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AN INITIAL APPROACH TO ESTIMATE THE TIME DEPENDENCY OF SEISMIC RISK IN URBAN AREAS – SEISMIC HAZARD COMPONENT

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Abstract

Recent devastating earthquakes and induced seismicity near infrastructures must become the centerpiece of analysis in reducing risk and increasing resilience, facing up to global urban population growth in the coming decades and the concentration of wealth in cities. The prediction of seismic ground motion and response of structures are key issues in the reduction of seismic urban risk. In this regard, topics like considering low probability/high consequences events and induced seismicity related to the exploitation of energy resources; the seismic ground motion prediction within the non-free-field urban area; the coupling between ground motion and structures/infrastructures responses for natural and induced seismicity including time dependency vulnerability; and the systemic risk of interconnected urban systems are getting more attention between the academic community and the privates companies. There is, therefore, a demand for highly trained scientists with a broad understanding of engineering seismology and earthquake engineering, skills being essential in academic research, in private companies with activities related to risk mitigation and energy facilities and for policymakers.

This study, which is part of the URBASIS-EU project, has the aim to quantify the risk time-dependency in urban areas and including this variability from seismicity and building degradation point of view. The hazard, mainshock-aftershock sequences can threaten the infrastructure, as well as stress changes, can locally and sustainably modify the seismicity rate and the hazard. The structural vulnerability, the building integrity can change through time due to different modifications and upgrades such as obsolescence, climactic event, earthquakes and retrofitting actions. In this initial approach, the topic is addressed only for the seismic hazard computation using the aftershock probabilistic seismic hazard analysis (APSHA) in a case study for the Albanian aftershock sequence on 26 November 2019. The hazard results are computed for different exposure periods and compared with the classical PSHA outcomes. Similarly, some further developments were established in the framework of the research project for the coming years.

Keywords: URBASIS-EU; time-dependency; probabilistic seismic hazard analysis; aftershock sequence; APSHA

1. Introduction

Seismic risk assessment of a region, a portfolio of assets or a single building is a common practice in areas where the seismic hazard level is considerably high or when the importance of the project requires a detailed analysis of the seismic hazard on the site of study. The widely used risk assessment framework follows a probabilistic approach proposed by Cornell, C.A. (1968) [1], where the annual rate of exceedance of a given ground motion intensity measure is evaluated for a given structural period and damping ratio. The occurrence rates are assumed time-invariant constant values and a homogeneous Poisson earthquake occurrence model is normally used. Conventional probabilistic seismic hazard assessment (PSHA) focusses on the mainshock event and considers that the structure does not have any damage from previous events, neither in the same sequence nor in the past.

However, earthquakes typically occur in clusters, in which a mainshock is followed by aftershocks, whose spatial and temporal distribution depends on the characteristics of the triggering mainshock. The aftershock ground motion hazard at a site is related to the magnitude and location of the causative mainshock, and the location of the aftershock is limited to an aftershock zone, which is also dependent on the location and magnitude of the initial mainshock [6]. Therefore, the aftershock occurrence rates are not time invariant, they are at the maximum immediately after the occurrence of the mainshock and decrease with increasing elapsed time from the mainshock. For those reasons, the homogeneous Poisson process is no longer applied and other methodologies must be taken into account to estimate the time-dependency of the seismic hazard. Likewise, the application of the classical PSHA framework to induced seismicity is not straightforward, due to the nonstationary spatiotemporal patterns of the man-made earthquakes. In that case, a similar approach to the post-mainshock situation could be implemented because the area of study is contained in a specific region and a decay in the rate of events is usually observed. This decay in the rate of events is usually modeled following the Omori law [2] and modified Omori law [3] because it predicts a decrease in the number of events as we move away in time from the main event. Nevertheless, the induced seismicity does not always follow this type of pattern, and it depends heavily on the area of study and the type of seismic generating source.

Several authors have addressed the post-mainshock situation, including the analysis of new methodologies for the seismic hazard assessment and structural vulnerability. However, the methodology presented by Yeo, G.L. and Cornell, C.A. (2005) [5], (2009) [6], called APSHA (Aftershock Probabilistic Seismic Hazard Analysis) which used the empirical relationship that describes the exponential decay of aftershocks to formulate a PSHA methodology for quantifying the aftershock seismic hazard at a given site due to the occurrence of a mainshock, was one of the starting point of new developments in this subject. Afterward, several studies have presented their findings including more complexity into the analysis such as the Sequence-based PSHA (SPSHA) [7] which allows to determination of the exceedance rate of the design intensity accounting for the aftershock potential, the closed-form approximation for the aftershock reliability of simple non-evolutionary elastic-perfectly-plastic damage cumulating systems, conditional on different information about the structure [8], the damage progression via Markov-chain-based approachable to account for the change in seismic response of damaged structures as well as uncertainty in occurrence and intensity of earthquakes [9], the Conditional Aftershock Hazard Assessment (CAHA) method which estimates the aftershock hazard at the site conditioned on the mainshock and aftershock events using a correlation between the epsilons registered for the two types of events [10], the Bimodal Hybrid model for time-dependency PSHA which consider a decreasing hazard of last large earthquake cluster, along with a constant hazard of random occurrence of small-to-moderate earthquakes [11]. Last but not least, the Epidemic Type Aftershock Sequence (ETAS) model which considers the aftershock generation process as the superposition of simple Omori's decays and which represents a benchmark in statistical and mathematical seismology [12]; although it was published several years ago, different authors all over the world have implemented and modified new features into the original model which continues as a research topic to date [13], [14], [15],[16].

