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Total Probability Theorem Versus Shakeability: A Comparison between Two Seismic-Hazard Approaches Used in Central Asia

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INTRODUCTION

The comparison of seismic-hazard maps produced in different countries, or computed for the same country but at different times, is often hampered by the difficulties encountered in properly accounting for the differences among the implemented methodologies. An example of such difficulty is given by the comparison between the hazard maps computed during the Cold War period for the former Soviet Union, which includes vast regions exposed to high seismic hazard (e.g., the central Asian countries and the Caucasus region), and recent assessments carried out for the same regions following approaches developed in Western countries (e.g., [Ullah *et al.*, 2015](#)). These comparisons should take into account the differences in the underlying methodologies used in the former Soviet Union and, in several cases, still in use. In the Western countries, the process of formalizing the seismic-hazard assessment within a probabilistic framework (probabilistic seismic-hazard assessment [PSHA]) was developed during the 1960s at the Universidad Nacional Autonoma de Mexico (UNAM) and at the Massachusetts Institute of Technology (MIT) ([Roseblueth, 1964](#); [Esteve, 1967, 1968, 1970](#); [Cornell, 1968](#)). With the works of [Cornell \(1971\)](#) and [Merz and Cornell \(1973\)](#), PSHA was finally formalized within the context of the total probability theorem, which accounted for ground-motion variability, and its use then became widespread through the implementation and dissemination of the EQRISK software ([McGuire, 1976](#)). A comprehensive review of the early development of PSHA can be found in [Bommer and Abrahamson \(2006\)](#) and in [McGuire \(2008\)](#). On the other hand, the development of a probabilistic framework for seismic-hazard assessment in the former Soviet Union (hereinafter referred to as the USSR [Union of Soviet Socialist Republics]) was initiated in the 1940s with the works of [Medvedev \(1947\)](#) and developed by Riznichenko in the 1960s (e.g., [Riznichenko, 1965, 1992](#)). To quantitatively represent the seismicity of a region, Riznichenko used the concept of “seismic activity,” representing the frequency of occurrence N of earthquakes of a certain energy class K limited by a certain area S and time t of observation ([Riznichenko, 1965](#)). We remember here that the energy class K ([Rautian *et al.*, 2007](#)) is routinely computed in the USSR countries to quantify the earthquake size, along with different magnitude scales ([Rautian and Khalturin, 1994](#)).

Riznichenko proposed to spatially smooth the discrete activity rate patterns to obtain a seismic activity map. To compute the expected seismic effects at the surface, Riznichenko also introduced the concept of “shakeability” maps, defined as the spatial distribution of the average annual number of shaking episodes that caused a seismic intensity equal to or greater than a certain fixed value (e.g., [Ulomov and the GSHAP Region 7 Working Group, 1999](#)).

The works of Riznichenko were central to many hazard studies performed in the USSR during the 1970s and 1980s. An example of their application is given in [Alvarez and Bune \(1985\)](#), in which the implementation of shakeability in the SACUDIDA software was described. In 1990s, a new generation of hazard maps in Russia and neighboring countries was constructed and included in the Global Seismic Hazard Assessment Program (GSHAP) ([Ulomov and the GSHAP Region 7 Working Group, 1999](#)). A large effort was spent in creating a source model for northern Eurasia, and the hazard assessment was based on the shakeability approach applied to the MSK-64 intensity scale. As observed in [Zhang *et al.* \(1999\)](#), the hazard map for Russia showed values higher than the neighboring Asian regions, and it was modified before its inclusion in the final global map. Zhang *et al.* attributed the overestimation to the usage of macroseismic intensity, although recent PSHA performed in terms of macroseismic intensity (e.g., [Bindi *et al.*, 2012](#)) also observed such overestimation.

This work focuses on the comparison between the assessment of seismic hazard following the Cornell–McGuire and the shakeability approaches. The aim is to highlight in a simple, but effective and transparent way, the possible systematic over- or underestimation of one approach with respect to the other that should be taken into account when the outcomes of recent studies are compared with earlier assessments performed during the Cold War period in the USSR.

