Testing the 2020 European Seismic Hazard Model (ESHM20) against observations from Romania

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Abstract. Evaluating the performance of probabilistic seismic hazard models against recorded data and their potential to forecast future earthquake's ground shaking is an emerging research topic. In this study, we evaluate and test the results of the recently released European Seismic Hazard Model (ESHM20; Danciu et al., 2021, Danciu et al 2024) against observations for several cities in Romania. The dataset consists of ground shaking recordings and macroseismic observations, which extend the observational time-period to a few hundred years. The full distribution of the hazard curves, depicting the epistemic uncertainties of the hazard at the given location was considered and the testing was done for peak ground acceleration (PGA) values~~, i.e.,~~ 0.1g and 0.2g.

The results show consistency~~close agreement~~ between the ESHM20 and the ground motion observations for the cities located near the Vrancea intermediate-depth source (VRI) for both selected PGA levels. ESHM20's estimated values appear~~ESHM20 appears~~ to be over~~overestimate~~ the VRI recorded ground motions along the Carpathian Mountain Range and below~~underestimate~~ those at the far-field locations outside the Carpathians, yet inside the expected model variability. Some of these differences might be attributed to the uncertainties in data conversion, local site effects, or differences in the attenuation patterns of the ground motion models. Our analysis suggests that the observed exceedance rates for the selected PGA levels are consistent with ESHM20 estimates, but these results must be interpreted with caution given the limited time and spatial coverage of the observations.

1 Introduction

Probabilistic seismic hazard analysis (PSHA) is an important framework in seismology and earthquake engineering, widely used worldwide to quantify the uncertainty inherent in both the occurrence and effects of earthquakes. PSHA underpins~~underlines~~ a wide range of applications, from the development of modern seismic design building codes to seismic risk assessments. It also informs various public policy and risk management strategies aimed at mitigating the impacts of seismic events.

Despite its widespread adoption, testing the PSHA results is not straightforward. The sporadic~~inherently random~~ nature of earthquakes, coupled with low rate of occurrence~~long recurrence periods~~, or low probabilities and high consequences events, makes the empirical validation of PSHA models and results a task that would typically require observations spanning multiple human lifetimes (e.g. Vanneste et al., 2018; Gerstenberger et al., 2020; Allen et al., 2023). For instance, in regions like France or Germany, where the installation of accelerometric stations began in the mid-1990s~~1970s~~, the availability of the instrumental records~~empirical data available~~ is limited to a short temporal window. Even in more seismically active regions like Italy, Turkey or Greece, subject to more frequent damaging events, validating probabilistic hazard models is challenging for the same reasons. In recent years, several procedures have emerged aimed at testing seismic hazard estimates against past observations (e.g., Hanks et al., 2012; Marzocchi and Jordan, 2018). These procedures are typically performed at short~~shorter~~ (e.g., Stirling and Gerstenberger, 2010; Tasan et al., 2014; Mousavi and Beroza, 2016; Mak and Schorlemmer, 2016; Iervolino et al., 2023; Stirling et al., 2023) or long~~longer~~ return periods (e.g., Rey et al., 2018; Salditch et al., 2020; Meletti et al., 2021), depending on the aim of the application.

The current study aims to compare the recently released European Seismic Hazard Model (ESHM20; Danciu et al., 2021, Danciu et al 2024) results against instrumental recordings and detailed macroseismic observations specific to Romania. This region offers a distinctive seismo-tectonic landscape, dominated by the Vrancea intermediate-depth seismic source (VRI). The VRI has a concentrated nest of seismicity at depths between 60 and 200 km, which is associated with the current dehydration of an oceanic subducted plate, as noted by Ferrand and Manea (2021) and Craiu et al. (2022). Macroseismic intensities maxima of strong VRI events are often observed/~~up to X Medvedev–Sponheuer–Karnik 1964 intensity scale (MSK-64, Medvedev et al., 1967) were~~ reported~~, with notable/maximum effects seen~~ outside of the epicentral area: values of IX+ for 1940 event with the moment magnitude Mw=7.7, and VIII+ (MSK-64 scale) for the 1977 event with Mw=7.4 (e.g. Kronrod et al., 2013). The largest intensity values are found outside of the Carpathian belt, where a substantial number of sedimentary structures are located (Marmureanu et al., 2016a; 2017; Manea et al., 2019). Beside this, the source properties imprint an asymmetric shape to the macroseismic field, elongating it in the NE-SW direction (Marmureanu et al., 2016b). In contrast, strong back-arc attenuation features are recorded within the Carpathian region and prescribe the current pattern of the macroseismic fields (e.g. Vacareanu et al., 2015; Manea et al., 2022). The VRI impact extends beyond~~overpass~~ the national borders and significant damage has been reported in neighbouring countries, with~~e.g.,~~ observed intensities of VII-VIII at more than 250 km epicentral distances during the 7.7Mw 1940 event (Cioflan et al., 2016).

~~-~~Furthermore, while the shallow crustal seismic activity in Romania is not as frequent as the one at intermediate depths in the Vrancea region, it still poses a significant contribution to the regional seismic hazard (~~.~~Marmureanu et al., 2016a). The main seismic sources for such events are located along the Carpathian Mountains, particularly in the Fă~~a~~gara~~s~~ş-C~~a~~âmpulung zone, as well as in the foreland regions of southwestern Romania, including Banat and Danubius, and extending northwest to Crisana-Maramures. Despite ~~the~~the lower rate of crustal activity in these areas compared to the Vrancea region, historical accounts and pre-instrumental catalogues document significant earthquakes with magnitudes Mw≥5 and epicentral intensities I0 ≥VI~~6~~ MSK scale~~, indicating substantial effects on the affected regions~~ (e.g., Radu, 1979; Oncescu et al., 1999). Thus, in this study, we consider intensity data spanning over three centuries from twelve important cities in Romania (see their locations in *Figure 1~~1A~~*). These urban areas are selected for their significant population and different exposure to seismic hazard levels. The present study begins with an overview of the ESHM20 and its specific relevance to Romania. It will then discuss the main components of the model and the results relevant at the regional level. The next section describes the main data, the curation and conversion procedure, which includes how historical macroseismic data were collected and converted into peak ground acceleration (PGA) values for different Romanian cities. Subsequently, a summary of the statistical testing process will be given, detailing the approaches taken to contrast the recorded seismic activity with the ESHM20 estimates. Next, the main outcomes of the statistical testing at two reference values for PGA - 0.1 and 0.2 g, are illustrated and interpreted, followed up by discussion and conclusions of our findings. ~~We also acknowledge the various attempts that have emerged in recent years aimed at testing seismic hazard estimates against past observations (e.g. Marzocchi and Jordan, 2018; Rey et al., 2018; Meletti et al. 2021, Stirling et al., 2023) and we try to use their experience when applying such techniques for Romania.~~

