{s,30}$ ranging on average between 360 and 720 m/s, while there is an additional zone close to the coastal area with softer soil materials classified as soil class C according to EC8 classification, with $V_{s,30}$ values ranging between 225 and 300 m/s (Figure 2a). The second $V_{s,30}$ model (Figure 2b), which is the most rigorous one, has been obtained from measured V_s profiles at the study area. Compared to this model, the slope-based model of Figure 2a fails to identify the very stiff, rock-like formations with $V_{s,30}$>800 m/s located at the eastern part of the study area, while there is a rather good agreement for the remaining parts of the city. Finally, a third $V_{s,30}$ model was applied (not depicted in Figure 2), which uses an average $V_{s,30}$ value based on EC8 classification obtained from the measured $V_{s,30}$ model shown in Figure 2b, i.e. $V_{s,30}$ values equal to 800 m/s, 580 m/s and 270 m/s were assigned to all regions classified as EC8 soil class A, B and C respectively. The third $V_{s,30}$ model tends to underestimate $V_{s,30}$ values in the regions classified as soil class C, which generally have $V_{s,30}$ values larger than 270 m/s (Figure 2b), and soil class A, and to overestimate $V_{s,30}$ in most regions classified as soil class B.

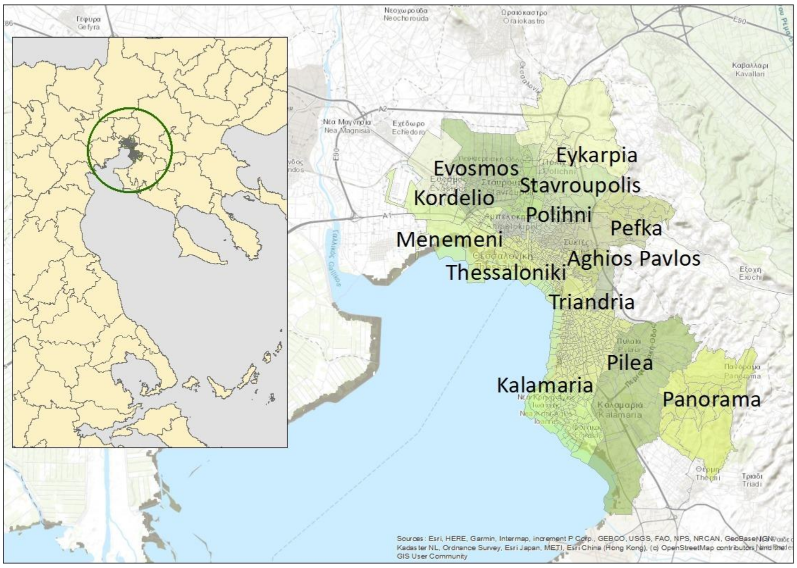
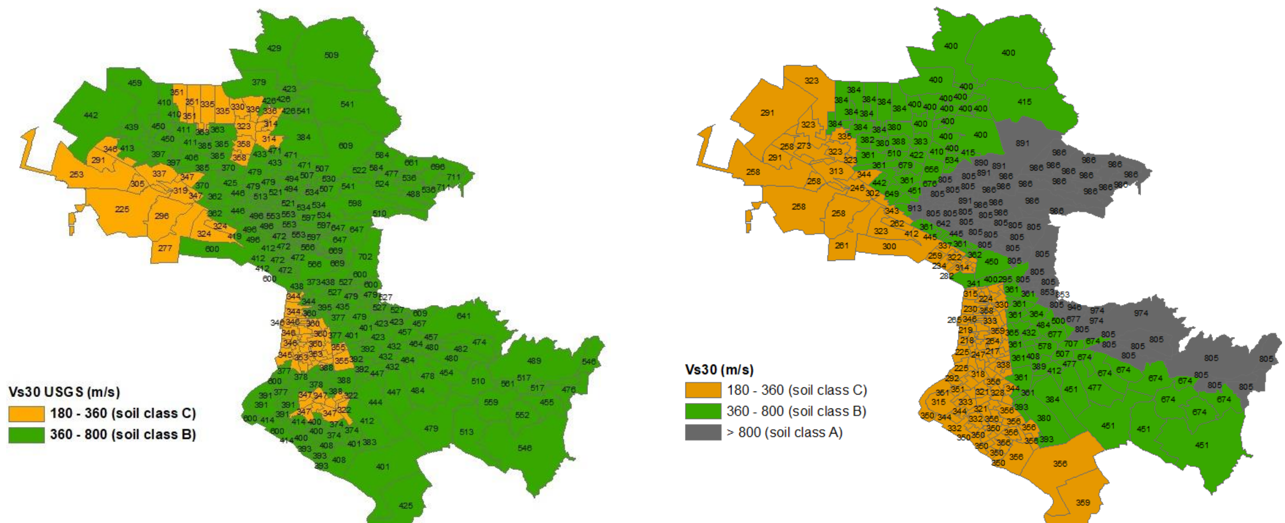