A BRIEF OVERVIEW ABOUT SEISMIC-HAZARD STUDIES IN THE USSR

Documentation about catastrophic seismic events in the Russian Empire started in the seventeenth and eighteenth centuries ([Tatevossian, 2004](#)), but only with the sequence of strong earthquakes that struck the northern Tien-Shan at the end of the nineteenth century (e.g., [Bindi *et al.*, 2014](#), and references

therein) was a scientific approach to seismic phenomena developed. One example is the 1887 Verny (former name of Almaty, at that time the capital of Kazakhstan) earthquake, for which a detailed survey about the effects generated in the region was performed under the guidance of Mushketov. A detailed description of the damage in Almaty was also compiled, providing an overview of the spatial variability of damages within the town and relating the damage to the building characteristics (Nurmagambetov *et al.*, 1999).

In 1893, the first comprehensive catalog of Russian earthquakes, including events up to 1887, was published (Mushketov and Orlov, 1893). The catalog completeness was qualitatively discussed, indicating from which year complete information was supposed to be available. Although the catalog was based on a descriptive approach, it exploited several primary sources (archive materials, newspapers, etc.) and it was used as a reference by several later studies. After the Verny earthquake, the Imperial Russian Geographical Society launched the first program for developing a seismic network across the empire's territory, and in 1902 the Permanent Central Seismological Commission (PCSC) was established in Saint Petersburg. Since 1902, annual bulletins were published, starting with the data collected by five seismic stations (Irkutsk, Nikolaev, Tashkent, Tiflis, and Yurev) and two astronomical observatories (Kharkov and Pavlovsk) where seismological observations were also performed (Levitski, 1902). During the first decade of the twentieth century, instrumental and macroseismic data collection and conservation were systematized and their distribution performed on a regular basis.

With the start of the First World War, and later with the Russian Revolution and the Russian Civil War, seismology studies in Russia stopped until the middle of the 1920s when the occurrence of destructive earthquakes, such as the M_w 6.2 Leninakan (Gyumri) earthquake in 1926 (Global Risk Identification Programme, 2010) and the M_w 6.8 Crimea earthquake in 1927 (Voznesensky, 1928), fostered again the interest in seismology. A number of catalogs on the seismic history of Armenia (Stepanyan, 1942), Azerbaijan (Malinovskiy, 1935), Lesser Caucasus (Bius, 1948), Turkmenia (Gorshkov, 1947), and many other areas were compiled. Although the catalog compiled by Bius (1948) was still descriptive, it contained the very first step toward parameterization, and intensities in many localities were evaluated in degrees of Mercalli–Cancani–Sieberg (MCS) scale (Sieberg, 1923).

After the 1948 devastating Ashkabad earthquake (M_w 7.3; Di Giacomo *et al.*, 2015), the expansion of the seismic network in the USSR was undertaken, as well as the replacement of old instruments with broadband seismographs of the Kirnos system, which allowed more precise determination of the amplitude of the ground displacement and, in turn, of the magnitude. After 1956, the sensitivity of seismic stations was further enhanced, and the dynamic and frequency ranges of the recorded signals widened. Short-period seismographs of high sensitivity were installed at the network stations, as well as long-period instruments and seismographs for recording strong ground motions. A detailed description of the seismic instru-

ments installed in the former USSR is given by Shishkevish (1974). In 1960s, Shebalin (1961) suggested a set of formulae that were used to determine earthquake parameters from initial macroseismic information, starting the compilation of parametric catalogs in the USSR (e.g., Kondorskaya and Shebalin, 1977, 1982). In the last two decades before the collapse of the Soviet Union, earthquake studies in the USSR mainly developed along the direction of catalog compilations for large areas and of the comprehensive analysis of major earthquakes. A detailed overview of the catalogs issued in the former USSR was provided by Rautian and Leith (2002).

An important component in the seismic-hazard assessment performed in the former Soviet countries is the seismic zoning, that is the general seismic zoning (GSZ), the detailed seismic zoning (DSZ), and the seismic micro zoning (SMZ). The differences among the three zoning levels are in the content, methods, and objectives of the investigation, leading to different scales of mapping (e.g., Nurmagambetov *et al.*, 1999). In particular, the GSZ-97 was compiled in the 1990s (Ulovom and the GSHAP Region 7 Working Group, 1999) and included in the GSHAP project (Giardini, 1999; Zhang *et al.*, 1999). This was the last hazard assessment in which the former USSR was considered as a whole. In the last two decades, single-country hazard studies have been mainly performed, such as those for Kyrgyzstan (Abdrakhmatov *et al.*, 2003) and Uzbekistan (Artikov *et al.*, 2012). Only recently have new cross-border initiatives been promoted for updating the hazard models, such as those carried out within the framework of the Global Earthquake Model regional project for central Asia (Earthquake Model Central Asia) (Bindi *et al.*, 2012; Ullah *et al.*, 2015), where Kazakhstan, Kyrgyzstan, Tajikistan, Uzbekistan, and Turkmenistan were involved.

