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Original Research Article

A Reliable Method for Determining the Tapered Minimum Magnitude in a Probabilistic Seismic Hazard Analysis

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Abstract

One of the inputs of probabilistic seismic hazard analysis (PSHA) is the minimum magnitude (m_{min}) of damaging earthquakes. Recent studies have shown that the choice of m_{min} can affect the results of PSHA. That is, if the m_{min} value is low, the PSHA will be overestimated. Therefore, it is important to choose the m_{min} value in such a way that earthquakes with greater magnitude than m_{min} have the capability to damage the structure. Obviously, the m_{min} depends on the characteristics of the structure and the earthquake. The mechanism of occurrence of earthquakes in each region is such that earthquakes with different characteristics can occur. Therefore, earthquakes with the same magnitude cause different levels of damage to the structure. This paper uses a tapered line instead of the cut-off magnitude for m_{min}. In this regard, we model The 3, 5, and 8-story intermediate concrete frame using Opensees software and perform time history dynamic analysis based on 246 earthquake accelerograms. The structural damage is assumed based on the drift ratio. The drift ratio of 0.004 is assumed as the limit state for the operational performance (OP) level. Using the non-uniform distance number, the m_{min} taper line is obtained as [4.5, 5.5]. This number can be used as the integral lower bound in the PSHA.

Keywords: Moment-resisting reinforced concrete structure, Performance level, Nonlinear dynamic analysis, Seismic risk.

1. Introduction

Diagnosis of the minimum magnitude of an earthquake that can cause damage to the structure, m_{min}, has always been of interest in earthquake engineering. The minimum magnitude of the earthquake that damages the structure depends on the characteristics of the structure and the earthquake. That is, earthquakes of equal magnitude may cause different levels of damage to a specific building, depending on their distances, frequency contents, and other intensity measures [1,2].

The first mention of the importance of m_{min} in the work of Bender and Campbell returns to 1989. They stated that the choice of m_{min} significantly affects the calculated maximum acceleration (PGA) and uniform hazard response spectrum in small earthquakes [3]. Halchuk and Adams (2010) explained that the selection of m_{min} significantly affects the calculated seismic hazard, especially for PGA and low-period hazards in areas with low seismicity. In these areas, the hazard mostly comes from small earthquakes at short distances [4]. Bommer and Crowley (2017) comprehensively reviewed the definitions of m_{min} and its role in probabilistic seismic hazard analysis (PSHA). They believed that the m_{min} is commonly used for integration in the PSHA, but its definition is usually lacking in describing its exact concept. They implied a collection of the incorrect definitions of m_{min} and proposed a correct definition. They stated that the m_{min} is an engineering parameter that is more about risk rather than hazard, and the ambiguity about this concept can be removed by defining the lower limit of a specific earthquake criterion instead of the minimum magnitude [5].

Cornell and Sewell (1987) showed that although an earthquake with a magnitude of 4.88 (Mw) can create a drift ratio (DR) of 0.15% in the structure, Earthquakes with magnitudes of 5.4 and 5.99 (Mw) cause a drift of 0.0017% and 0.0046% in the structure, which are almost negligible values. They also showed that two earthquakes with approximately the same magnitude of 5 and 5.01 caused DR of 0.31% and 0.023%, respectively. Also, earthquakes with a magnitude of 5.99 (Mw) create a DR of 0.0153% in their model [6]. In this way, it is very challenging to determine the specific value for m_{min}.

Currently, the value of m_{min} is selected as a number based on engineering judgment. For example, in Tehran's hazard analysis, Yazdani et al. (2015) used m_{min}=5 [7], Amini et al. selected m_{min}=4.8 [8], and Shahbazi & Mansouri (2021) used m_{min} =4 [9]. These different values can be responsible for part of the changes in hazards by them for the Tehran region. This dispersion can cause ambiguity in decision-making.

In this paper, we use the probable m_{min} instead of the cut-off m_{min}. This idea is based on some previous studies [5]. The proposed method has been tested on some moment-resisting reinforced concrete buildings. The studied buildings have 3, 5, and 8 stories and three bays. These structures are located in the range of medium-height buildings in Tehran with high seismicity, in accordance with the 2800 standard [10]. Buildings are designed based on Iranian national building regulations [11,12]. The response of the structure, under 246 accelerograms, is measured in terms of damage indices such as displacement, drift or drift ratio. The plot of accelerograms intensity measures (IM) versus damage measures (DM) of the buildings is used for m_{min} selection.

