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A sensitivity analysis of sequence-based seismic hazard assessment for the United Kingdom

Mabel Orlacchio – Università degli Studi di Napoli Federico II, Napoli, Italy, mabel.orlacchio@unina.it

Pasquale Cito – Università degli Studi di Napoli Federico II, Napoli, Italy, pasquale.cito@unina.it

Iunio Iervolino – Università degli Studi di Napoli Federico II, Napoli, Italy, iunio.iervolino@unina.it

Abstract: Even if earthquakes occur as time-space clusters, classical probabilistic seismic hazard analysis (PSHA) typically considers only the largest-magnitude event within each cluster; i.e., the mainshocks. This implies assuming that the earthquakes, preceding and following the mainshock in each sequence, that is, foreshocks and aftershocks, respectively, have a negligible effect on the seismic hazard at the construction site. On the other hand, the recent advances of earthquake engineering allow to include aftershocks in the hazard assessment through the so-called sequence-based PSHA (SPSHA). SPSHA modifies the formulation of PSHA and models aftershocks occurrence relying on the modified Omori law. For the United Kingdom (UK), the Omori parameters were recently estimated using a relatively simple procedure, and data from only four sequences. This study investigates the implications, on SPSHA results, of the Omori parameters, considering uniform hazard spectra (UHS) for three sites across the country, characterized by different seismic hazard according to PSHA. It found that, in the UK, the sensitivity of the UHS' to the parameters choice is limited, whatever the seismic hazard of the site and the exceedance return period, likely because of the generally limited seismic hazard in the country.

Keywords: probabilistic seismic hazard analysis, mainshock-aftershocks sequences, Omori law, hazard increments.

1. Introduction

Earthquakes occur within time-space clusters. In each cluster, the largest magnitude event is usually identified as the mainshock, whereas those preceding and following the mainshock are the foreshocks and aftershocks, respectively. The information about the earthquakes (e.g., magnitude, date and location of the events), that occurred in a region of interest, are included in so-called earthquake catalogs, which are one of the main inputs to probabilistic seismic hazard analysis (PSHA; McGuire, 2004). In its classical formulation, PSHA assumes that earthquakes occur in time at the source following a homogenous Poisson process (HPP). The latter is completely defined by the mean number of earthquakes in the unit-time (usually one year), that is, the rate, which is calibrated using the catalog. However, in order to comply with the HPP model, foreshocks and aftershocks are removed from the catalog via de-clustering techniques (e.g., Gardner and Knopoff, 1974). In these hypotheses, PSHA allows deriving the rate of (only) mainshocks exceeding a ground motion intensity measure (IM) threshold (im) at the site of interest.

Literature shows that it is actually possible to include the effects of aftershocks in the seismic hazard assessment (i.e., neglecting foreshocks) by means of the so-called sequence-based PSHA (SPSHA; Iervolino et al., 2014). Acknowledging that mainshock-aftershock sequences occur at the same rate as the mainshocks, SPSHA allows to get the rate of mainshock-aftershocks sequences exceeding im at least once at the site of interest.

In the context of SPSHA, occurrence of aftershocks in time is modelled via nonhomogeneous Poisson process (NHPP), conditional to magnitude and location of the mainshock triggering the sequence. The time-variant rate of such a NHPP is modelled by means of the modified Omori law (Utsu, 1961). The parameters of the Omori law are calibrated based on the available instrumental data about the sequences in the region of interest. For example, Lolli and Gasperini (2003) and Reasenberg and Jones (1989) estimated the Omori model parameters for Italy and California, respectively.

Orlacchio et al. (2022) calibrated the Omori parameters for the UK, based on the earthquake catalog by Villani et al. (2020). Because of a general paucity of data pertaining to aftershocks, a relatively simple estimation procedure, relying on only four sequences, was performed. The uncertainty of the estimated parameters, an issue that is taken into account instead according to literature (e.g., Ogata, 1978), was not quantified. It was also assumed that the considered sequences are complete above a certain magnitude, without any specific completeness assessment.