Figure 1. Thessaloniki study area



(a) (b)

Figure 2. Local site conditions in Thessaloniki. Spatial distribution of $V_{s,30}$ based on (a) the USGS global $V_{s,30}$ model and (b) the measured $V_{s,30}$ model.

3 SEISMIC RISK

3.1 Methodology

In order to investigate the effect of the different $V_{s,30}$ models on the estimated economic losses for the city of Thessaloniki, we used the "Stochastic Event Based Probabilistic Seismic Risk Analysis Calculator" available in OpenQuake-engine. This calculator employs an event-based Monte Carlo simulation approach to probabilistic risk assessment in order to estimate the loss distribution for individual assets and aggregated loss distribution for a spatially distributed portfolio of assets within a specified time period (GEM, 2018). The calculator requires the definition of three components, i.e. (a) an exposure model, (b) a vulnerability model with vulnerability functions for each taxonomy represented in the exposure model, and (c) a hazard input in the form of a set of ground motion fields representative of the spatial distribution of the ground shaking at the surface, which can be generated either with OpenQuake's Event Based Probabilistic Seismic Hazard Analysis (PSHA) calculator or provided by the user.

When the "Event-based PSHA Calculator" is used for the seismic hazard computation, the provided seismogenic source model is used to create an earthquake rupture forecast (i.e. list of all of the possible ruptures that can occur in the region of interest), which is then employed to generate stochastic event sets (SES). Due to the random nature of the process, a large number of SES is required in order to reach statistical convergence in both the seismic hazard and risk assessments. For each event in the SES, a ground motion field (i.e. a spatial representation of the surface ground shaking) will be generated, considering the GMPEs (described through a ground motion logic tree) associated with the respective tectonic region as well as the local site conditions, which are taken into account through $V_{s,30}$.The surface ground shaking at a given coordinate will be combined with the physical vulnerability functions for the building classes identified at that location, and multiplied by their replacement costs to compute the expected loss for each event in the SES. This will lead to the derivation of event loss tables, comprising the losses per building class and location for each event in the SES. These tables can be used for the calculation of several risk metrics, including exceedance probability curves and average annualized losses (Silva et al., 2020).

3.2 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) (Brzev et al., 2013), 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 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 (Crowley et al., 2018).

For the development of the exposure model for Thessaloniki we used the results from the 2011 Population - Housing and Buildings Census (ELSTAT, 2011), 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 75342 residential buildings. Figure 3 illustrates the distribution of residential buildings in Thessaloniki based on (a) the construction material, (b) number of storeys and (c) period of construction. The most common building typologies in Thessaloniki city exposure model are reinforced concrete buildings (CR) designed with low to high seismic code (DUCL to DUCH), constructed after 1960. More specifically, the Thessaloniki exposure model consists of around 71300 reinforced concrete buildings and about 44% of buildings have 3-5 storeys. The three prevailing typologies are: CR/LDUAL+DUCL/HBET:3,5; CR/LFINF+DUCH/HBET:3,5; CR/LFINF+DUCL/HBET:3,5.

