Developing Ground Motion Shaking Map for Sarpol-e Zahab, Iran (2017) Earthquake

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ABSTRACT

Providing appropriate near real time ground motion shaking map is a critical requirement to effectively manage the consequence of an earthquake. In the present study, the standard procedure adopted by USGS ShakeMap to develop the ground motion shaking map is calibrated to implement in Iran. Selecting appropriate ground motion predictions equation and properly modeling of the local site condition are two important parameters that should be properly modeled to provide an appropriate ground motion shaking map. Here, a set of local, regional and global GMPEs that show good performance in the previous studies are adopted. Besides, the approach developed by Borcherdt [1] is used to take into account the local site condition. The VS30 of the region exploited from the proxy approach proposed by Wald and Allen [2]. The study evaluates the potential applicability of this method by compiling a database of measured and estimated VS30. The results indicate that the method outperforms than random selection of the site class. The calibrated model implements to generate the ground motion shaking map of the Sarpol-e Zahab, Iran earthquake (2017). The result shows that the approach performs better than employing GMPEs alone. The calibrated model can be used to generate the database of ground motion shaking of past earthquakes in Iran, which is an important requirement to develop empirical fragility or vulnerability models.

Keywords:
Ground motion shaking map; Rapid loss estimation;
Sarpol-e Zahab; Iran

1. Introduction

Appropriate earthquake risk management is a process that involves three steps of pre-event, co-event and post-event phases [3]. The co-event phase encompasses measures in the early seconds to hours after an earthquake to reduce the casualties and losses. In this regard, the earthquake early warning systems and rapid loss estimation systems are considered as appropriate tools to provide effective emergency response. Earthquake early warning systems, by shutting down the nuclear power plants or turning off the gas and other critical facilities, will mitigate the secondary damages of earthquakes. Rapid loss estimation tools, by providing an initial estimation of casualties and damages, help the decision-maker to take proper measures to reduce the consequences of earthquake. Experiences of past earthquakes in undeveloped countries show confusion among authorities in initial response to the

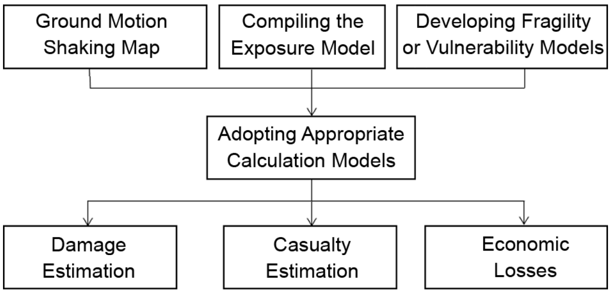

Figure 1. The main components of earthquake rapid loss estimation systems.

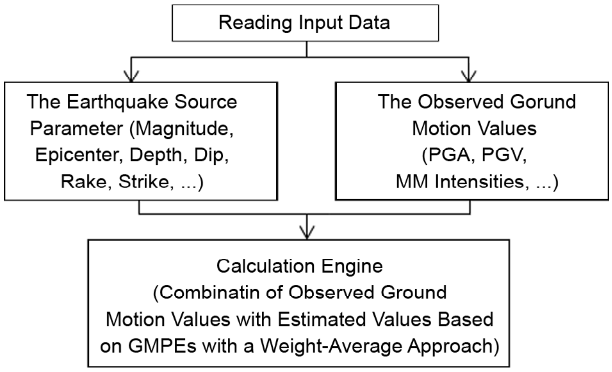

Figure 2. The general procedure to quantify the ground motion shaking map.

damages of earthquakes. This issue exacerbates the losses of earthquake. As a case in point, in Kocaeli earthquake (1999) hours after the earthquake, the full severity and scale of damages is not known to the central governing authorities [4]. Similar experiences are observed in destructive earthquakes of Iran such as Manjil (1990), Bam (2003) and Sarpol-e Zahab (2018). Based on the above discussion, developing a proper rapid loss estimation system is a necessity to reduce the losses of earthquakes. Figure (1) shows the main components of earthquake rapid loss estimation systems. As illustrated, providing a near real time map of the ground motion shaking is an important component of earthquake rapid loss estimation.

The ground motion shaking map portrays the distribution and severity of shaking in the region. This information is critical for understanding the extent of the area affected, determining which areas are potentially hardest hit, and allowing for rapid estimation of losses. So far, various approaches have been presented in literature to quantify the ground motion shaking map that differ in detail [5-6]. These approaches varies from the simple approach of using the Ground Motion Prediction Equations (GMPEs) or Krigin trend approach to the more advanced methods, which developed based on the combination of the observed values and estimated values given by GMPEs. The main purpose of this paper is to calibrate the methodology developed by Worden et al. [5] for earthquakes in Iran. This approach currently is applied by USGS in Shake Map system to make near real time ground motion shaking map following significant earthquakes.