In terms of structural vulnerability, the cumulative damage is a condition that must be considered if the intention is to quantify the seismic risk. In this regard, the purpose is not just to estimate the damage in the lateral resistant system of the structure from the mainshock, but also from the entire sequence of events. Some examples of the potential for larger ground motions due to aftershocks such as the events of 1983 Coalinga (USA), 2004 Niigata (Japan), 1999 Kocaeli (Turkey), showed that even buildings that have not been damaged by the mainshock have some likelihood of being damaged due to the occurrence of an aftershock. Mainshock-damaged buildings are more susceptible to incremental damage due to aftershocks because their reduced structural capacity decreases the threshold of the ground motion intensity needed to cause further damage [4]. This subject has been studied by several authors from different perspectives, using Markov-chains to capture the cumulative degradation of the structures, scaling mainshock records as aftershock events to determine the damage states, performing cloud analysis for the prediction of the cumulative damage due to the aftershocks, considering the change in the structural fundamental period in the seismic hazard to estimate new vulnerability functions, among others [17], [18], [19], [20], [21].

The ITN Maria Sklodowska-Curie URBASIS-EU project [22] has the aim to address a diverse range of topics in engineering seismology, seismic hazard and risk assessment putting the urban environment as the centerpiece of the project. In order to do that, the project aims to provide a multi-disciplinary training platform for the Early-Stage Researchers (ESR) to develop their individual project and to promote their entrepreneurship and their employability toward the academic, private and insurance or decision-making sector. Nevertheless, this study is focused on the quantification of the seismic risk in urban areas taking into account the time-dependency from the seismicity and the building degradation point of view into the assessment. In other words, on one hand, the hazard, mainshock-aftershock sequences can threaten the infrastructure, as well as stress changes, can locally and sustainably modify the seismicity rate and the hazard; on the other hand, the structural vulnerability, the building integrity can change through time due to different modifications and upgrades such as obsolescence, climactic event, earthquakes and retrofitting actions. However, the project is in the early stages and an initial approach to address the specific subject is presented here focused on including this time-dependency into the seismic hazard assessment. In order to do so, a case study of a real earthquake sequence following the mainshock on 26 November 2019 (02:54, UTC), M_w = 6.4, Durres, Albania earthquake was analyzed according to the APSHA methodology and the results are compared with the PSHA outcomes from the SHARE project [23] for three cities of interest. It is worth mentioning that including the temporal variability in the estimation of the cumulative damage of the structures and therefore, the structural vulnerability and risk assessment will be addressed in later stages of this research project.

2. Methodology

In the framework of the classical probabilistic seismic hazard analysis (PSHA), one of the main goals is to estimate the annual probability of exceedance from a particular intensity measure (i.e. spectral acceleration). For this purpose, seismic sources must be characterized in the area of study with the information of the earthquake catalog which contains details from the recent and historical events. Therefore, a declustering process is performed to the resulted catalog in order to remove foreshocks and aftershocks due to the assumption of a homogenous Poison's process. After the declustering, Gutenberg and Richter's law is used to determine the distribution or the exceedance rate of mainshock magnitudes. Later on, using the ground motion prediction equations, the exceedance rate from one magnitude can be transformed into the exceedance rate from another intensity measure. All the previous information combined with the total probability theorem will result in the Eq. (1) used to compute the mean rate of exceeding an intensity measure (*Y*) from the level *y* [6].

$$\widetilde{\upsilon}(y,T)=\upsilon T\int_R\int_{m_l}^{m_u} P(Y>y|m,r)\, f_{R|M}(r|m)\, f_M(m)\,\mathrm{d}m\,\mathrm{d}r \tag{1}$$

Where υ is the mean annual rate of the mainshocks, *T* is the time interval, $P(Y>y|m,r)$ is the conditional probability of IM > x given an event (m, r), f_M is the probability density function (PDF) of mainshock magnitudes and $f_{R|M}$ is the conditional PDF of distance given magnitude.

In the case of the APSHA [6], which neglects the foreshocks and considers the mainshock as the main event of the sequence, the interest is to find out the rate of occurrence of aftershocks and its decay with increasing the elapsed time from the occurrence of the main event. This decrease can be modeled by the modified Omori law and by the Gutenberg-Richter relationship to determine the mean aftershock rates to a specific area.