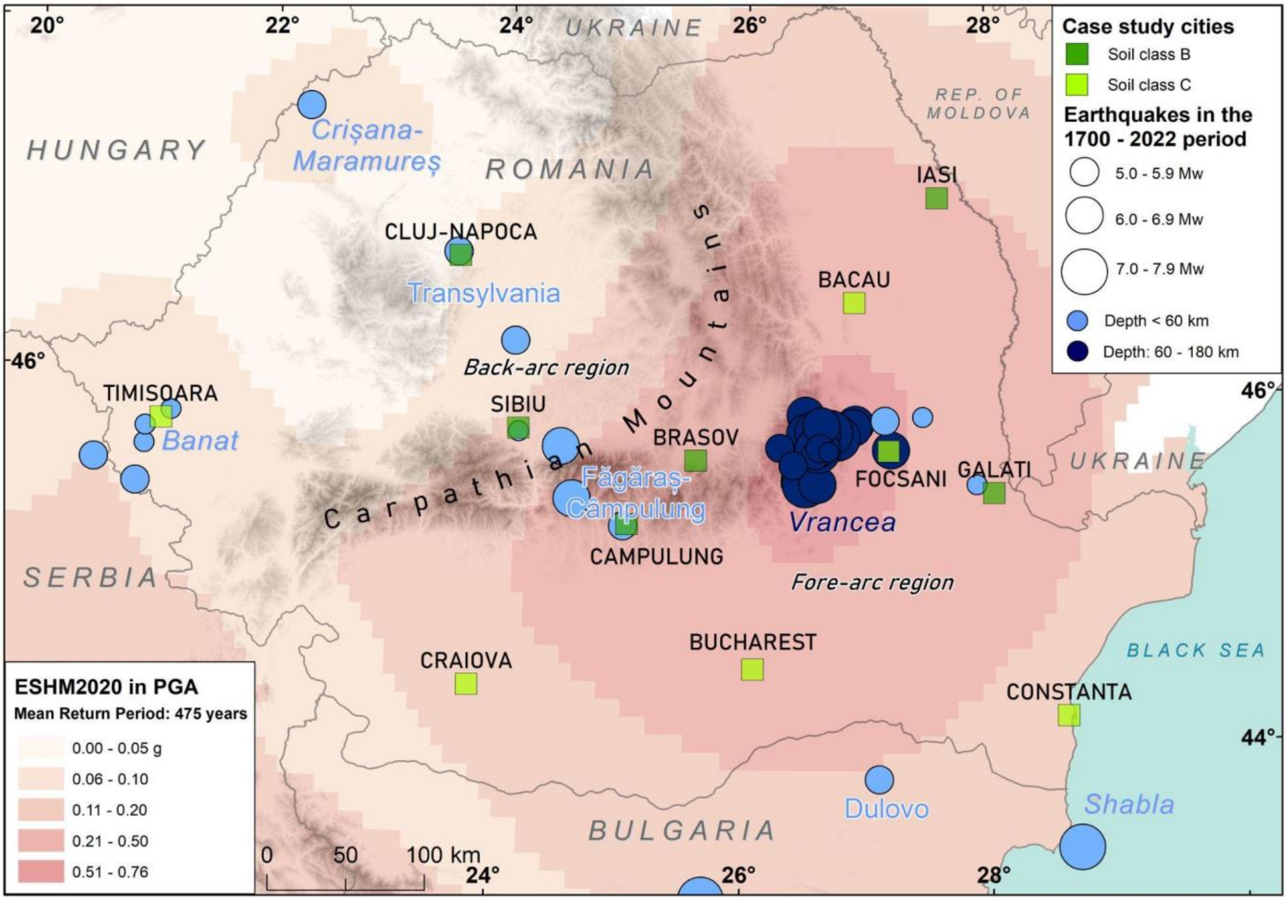


Figure 1: Location of the selected twelve cities and the post-1700 earthquakes (according to the Unified Earthquake Catalogues of the European Seismic Hazard Model 2020 - ESHM20; Danciu et al., 2021) used in this study. Only events with moment magnitude Mw ≥ 5, for which at least one macroseismic intensity exceeding VI MSK-64 is recorded at the selected locations, were considered. The background is the ESHM20's ground shaking map in terms of peak ground acceleration (PGA) for a return period of 475 years.

2 ESHM20 Results for Romania

The 2020 European Seismic Hazard Model (ESHM20, Danciu et al 2021, 2022) is the latest revision and update of the seismic hazard assessment for the Euro-Mediterranean region. ESHM20 is constructed using harmonised datasets that include information on ground motion, earthquake catalogues, active faults, and tectonic data across different borders. The ground shaking hazard in the region is estimated by combining a complex seismogenic source model, which includes distributed seismicity, active faults, and subduction sources, with regionally scaled backbone ground motion models (Weatherill et al., 2023). More specifically, the seismogenic source model consists of two branches of sources: the area source models and a hybrid combination of active faults and background smoothed seismicity. In Romania, due to the lack of available data on active faults, the seismogenic source model is based on an area source model and a smoothed seismicity with an adaptive kernel. Furthermore, the seismogenic sources depicting the nested seismicity with depth in the Vrancea region are also considered and modelled with a set of uniform area source zones located between 70 to 150 km depth. The ground motion characteristic models for Romania are scaled based on regional factors to capture the ground shaking characteristics of both the active shallow crust and non-subduction deep seismicity. These models are described by Weatherill et al., (2020, 2023). A complex logic tree was developed to address the spatial and temporal variability in the earthquake rate forecast as well as the regional backbone ground motion models. The computation was performed using OpenQuake (Pagani et al 2014) and the full logic tree was sampled to obtain the distribution of the hazard results. For this analysis, we selected twelve major cities in Romania, as illustrated in *Figure 1*, where we superimposed the ESHM20's ground shaking map in terms of peak ground acceleration (PGA) for a return period of 475 years. Also, the relevant earthquakes with moment magnitude, Mw ≥ 5 at which at least one macroseismic intensity exceeding VI MSK-64 is recorded at the selected locations, are also plotted in the same map. The highest PGA mean value is observed in the proximity of the Vrancea source, a region of high seismicity as indicated also by the density of the seismic events (*Figure 1*). The pattern of PGA values follows the Carpathian Arc, with values decreasing in the backarc towards the north-western part of the region. The range of PGA values is rather large, spanning from 0.15g in Cluj to 0.9 g observed for Focș~~s~~ani. The ESHM20's hazard curves for the mean PGA values at the selected cities in Romania are presented in *Figure 2A* and show that the decay of the hazard curves is different, with a fast decay indicating lower hazard and vice-versa. A significant spreading of the mean hazard curves is present between the locations outside and within the Carpathian arc, following the same pattern as the 475 year mean ESHM20's ground shaking map (*Figure 2A*). The highest annual probability of exceedances (APEs) is seen at locations in the proximity of the Vrancea source, which dominates the hazard at all the return periods, while the lower values are observed at cities located in the far-field extent of this region, where low-recurrence shallow seismicity is present. The full distribution of hazard curves for 10000 random sampled hazard curves along the ESHM20 logic tree for Bucharest is shown in *Figure 2B* together with the mean and the 5 and 95 percentiles~~.~~ ~~-~~At this location, the variability of the hazard curves presents a narrow range and depict the combined uncertainties of mainly the Vrancea source and ground motion (Danciu et al., 2024).

Finally, we used the full distribution of the ESHM20 hazard curves to retrieve the statistical testing input, as described in the testing procedure section.