In Figure (2), the general procedures to provide the ground motion shaking map based on the approach of Worden et al. [5] is presented. As shown, the fundamental elements of generating the ground motion shaking maps are: 1) the earthquake source parameters including the epicenter, magnitude, depth, dip, rake, strike, etc. 2) the measured ground motion values such as PGA and PGV in seismic stations, and 3) implementation of appropriate calculation algorithm.

In following, first, the general procedure in quantifying the ground shaking map based on the approach of Worden et al. [5] will be described. Then, the procedure to select appropriate GMPEs will be presented. This is followed by a comprehensive discussion regarding the procedure to take into account the soil response. In the final section, the application of the procedure for the earthquake of Sarpol-e Zahab (2018, 7.3 Mw) will be presented.

2. The General Procedure to Quantify the Ground Motion Shaking Values

In general, the procedure adopted by Worden et al. [5] to generate the ground motion shaking map is based on the combination of the recorded ground motion values (such as PGA, PGV) or reported intensities and the estimated value given by GMPEs [7]. In Figure (3), the general framework of that approach is presented. As illustrated, in the first step, the observed ground motion values including the measured values in strong ground motion stations should be mapped on the engineering bedrock. This is done by employing the de-amplification factor. Then, the interpolation process based on the weighted-average approach developed by Worden et al. [5] is adopted. In that approach, in vicinity of the seismic stations or reported intensities, the corresponding weight of the observed values are dominant and uncertainty is negligible; by getting distance from the

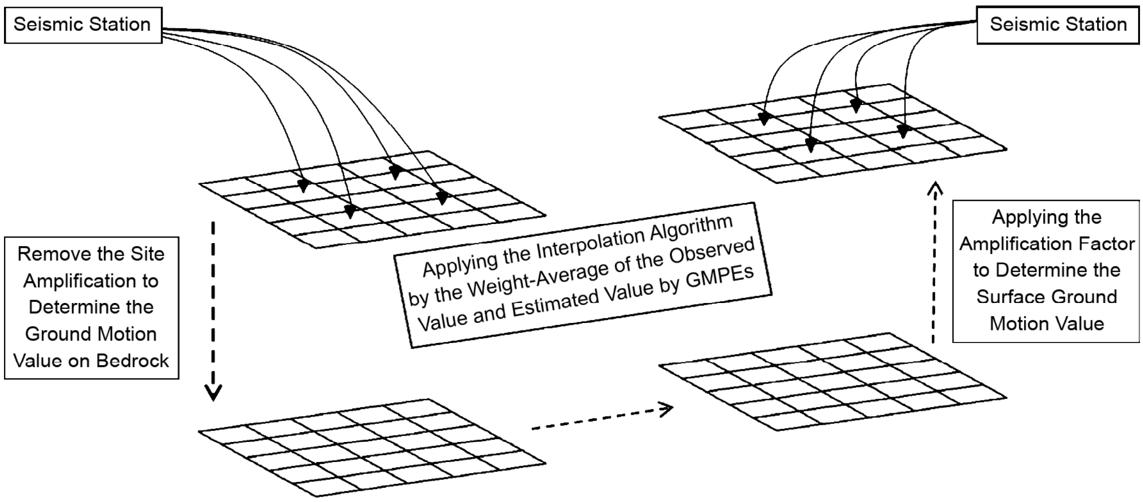

Figure 3. The general framework of interpolation process developed by Worden et al. [5] for generating the near real time ground motion shaking map.

observed values, the corresponding weight of recorded value or reported intensities are decreased and estimated value represented by GMPEs play an important role [5]. Finally, ground motion values at surface are obtained by applying the amplification factor. Clearly, this approach provides the best possible distribution of ground shaking maps in region with dense seismic stations network.

The overview above of the strategy for developing the ground motion shaking maps highlights the critical role of: 1) the ground motion predictive models, and 2) realistic description of amplification factors in generation of ground motion shaking map. In fact, the selected GMPEs should be compatible with seismic characteristic of the region. Moreover, the proper modelling of site effect will reduce the uncertainty of shaking values. These are the key points that motivate the other countries such as Italy, Swiss, Turkey, Portugal, etc. to optimize the general procedure adopted by USGS in ShakeMap system based on their local seismic characteristics [4, 8-10].