2. Problem definition

2.1 An overview of the concepts and relationships of the *PSHA*

The purpose of the *PSHA* is to quantify the rate (or probability) of exceeding the various levels of ground motion at the site, taking into account all probable earthquakes. The computational solution of the *PSHA* was first modeled by Cornel in 1968 [13]. The most conceptual document published in this field is the *SSHAC* (1997) report [14]. Any measure of ground motion (IM) can be considered as the output of the *PSHA*, but the two most well-known IMs, *PGA* and *Sa*. The *PSHA* is a process of integration of all possible magnitudes and distances of earthquakes parameter considering their uncertainties. The result of the *PSHA* is the average annual rate of exceedance of a strong ground motion parameter of a certain value in the site. In this approach, the participation of all possible earthquakes leads to finding the probability of exceeding a certain characteristic of the IM in a certain period of time in the site [15].

In *PSHA* formulation, the distance is introduced by $(f_R(r))$. $(f_R(r))$ is the probability density function of the distance from the nucleation point of the fault to the site that is obtained by dividing seismic sources into smaller parts and measuring the distance of each component from the site. With the density probability function of the magnitude of each source $f_M(m)$, the probability density function of the nucleation point of the fault $(f_R(r))$ and the probability distribution function of the occurrence of different levels of the magnitude of the earthquake, provided that a magnitude *m* occurs at a distance *r* from the site, $P(IM>x)|m,r)$, can be obtained as the probability of the ground motion from a specified level based on Equation 1:

$$P(IM>x)= \sum_{i=1}^{n_{source}} \lambda(M_i>m_{min}) \int_{m_{min}}^{m_{max}} \int_{0}^{r_{max}} P(IM>x)|m, r) f_{M_i}(m) f_{R_i}(r)\,dr\,dm, \tag{1}$$

Where $\lambda\ (M_i > m_{min})$ is the rate of occurrence of earthquakes greater than m_{min} for source *i*. $P(IM> x)$ is the probability of an annual occurrence of $IM> x$ where x is the parameter of the desired ground motion (For example, the maximum ground acceleration or spectral acceleration in a given period, etc.). 1/ λindicates the return period of earthquakes with the *IM* larger than desired *IM*. n_{source} is the number of specified sources. It is worth noting that the phrase $P(IM> x)|m,r)$ is derived from the selected attenuation relationships. By calculating the annual occurrence rate of different levels of the ground motion parameter using the above integration process and drawing the result, the hazard curve is obtained [15].

In *PSHA*, the contribution of different ranges of the magnitude of ground motion from different sources is considered. In fact, *PSHA* calculates the probable compositions of earthquakes in the range of $m_{min} \leq m \leq m_{max}$ to estimate the levels of maximum horizontal accelerations or other IMs to indicate the exceedance probability at a specific location within a specified time interval. A lower bound magnitude (m_{min}) is necessary for integration in *PSHA*. Selecting the m_{min} can have a significant effect on hazard outcomes, especially for peak ground acceleration (*PGA*) and in short periods in areas with low seismicity. In low seismicity areas, the hazard comes from the majority of small earthquakes in short distances [16]. Also, the m_{min} can affect the shape and level of the response spectrum [17]. Despite such effects, however, m_{min} remains unclear and the available definitions of the m_{min} are often accompanied by a lack of accurate knowledge and understanding of its meaning.

PSHA consists of four basic components: 1) seismic source model, 2) earthquake recurrence model, 3) ground motion prediction model (*GMPE*), and 4) occurrence model. The main input parameters of *PSHA* include the minimum magnitude, m_{min}, the annual rate of seismicity, λ (corresponding to m_{min}), and the value of *b* related to the Gutenberg-Richter relation, the upper limit of the earthquake magnitude, m_{max}. Numerous studies have been performed on the contribution of input parameters in the results of *PSHA* [18]. Some of these publications have shown the high importance of m_{min} in the *PSHA* [19, 20].

Due to the role of the selected m_{min} in the results of *PSHA* [21], and the high importance of this choice on the economy and safety measures, it is necessary to determine this parameter based on a detailed analysis of the condition of structures exposed to earthquakes. Thus, determining the m_{min} seems to require more attention and feedback analysis concerning the risk issues.