HAZARD ASSESSMENT

Following Cornell (1971), the PSHA for a generic site of interest is expressed in terms of mean annual rate of exceedance (MARE) for any selected intensity measure y and computed through the total probability theorem (e.g., Kramer, 1996):

$$\lambda_{y^*} = \sum_{j=1}^{N_s} \nu_j \iint P[Y > y^* | m, r] f_m f_{R_j} dm dr, \quad (1)$$

in which the summation j is taken over the N_s sources relevant for the hazard at the site of interest. Each source has an average magnitude exceedance threshold equal to $\nu_j = \exp(\alpha_j - \beta_j m_0)$, in which the parameters $\alpha = a \ln(10)$ and $\beta = b \ln(10)$ describe the Gutenberg–Richter (G-R) magnitude occurrence relationship $\lambda_m = \exp(\alpha - \beta m)$ for the specific source area, and m_0 is the minimum magnitude of interest. The term $P[Y > y^* | m, r]$ represents the conditional probability that the intensity measure Y exceeds any given value y^* for an earthquake of magnitude m occurring at distance r . It is represented by the ground-motion prediction equation (GMPE) or the macroseismic intensity prediction equation (IPE) in terms of some intensity measure (e.g., logarithm of the

▲ Figure 1. Numerical example for the hazard assessment considered in this work, including a single source area (gray rectangle in panel a). The site of interest is located at (0,0). The dimensions are given in kilometers. The probability density functions (PDFs) for (b) distance and (c) magnitude distributions are also shown.

peak ground acceleration or the macroseismic intensity) considered suitable for the analyzed area and for the specific tectonic regime. For any magnitude and distance, the GMPE describes a normal distribution $N(\bar{y}, \sigma)$ centered on the median predicted value $\bar{y}$ with a standard deviation σ . The probability of exceeding y^* corresponds to the area under a Gaussian distribution computed from y^* to the upper integration limit.

The conditional probability is marginalized with respect to magnitude and distance considering the probability density function (PDF) distributions f_{mj} and f_{Rj} . The former is given by the PDF of G-R recurrence law with upper and lower bounds (truncated G-R):

$$f_M(m) = \frac{\beta \exp[-\beta(m - m_0)]}{1 - \exp[-\beta(m_{\max} - m_0)]}, \quad (2)$$

in which $m_{\max}$ is the maximum expected magnitude for the considered source. In the simplified numerical example considered in this study (Fig. 1), the PDF for distance is constructed numerically considering the distribution of distances computed for a regular grid of points over the source area. Each grid element has a dimension of 1 km $\times$ 1 km and the bin width of the histogram representing the PDF is 3 km. The G-R distribution is described by the parameters $a = 3$, $b = 1$, $m_0 = 4$, and $m_{\max} = 8.5$.

Considering a discrete version for the magnitude and distance PDFs, that is substituting the double integral in equation (1) with a double summation over the magnitude and distance discrete values (e.g., Kramer, 1996), the hazard assessed via equation (1) consists of three nested loops: the external one for the source areas (a single source in the example considered in Fig. 1) and the other two for the magnitude and distance intervals.

The contribution of each magnitude and distance bin is given by the product of the PDF values for that specific bin

times the probability of exceeding the considered value y^* for the intensity measure. These contributions are later summed and multiplied by the rate ν . It is worth noting the α parameter of the G-R recurrence law enters in the computation through ν . Finally, the hazard curve $\lambda = \lambda(y)$ is formed by repeating the computations for different values of y^* .

In the USSR, the computation of the MARE was based on the concept of seismic shakeability. The shakeability B_{y^*} , computed at the selected site of interest as a function of y^* , was defined by Riznichenko (1965) as

$$B_{y^*} = \int_V N_{\Sigma}(M_{y^*})_{ij} dx dy dz, \quad (3)$$

in which M_{y^*} is the minimum magnitude generating, at the site of interest, an intensity measure y equal to or larger than y^* , $N_{\Sigma}(M_{y^*})$ is the cumulative frequency magnitude distribution, and V is the volume in which the considered sources are located. Although λ and B both give estimates of MARE, we use different variables to be consistent with the original literature. If we consider depth as a parameter of the selected GMPE or IPE and we integrate the sources over a discrete surface, the shakeability can be approximated by

$$B_{y^*} = \sum_{ij} N_{\Sigma}(M_{y^*})_{ij} \Delta x \Delta y, \quad (4)$$

in which the index ij identifies the elementary source area $\Delta x \Delta y$. In typical applications during the Soviet time, the intensity measure y was the macroseismic intensity in the MSK-64 scale, and the size of the earthquake was measured considering the K class (Rautian et al., 2007). Because of the K class is related to the logarithm of the energy, the slope of the G-R considering K is about half of the typical values for M and generally indicated with γ in the USSR literature.