The objective of the study herein presented is to investigate how the simplified calibration procedure of the Omori law affects the SPSHA results for the UK. In turn, this may be helpful in understanding if a more refined estimation procedure, which could possibly lead to different values of the Omori parameters, would introduce appreciable differences on the sequence-based seismic hazard results. To do so, SPSHA is carried out using the source model for the UK developed by the British Geological Survey (BGS; British Geological Survey, 2020) and assuming seven sets of Omori parameters. These sets include the parameters for the UK estimated pooling together all the sequences, the parameters from the consolidated models of Lolli and Gasperini (2003) and Reasenberg and Jones (1989) , and the parameters fitted specifically for each of the four sequences detected for the UK. The assessment is conducted considering three sites across the country characterized by different seismic hazard according to classical PSHA.

The remainder of the paper is structured such that PSHA and SPSHA are briefly recalled, first. Subsequently, the considered models for the UK and the procedure for calibrating the Omori parameters are illustrated. Before assessing the sensitivity to such parameters of the SPSHA results, in terms of uniform hazard spectra (UHS) with selected exceedance return periods $\left(T_r\right)$, the effects of aftershocks on the seismic hazard for the three sites are explored by comparing the UHS to the PSHA counterpart.

2. Classical and Sequence-Based Probabilistic Seismic Hazard Analysis

Classical PSHA (Cornell, 1968) provides the average number of mainshocks that cause exceedance of im at the site of interest in one unit time. This rate, indicated herein as $\lambda_{im,E}$, defines the HPP regulating the occurrence of earthquakes that cause im to be exceeded at the site over time. $\lambda_{im,E}$ is computed as per equation (1); i.e., the hazard integral:

$$\lambda_{im,E} = \nu_{\mathrm{E}} \cdot \int_{r_{E,min}}^{r_{E,max}} \int_{m_{E,min}}^{m_{E,max}} P\left[IM_E > im \mid M_E = m, R_E = r, \underline{\theta}\right] \cdot f_{M_E,R_E}\left(m,r\right) \cdot dm \cdot dr \,. \quad (1)$$

In the equation, the subscript $\left(E\right)$ is used to distinguish the terms referring to mainshock from those pertaining to aftershocks (to follow). Thus, ν_E is the rate of mainshocks with a magnitude equal to or greater than the minimum ($m_{E,min}$) deemed possible for the source and it is calibrated based on a de-clustered catalog. The term $\mathrm{P}\left[IM_E > im \mid M_E = m, R_E = r, \underline{\theta}\right]$, provided by a ground motion prediction equation (GMPE), represents the conditional probability that im is exceeded due to a mainshock with magnitude equal to m and source-to-site distance equal to r. This probability also depends on $\underline{\theta}$, which represents additional covariates, such as local soil site conditions and/or rupture mechanism of the source, to be taken into account. The $f_{M_E,R_E}(m,r)$ term is the joint probability density function (PDF) of the mainshock magnitude (M_E) and source-to-site distance (R_E) random variables. Usually, M_E and R_E are assumed to be stochastically independent, therefore $f_{M_E,R_E}(m,r)$ is calculated as $f_{M_E}(m) \cdot f_{R_E}(r)$, where $f_{M_E}(m)$ and $f_{R_E}(r)$ are the marginal distributions of magnitude and distance of the mainshocks, respectively. The $f_{M_E}(m)$ PDF is defined between $m_{E,min}$ and the maximum magnitude considered for the source, $m_{E,max}$, and it is often assumed to follow a truncated exponential distribution derived by the Gutenberg-Richter (GR) relationship (Gutenberg and Richter, 1944). The $f_{R_E}(r)$ PDF, defined between $r_{E,min}$ and $r_{E,max}$, only depends on the geometry of the source and the position of the site with respect to the source itself.