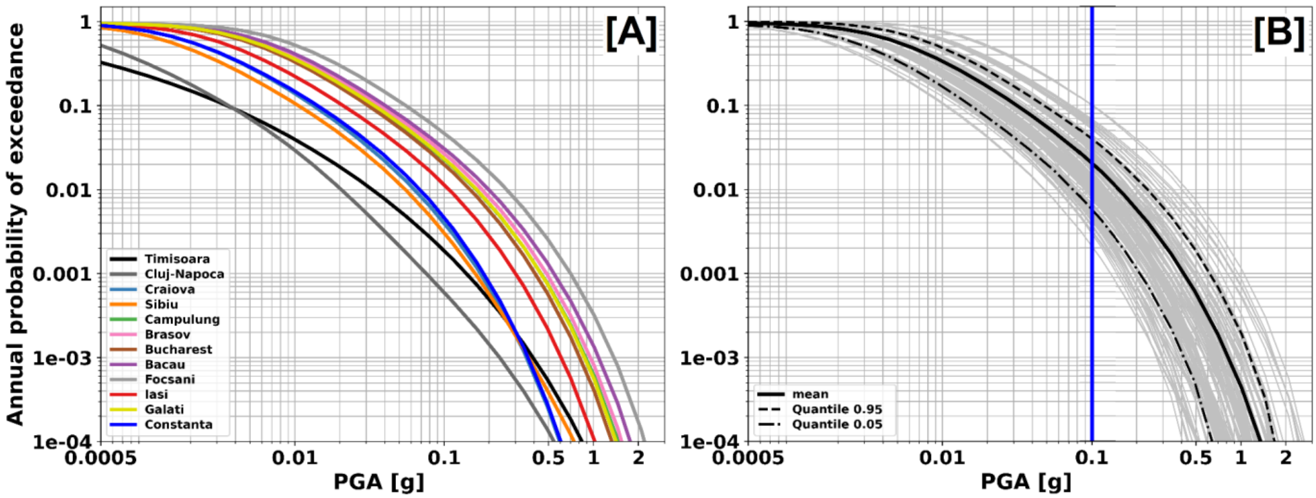


Figure 2: [A] The ESHM20's annual probability of exceedance as a function of PGA (so called hazard curves) at the selected cities in Romania. [B] Full distribution of hazard curves for 10,000 samplings extracted across all the ESHM20 hazard branches for Bucharest city. The mean hazard is presented as a continuous black line, while the dashed ones represent the 5 and 95 percentiles.

3 Available Data and Conversion

Macroseismic intensity observations recorded over several hundreds of years (starting with 1700) at the main cities across Romania are used to test ESHM20's results. The selected cities are among the most highly populated urban areas across Romania and are well-distributed with respect to the various seismic hazard levels and source characteristics shown by the ESHM20's PGA hazard map for the 475 year return period (see *Figure 1~~1A~~*). It is noteworthy~~,~~ that these observations were collected within this study and were not directly used in the derivation of the ground motion~~any~~ component of the ESHM20, securing their independence for statistical testing. Intensity data points (IDP) were acquired from multiple available sources: Atanasiu (1961), Constantin et al. (2011, 2013, 2016, 2023), Kronrod et al. (2013), Marmureanu et al. (2018), Rogozea (2014; 2016) and Shebalin et al. (1974). Beside compiling original information (i.e., intensity values), most of these studies are also providing new evaluations at locations where new macroseismic information became available. Note that, while IDPs of the XVII-XVIII centuries had been evaluated from scarce information, the ones related with strong Vrancea earthquakes of the

20th century were collected through wide national campaigns (see details in Kronrod et al., 2013, Constantin et al., 2016). Several IDPs of our initial dataset have a very local character as they strictly reflect the effects of strong intermediate-depth earthquakes on specific buildings existing at the respective time (e.g. churches, monasteries; Marmureanu et al., 2018). Where available, such site-specific intensity estimations are averaged with macroseismic data from other authors and various sources (especially isoseismal maps). Additionally, maps published before 2000 have been checked against the information available in the European Archive of Historical Earthquake Data platform (AHEAD; Rovida et al., 2020) which also helped us to fill in the data gaps for some cities. If an IDP was not available at the specific location, a natural neighbour interpolation scheme (Sibson, 1981) was used to extract it from georeferenced isoseismal maps selected from the above-mentioned sources. Some of the collected IDPs were reported in the Rossi-Forel intensity scale (e.g., 7.1 Mw 1908 VRI earthquake) and were homogenised to MSK-64 using the conversions proposed by Musson et al. (2010). Thus, we also treat MMI and EMS-98 intensity values as equivalent to MSK-64 ones. The MSK-64 is preferred as the VRI's intensity to ground motion conversion equations (IGMCEs) were developed using this intensity scale for Romania.

From this collected dataset, we considered only IDP data from events with Mw ≥ 6 for VRI and Mw ≥ 5 for shallow seismicity (see their locations in *Figure 1~~1A~~*) and with a minimum observed epicentral intensity I0 of VII MSK-64, which corresponds to a PGA value of 112 cm/s^2 for VRI (e.g. Ardeleanu et al., 2020) and/or 154 cm/s^2 (Caprio et al., 2015) for shallow seismicity. The testing dataset at the twelve major cities contains 199 IDPs recorded from 58 earthquakes (see *Figure 1~~2~~*), from which 39 are located in the VRI region. For each city, the time window of data completeness (Table 1) is visually evaluated based on IDPs higher or equal to V (see Figure 3) from events ~~and are~~ considered as mainshock~~main events~~ in the ESHM20 declustered catalogue (Danciu et al., 2021; 2022). Where available, the converted PGA values were replaced by the recorded ones from the post~~pre~~-1977 VRI events dataset of Manea et al., (2022). We did not include any intensity measure which is related to the events identified as foreshock, aftershock, or swarm events. Depending on the available data

~~To perform a comparison between the ESHM20 results and the collected MSK-64 IDP~~, the intensity values were translated to PGA using the latest conversion equations proposed by Ardeleanu et al., (2020) for the VRI source and Caprio et al., (2015) for global crustal as no local shallow models are available. A different conversion equation was used for VRI as the observed macroseismic field presents unique features which are not seen for shallow seismicity, such as: an azimuthal asymmetric shape due to the source properties (Marmureanu et al., 2016b; Craiu et al., 2023), different apparent attenuation patterns due to the unique tectonic environment (e.g. Manea et al., 2022) and far-field strong site effects (Cioflan et al., 2022). The equation of Ardeleanu et al., (2020) was selected as it is the most recent intensity to PGA conversion equations proposed for VRI and its predictions agree with the ones from the previous studies, such as Vacareanu et al., (2015) and~~),~~ Marmureanu et al., (2011). The distribution of the MSK to PGA conversions and their corresponding standard deviations up to X~~within the range of 1-10~~ MSK-64 are presented in *Figure S1*, which can be found in the electronic *Supplementary Materials*. Each~~We decided to do the translation from~~ IDP was translated into three ~~to~~ PGA values, i.e the mean IPE model and its standard deviation, to consider the variability of this conversion into the final results. The IDP was translated to PGA~~,~~ as it's simply less challenging and~~it is~~