3. m_{min} definitions

Before giving a precise definition for m_{min}, we review a summary of the various properties attributed to m_{min} in the explanations of seismologists and earthquake engineers [5]:

1- m_{min} is required for integration as a lower bound. The high values of m_{min}, make integration easier (regarding the computational efforts). But m_{min} is not selected for easier or faster calculation of hazard. So this attribution does not give a precise value for m_{min} and can't be regarded as a basis for m_{min} definition.

2- m_{min} is neither the lower limit of completeness of the earthquake catalog nor the smallest magnitude used in earthquake recurrence relations. The smallest magnitude in determining the Gutenberg-Richter values (a (or λ) and b) may be equal to m_{min}, or more or less, occasionally. So this attribute does also not specify the exact value for m_{min}.

3. Each *GMPE* equation has a certain range of inputs, so GMPEs input values should be in this range. m_{min} is not the minimum value that can be used in *GMPE*. m_{min} may be smaller than the lower bound that is used in *GMPE*. This issue can inter difficult in PSHA; because such relationships are usually not capable of extrapolation for larger or smaller events, especially at low values, and the order of the error is higher [22]. It should be noted that in recent years the tendency to use records with smaller magnitudes in the *GMPE*s has increased, which can lead to lower slopes at lower magnitudes [23].

4- m_{min} does not guarantee a specific hazard estimate. Large values of m_{min} underestimate the hazard. The main goal of m_{min} is to eliminate the lower part of the participants in the hazard assessment. Obviously, the data elimination limit affects the results. Thus, a more precise definition of $\mathrm{m}_{\mathrm{min}}$ needs to be considered.

After identifying some common misconceptions about m_{min}, this section provides definitions of this parameter in *PSHA*. It can be said that some ambiguities about m_{min} (sometimes indicated by m_0) are due to the obvious expressions that have been said about it in the literature [5]. For example, in 1968, Cornell stated that m_0 (m_{min}) is a small magnitude, for example, 4, that events of smaller magnitude have no engineering significant [13].

In 1989, Bender and Campbell stated that the maximum acceleration of small earthquakes is too low and may not cause significant damage to engineering structures. Therefore, it raises the question of whether ground motion due to small earthquakes should be included in seismic hazard calculations. If a_{max} (maximum ground acceleration in a given return period) is used in seismic safety decisions of a structure, only potentially damaging earthquakes should be included in the hazard analysis [3]. Similar expressions that give rise to these notions of m_{min} can be found in seismic reference books and earthquake engineering, such as Ritter in 1990: the low or minimum limit indicates the level of an earthquake that its lower has no engineering value [23]. Kramer 1996, said that for engineering purposes, the effects of very small earthquakes are less important, and those that are not capable of significant damage are usually ignored. In most cases, the *PSHA* threshold value is set at a minimum of about 4 or 5 because smaller values rarely cause significant damage [24]. In 2004, McGuire made the following statement; lower limit m_{min} is selected based on the minimum magnitude that causes damage or loss and should be considered for hazard reduction purposes [18]. Although these expressions have different expressions, they all convey the same meaning. This concept can be expressed as follows: m_{min} indicates the smallest magnitude of an earthquake that has the potential to cause damage. Therefore, m_{min} is a necessary and not sufficient condition for damaging earthquakes. In other words, an earthquake with values equal to or greater than m_{min} does not mean that the resulting ground motion causes damage. But it is assumed that earthquakes smaller than m_{min} never induce damage [3].

However, this definition immediately raises questions: damage to what? And to what extent? It is clear that the value of m_{min} for partial cracking in masonry structures and the inelastic response of a nuclear reactor structure can be quite different. As a result, a more complete and clear definition of m_{min} is essential. m_{min} is the lower limit of integration on the magnitude of an earthquake, so values below that provide overestimates of hazard but do not have a significant impact on the structural hazard. Hazard estimation in this framework is probable and indicates the annual repetition or probability of exceeding the defined limit (performance target). Despite the slight complexity of the proposed definition, it fully covers the purpose of the m_{min} definition and also reveals that m_{min} is necessarily an engineering parameter affected by risk [5].