In Eq. (2), $\gamma(t,m;m_m)$, is the mean daily rate of aftershocks with moment magnitude *m* or larger at time *t* following a mainshock of moment magnitude m_m, and can be calculated using the following equation.

$$\gamma(t,m;m_\mathrm{m})=\frac{10^{a+b(m_\mathrm{m}-m)}}{(t+c)^p} \tag{2}$$

After several derivations and assumptions made, the mean number of aftershocks with magnitudes between m_l and m_m in the time interval $[t, t+T]$ following a mainshock of magnitude m_m, denoted $\mu^*(t,T;m_m)$, can be computed using the Eq. (3)

$$\mu^*(t,T;m_\mathrm{m}) = \int_t^{t+T} \mu(\tau;m_\mathrm{m})\,\mathrm{d}\tau = \frac{10^{a+b(m_\mathrm{m}-m_\mathrm{l})}-10^a}{p-1}\left[(t+c)^{1-p}-(t+T+c)^{1-p}\right] \tag{3}$$

Therefore, to calculate the mean number of aftershocks in $[t, t+T]$ exceeding site ground motion y, where there is explicit dependence on both t and T. This mean number is represented by $\mu(y,t,T;m_m)$, which can be calculated using the Eq. (4)

$$\mu(y,t,T;m_\mathrm{m}) = \mu^*(t,T;m_\mathrm{m}) \int_R \int_{m_\mathrm{l}}^{m_\mathrm{m}} P(Y>y|m,r)\, f_{R|M}(r|m)\, f_M(m;m_\mathrm{m})\,\mathrm{d}m\,\mathrm{d}r \tag{4}$$

It can be noted that the formulation for APSHA is almost identical to the conventional PSHA, except that $\upsilon(y,T)$ is replaced by $\mu(y,t,T;m_m)$, which is a function of t, T and m_m.

3. Results and discussion

On November 26, 2019, an earthquake struck the central-western part of Albania. It was a M_w 6.4 event with an epicenter located offshore northwestern Durres, around 7 km north of the city and 30 km west from the capital city of Tirana and with a focal depth about 10 km. This event was felt in Bulgaria, Italy, Serbia, Bosnia and Herzegovina and part of Greece. As a consequence of the earthquake, several people were killed and hundreds injured in the region, concentrated in the coastal city of Durres and the town of Thumanë, 40 km to the north-west of Tirana [24]. Fig. 1 on the left, shows the seismic activity of the area joining the ISC and EMSC catalogs from 1920 to 2020 and locating with a red star the mainshock of the event.

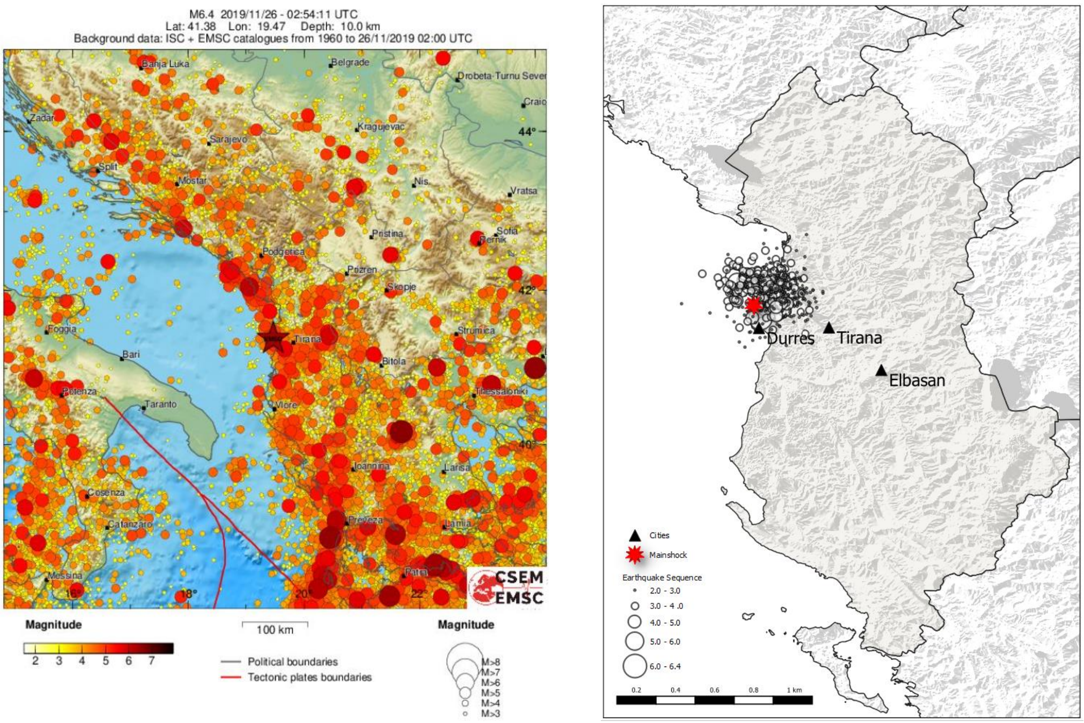

Fig. 1 – Left: ISC + EMSC catalogues from 1960 to 2020 [25]. Right: Location of the mainshock-aftershock sequence (26/11/2019 - 10/02/2020) and nearby cities.

In addition, a seismic sequence of events was recorded for several days, even months after the mainshock. Fig. 1 on the right, illustrates the location of the mainshock-aftershock sequence between November 26, 2019, to February 8, 2020, and the location of some nearby cities.

Based on the located aftershocks, a catalog comprising 682 events was found. 403 events have a magnitude greater than M_{min} = 2.5 and that catalog is assumed to be complete. Fig. 2 shows the time and depth histogram of the earthquake sequence, while Fig. 3 depicts the magnitude histogram and distribution of the earthquake sequence. As can be seen, there is a slow decrease in the aftershock number with time, where several gaps are presented and some smaller increases while the tendency continues over time. In terms of depth, there is a clear selection of events bellow 40 km with special attention around 10-20 km. Regarding the magnitudes, a general trend to decrease over time, although some fluctuations are presented within magnitudes.