more efficient than converting all~~to convert the relatively small number of~~ the PGA hazard curves~~reported intensities and more importantly,~~ to intensity.
~~minimises potential errors at the data levels, rather than at the results.~~ To align to the ESHM20 rock conditions, for which the time-averaged shear-wave velocity to 30 m depth (Vs30) is set to 800 m/s, the ground-motion amplitudes were corrected for site effects considering amplification in each city by means of soil factors recommended in Eurocode 8 (Comité Européen de Normalisation (CEN), 2004, EC8) for crustal seismicity and the ones adjusted for Vrancea earthquakes ~~ones~~ proposed by Vacareanu et al., (2014). The ~~site classification parameters, such as Vs30 and~~ EC8 site classes~~,~~ were gathered from Manea et al., (2022) and Coman et al., (2020) studies and are presented in Table 1.~~).~~ The use of observational intensity data to compare against hazard curves introduces additional layers of uncertainty. One must acknowledge the complex process of converting subjective intensity measures into objective ground acceleration values, given the uncertainty nature of intensity observations and the variability in the human experience of ground shaking (e.g. Rey et al., 2018). Furthermore, the determination of complete and reliable historical records for specific macroseismic intensity levels is equally challenging, presenting a considerable difficulty in aligning the past seismicity with probabilistic forecasts. We~~To evaluate how much these uncertainties impact the results of the hazard testing, we~~ incorporated the full uncertainty variability within the PGA calculations by considering the uncertainty on~~standard deviations of~~ the conversion from intensity to PGA, to evaluate how much these uncertainties impact the results of the hazard testing. ~~ground shaking conversion models.~~

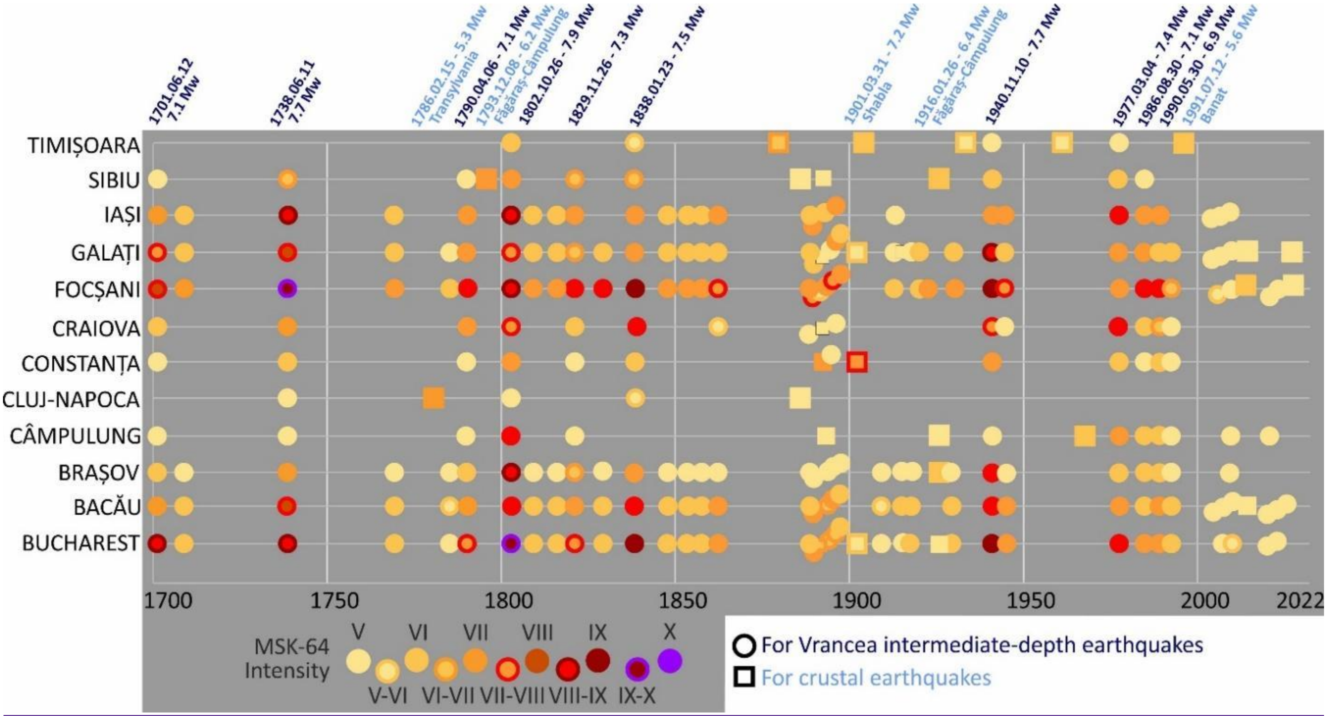


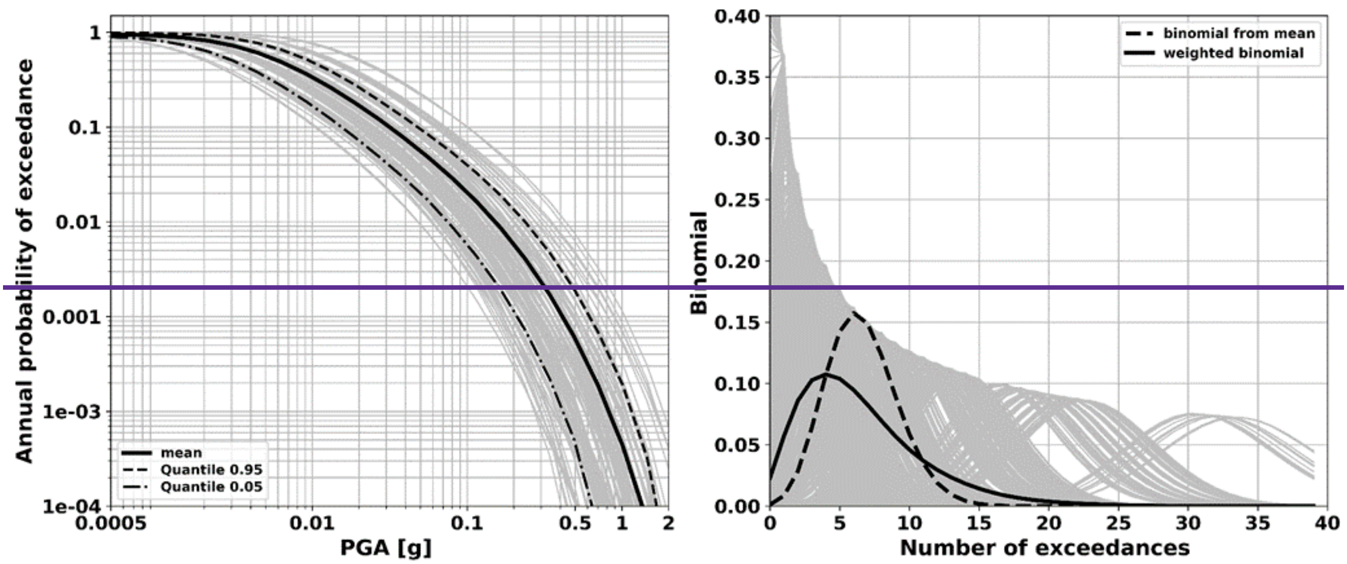
Figure 3~~2~~: The distribution of the selected intensity data points used for the ESHM20 hazard testing at the twelve cities, with a threshold above V MSK-64. The timeline and primary source information for the major earthquakes, which significantly affected ~~the~~ Romanian territory, are presented in the upper side of the plot.