4. Methodology

The current method of determining the m_{min} is based on engineering judgment. Regarding the above discussion, it can be noted that the first issue in determining the m_{min} is the definition of damage. The second point in determining the damage is that there is no clear boundary between a damaging earthquake and a non-damaging earthquake. Thus, it can be concluded that replacing the current cut-off m_{min} with a tapered line is a more realistic assumption. In this way, damage of earthquakes in the distance between m_{c} (completeness earthquake) and m_{min} is calculated so that in m_{min} the number of damaging earthquakes vanishes. The gradual reduction line (curve) can be used as the lower limit of integration n the *PSHA* instead of the minimum cut magnitude. Of course, the concept of probable minimum magnitude is different from the minimum amount for narrowing magnitude. In the first case, it is assumed that there is a minimum of "correct" damage magnitude, and the uncertainty resulting from determining this value is modeled. In the second case, the claim is that some, but not all, of the smaller earthquakes, can be damaging, and that these damaging earthquakes do not suddenly break off at magnitudes of m_{min}.

Therefore, a taper minimum magnitude can be used to select a wide range of earthquake magnitudes that are more likely to cause damage to the structure. In the next section, the issue will be studied as a case study on 3, 5, and 8-story concrete structures.

5. Case study

Structural seismic evaluation is usually performed for a wide range of criteria, including different levels of damage and loss. The selected criteria can be related to the nonlinear response of a structural model derived via the nonlinear dynamic analysis. In this way, the relationship between the earthquake measure (IM) and the condition of the building can be established. With such a relationship, the building risk can be calculated. The following method can be used to perform a risk assessment for a specific structure [25-26].

A set of compatible accelerograms is selected or simulated in the distance R from the site (site to source distance) as the input for dynamic analysis, and then the structural damage under each accelerogram is calculated (Figure 1).

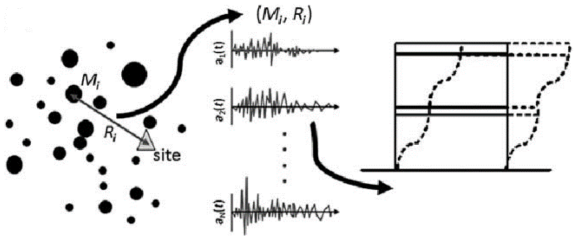


Figure 1. Damage calculation

The selection of earthquakes for nonlinear dynamic analysis has always been an important issue in earthquake engineering. If more conform earthquakes can be used, the uncertainty of ground motion will be modeled better. In this study, 246 records were selected in the magnitude interval 3.5 to 7.62 from the peer database, compatible with the site condition at a distance of 18 to 24 km [27]. It is assumed that the selected accelerograms can represent the range of possible ground motions for the intended scenario in terms of amplitude, frequency content, and duration. Some accelerograms are shown in Table 1 and Figure 2.

Today, a large number of existing structures are of the moment-resistant frame system. Considering the advantages and wide application of this system, in this research, the medium ductility moment-resistant frame was used as the case study. For this purpose, three regular 3, 5, and 8-story buildings with three bays of reinforced concrete residential buildings in metropolitan Tehran with high seismicity, following the fourth edition of Iran 2800 regulations and other Iranian national building regulations, were designed [10-12] .The response of the structure under each accelerogram is measured according to parameters such as displacement, drift, or drift ratio.

The floors height in all structures is assumed to be 3 meters, the load-bearing width of each frame is 4 meters, the gravity-bearing system is joist, the middle bay of all frames is 5 meters, the side bays are 4 meters, and the construction site is of soil type II (shear wave velocity between 360-720 m/s). The designed structures are shown in Figure 3.

Table1. Some of the accelerograms used in the study

a) Event	**b) Year**	**c) Station**	**d) Mag**
e) Chi-Chi, Taiwan-02	f) 1999	g) TCU071	h) 5.9
i) Chi-Chi, Taiwan-02	j) 1999	k) TCU137	l) 5.9
m) Chi-Chi, n) Taiwan	o) 1999	p) TCU036	q) 7.62
r) Irpinia, Italy-01	s) 1980	t) Brienza	u) 6.9
v) Duzce, Turkey	w) 1999	x) Lamont 362	y) 7.14
z) Loma Prieta	aa) 1989	bb) Anderson Dam (Downstream)	cc) 6.93
dd) 30225187	ee) 2002	ff) Brushy Peak	gg) 3.9
hh) Umbria Marche (aftershock 13), Italy	ii) 1997	jj) Colfiorito-Casermette	kk) 4.9
ll) Parkfield -02, CA	mm) 2004	nn) COALING A -PRIEST VALLEY	oo) 6
pp) 21305648	qq) 2003	rr) Round Hill	ss) 4