Iervolino et al. (2014) demonstrate that it is possible to get the mean number of seismic sequences (mainshocks and following aftershocks) that cause at least one exceedance of im at the site in the unit time, λ_{im}. In fact, SPSHA enables to account for the effects of aftershocks (i.e., neglecting foreshocks) using the same input as in the PSHA (i.e., the rate of mainshocks from a de-clustered catalog) and modelling the occurrence of aftershocks using a NHPP, conditional to the mainshock magnitude and location, in accordance with Yeo and Cornell (2009). Thus, λ_{im} can be computed via equation (2):

$$\lambda_{im} = \nu_E \cdot \left\{ 1 - \int_{r_{E,min}}^{r_{E,max}} \int_{m_{E,min}}^{m_{E,max}} P\left[IM_E \le im \mid M_E = m, R_E = r, \underline{\theta}\right] \times \right. \\ \left. \times e^{-E\left[N_{A|m}(0,\Delta T_A)\right] \cdot \int_{r_{A,min}}^{r_{A,max}} \int_{m_{A,min}}^{m} P\left[IM_A > im | M_A = m_A, R_A = r_A, \underline{\theta}\right] \cdot f_{M_A,R_A|M_E,R_E}(m_A, r_A | m, r) \cdot dm_A \cdot dr_A} \cdot f_{M_E,R_E}(m,r) \cdot dm \cdot dr \right\}. \quad (2)$$

In the equation, the (A) subscript denotes the variables referring to aftershocks. The terms ν_E, $\mathrm{P}\left[IM_E \le im \mid M_E = m, R_E = r, \underline{\theta}\right] = 1 - \mathrm{P}\left[IM_E > im \mid M_E = m, R_E = r, \underline{\theta}\right]$ and $f_{M_E,R_E}(m,r)$ are the same defined in equation (1). The exponential term within the integral represents the probability that none of the aftershocks, triggered by the mainshock with magnitude $M_E = m$ and distance $R_E = r$, causes exceedance of im between $t = 0$ (i.e., the occurrence time of the mainshock) and the duration of the sequence, ΔT_A. $P\left[IM_A > im_A \mid M_A = m_A, R_A = r_A, \underline{\theta}\right]$, which is provided by the GMPE, is the probability that im is exceeded due to an aftershock of magnitude $M_A = m_A$ and source to site distance $R_A = r_A$. The term $f_{M_A,R_A|M_E,R_E}$ is the joint PDF of magnitude and distance of aftershocks, which is conditional on $\{M_E, R_E\}$. Assuming that M_A and R_A are conditionally independent random variables (usually in the case of a single seismic source), it is $f_{M_A,R_A|M_E,R_E} = f_{M_A|M_E} \cdot f_{R_A|M_E,R_E}$, where $f_{M_A|M_E}$ is the conditional distribution of aftershocks magnitude (i.e., following the GR), whereas $f_{R_A|M_E,R_E}$ is the conditional distribution of the distance of the site to aftershocks. The magnitude distribution of the aftershocks is bounded by a minimum magnitude, $m_{A,min}$ and m (i.e., the mainshock magnitude). The distribution of the aftershocks' distance is bounded within $r_{A,min}$ and $r_{A,max}$, which are the minimum and maximum values possible for R_A, respectively. Finally, $E\left[N_{A|m}\left(0,\Delta T_A\right)\right]$ is the expected number of aftershocks, with magnitude between $m_{A,min}$ and m, generated by a mainshock with magnitude $M_E = m$, in ΔT_A. It is computed assuming that aftershocks occurrence in time follows the modified Omori law (Yeo and Cornell, 2009), with parameters $\{a,b,c,p\}$, as per equation (3):

$$E\left[N_{A|m}\left(0,\Delta T_A\right)\right]=\frac{10^{a+b\cdot\left(m-m_{A,min}\right)}-10^{a}}{p-1}\cdot\left[c^{1-p}-\left(\Delta T_A+c\right)^{1-p}\right]. \tag{3}$$

3. Hazard input models

The BGS study describes the source model and the analysis at the basis of the official PSHA for the UK. As discussed in Mosca et al. (2022), such an analysis is carried out via a complex logic tree, consisting of several branches. The branches share the source model, which is based on twenty-two seismogenic zones, whose geometry and ID are shown in Fig. 1 (together with three sites of interest that will be considered later). For each zone, the magnitude frequency distribution of the earthquakes follows a GR relationship, with minimum (moment) magnitude equal to 3.0. Four maximum magnitude (i.e., 6.5, 6.7, 6.9 and 7.1) and twenty-five couples of b values and $\nu_E\left(M_E \geq 3.0\right)$ (i.e., the annual rate of mainshocks with magnitude equal to or larger than 3.0) are identified for each seismogenic zone (values are given in British Geological Survey, 2020). The study considers five different GMPEs, which are adapted, considering rock site conditions, to account for both the effects of elastic amplification due to shear wave velocity structure and near-surface attenuation specific for the UK, via the host-to-target adjustments factors.