4 Statistical Testing Procedure

In the following section, we provide an overview of our methodology for evaluating the performance of the ESHM20 ground shaking estimates by comparing them to instances of ground motion exceedances at twelve main cities in Romania. The statistical testing relies upon comparing the actual occurrences of ground acceleration surpassing specific thresholds (0.1 and 0.2g PGA) with the ESHM20 estimates, by considering the associated uncertainties. The selected ground motion levels are of relevance to PSHA in Romania, with 0.1g approximating the lower bound of damaging ground motions. First, we compile the full dataset of ground shaking that includes both the recordings (where available) and the macroseismic observations converted to PGA by considering uncertainties of the conversion process and the influence of site conditions.~~.~~ Next, we determine the specific time period of this dataset and count the instances where the acceleration thresholds are surpassed to obtain~~, by considering~~ the ~~influence of site conditions and uncertainties in the conversion process. Subsequently, we forecast the anticipated number of exceeding occurrences by using a binomial~~ distribution of the observed~~(Stirling et al., 2023) to evaluate the likelihood of observing the exact~~ number of exceedances over the time period of completeness.

~~. This~~ Subsequently, we follow closely the statistical testing approach ~~follow closely the procedures~~ proposed by Marzocchi and Jordan (2014, 2017, 2018), which accounts for both the aleatory and the epistemic uncertainties of the hazard (Meleti et al., 2021; Stirling et al., 2023). The above-mentioned methodology considers that the exceedance rate variability is well represented by a binomial distribution. We forecast the anticipated number of exceeding occurrences for each logic-tree branch by using the proposed binomial distribution (Stirling et al., 2023) and build the sum of all the weighted distributions by considering each branch weight to evaluate the likelihood of observing the exact number of exceedances. 2021; Stirling et al., 2023).

Figure 3 illustrates the The variability of the 10000 random samples of the hazard curves for Bucharest, city, the capital of Romania, is presented in *Figure 2B*, while the contribution of various logic tree branches to. The distribution of the 10,000 random sampled hazard at 0.1g PGA is illustratedcurves along the ESHM20 logic tree is shown in *Figure* *4A*. It shows that*3A* together with the mean hazard value doesn't explain the APEs asymmetric distribution. Thus, for this analysis we useand the weighted binomial distribution considering the APEs distribution of the entire ESHM20 logic tree branches5 and 95 percentiles. The variability of all the computed binomials for the entire ensemble of the hazard curves are presented in *Figure 4B*, alongside the final weighted mean considering the full distribution of the uncertainties and the resulting binomial retrieved from the statistical mean. The distribution of the APEs reflects the contribution of various logic tree branches, andNote that the statistics are summarized for the Annual Probability of Exceedance (APE) and that the differences between the two statistical descriptors i.e., weighted mean versus statistical mean is evident in *Figure 4B*. To identify potential influences due to the selection of a specific distribution, we fitted several distributions to the APE range at 0.1g, as illustrated *Figure S2* in the *Supplementary Materials*. The distribution of the APEs reflects the contribution of various logic tree branches, and given the fitted distribution the statistical mean, might be different. Thus, for this analysis we consider the weighted binomial distribution considering the asymmetric APEs distribution.



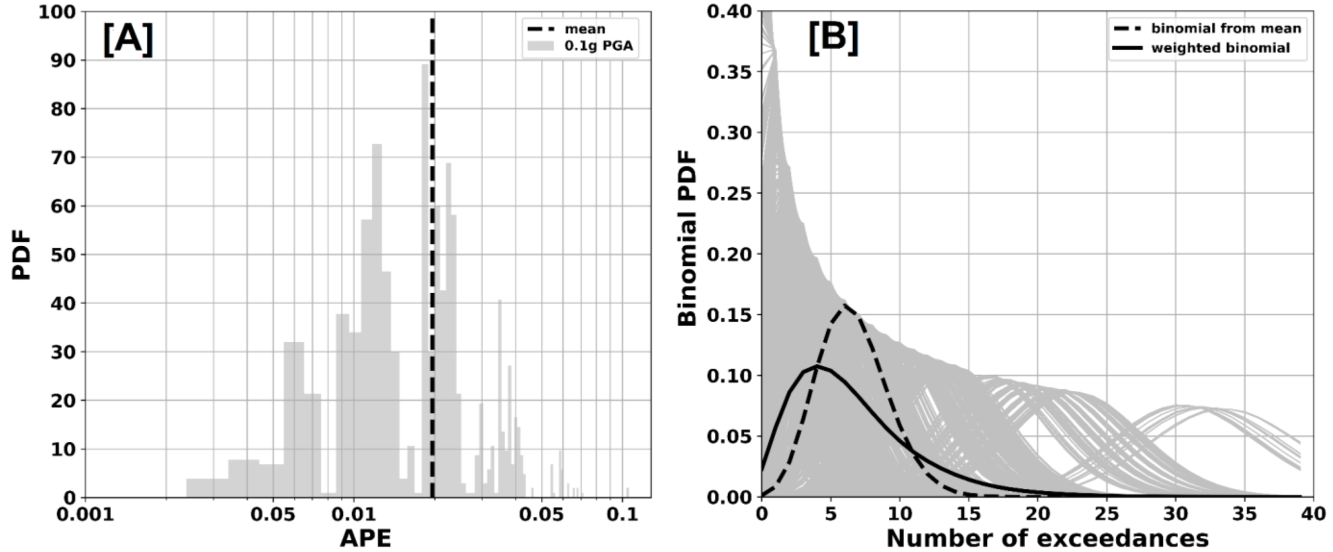


Figure ~~4~~3: [A] Probability density functions computed for 0.1g PGA level versus annual probability of exceedance - APE.~~Hazard curves from the 10,000 samplings extracted across all the ESHM20 hazard branches in Bucharest city.~~ The vertical~~mean hazard is presented as a continuous~~ black line indicates the traditional hazard mean value.~~, while the dashed ones represent the 5 and 95 percentiles.~~ [B] The variability of the computed binomials for all the hazard ensembled~~ensemble~~ curves (grey lines) is shown together with the final weighted mean curve considering the full distribution of the uncertainties, and the one computed from the commonly used mean hazard curve.

Based on the above-mentioned methodology, we perform point-based ~~assessment~~ testing at each of the twelve cities using the following steps:

1. Estimate the time-period of available ground motion for each city in the compiled~~complied~~ ground motion dataset ~~(~~ ~~in~~(in terms of PGA corrected values for site effects).~~.~~
2. Count observed exceedances of PGA~~(after correcting the values for site effects)~~ at ~~PGA for~~ 0.1g~~1~~ and 0.2g levels for each city complete time window and calculate their corresponding standard deviations considering the uncertainties in the intensity to PGA conversions.
3. Calculate the predicted number of exceedances for each of the PGA thresholds considering every end-branch of the ESHM2022 logic tree (i.e., annual probability of exceedance × total time-period)
4. Compute the~~a~~ weighted mean binomial distribution by combining all the binomial distributions applied to~~from~~ (3) considering the full distribution of the hazard uncertainties. Calculate~~ and calculate~~ the probability (p-value) that the observed number of exceedances could be drawn from the weighted mean binomial distribution.
5. Compute the p-value where there will be N observations or more than the observed number of exceedances from the weighted mean binomial distribution.