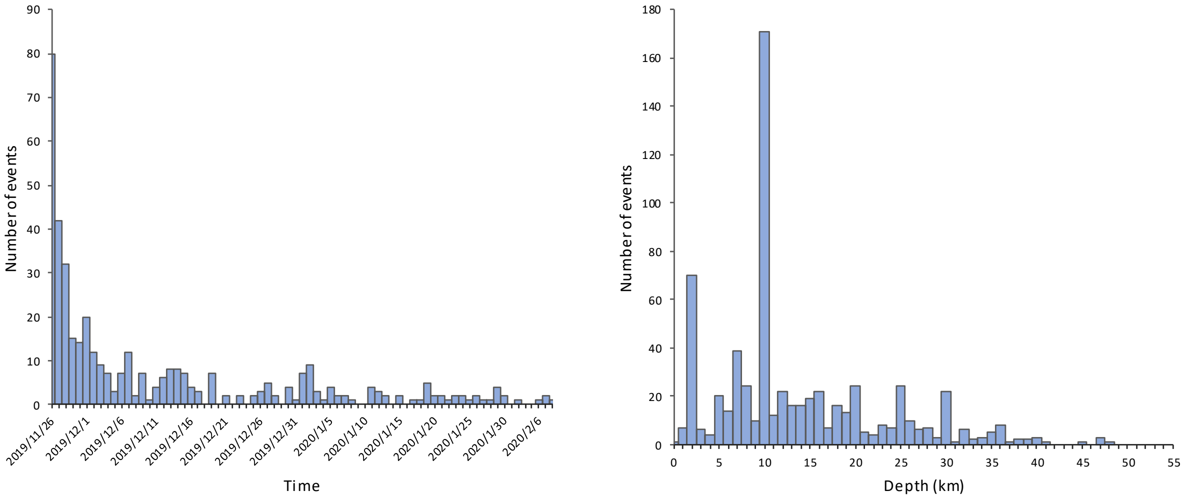

Fig. 2 - Right: Time histogram of the sequence. Left: Depth histogram of the sequence

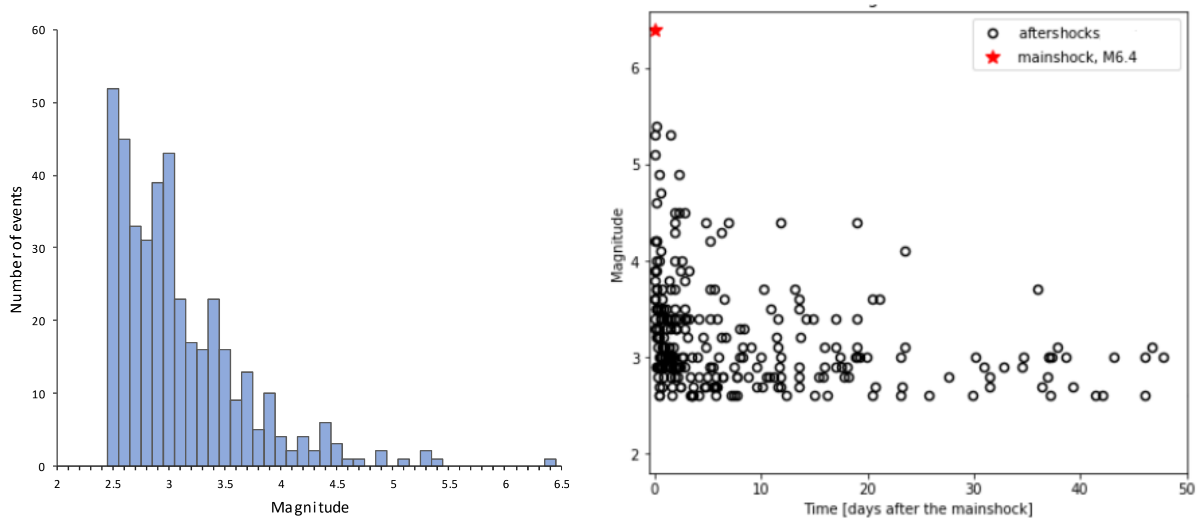

Fig. 3 - Right: Magnitude histogram of the sequence. Left: Magnitude distribution of the sequence.

By applying the modified Omori law, on the selected data, the parameters required for Eq. (2) are determined having as a result $c = 0.96$, $K = 114.11$ and $p = 1.22$. Fig. 4 on the left, shows the fitting of the selected data using the modified Omori law, and it can be seen as a reference to the preliminary estimation presented in the first 10 days [26]. Likewise, Fig. 4 on the right, presents a Gutenberg-Richter analysis of the dataset in order to estimate the *b-value* required for the analysis, the result is $b = 0.74$. Nonetheless, it must be said that a credible *b-value* came from a complete catalog within the magnitude range assumed and some small events have probably gone undetected especially during the first hours or days, as well as merged in the coda of bigger events [27]. Therefore, and according to the purpose of this study, the *b-value* obtained is considered suitable to represent the seismic activity of the area of analysis.