The steps followed to compute the shakeability are: (1) for the selected site of interest and for a given value of the intensity measure y^* , the distances between each elementary source $\Delta x \Delta y$ and the site are computed; (2) for each distance, and considering the GMPE or IPE, the minimum magnitude (or K) that produce at that distance a value of y greater than or equal to y^* is computed; (3) the cumulative number of events with magnitudes greater than or equal to the minimum one evaluated in step (2) is computed and the summation in equation (4) is performed.

In equation (4), $N_{\Sigma}(M_{y^*})_{ij}$ is computed from the cumulative density function of the truncated G-R law, given by

$$F_M(m) = \frac{1 - \exp[-\beta(m - m_0)]}{1 - \exp[-\beta(m_{\max} - m_0)]}. \quad (5)$$

The contribution of the source area ij accounts for the rate $\nu_{ij} = 10^{(a_{ij} - b m_0)}$. Because of the activity rate parameter a of the G-R is computed for the whole source region Σ , then the rate ν_{ij} is normalized to the total area S_{Σ} of Σ , that is

$$\nu_{ij} = \exp^{[a_{ij} - \ln(S_{\Sigma}) - \beta m_0]}. \quad (6)$$

▲ **Figure 2.** Cumulative density function (CDF) as a function of MSK-64 intensity for a mean predicted intensity equal to 7 and considering $\sigma = 0.75$ (black), $\sigma = 0.30$ (gray), and $\sigma = 0$ (dashed).

It is worth noting the shakeability is not accounting for the variability of the predictive model. As discussed by [Bommer and Abrahamson \(2006\)](#), in the original formulation of the PSHA the aleatoric part was either not considered or considered optional until the studies carried out in the 1980s.

If the standard deviation σ of the GMPE or IPE used in equation (1) tends to zero, the Gaussian $N(\bar{y}, \sigma)$ tends to a delta function centered at $\bar{y}$, that is $\delta(y - \bar{y})$. Therefore, the probability of exceedance becomes

$$\int_{y^*}^{+\infty} N(\bar{y}, \sigma) dy \approx \int_{y^*}^{+\infty} \delta(y - \bar{y}) dy = \begin{cases} 1 & \text{for } y^* \leq \bar{y} \\ 0 & \text{otherwise.} \end{cases} \quad (7)$$

In the case of σ close to zero, the sigmoid describing the integral of the normal distribution tends to a step function centered at $\bar{y}$, as shown in Figure 2, and the annual rate of exceedance λ approaches the shakeability B .

Figure 3 shows the matrices representing the contribution to the hazard assessment for each magnitude and distance combination in Figure 1 and considering a macroseismic intensity $I = 7$ as the value for y^* . Panel (a) shows the matrix relevant to the total probability theorem (equation 1) assuming the standard deviation σ of the IPE is 0.75; panel (b) shows the matrix for the shakeability defined in equation (4); panel (c) is the same as for panel (a), but considering $\sigma = 0.3$. By comparing panels (a) and (b), it is clear that the magnitude–distance contribution to the Cornell–McGuire and shakeability approaches is different: while for shakeability, magnitudes below 6 are not contributing to the hazard because they generate a median

▲ **Figure 3.** Matrices for the hazard assessment considering $I = 7$: (a) contributions to equation (1) for $\sigma = 0.75$. The magnitude and distance distributions (histograms) are also shown. (b) Contribution to shakeability defined in equation (4); (c) the same as in (a) but for $\sigma = 0.30$. The values in the matrices are normalized to be between 0 (white) and 1 (black), and the maximum value used for the normalization is reported above each matrix.