5 Statistical Testing Procedure: Results

The results of the statistical testing of ESHM20 at 0.1 and 0.2g PGA are illustrated in *Figures 4* and *5* for six cities (Focșani~~Focsani~~, Braș~~s~~ov, Bucharest, Iaș~~s~~i, Constanț~~t~~a, and Timișoara~~Timisoara~~), while for the others (Bacă~~a~~u, Câ~~a~~mpulung, Cluj-Napoca, Craiova, Galaț~~t~~i, Sibiu) are given in *Figures S2~~S3~~ and S3~~S4~~* of the *Supplementary Materials*. These plots depict the histogram of the weighted mean of ESHM20, the observed number of exceedances (i.e., black vertical line) and its one sigma variability (i.e., dashed vertical lines). The total time of the observations is specified in each subplot for their respective city. As mentioned before, the average time period of the observations of both ground shaking recordings and macroseismic data spans over 322 years for all the cities, except the ones in the within the Carpathian region, such as: Sibiu and Cluj-Napoca, as well as Timișoara~~Timisoara~~, the westernmost city. For these cities, the time period is about 220 years. Overall, there is a consistent alignment of estimated ground shaking hazard of ESHM20 with the observed data at 0.1g PGA level, as shown by *Figure 5*. Notably, cities located along the northeast-southwest trajectory outside the Carpathians - such as Iaș~~s~~i, Focșani~~Focsani~~, and Bucharest (see *Figure 4*) - show a robust correlation with the ESHM20 PGA estimates. Of particular interest, it's~~is~~ the consistency of the ESHM20 with observations for Focș~~s~~ani, the city found in the proximity of the Vrancea deep seismicity sources, the main seismogenic source of the region. A slight shift from the ESHM20 prediction is observed in the capital city of Romania, i.e.~~.,~~ Bucharest, where more~~an increased number of~~ intensities over VII MSK-64 were recorded than predicted; this fact ~~and~~ might reflect the impact of the way humans experienced ground shaking within different typologies of buildings in megacities (Rogozea, 2016; Cioflan et al., 2016). Also, such a shift might be attributed to the effect of different source and path features, such as directivity, or uncertainties in correcting for site-effects. Furthermore, the values expected from ESHM20 are over the~~an overestimation is~~ observed ones for cities along and in the proximity to the Carpathian bend, e.g., Bacă~~a~~u, Brașov~~Brasov~~ and Câ~~a~~mpulung, and might suggest that a local attenuation effect is not currently captured or modelled using the ESHM20 scaled backbone logic tree for the Vrancea in-slab region (Weatherill et al., 2020). The impact of different attenuation patterns due to the complex tectonic configuration was previously seen on both human-felt and instrumental observations (e.g, Radulian et al., 2006; Ivan, 2007; Marmureanu et al., 2016b) and captured within the recent region-specific ground motion models (GMMs; e.g. Vacareanu et al., 2015; Manea et al., 2022). The results at the cities beyond the Carpathian Mountains (e.g., Sibiu, Cluj-Napoca, Timișoara~~Timisoara~~) exhibit hazard predictions that reflect the frequent crustal seismic activity as a significant attenuation behind the arc reduces~~dampened~~ VRI-related ground motion. It appears that a longer and more comprehensive dataset may be required to accurately assess the distribution of ground shaking hazard levels. For cities located in the far-field area of VRI and outside of the Carpathian arc (fore-arc region), such as Consț~~t~~anta and Craiova, ~~an underprediction of~~ the computed hazard is slightly lower than~~can be observed with respect to~~ the recorded data. The same feature can be seen from the 475 return-period PGA map (see *Figure 1A*), and it contrasts with the recorded ground motion field and pre-instrumental intensity data (e.g., Cioflan et al., 2022). Manea et al. (2022) provide insights of the apparent attenuation of the ESHM20 ground motion model for the fore-arc area and future adjustments of the ESHM20 are recommended to capture the ground motion characteristics within this region of Romania. However, the estimates of ESHM20 at 0.1g PGA appear overall to be consistent~~in good agreement~~ to the data, ~~and~~ given all the uncertainties involved in this analysis.~~, they are acceptable.~~ Similarly, for the 0.2 g PGA level, the results suggest a strong correlation in areas near the VRI source (see *Figure 5* and *Figure S4*). ~~As in the case of the 0.1g PGA level,~~ Focș~~s~~ani experiences multiple instances of surpassing the 0.1g~~this~~ PGA level~~,~~ and the observed exceedances are ~~in good agreement~~ within the ESHM20 estimated binomial distribution. Nevertheless, for the remaining cities, ESHM20 exceedances are ~~prone to~~ slightly below~~underestimate~~ observed exceedances in Bucharest and Ia~~s~~și, due to the influence of source/path effects and/or uncertainties in correcting for site-effects. For the cities located along the Carpathian arc (Bacă~~a~~u, Brаș~~s~~ov and Câ~~a~~mpulung), the trend is reversed, with ESHM20 exceedances being higher than the observed ground shaking recurrences. For the rest of the cities (Galaț~~t~~i, Craiova, Timișoara~~Timisoara~~, Sibiu, Consț~~t~~anta, Cluj-Napoca), the ESHM20 estimates fit the observations relatively well. The comparison~~We also summarize the results as annual probabilities of exceedance at the two PGA levels (i.e., 0.1g and 0.2g) for all the cities in *Figure S5* in the *Supplementary Materials*. The observed consistency~~ between the observations and the weighted mean and the range of annual probabilities of exceedance from ESHM20 hazard curves~~ and those based on the observations~~ are consistent for the 0.1g PGA level. For the 0.2g PGA level, the consistency is valid for the cities located in the proximity of the VRI. ~~Additionally, the measured and expected ESHM20 numbers of exceedances for each city are listed in Table 1 together with their associated rate and probability of exceedances.~~

The overall results are listed in Table 1 and the probability that the observed record could be drawn from the combined distribution (p-value) is presented at each location as "P 0.1" and "P 0.2". These results show that nine out of twelve locations provide no evidence for poor performance of the ESHM20 for 0.1g PGA (poor performance - p-value < 0.05), while only at one location the hazard doesn't pass the test at 0.2g. Overall, the testing results suggest that there are no reasons to reject the ESHM20 in Romania for 0.1 and 0.2g PGA.

6 Conclusions

Evaluating the performance of seismic hazard models against recorded data, is an emerging research topic. In this study, we evaluated the performance of the recent update of the ESHM20 (Danciu et al., 2021) in Romania. The compiled ground shaking database combines strong motion records and macroseismic intensity data. The inclusion of the macroseismic intensity data, allows expansion of the observational time period to over two to three hundred years, at the cost of increased uncertainties of the ground motion estimates. The result of the statistical testing suggests that the ESHM20 is consistent~~in a good agreement~~ with the observations for two PGA levels, at the locations of the twelve cities selected across Romania. We found a strong consistency~~agreement~~ between the weighted mean of ESHM20 and the exceedances of the observations for the cities (Focș~~s~~ani and Gala~~t~~ți) located in the proximity of the VRI source for both PGA levels i.e., 0.1g and 0.2g.