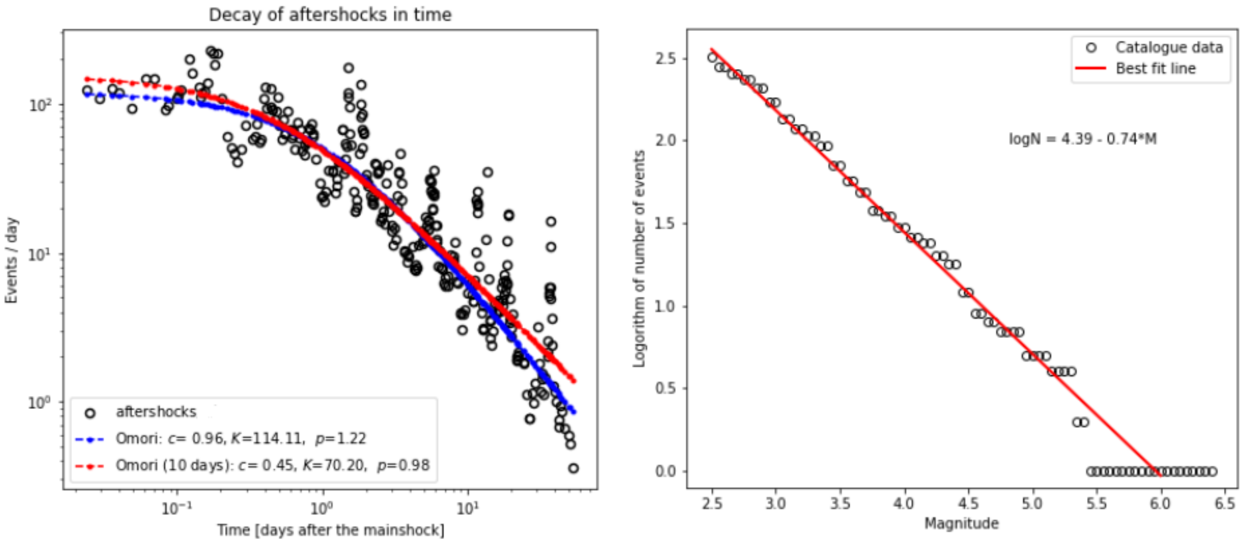

Fig. 4 - Right: Modified Omori Law calculation (10 days calculation [26]). Left: Mean number of aftershocks with magnitude m, for different time frames.

Similarly to Yeo, G., and Cornell, C.A. (2009) [6] the Eq. (3) was employed to compute the mean number of aftershocks with magnitudes between $m_l < m < m_m$ in the time interval [t, $t+T$]; it is worth remembering that [t, $t+T$] is the time interval after the mainshock considered with magnitude, m_m. In order to see the behavior and the equation, two analysis was made. First, the time parameters were set to $T = 365$ *days* and varying t from *1 day*, *7 days*, *1 month*, *6 months* and *1 year* to capture the variation of the decay in terms of magnitude. Fig. 5 on the left, illustrates how with the increase of the time frame the decay of the mean number of aftershock decreases in terms of magnitude.

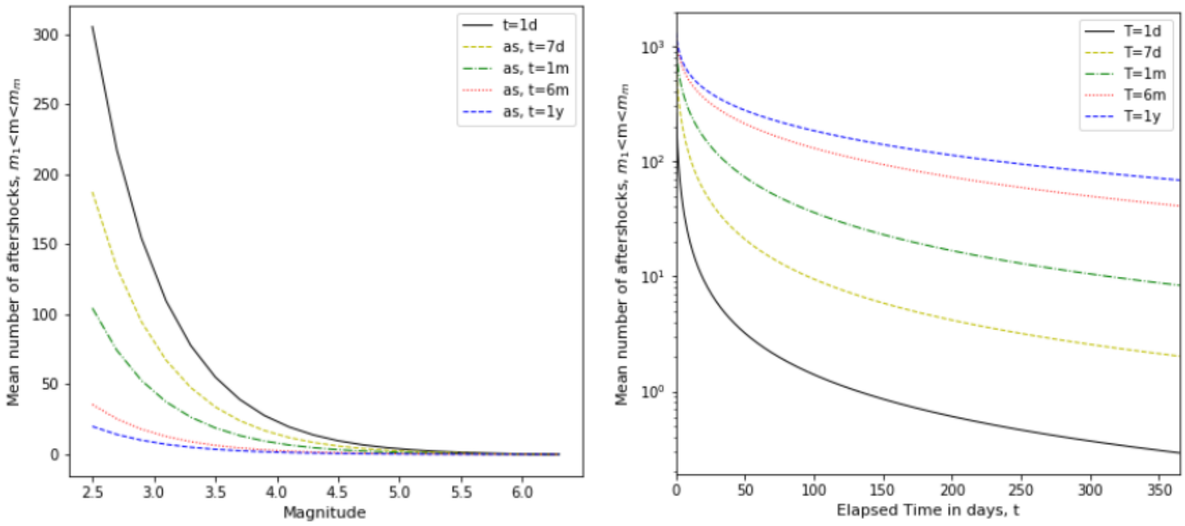

Fig. 5 - Mean number of aftershocks with magnitude m, for different time frames.

Second, the duration time was modified between T = *7 days*, *1 month*, *6 months* and *1 year*, and the mean number of aftershocks was computed as a function of elapsed time, t. Fig. 5 on the right, shows this behavior, and as it can be seen, the number of aftershocks decreases if the exposition time decrease when the elapsed time increases.