Table 1. Values of attributes of the GEM Building Taxonomy (Brzev et al., 2013)

Attribute	Element Code	Level 1 Value	Element Code	Level 2 Value
MATERIAL	CR	Concrete, reinforced	PC	Precast concrete
	MUR	Masonry, unreinforced	CL99	Fired clay unit, unknown type
	MR	Masonry, reinforced	ST99	Stone, unknown technology
	MCF	Masonry, confined	ADO	Adobe blocks
	MATO	Material, other	CB	Concrete blocks, unknown type
	W	Wood		
	S	Steel		
Lateral load-resisting system (LLRS)	LWAL	Wall	DNO	Non-ductile (Period of construction: before 1959)
	LDUAL	Dual frame-wall	DUCL	Ductile, low (Period of construction: 1960-1985)
	LFM	Moment frame	DUCM	Ductile, medium (Period of construction: 1986-1995)
	LFINF	Infilled frame	DUCH	Ductile, high (Period of construction: 1996-present)
Height	H	Number of storeys above ground	HBET	Range of number of storeys above ground
			HEX	Exact number of storeys above ground
	SOS	Soft Storey Buildings		

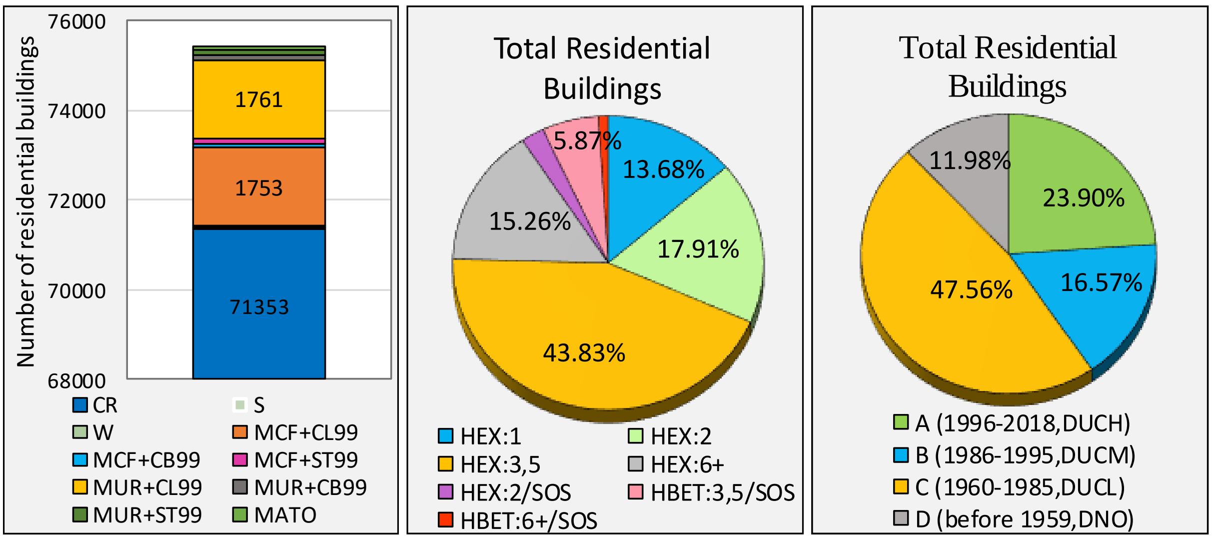


Figure 3. Distribution of residential buildings in Thessaloniki according to (a) construction material, (b) number of storeys and (c) period of construction.

3.3 Vulnerability model

In order to perform seismic loss calculation, we employed appropriate to the Thessaloniki building typologies vulnerability models (Martins and Silva, 2020), which describe the probability distribution of loss ratios for a set of intensity measure levels. The methodology employed by the Global Earthquake Model for their Global Seismic Risk Map (v2018.1) (Martins and Silva, 2020) has been applied to develop the fragility models for European building classes, and consequence models are used to transform the fragility functions to vulnerability functions. The utilized vulnerability functions for the most common building typologies in Thessaloniki city, Greece are presented in Figure 4. We should stress that for these building typologies the adopted vulnerability curves are given in terms of spectral acceleration at 0.3s spectral period which is appropriate for the seismic code plateau values of most RC buildings in Thessaloniki.