For cities located along the Carpathian arc (Bacă~~a~~u, Brașov~~Brasov~~ and Câ~~a~~mpulung), the ESHM20 exceedances are above~~appear to overestimate~~ the recorded ground motions and suggest that the along-arc attenuation effect (Manea et al., 2022) might not be captured or modelled in the ESHM20 ground motion model (Weatherill et al., 2020). Furthermore, the testing results at cities located in the VRI far-field area and outside of the Carpathian arc (Cons~~t~~ţanta, Craiova), might suggest that the ground motion models used in ESHM20 attenuate too fast compared to the recorded PGA, as observed by Manea et al. (2022). For the Iaş~~s~~i and Bucharest sites, located along the NE-SW direction from the VRI source, the ESHM20 estimates appears to be below~~underestimates~~ the recorded data at the 0.1g PGA level and this feature become more prominent at 0.2 g; these differences might be attributed to: 1) source directivity effects which are significant for major events occurring in Vrancea (Cioflan et al., 2022),~~,~~ 2) potential bias in the conversion of the intensity to PGA, or 3) possible complex local site effects which might~~were~~ not been completely removed from the observations. While informative conclusions could be drawn~~draw~~ from evaluating the comparison at cities along and outside of the Carpathian range, limited conclusions can be derived for locations in regions of low seismic hazard, such as Sibiu and Cluj-Napoca, or Timişoara~~Timisoara~~, in the western Romania. The seismic hazard of these regions is dominated by episodic clusters of small to moderate shallow seismicity with regional effects, which are not well captured in the macroseismic data or the amount of strong motion recordings. We acknowledge that even with a time period of two to three centuries, the observations remain largely incomplete in time and space. The Romanian seismic network (Marmureanu et al., 2021~~2022~~) has evolved over time, however limited ground motion data is available due to lack of significant earthquakes occurring in the recent decade or so. Uncertainties associated with the ground motion dataset are increasing with the conversion of the macroseismic data, as illustrated in the results given in *Figures 4* and *5*. Moreover, ~~we also acknowledge that~~ the statistical testing is~~are~~ limited in scope given all the uncertainties are associated also with the distribution of the hazard results, configuration of the logic tree, sampling technique, and/or use of a certain distribution i.e., binomial or log-normal. All these factors are contributing to the overall stability of the statistical testing.

In conclusion, our analysis suggests that observed exceedance rates for these two PGA levels, i.e., 0.1g and 0.2g, are consistent with ESHM20 estimates. These~~, but these~~ results must be interpreted with caution given the ~~above mentioned~~above-mentioned limitations in~~ the~~ time and spatial coverage of the observations, both the ground shakings and the macroseismic intensity dataset.

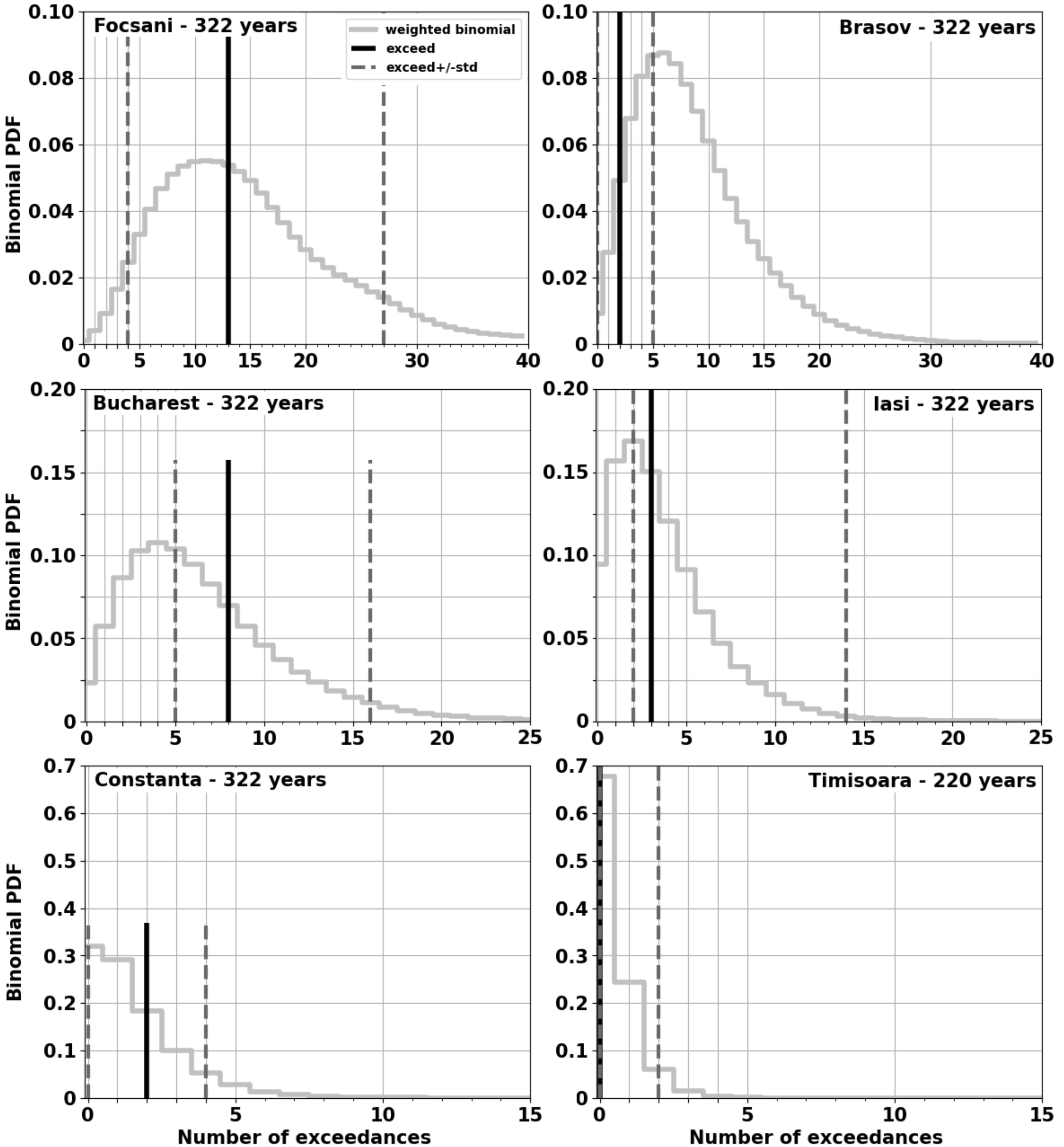


Figure 4. Consistency test results of ESHM20 with the observed PGA values at 0.1 g for each of six cities: Focsşani, Brasşov, Bucharest, Iaşsi, Consţtanta, and Timişsoara. The histogram depicts the ESHM20 weighted mean, the observed number of exceedances <u>over the time window of completeness</u> is given as the black vertical line and its one sigma variability i.e., dashed vertical lines; the total completeness time is specified in each subplot for their respective city.