Then, the 2013 Euro-Mediterranean Seismic Hazard Model (ESHM13), which was developed within the SHARE Project [23], was employed to obtained all the necessary seismic parameters (i.e. seismic sources, ground motion prediction equations, weighting factors, etc.) as well as to compare our estimations with a PSHA outcomes for the cities under analysis. Fig. 6 on the left, illustrates the tectonic regionalization used in the ESHM13 model for the selection of GMPEs, area sources are depicted as thin black lines and tectonic regime is shown for each case [28]; on the right, a zoom in the zone of analysis depicts the area sources of the ESHM13 model.

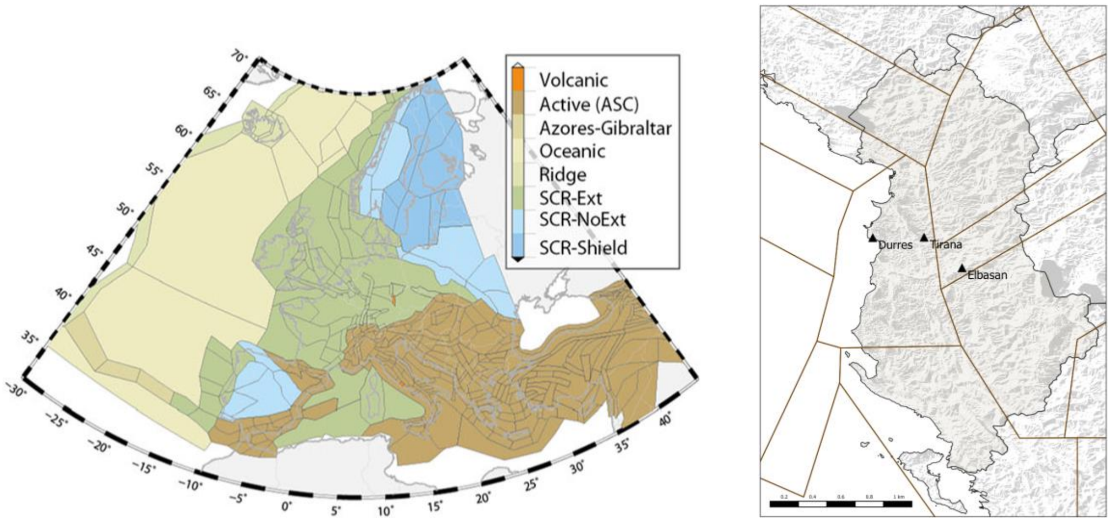

Fig. 6 - Left: Tectonic regionalization used in the ESHM13 model [28]. Right: Location of the cities under study and area sources (Active ASC) from the ESHM13 model.

The GitHub repository (https://github.com/gem/oq-engine) of the OpenQuake engine [29] was used to modify the mean rates of exceedance for the ones computed in this study for the area of analysis. Fig. 7 to Fig. 9 show the APSHA curves for the time interval of *1 day*, *1 week*, *1 month*, *6 months* and *1 year* after the occurrence of the mainshock for the cities of Durrës, Tirana, and Elbasan at PGA and SA(0.5) respectively.

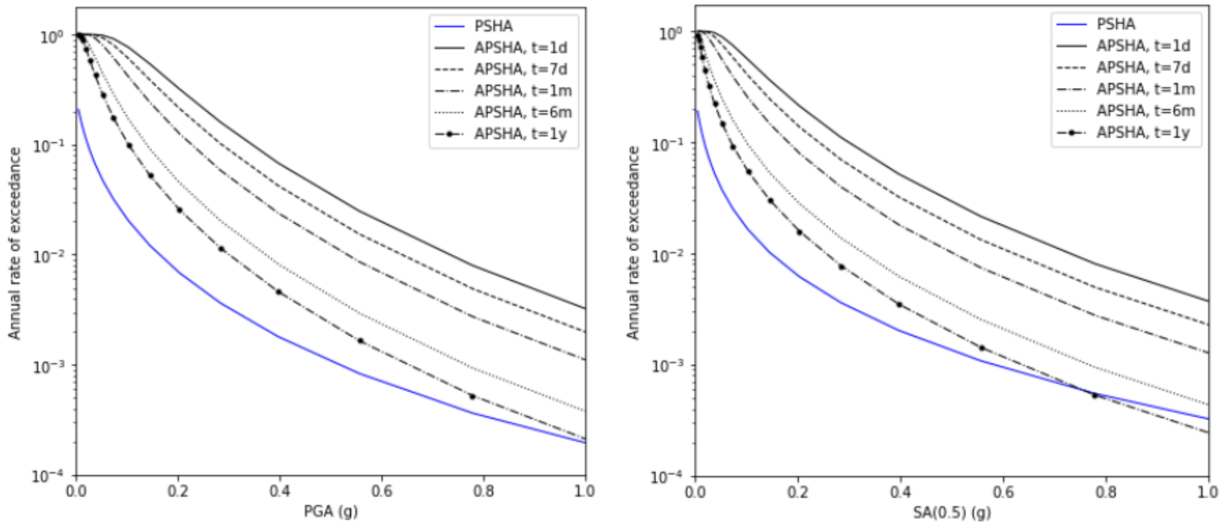

Fig. 7 - Comparison of mainshock and aftershock site hazard curves at Durrës city for a different elapsed interval from the occurrence of the main event. Left: PGA. Right: SA(0.5).