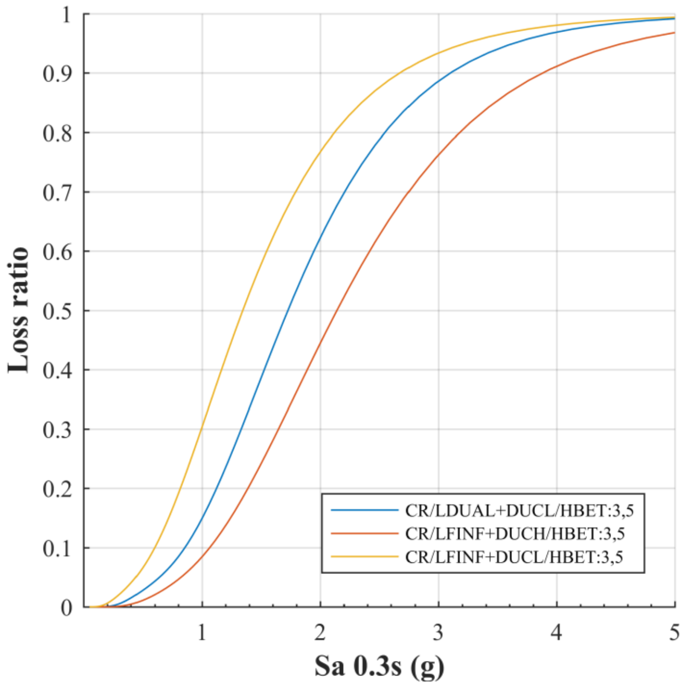


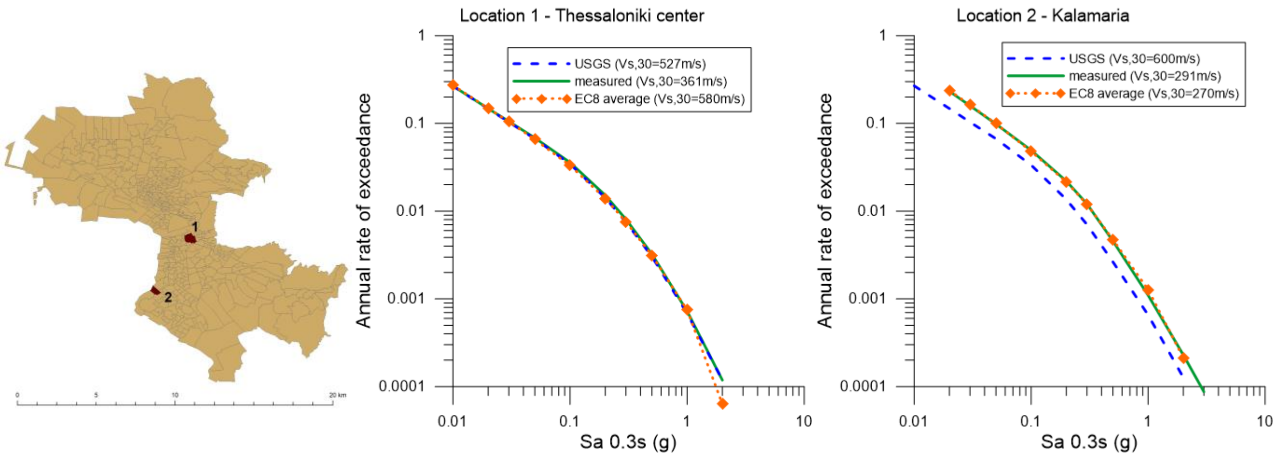
Figure 4. Vulnerability models for the most common building typologies in Thessaloniki city, Greece