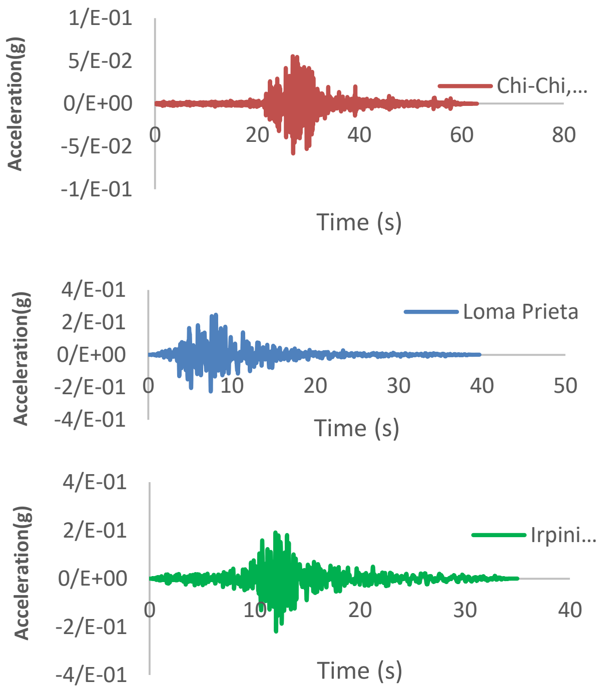
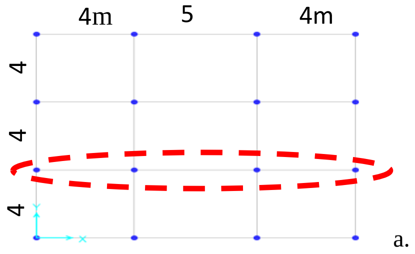
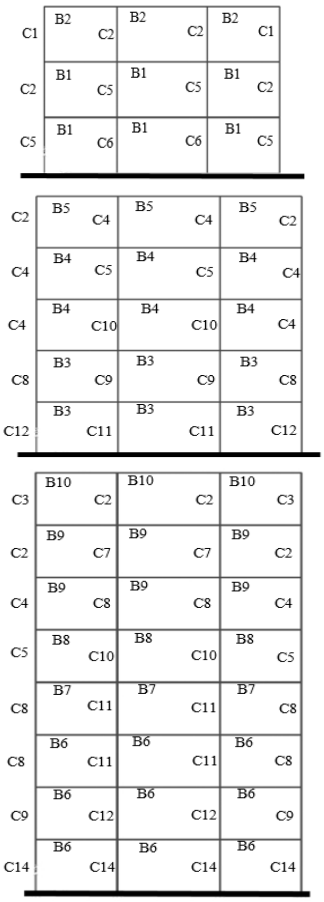


Figure 2. Examples of accelerograms



plan view



b. elevation view

Figure 3. The under study buildings a. plan and b. elevation views

Table 2. Specifications of structural beams

Type	width(cm)	Depth	Up-bars	Down-bars
B1	35	45	4Φ16	2Φ18
B2	30	40	3Φ16	2Φ14
B3	45	65	4Φ20	5Φ16
B4	40	45	4Φ18	3Φ16
B5	35	30	5Φ16	2Φ14
B6	50	60	4Φ20	3Φ18
B7	50	50	4Φ20	4Φ18
B8	40	50	4Φ20	4Φ18
B9	40	50	4Φ20	3Φ18
B10	35	55	3Φ18	2Φ16

Using Opensees software, the DRs of structures are calculated using 246 earthquake accelerograms. Assuming damage in the range of operational performance (DR= 0.004), we can compute the probability that each magnitude induces this DR to the structures. Now, we can use the concept of non-uniform distance numbers to represent the m_{min}. The obtained m_{min} for 3, 5, and 8-story structures are shown in Figure 4.