In this study, these models are used for developing both PSHA and SPSHA, yet with some simplifications aimed at avoiding the implementation of the full logic tree. Thus, for each seismogenic zone, the GR relationship is defined by considering the weighted mean values over values of $\nu_E\left(M_E \geq 3.0\right)$ and b, and maximum magnitude equal to 6.5 (i.e., the magnitude with the largest weight). As pertaining to GMPEs, only the one of Bindi et al. (2014) was selected (again, the one with the largest weight). This GMPE applies within the 4.0-7.6 magnitude interval and Joyner-Boore distance (R_{JB}; Joyner and Boore, 1981) up to 300 km. In the analyses, assuming a uniform distribution for earthquake epicenters (both mainshocks and aftershocks), the epicentral distance was converted into R_{JB} according to Montaldo et al. (2005). The predominant strike-slip style was attributed via terms provided by Bindi et al. (2014) for that rupture mechanism. Finally, the PSHA and SPSHA discussed in the following are developed assuming the average shear-wave velocity of the upper 30 m equal to 800 m/s (i.e., rock site conditions) at the considered sites, and correcting the GMPE to account for the host-to-target adjustment, using the median value of spectral decay parameter equal to 0.027 s.

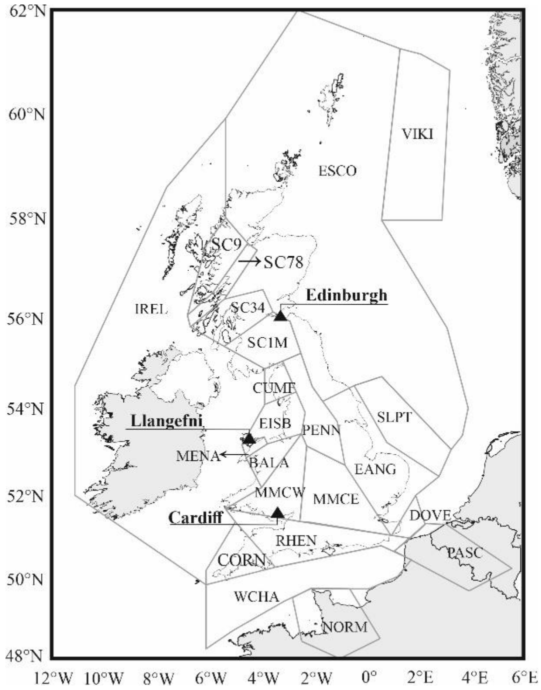

Fig. 1 - The seismic source model and sites considered in this study.

As pertaining to the source of aftershocks, it is assumed that they may occur, with the same probability, within a circular area, centered on the mainshock location, whose size, S_A, expressed in squared kilometers, depends on the magnitude of the mainshock according to the model of Utsu (1970):

$$S_A = 10^{m-4.1}. \tag{4}$$

Finally, the duration of the aftershock sequence, ΔT_A, was assumed arbitrarily equal to 90 days from the occurrence of the mainshock, consistent with the other studies applying SPSHA (Iervolino et al., 2018; Chioccarelli et al., 2021).

4. Aftershocks' occurrence model

In order to calibrate the $\{a, b, c, p\}$ parameters of the Omori law, two earthquake catalogs available for the UK were preliminarily investigated. One is that provided by the BGS (British Geological Survey, 2020), which includes seventy-three mainshock-aftershocks sequences occurring in the whole UK and the surrounding areas; however, this one was not considered due to lack of precise information regarding the time of earthquakes occurrence. The other one, which is therefore the only considered, is that of Villani et al. (2020), which includes forty-eight mainshock-aftershocks sequences occurring mostly in North Wales.