It is also worthwhile to stress that this methodology is associated with uncertainties. In fact, this approach provide a fast, first-order portray of the ground motion shaking in the region. As mentioned, providing a stable and dense seismic network in the region will enhance the quality of ground motion shaking maps. In an optimized case, the seismic network should be dense in urban fabrics where the population is high and exposed exposure at risk is great.

In the following, first the procedure to select appropriate GMPEs to employ in generating the near real time ground motion shaking map in Iran will be introduced. Then, the procedure to incorporate the site effect in analysis will be discussed.

3. Selecting Appropriate GMPE Models

The GMPEs play an important role in the region where the seismic stations or reported intensities are sparse. The GMPEs describe the decay of ground motion with distance as a function of earthquake magnitude, distance, and site characteristics, to present the ground motion value at the location of interest. The key point that should be considered in this regard is that the GMPEs are derived from incomplete knowledge about the earthquake source and wave propagation through complex media. Therefore, full reality cannot be modeled in GMPEs. This means that all GMPEs are approximate relation for estimation of unknown true value [11]. Thus, selecting appropriate GMPEs and modelling their associated uncertainties to be used in generating the near real time ground motion shaking map is of utmost importance. The epistemic uncertainty regarding the GMPEs is considered in analysis through the logic tree; the aleatory uncertainty of GMPEs is incorporated in analysis through the random sampling of GMPEs variability [12].

The general procedure for selecting appropriate GMPEs and determining their corresponding weights is measuring the goodness-of-fit which describes how well a model fit a set of recorded observations. In this regard, two approaches of the likelihood and average log likelihood (LH and

LLH) proposed by Scherbaum et al. [13-14] are popular among seismologists. In both approaches, the appropriateness of a GMPE model is examined by residual of observed data with respect to the predictive models. Mousavi et al. [15], Zafarani and Mousavi [16] and Tafti et al. [11] used these approaches for selection and ranking of GMPEs in different regions. In the present study, a set of local, regional, global GMPEs including Ghasemi et al. [17], Zafarani et al. [18], Kanno et al. [19], Kotha et al. [20] and Abrahamson et al. [21] are used. It should be remarked that the aforementioned GMPEs show good performance in the studies of Tafti et al. [11], Mousavi et al. [15] and Zafarani and Mousavi [16], which assess the appropriateness of those relations against observed ground motion database of Iran. The results of LLH test for Zagros region based on the compiled database from the study of Tafti et al. [11] for candidate GMPEs are presented in Table (1). The corresponding weight of GMPEs is also presented. As shown, the corresponding weights of GMPEs do not show significant differences. Thus, a logic-tree by assigning equal weights to GMPEs is used.

The aleatory uncertainty in GMPEs is incorporated in analysis by adding a random coefficient of GMPEs standard deviation to logarithm of median value. It should be remarked that the total variability of GMPE is composed of two components; the inter-event and intra-event variability. The inter-event uncertainty represents variability from one earthquake to another and the intra-event uncertainty represents variability from one location to another [12, 22]. Here, the variability of inter-event is set aside (the random coefficient of inter-event variability is set to zero) and only the intra-event variability, that related to a single event, is randomly added to the logarithm value of GMPE. With respect to the aforementioned discussion the Ground Motion Value (GMV) at the location of exposure is determined based on Equation (1).

$$Ln\,(GMV_{ij}) = Ln\,(\overline{GMV}_{ij}) + \varepsilon_{ij}\sigma_{ij} \qquad (1)$$

where $\overline{GMV}_{ij}$ is the median ground motion value represented by GMPEs; σ_{ij} is intra-event uncertainty and ε is random coefficients. The intra-event spatial correlation variability is an important issue to provide a realistic ground motion shaking map [23]. Various studies regarding the modeling spatial correlation can be found in literature [24-25]. In the present study, the model developed by Jayaram and Baker [24] is employed for considering the intra-event variability coefficients. In that approach, the correlation between spatially distributed ground motion shaking is exponentially reduced by increasing the distance among grids.

4. Considering the Local Site Condition

Proper modelling of the local site condition or amplification factor is an important step in developing the ground motion shaking map. Variation in the geological and geophysical properties of near-surface has a significant impact on the recorded ground motion characteristic on the surface, in such a way that even two structures with short distance will experience remarkably varied surface ground motion shaking [26]. Thus, it should be properly incorporate in analysis. Generally, time average shear wave velocity in the first 30 meters of the surface (V_{S30}) is considered as appropriate

Table 1. The main characteristics of selected GMPEs to be used in logic tree.