3.4 Seismic hazard

For the computation of seismic hazard, we performed an Event-Based Probabilistic Seismic Hazard Analysis (PSHA) in OpenQuake, using the ESHM13 seismic hazard logic tree (Woessner et al., 2015). This specific type of analysis allows calculation of ground-motion fields from stochastic event sets. Traditional results, such as hazard curves and hazard maps, can be obtained by post- processing the set of computed ground-motion fields. The ESHM13 ground motion logic tree, for active shallow crustal regions, uses the GMPEs by Akkar and Bommer (2010), Cauzzi and Faccioli (2008), Chiou and Youngs (2008) and Zhao et al. (2006). Among these models, only the Chiou and Youngs (2008) GMPE adopts directly $V_{s,30}$ as an amplification parameter (and has a relatively low weighting factor in the logic tree equal to 0.20), while the other three GMPE models use broad $V_{s,30}$-based site classes. The Akkar and Bommer (2010) and Cauzzi and Faccioli (2008) GMPEs adopt the EC8 $V_{s,30}$ ranges, while the Zhao et al. (2006) GMPE adopts the $V_{s,30}$ ranges of the U.S. National Earthquake Hazards Reduction Program (NEHRP) Recommended Seismic Provisions for New Buildings and other Structures (BSSC, 2015).

In order to examine the effect of $V_{s,30}$ modeling on the seismic hazard, we compare in Figure 5 the hazard curves computed with the three $V_{s,30}$ models at two different locations, i.e. location 1 (Thessaloniki center) and location 2 (Kalamaria) shown in Figure 5a. For location 1 USGS provides a much higher $V_{s,30}$ value compared to the measured model (527 compared to 361 m/s). Nevertheless, this site is classified as EC8 soil class B and NEHRP soil class C with both models, and, consequently, the resulting amplification due to the ground motion logic tree is similar. The EC8-average curve follows closely the hazard curves of the two other models (Figure 5b). On the contrary, for location 2 (Kalamaria), the site is classified as EC8 soil class B/NEHRP soil class B based on the USGS model ($V_{s,30}$=600 m/s) and as EC8 soil class C/ NEHRP soil class D based on the measured model ($V_{s,30}$=291 m/s), and as a result the hazard curve for the USGS model is below the one for the measured model. The EC8-average curve follows closely the hazard curves of the measured model (Figure 5c).

Figure 6 illustrates the spatial distribution of spectral acceleration at 0.3 s spectral period in the whole study area for a mean return period equal to 475 years, using (a) the USGS $V_{s,30}$ model, (b) the measured $V_{s,30}$ model and (c) the average $V_{s,30}$ value based on EC8 classification. The EC8-average $V_{s,30}$ model (Figure 6c) generally overestimates seismic hazard compared to the other two models, especially due to the lower $V_{s,30}$ values considered for soil class C. The discrepancies between the USGS (Figure 6a) and measured (Figure 6b) $V_{s,30}$ models do not follow a consistent pattern, with the USGS model either underestimating or overestimating seismic hazard compared to the measured $V_{s,30}$ model.



(a) (b) (c)

Figure 5. Hazard curves computed with the 3 different $V_{s,30}$ models at the two locations in Thessaloniki city shown in (a), and more specifically for b) Thessaloniki center and c) Kalamaria.