▲ **Figure 4.** Comparison between the mean annual rate of exceedance (MARE) computed using the total probability theorem in equation (1) (black) and the shakeability B as defined in equation (4) (gray). (a) $\sigma = 0.75$ and $b = 1$, (b) $\sigma = 0.30$ and $b = 1$, (c) $\sigma = 0.75$ and $b = 0.9$, (d) $\sigma = 0.75$ and $b = 0.6$.

intensity smaller than 7; for the Cornell–McGuire approach, the magnitude range contributing to hazard is broader as a consequence of the aleatoric variability, and it extends below $M = 6$. Considering that the frequency of smaller magnitudes is higher according to the G-R recurrence law, the largest contribution to hazard in panel (a) is coming from magnitudes of around 5.5. Decreasing σ , the contribution over the magnitude–distance ranges becomes more similar to the shakeability one, as shown by the matrix in panel (c).

Figure 4 shows the comparison between the MARE computed with equation (1) and the shakeability defined in equation (4) for different σ and b values. Considering the results for $b = 1$, the shakeability underestimates the hazard with respect to the Cornell–McGuire approach (panel [a]) while the estimates from the two approaches converge for small σ values (panel [b]), which is in agreement with the discussions in Bommer and Abrahamson (2006) about the effect of changes in σ on seismic hazard. Because the relative contribution of large magnitudes with respect to the small ones increases by decreasing the b value, the estimates from the two approaches for $\sigma = 0.75$ become closer when b is reduced to 0.6 (panel [d]).

To exemplify the comparison between the two approaches in a real situation, Figure 5 shows two seismic zones used for the PSHA in central Asia (Ullah et al., 2015): SZ15 is located in northern Tien-Shan where several strong earthquakes, even above magnitude 8, have occurred in the past, while SZ18 includes the very active region of the Alay Valley, between the Pamir front and the southern Tien-Shan range. According

▲ **Figure 5.** (a) Map of Kyrgyzstan (central Asia) with two seismic zones (SZ15: northern Tien-Shan; SZ18: Alay Valley) defined in Ullah et al. (2015). The main faults (white lines) and the location of earthquakes with magnitude larger than 7 (stars) are also shown. (b) MARE computed with the total probability theorem (black) and considering the shakeability (gray) for the two seismic zones (the continuous and broken lines are used for SZ18 and SZ15, respectively). The two white triangles indicate the sites where the hazard is computed for each zone.

to Ullah et al. (2015), SZ15 is characterized by $b = 0.5$, $a = 1.7$, and maximum magnitude $m_{\max} = 8.3$, whereas the parameters for SZ18 are $b = 0.89$, $a = 3.4$ and $m_{\max} = 7.5$. The standard deviation of the IPE considered for the assessment is 0.7. For each of the two seismic zones, the MARE and the shakeability is computed for a site located at the lower-left corner of the seismic zone, and the comparison of the curves is shown in panel (b). As expected from the previous discussions, the shakeability underestimates the MARE, and the underestimation is larger for the large b -value area (SZ18). For example, the rate of exceedance to shakeability ratio for SZ18 is 3.4 and 7.3 for intensities 7 and 8, respectively, whereas the same ratios reduce to 1.7 and 2.1 when SZ15 is considered.

CONCLUSIONS

We showed the MARE computed following the shakeability approach underestimates the hazard levels with respect to the standard Cornell–McGuire approach. The underestimation is related to the aleatoric variability, which is not accounted for in the shakeability approach, and the underestimation is larger for areas with b values approaching 1. It is worth noting that in some hazard studies performed during the Soviet time, the minimum magnitude M_{y*} was systematically reduced by removing $\Delta M/2$, in which ΔM was the bin width used for the G-R distribution (e.g., Alvarez and Bune, 1985). Using this correction, the underestimation of the shakeability was partially mitigated, although we think that a more transparent handling of the uncertainties should be preferable. This study, in our opinion, helps us to better understand the pros and cons of the different approaches in a transparent way that can be easily communicated to find common bases for the future development of seismic hazard in these regions. Furthermore, it is meant to easily and directly explain to Western scientists interested in these regions where some key differences and similarities between the two approaches lie.

We conclude the overestimation of the hazard for some of the former Soviet countries observed in previous studies (e.g., Zhang *et al.*, 1999) cannot be related to the implementation of the shakeability concept. Although Zhang *et al.* (1999), in compiling the GSHAP map for continental Asia, ascribed this overestimation to the usage of the macroseismic intensities in northern Eurasia (Ulomov and the GSHAP Region 7 Working Group, 1999), recent studies for central Asia performed in terms of intensity also obtained lower hazard values (Bindi *et al.*, 2012; Ullah *et al.*, 2015). Possible causes of the previous overestimation may be related to the parametrization of the employed model and its attributes and are the subject of ongoing research. ☒

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