Table 3. Specifications of structural columns

Type	Dimension	Reinforcement
C1	30X30	4Φ18
C2	30X30	8Φ12
C3	30X30	8Φ14
C4	35X35	8Φ14
C5	35X35	8Φ16
C6	35X35	8Φ18
C7	35X35	12Φ18
C8	40X40	8Φ16
C9	40X40	8Φ18
C10	40X40	8Φ20
C11	45X45	8Φ18
C12	45X45	8Φ20
C13	45X45	14Φ16
C14	50X50	8Φ22

Table 4. Damage probability of different earthquakes

magnitude		3-4	4-5	5-6	6-7	7-7.62
Records (total)		50	50	50	50	46
Number of Records with drift ratio equal to or greater than 0.004	3-floor	0	0	2	18	41
	5-floor	0	0	3	21	43
	8-floor	0	0	3	21	43
Damage probability	3-floor	0	0	0.04	0.36	0.89
	5-floor	0	0	0.06	0.42	0.93
	8-floor	0	0	0.06	0.42	0.93
Damage complementary probability	3-floor	1	1	0.96	0.64	0.11
	5-floor	1	1	0.94	0.58	0.06
	8-floor	1	1	0.94	0.58	0.06
	average	**1**	**1**	**0.94**	**0.6**	**0.07**

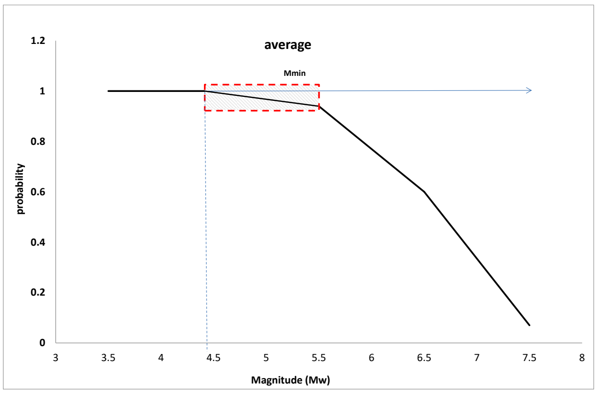


Figure 4. The m_{min} used in PSHA

According to Figure 4, which shows the average probability of no damage to this type of structure in terms of the magnitude of the earthquake, the minimum value can be determined according to the target for the m_{min}. For example, if the goal is to have no damage, a m_{min} of 4.5 is chosen. If 5% of the damage is acceptable, a minimum of 5.5 is appropriate. For other cases, the m_{min} can be selected. The dashed area in Figure 5 shows the considered boundary for m_{min}. By separating and normalizing this area, the density function of the truncated probability of m_{min} is determined. In this way, the distance number of tapered m_{min} is obtained. The tapered m_{min} is shown in Figure 5.

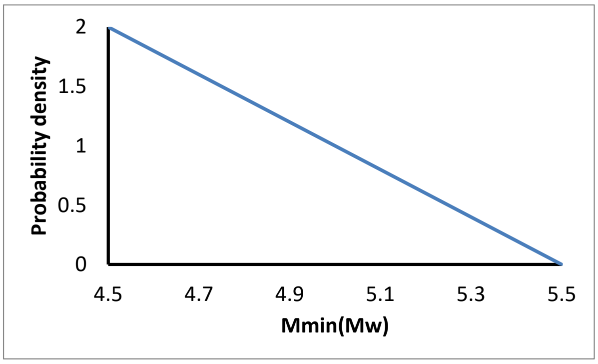


Figure5. The probability density function of m_{min} (tapered m_{min})

According to Figure 5, the cutting m_{min} is replaced by the tapered m_{min} as a distance number in the current PSHA. In this way, the m_{min} can be considered based on the real damage.

6. Conclusion

The minimum magnitude of the earthquake that can damage the structure is one of the main parameters of the *PSHA*. This parameter is usually selected based on expert opinion. In this paper, we propose the method for the probable m_{min} calculation. Based on this method, the value of m_{min} is considered with a linear distribution. In this way, different values of m_{min}, with different likelihoods, are entered in the *PSHA*, and the method's reliability will increase.

The results show that by applying gradual cuts instead of immediate cuts of a minimum magnitude, more reliable results for earthquake hazards can be achieved.

Also, the results of this research show that the importance of m_{min} in PSHA cannot be neglected, and it is necessary to be more careful in determining this parameter. The topics raised in this article can be considered as the beginning of this discussion.

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