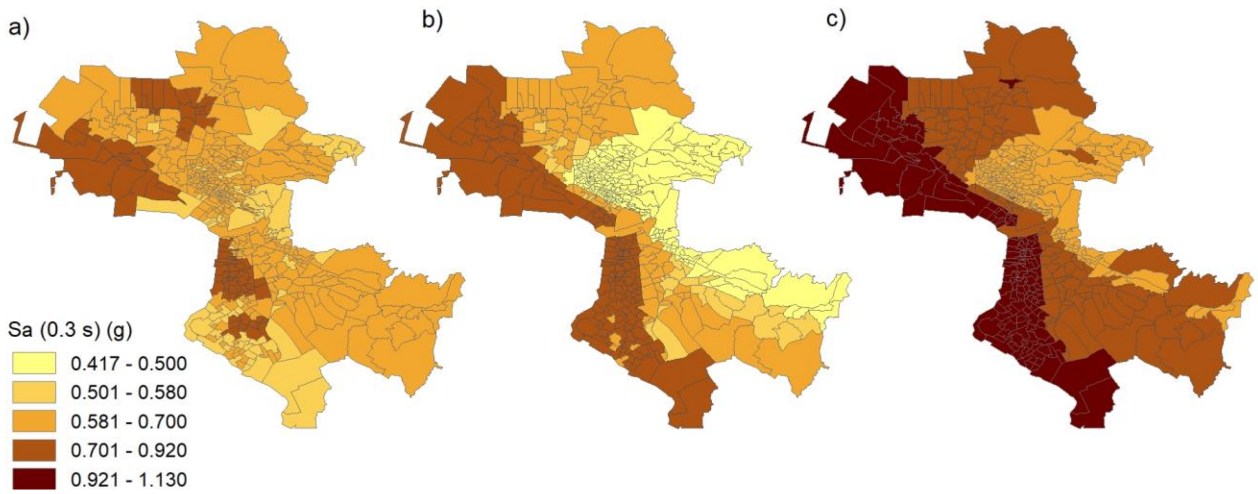


Figure 6. Spatial distribution of spectral acceleration at 0.3s (g) in the city of Thessaloniki for a mean return period equal to 475 years using (a) the USGS $V_{s,30}$ model, (b) the measured $V_{s,30}$ model from the microzonation study of Thessaloniki and (c) an average $V_{s,30}$ value based on EC8 classification.

3.5 Economic losses

Economic losses resulting from the three site models using three different $V_{s,30}$ models are presented in terms of average annual loss in Figure 7, assuming a replacement cost equal to 800 €. As expected, the EC8-average $V_{s,30}$ model (Figure 7c) gives higher average annual losses, as it overestimates seismic hazard compared to the other two models. Generally, for all three $V_{s,30}$ simulations, the average annual losses at urban scale are comparable (ranging between 30.6 and 31.1 million €). However, at local scale, significant discrepancies occur at sites where there are differences in the associated $V_{s,30}$ values of the different models. These discrepancies are smoothed down when considering the whole study area.