As expected, the aftershock hazard decreased as time frame after the mainshock increases and also, APSHA curves are greater than the PSHA curves in most of the cases, the analysis of *t = 1 year* for SA(0.5) presents different behavior at higher values of intensity measure. These results allow observing the significant difference that may exist between mainshock hazard and aftershock hazard using the APSHA methodology for the cases described in this study.

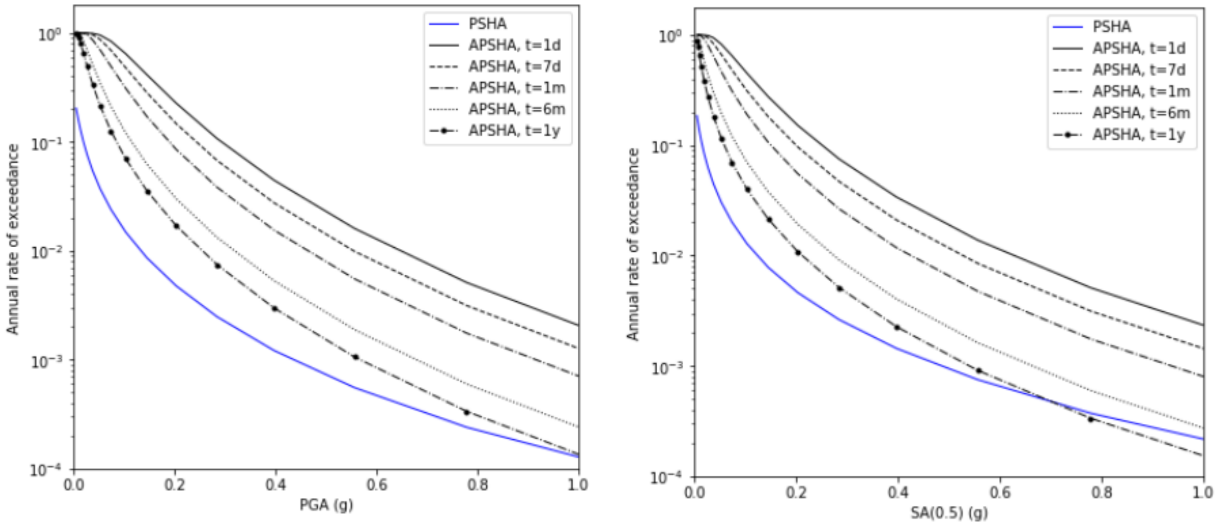

Fig. 8 - Comparison of mainshock and aftershock site hazard curves at Tirana city for a different elapsed interval from the occurrence of the main event. Left: PGA. Right: SA(0.5).

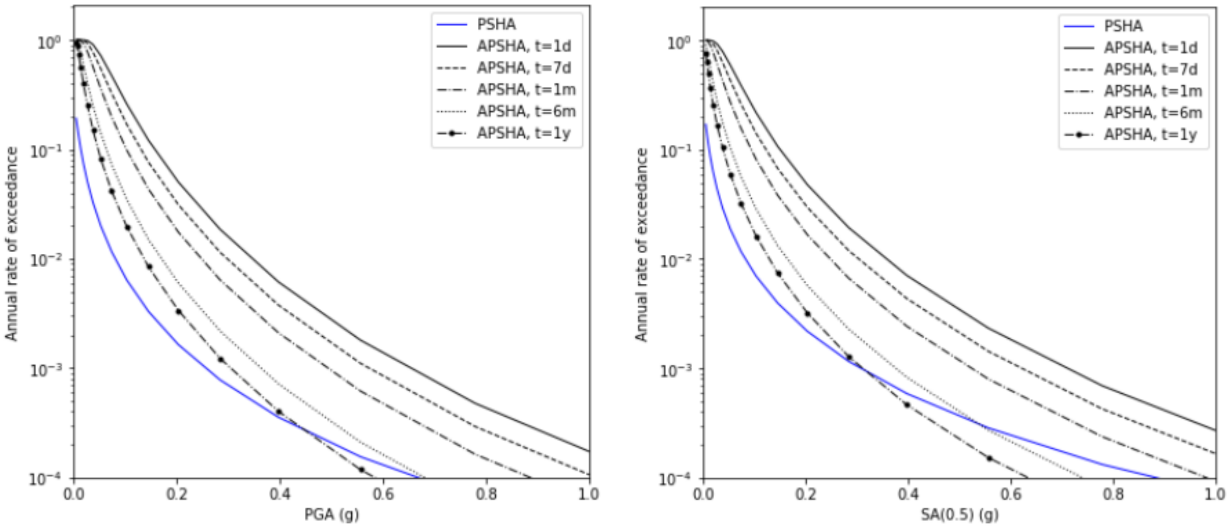

Fig. 9 - Comparison of mainshock and aftershock site hazard curves at Elbasan city for a different elapsed interval from the occurrence of the main event. Left: PGA. Right: SA(0.5).