The parameters were estimated, for each sequence, using the maximum likelihood method (e.g., Ogata, 1983; Utsu and Ogata, 1995), whereas the b value was set equal to one (Helmstetter, 2003). However, the algorithm was found to be affected by convergence issues when applied to sequences of the catalog with less than five aftershocks, which are forty-four in number; consequently, only four sequences were considered. Table 1 provides their main features; i.e., the ID according to the considered catalog, the event name, the date and time of the mainshock, latitude and longitude of the epicenter of the mainshock, the mainshock magnitude, the minimum magnitude of aftershocks and the number of aftershocks in each sequence N_{aft}.

The paucity of data has led to a relatively simple calibration, in which the sequences are assumed to be complete above the minimum aftershock magnitude assumed in SPSHA, which is $m_{A,min} = 4.0$; i.e., the minimum magnitude of the considered GMPE; also, the uncertainty affecting $\{a, c, p\}$ was not assessed. The mean values of $\{a, c, p\}$, which are used for the SPSHA, are reported in Table 2. The table also gives the Omori parameters specific for each sequence. It can be noted that the largest a value (i.e., a proxy for the sequence productivity) is found for sequence 515. In fact, this sequence has the largest N_{aft} and pushes upwards the mean a value for the UK. Finally, Table 2 also includes the Omori parameters for Italy and California as provided by Lolli and Gasperini (2003) and Reasenberg and Jones (1989), respectively, which will be used in the next section.

Table 1. List of sequences used for the calibration of the Omori law parameters for the UK.

Seq. ID	Event name	Date	Time	Lat	Long	$M_E = m$	$m_{A,\min}$	N_{aft}
155	Caernarvon	19-06-1903	10:40	53.03°	-4.28°	4.60	2	14
200	Caernarvon	12-12-1940	21:20	53.03°	-4.18°	4.40	2	7
313	Lleyn Peninsula	19-07-1984	6:56	52.96°	-4.28°	5.00	2	22
515	Manchester	21-10-2002	11:42	53.48°	-2.20°	2.90	2	51

Table 2. Mean values of the Omori parameters obtained for the UK, parameters estimates obtained for each sequence and Omori parameters provided by Lolli and Gasperini (2003) and Reasenberg and Jones (1989).

	a	b	c	p
Mean Parameters for the UK	-1.71	1.00	2.26E-03	0.68
Sequence 515	-0.15	1.00	5.69E-07	0.61
Sequence 313	-2.66	1.00	2.34E-07	0.59
Sequence 155	-2.29	1.00	2.10E-03	0.92
Sequence 200	-1.74	1.00	6.94E-03	0.59
Lolli and Gasperini	-1.66	0.96	2.90E-02	0.93
Raesenberg and Jones	-1.67	0.91	5.00E-02	1.08

5. Analysis and Results

Both PSHA and SPSHA are carried out, through the REASSESS software (Chioccarelli et al., 2019), for the sites of Edinburgh (3.19° W, 55.95° N), Cardiff (3.18° W, 51.49° N) and Llangefni (4.31° W, 53.25° N). They were selected because representative of comparatively low-, medium- and high-hazard level across the country according to PSHA, respectively. The location of the considered sites is shown in Fig. 1. The selected IMs are the spectral pseudo-accelerations (Sa), corresponding to different vibration periods (T); i.e., $Sa(T)$, considered by the GMPE of Bindi et al. (2014), twenty-four in number. For each site, the considered PSHA and SPSHA results are the UHS with four exceedance return periods, that is, 95, 475, 1100 and 2475 years.

5.1 PSHA vs SPSHA

PSHA and SPSHA results are given in Fig. 2. Panels from (a) to (c) represent the UHS for the three sites according to PSHA (grey lines) and SPSHA (black lines). Panels from (d) to (f) give, for each exceedance return period, the relative differences between the spectral ordinates, that is, $(sa_{SPSHA} - sa_{PSHA})/sa_{PSHA}$. Considering the ensemble of the $Sa(T)$ and T_r values, the relative hazard increments due to the inclusion of aftershocks in hazard analysis are within 6.6%-13.6% for Edinburgh, 6.6%-14.6% for Cardiff and 7.5%-16.0% in the case of Llangefni. This indicates that, larger seismic hazard according to PSHA, the larger the SPSHA hazard increments. For each site and T_r, the largest hazard increases are found at the low-to-mid vibration periods (i.e., lower than 0.3 s), something that has also been discussed for Italy in Iervolino et al. (2018) and Chioccarelli et al. (2021).