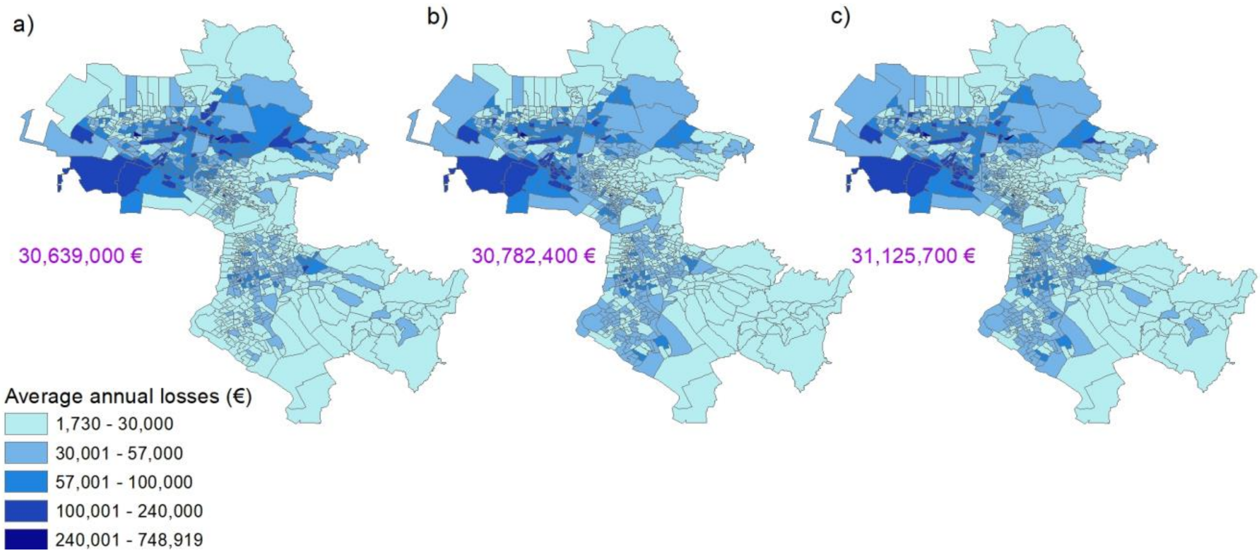


Figure 7 – Average annual losses in Thessaloniki city using (a) the USGS $V_{s,30}$ model, (b) the measured $V_{s,30}$ model and (c) an average $V_{s,30}$ value based on EC8 soil classification.

4 CONCLUSIONS

In this study we investigate whether a very detailed knowledge of site conditions in terms of shear wave velocity $V_{s,30}$ compared to more simplified approaches may affect the seismic losses at large scale. We use 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. The case study is the Thessaloniki city, Greece where we have a very good knowledge of the soil conditions. We used three $V_{s,30}$ models of increasing accuracy, including a simplified one obtained via correlation to topographic slope and a rigorous one, obtained from in situ investigation of the V_s profiles. For the risk assessment, we applied the taxonomy scheme and vulnerability models developed by the Global Earthquake Model. The results are presented in terms of average annual losses. For the specific case study and seismic hazard model, the total estimated average annual losses at urban scale are not significantly affected by the precision of $V_{s,30}$ model, although significant discrepancies may occur at local scale. The low impact of the accuracy of $V_{s,30}$ models on the risk results is mainly attributed to the specific GMPEs used by the applied seismic hazard model, which mainly adopt broad $V_{s,30}$ soil classes instead of the direct use of $V_{s,30}$. The repetition of the seismic risk analyses with the new European seismic hazard model (ESHM20) developed within SERA project, scheduled to be publisher in October 2020, is expected to result in a significant differentiation of the results obtained in this study. Consequently, the main conclusion of this research study is that when the goal is the estimation of the average annual economic losses at large scale (i.e. urban or regional scale), the simplified modeling of the site conditions in the seismic hazard evaluation might not affect substantially the final estimated figure. More rigorous estimates and mapping of the site conditions should necessitate a more advanced modelling of the seismic hazard beyond the simple use of the GMPE approach.

REFERENCES

Akkar, S. & Bommer, J.J. 2010. Empirical equations for the prediction of PGA, PGV, and spectral accelerations in Europe, the Mediterranean region, and the Middle East, *Seismological Research Letters*, Vol 81 (2): 195–206.

Brzev, S., Scawthorn, C., Charleson, A.W., Allen, L., Greene, M., Jaiswal, K. & Silva, V. 2013. GEM Building Taxonomy Version 2.0, GEM Technical Report 2013-02 V1.0.0, 188 pp., GEM Foundation, Pavia, Italy.

BSSC (Building Seismic Safety Council) 2015. NEHRP recommended seismic provisions for new buildings and other structures (FEMA p-750). Washington, D.C.: Building Seismic Safety Council, National Institute of Building Sciences.

Cauzzi, C. & Faccioli, E. 2008. Broadband (0.05 to 20 s) prediction of displacement response spectra based on worldwide digital records, *Journal of Seismology*, Vol 12: 453–475.

CEN, 2004. Eurocode 8: Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings, *European Standard EN 1998-1:2004. Brussels, Belgium: European Committee for Standardisation*.

Chiou, BSJ. & Youngs, RR. 2008. An NGA model for the average horizontal component of peak ground motion and response spectra, *Earthquake Spectra*, Vol 24:173–215.

Crowley, H., Rodrigues, D., Silva, V., Despotaki, V., Romao, X., Castro, J.M., Akkar, S., Hancilar, U., Pitilakis, K., Pitilakis, D., Belvaux, M., Wiemer, S., Danciu, L., Correia, A.A., Bursi, O.S. & Wenzel, M. 2018. Towards a uniform earthquake risk model for Europe, *16th European Conference on Earthquake Engineering*, Thessaloniki, Greece.