Moreover, in order to appreciate the difference in terms of location, the PSHA and APSHA curves with a fixed value of elapse time (*t = 7 days*, *T = 365 days*) were estimated for the three cities under study, Durrës, Tirana, Elbasan. Fig. 10 exhibits the results for the cities mantioned and as it can be observed, the distance plays a roll in the hazard level for both methodologies (left: PSHA, right: APSHA). The tendency of higher hazard values for APSHA remains the same for all sites.

The results presented in this study show the application of the APSHA methodology to a specific site under an aftershock sequence and its impact in the estimation of the seismic hazard level at a site.

Introducing the temporal variable in the hazard's estimation plays an important role in the outcomes and must take into account carefully.

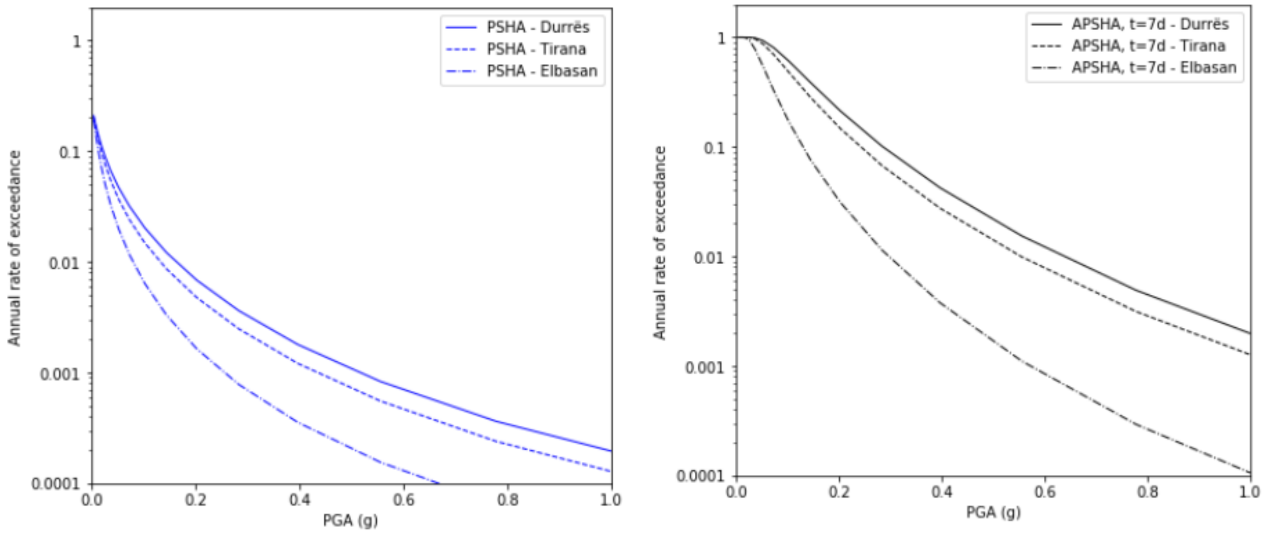

Fig. 10 - Annual rate of exceedance PGA for the three cities. Left: PSHA. Right: APSHA considering t = 7 days and T = 365 day.

Finally, it is worth mentioning that some assumptions made here to obtain the requires parameters for the aftershock decay could be improved, such as:

- The completeness of the catalog for a magnitude threshold.
- The calibration of the *b-value* for the aftershocks.
- The area interest of the earthquake sequence.
- The consideration of previous clusters in the region.
- The contribution of different seismogenic sources.
- The whole weighting scheme of the logic tree used in the PSHA.
- Among others.

However, for the initial approach stated for this study, the parameters found and the results obtained are suitable to represent the impact to take into account the time-dependency into the seismic hazard calculations.

4. Conclusions and future developments

A case study using the APSHA methodology was performed for the aftershock sequence of the Albanian earthquake on November 26, 2019, M_w 6.4. The outcomes presented suggest that the sites under analysis experienced spectral acceleration values in the first days higher than those estimated with PSHA. In addition, the estimations for different time frames since the occurrence of the mainshock show higher hazard levels for APSHA than PSHA results.

Some assumptions were made in order to obtain the parameters of the aftershock decay that could be improved, such as a reliable and complete catalog for the magnitudes-threshold, the detailed area of influence of the aftershock sequence, the contribution of different seismogenic sources, the whole weighting scheme of the logic tree, among others.

The APSHA methodology was used to estimate the contribution of the aftershock sequence to the hazard level for a specific location. However, other methodologies briefly commented on the introduction of this document could offer a better interpretation of the complexity of the problem and those will be considered in future developments of this project.

The Modified Omori law is well-known and used for induced seismicity problems to estimate the rate of small events after stimulation of geothermal reservoirs or any other human activities. Further analysis of this regard during this project will be made, and specific case study applications to include the time-dependency into the quantification of the seismic risk.

The purpose of the initial approach for this research project is to create the basis for understanding the problem to develop the tools and knowledge to achieve the proposed objectives. For that reason, improvements and complexity will be added in the coming years, with the idea to contribute to the knowledge of this subject and also in the reduction of the seismic risk in urban areas. Although this study was focus on the contribution of the time-dependency into the seismic hazard calculations, analysis of the cumulative damage of the structure, and derivation of fragility curves will be performed to estimate seismic risk for aftershock sequences and induced seismicity.

5. Acknowledgements

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6. Copyrights

7. References

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