These results may suggest that the aftershock effects can be considered of limited relevance, something that will be recalled later on. This is somehow expected, being the UK a country with generally low seismicity. For instance, in Italy, where seismic hazard due to mainshock is larger than that for the UK, the hazard increases due to aftershocks can be as high as 30% (for $T_r = 2475\,\text{yr}$).

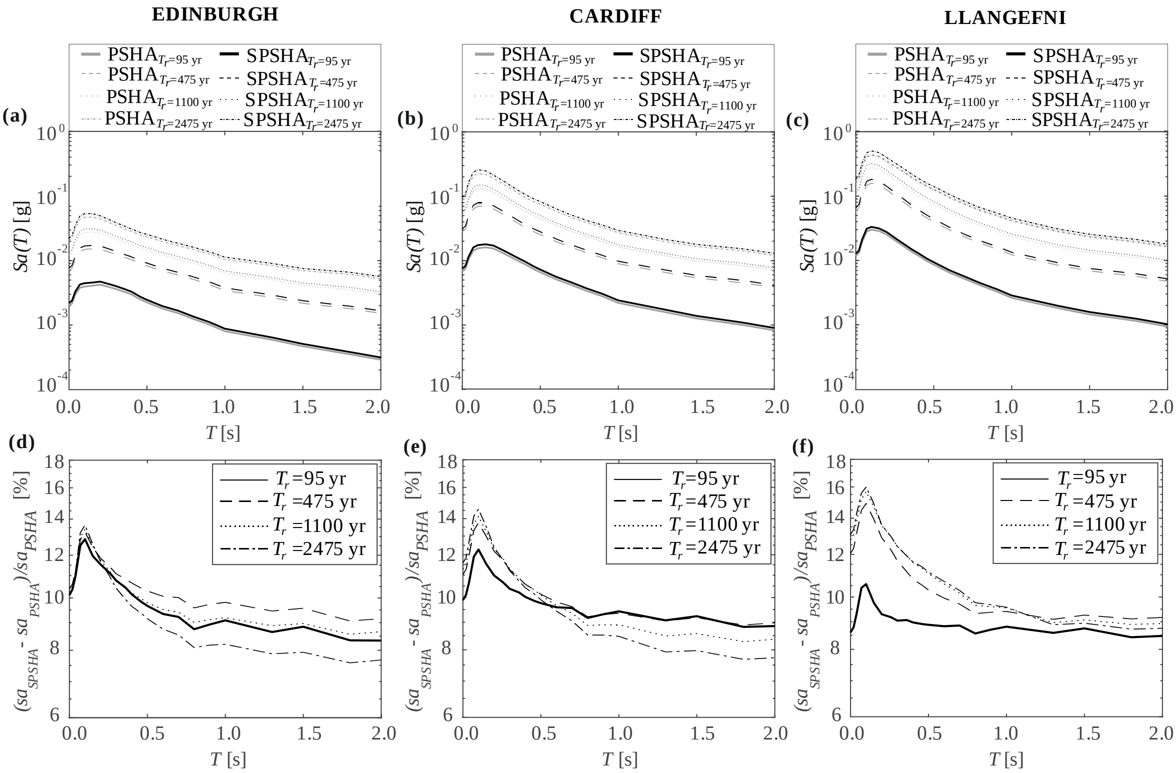

Fig. 2 - UHS obtained via PSHA and SPSHA, with $T_r = 95\,\text{yr}$, $T_r = 475\,\text{yr}$, $T_r = 1100\,\text{yr}$ and $T_r = 2475\,\text{yr}$, for Edinburgh (a), Cardiff (b) and Llangefni (c); panels from (d) to (f) give the relative hazard increments due to aftershocks.