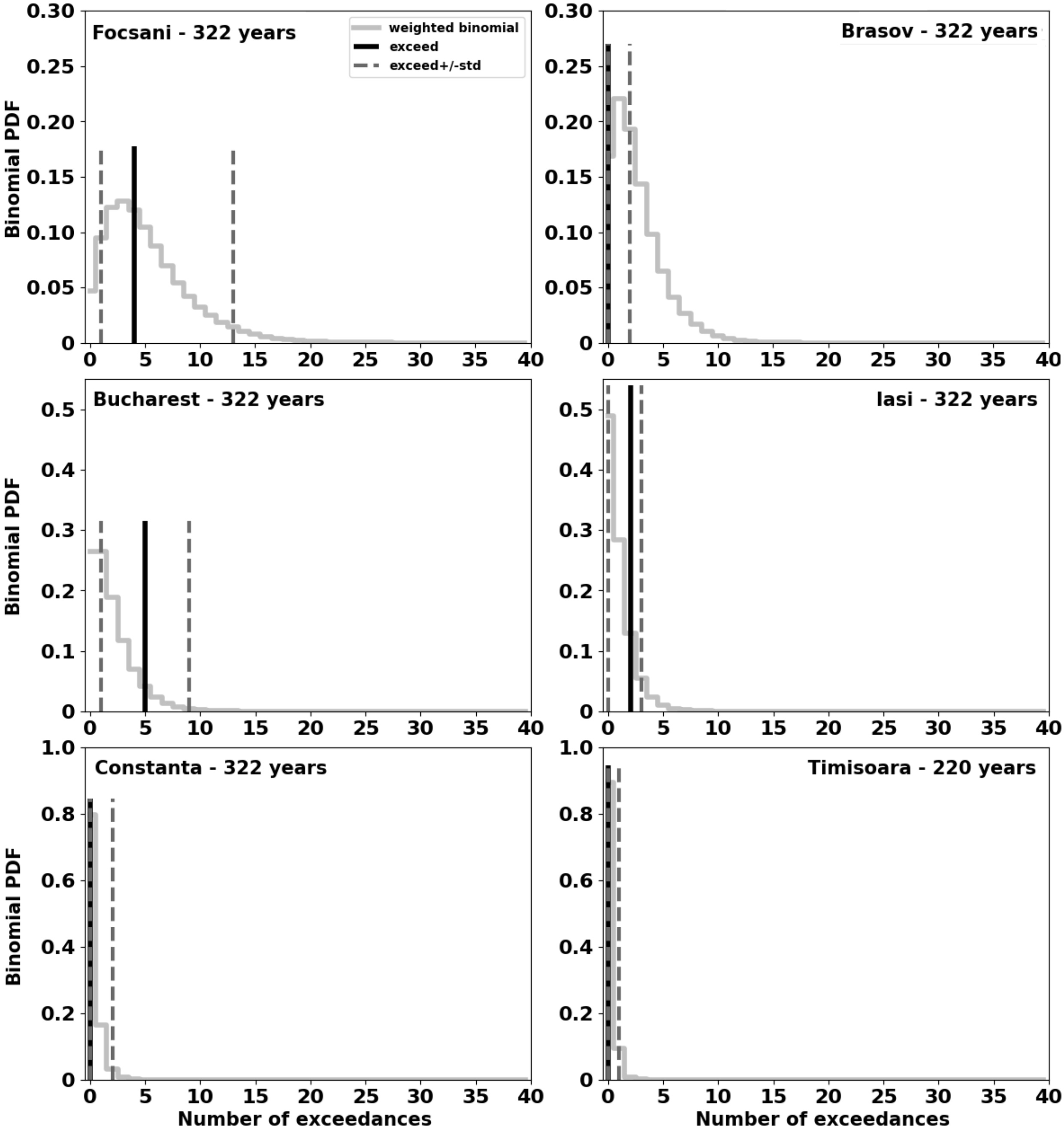


Figure 5. Consistency test results of ESHM20 with the observed PGA values at 0.2 g for six representative cities. The histogram depicts the ESHM20~~Where: ESHM~~ weighted mean~~ predicted - histogram~~, the observed number of exceedances over the time window of completeness is given as the~~-~~ black vertical line and its one sigma variability i.e.,~~-~~ dashed vertical lines; the total completeness time is specified in each subplot for their respective city.

Table 1. Observed and the ESHM 2020 predicted exceedances for 0.1 and 0.2g PGA at twelve Romanian cities.

City	T	SC	N 0.1	Rate 0.1	APE 0.1	P 0.1	P> 0.1	N 0.2	Rate 0.2	APE 0.2	P 0.2	P> 0.2
Bacău	322	C	4	0.01242	0.01235	0.06551	0.88613	2	0.00621	0.00619	0.12691	1.00000
Braşov	322	B	2	0.00621	0.00619	0.04927	0.96333	1	0.00311	0.00310	0.16854	1.00000
Bucharest	322	C	8	0.02484	0.02454	0.06947	0.34191	5	0.01553	0.01541	0.04063	0.09541
Câmpulung	322	B	1	0.00311	0.00310	0.04146	0.98512	1	0.00311	0.00310	0.21444	1.00000
Cluj-Napoca	284	B	1	0.00352	0.00351	0.13002	0.14835	1	0.00352	0.00351	0.95985	1.00000
Constanţa	322	C	2	0.00621	0.00619	0.18241	0.38990	1	0.00311	0.00310	0.79675	1.00000
Craiova	322	C	3	0.00932	0.00927	0.08392	0.16519	1	0.00311	0.00310	0.82129	1.00000
Focşani	322	C	13	0.04037	0.03957	0.05461	0.55554	4	0.01242	0.01235	0.11991	0.60844
Galaţi	322	B	4	0.01242	0.01235	0.09490	0.78712	1	0.00311	0.00310	0.24510	0.77985
Iaşi	322	B	3	0.00932	0.00927	0.15007	0.58011	2	0.00621	0.00619	0.12878	0.22567
Sibiu	250	B	1	0.00400	0.00399	0.30161	0.48469	1	0.00400	0.00399	0.87168	1.00000
Timişoara	220	B	1	0.00455	0.00454	0.67819	1.00000	1	0.00455	0.00454	0.89580	1.00000

Where:

T = time window of completeness [years];

SC = EC8 site class (CEN, 2004);

N 0.1 (N 0.2) = number of observed exceedances in T for 0.1 (0.2) g PGA;

Rate 0.1 (Rate 0.2) = observed annual rate of exceedance for 0.1 (0.2) g PGA;

APE 0.1 (APE 0.2) = Annual probability of exceedance for 0.1g - calculated from observed rate;

P 0.1 (P0.2) = *P-value* that the observed number of exceedances within T could be drawn from ESHM20 for 0.1 (0.2) g;

P>0.1 (P>0.2) = *P-value* where there will be N observations or more than the observed number of exceedances within T from ESHM20 for 0.1 (0.2) g PGA

Supplementary Material

The electronic Supplement contains additional plots of the distribution of the MSK-64 Intensity to PGA conversions for the two selected equations, the ESHM20 annual probability of exceedance distribution for Bucharest, the testing results for six cities and a summary plot of the results at all the locations.

Data availability

The collected intensity data can be made available by the authors only upon request as this study was done within~~withing~~ an ongoing project. The OpenQuake Engine input files and running scripts for ESHM20 can be downloaded from: https://gitlab.seismo.ethz.ch/efehr.

Author contributions

EFM, LD and CCO designed the framework of the work. EFM, LD and MG developed the codes and performed the testing analysis. CCO and DTD collected and harmonised the intensity data. EM and LD designed and wrote the paper with contributions from the other co-authors.

Competing interests

The authors declare that they have no conflict of interests.

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