ELSTAT (Hellenic Statistical Authority). 2011 Population - Housing and Buildings Census

GEM (2018). The OpenQuake-engine User Manual. Global Earthquake Model (GEM) Open- Quake Manual for Engine version 3.2.0. doi: 10.13117/GEM.OPENQUAKE.MAN.ENGINE.3.2.0, 189 pages.

Kwok, O.L.A., Stewart, J.P., Kwak, D.Y. & Sung, P-L. 2018. Taiwan-specific model for V_{s30} prediction considering between-proxy correlations, *Earthquake Spectra*, Vol 34(4): 1973–1993.

Martins, L., Silva, V. 2020. Development of a Fragility and Vulnerability Model for Global Seismic Risk Analyses, *Bulletin of Earthquake Engineering*, https://doi.org/10.1007/s10518-020-00885-1.

Panou A.A., Hatzidimitriou, P.M., Theodoulidis, N., Stylianidis, K.C., Triantafyllidis, P. & Zacharopoulos, S. 2014. Comparison of damage data from questionnaires and field survey: the case of the June 20, 1978 Thessaloniki (Northern Greece) M6.5 earthquake. *Bulletin of Earthquake Engineering*, Vol 12(6): 2821–2841.

Pagani, M., Monelli, D., Weatherill, G., Danciu, L., Crowley, H., Silva, V., Henshaw, P., Butler, L., Nastasi, M., Panzeri, L., Simionato, M. & Vigano, D. 2014. OpenQuake Engine: An open hazard (and risk) software for the Global Earthquake Model, *Seismological Research Letters*, Vol 85 (3), 692-702.

Papazachos, B. & Papazachou, C. 1997. *The earthquakes of Greece.* Thessaloniki: Ziti Editions

Penelis, G., Sarigiannis, D., Stavrakakis, E. & Stylianidis, K. 1988. A statistical evaluation of damage to buildings in the Thessaloniki, Greece, earthquake of June 20, 1978. In: Proceedings of the 9th world conference on earthquake engineering, Tokyo-Kyoto, Japan, 1988, vol II: 187–192

Silva, V., Crowley, H., Pagani, M., Monelli, D. & Pinho, R. 2014. Development of the OpenQuake engine, the Global Earthquake Model's open-source software for seismic risk assessment. *Natural Hazards*, Vol 72 (3): 1409-1427.

Silva, V. , Amo-Oduro, D., Calderon, A., Costa, C., Dabbeek, J., Despotaki, V., Martins, L., Pagani, M., Rao, A., Simionato, M., Viganò, D., Yepes-Estrada, C., Acevedo, A., Crowley, H., Horspool, N. Jaiswal, K., Journeay, M. & Pittore, M. 2020. Development of a global seismic risk model. *Earthquake Spectra*, https://doi.org/10.1177/8755293019899953

Wald, D.J. & Allen, T.I. 2007. Topographic slope as a proxy for seismic site conditions and amplification, *Bulletin of the Seismological Society of America*, Vol 97 (5): 1379-1395

Woessner, J., Danciu, L., Giardini, D., Crowley, H., Cotton, F., Grünthal, G., Valensise, G., Arvidsson, R., Basili, R., Demircioglu, M.B., Hiemer, S., Meletti, C., Musson, R.M.W., Rovida, A.N., Sesetyan, K. & Stucchi, M.. The SHARE Consortium (2015): The 2013 European Seismic Hazard Model: Key Components and Results, *Bulletin of Earthquake Engineering*, 13 (12), 3553–3596.

Zhao, J.X., Zhang, J., Asano, A., Ohno, Y., Oouchi, T., Takahashi, T., Ogawa, H., Irikura, K., Thio, H.K., Somerville, P.G., Fukushima, Y. & Fukushima, Y. 2006. Attenuation relations of strong ground motion in Japan using site classification based on predominant period, *Bulletin of the Seismological Society of America* 96:898–913. doi:10.1785/0120050122.

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