5.2. Sensitivity to the Omori parameters

As discussed, due to the small aftershocks' dataset available for the UK, the parameters of the modified Omori's law, that is, $\{a,b,c,p\}$, were calibrated following a relatively simple estimation procedure. In fact, fitting a reduced number of sequences, thus possibly not including the less productive ones (i.e., those characterized by a small number of aftershocks), may impair the estimation of the mean parameters (e.g., Hardebeck et al., 2018). For this reason, a sensitivity analysis of the SPSHA results to such parameters is presented in this section. The aim is to quantitively assess how much the results vary, with respect to those presented in the previous section, when the Omori law is calibrated with different sets of parameters, something that can be of help in understanding if and how a more refined estimation of $\{a,b,c,p\}$ would affect the sequence-based seismic hazard results in the UK. Thus, the UHS derived via the SPSHA based on the mean parameters (mp) estimated for the country are compared to those obtained using the parameters by Lolli and Gasperini (2003) for Italy and by Reasenberg and Jones (1989) for California (see Table 2). The comparison is given in Fig. 3, in terms of $\left(sa_{LG03} - sa_{mp}\right)/sa_{mp}$ and $\left(sa_{RJ89} - sa_{mp}\right)/sa_{mp}$ at the top and bottom panels, respectively.

The figure shows that the sensitivity of SPSHA results to the Omori parameters is minor, whatever the site and exceedance return period, at least for those considered herein. Overall, considering the two sets of parameters for Italy and California, the relative differences are lower than 4% in the former case and lower than 8% in the latter. This can be explained by observing that, in a generally low seismicity country such as the UK, the aftershock effects are limited (see Fig. 2). Indeed, recalling equation (3) it is easy to acknowledge that the differences between the $E\left[N_{A|m}\left(0,\Delta T_A\right)\right]$ values obtained using the mp, $LG03$ and $RJ89$ parameter sets are relatively limited up to mainshock magnitude equal to 6.5, which is the maximum considered in the analyses (see Section 3). Such differences are more relevant at the larger mainshock magnitude, something suggesting that the sensitivity to $\{a,b,c,p\}$ of SPSHA results may increase with the seismicity of the region of interest.

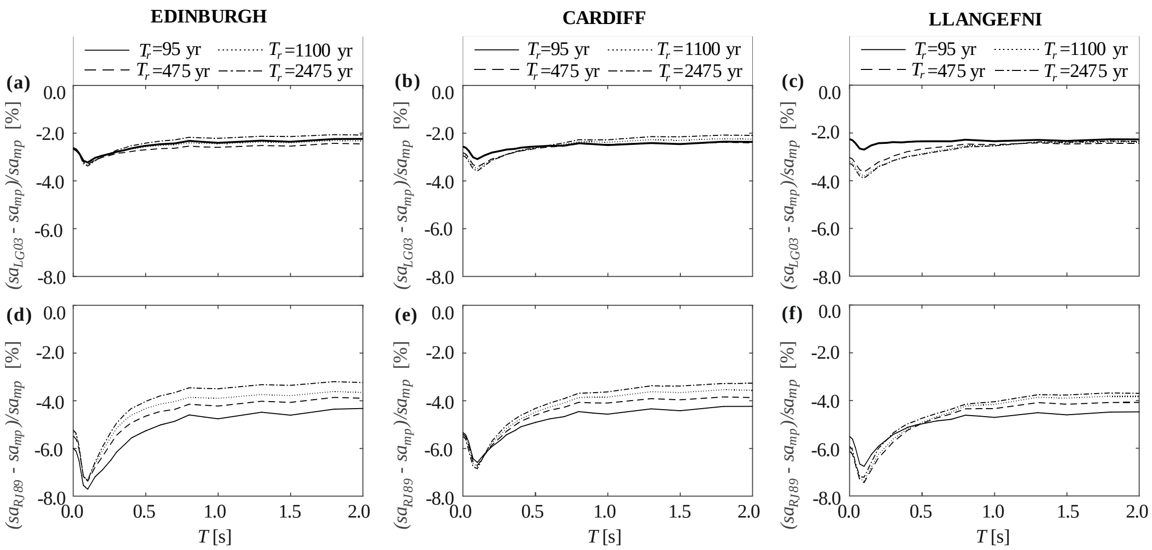

Fig. 3 – Sensitivity analysis of SPSHA results to the Omori parameters by Lolli and Gasperini (2003), panels from (a) to (c), and those by Reasenberg and Jones (1989), panels from (e) to (f).

Another reason behind the low differences in Fig. 3 is that the three parameter sets are characterized by similar a values, despite they are fitted on data from countries with different seismicity. However, as pertaining to the UK, it has been shown that the sequence-specific Omori parameters vary from one sequence to another, even significantly in some cases (see Table 2). Thus, computing SPSHA with the parameters fitted for one sequence, in lieu of the mean values estimated using all the sequences, may have an appreciable impact on results. This is shown in Fig. 4, which gives the relative differences between the 2475 yr UHS' obtained with the four $\{a,b,c,p\}$ specific sets (Seq) and the (mp) counterparts. While for three out of four sequences the differences are relatively low, being within 0.6-11.5% overall, values as high as 152.9% are found in the case of sequence 515. This is somehow expected, being this sequence the most productive one.

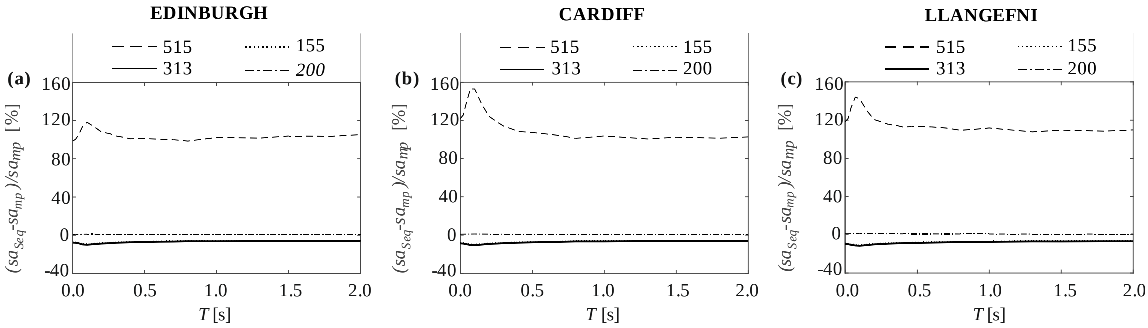

Fig. 4 – Sensitivity analysis of SPSHA results to the Omori parameters fitted specifically for each sequence.

6. Conclusions

SPSHA provides the mean number of sequences causing at least one exceedance of a ground motion intensity measure threshold at the construction site. It needs to probabilistically model the occurrence of aftershocks following each mainshock. This is addressed by using the modified Omori law, the calibration of which is based on the aftershocks' instrumental data available for the area where seismic hazard is assessed.

Authors of this study recently calibrated the parameters of the Omori law for the UK. Due to the paucity of data actually available for the country, they used a relatively simple estimation procedure, relying on only four sequences and neglecting some issues that are usually taken into account instead; e.g., aftershocks completeness assessment. Also, literature discusses that considering a reduced number of sequences may impair the estimation of the Omori parameters. For these reasons, the work presented herein assessed the implications the parameters choices on SPSHA results, via a sensitivity analysis to such parameters.

Using the mean estimated parameters, SPSHA results, in terms of UHS with exceedance return periods from 95 years to 2475 years, were compared to the PHSA counterpart, considering three sites in the UK; i.e., Edinburg (low-), Cardiff (medium-) and Llangefni (high-seismic hazard). Then, the sequence-based UHS' were compared to those obtained using additional sets of Omori parameters. The following is worth remarking.

- Including the aftershocks effect implies an increase in the seismic hazard between 6.6%-16.0%, depending on the site, vibration and exceedance return period considered.
- SPSHA results are not significantly sensitive to the Omori parameters selected for the analysis. Using the parameter sets for Italy and California, the UHS ordinates vary, with respect to the counterparts based on the mean estimated parameters, by 8% at most.
- On the other hand, SPSHA results may significantly vary if the Omori parameters, fitted specifically for one sequence, are selected in lieu of those obtained pooling together all the sequences.

These findings are consistent with the fact that in the UK the aftershock effects can be considered limited, especially if compared to other countries characterized by generally larger seismic hazard such as Italy.

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