GMPE	Main Region	Magnitude (Mw)	Distance Metric	Component*	Period Range	LLH	Weight
Zafarani et al. [18]	Iran	4.0-7.3	R_{jb},0-200 Km	PGA, SA in G	0-4.0 sec	2.35	0.205
Kotha et al. [20]	Europe, Middle East	4.0-7.6	R_{jb}, 0-360	PGA, PGV, SA in G	0-4.0 sec	2.37	0.205
Ghasemi et al. [17]	Iran, West Eurasia	5.0-7.4	R_{hyp}, 0-100	PSA in $GMRotI_{50}$	005-3.0 sec	2.50	0.185
Abrahamson et al. [21]	Worldwide Shallow Crustal	3.0-7.9	R_{rup}, 0-400	PGA, PGV, SA in $RotD_{50}$	0-10 sec	2.51	0.200
Kanno et al. [19]	Japan + Some Foreign	5.0-8.0	R_{rup}, 1-400	PGA, PGV, SA in G	0-5.0 sec	2.41	0.205

parameter in building codes to quantify the local site effect. To this end, several researches have been attempted to develop procedures for estimation of average shear velocity in upper 30 meters of surface (V_{S30}) [2, 27-29]. Here, the prominent approach developed by [27] is adopted for estimating V_{S30}. In this approach, the V_{S30} is determined using the gradient of topography as a proxy method. Steep topographies (i.e. large gradient values) are assimilated to the hard rock sites whereas plain areas (i.e. zero or very low gradient values) are thought to represent areas that feature thick alluvial low velocity deposits. Although this is a very simplified approach, it shows well correlation with the results of other approaches such as geological-based classification scheme [30]. In Table 2) ranges of topographic slopes proposed by Wald and Allen [2] and Allen and Wald [27] for classification of sites into NEHRP classes is presented. In Figure (4), the distribution of soil classes in Iran based on the approach developed by Wald and Allen [2] is presented. To evaluate the accuracy of the approach in estimation of V_{S30}, a statistical analysis is performed based on measured V_{S30} in the seismic network of Iran Strong Motion Network (ISMN). The ISMN consists of 1160 strong ground motion stations, which the V_{S30} is only available for 518 stations (https://ismn.bhrc.ac.ir/en/). In Figure (5), the distribution of strong ground motion of ISMN is presented. The V_{S30} is only available for yellow triangles. In Table 3), the performance of the approach of Wald and Allen [2] is presented based on the measured V_{S30} in the seismic network of ISMN. As it is clear, the maximum range of success is attributed to the class C with 41 percent of correct estimation. The result indicates that the approach does better than selecting the soil class by chance. Although the accuracy of the approach in estimation of V_{S30} is not acceptable, this approach can be considered as the best practicable method in area with poor and crude geological information such as Iran.

Table 2. Ranges of topographic slopes proposed by Wald and Allen [2] and Allen and Wald [27] for classification of sites into NEHRP classes.

NEHRP Class	V_{S30}	Roughly Equivalent EC8 Class	Slope Range (m/m)		
			Active Tectonic [2]	Active Tectonic [27]	Stable Continent [2]
A/B	> 760	A	> 0.138	> 0.14	> 0.025
C	360 - 760	B	0.018 - 0.138	0.018 - 0.14	0.0072 - 0.025
D	180 - 360	C	0.0001 - 0.018	0.0003 - 0.018	2×10^{-5} - 0.0072
E	< 180	D	< 0.0001	< 0.0003	$< 2\times10^{-5}$

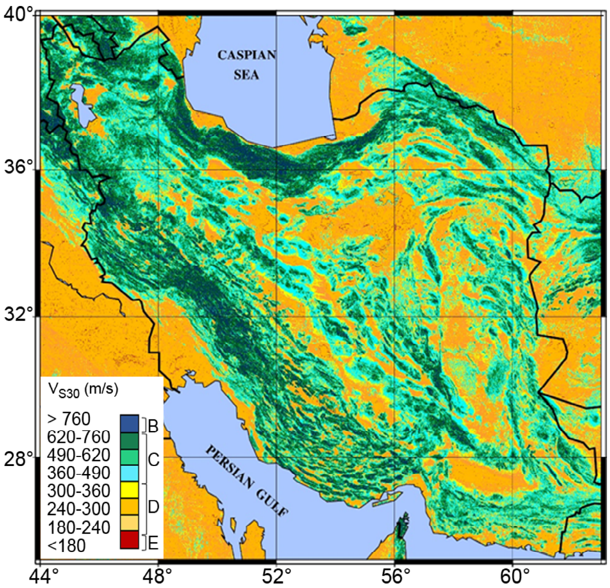

Figure 4. Distribution of soil classes in Iran based on the approach developed by Wald and Allen [2].

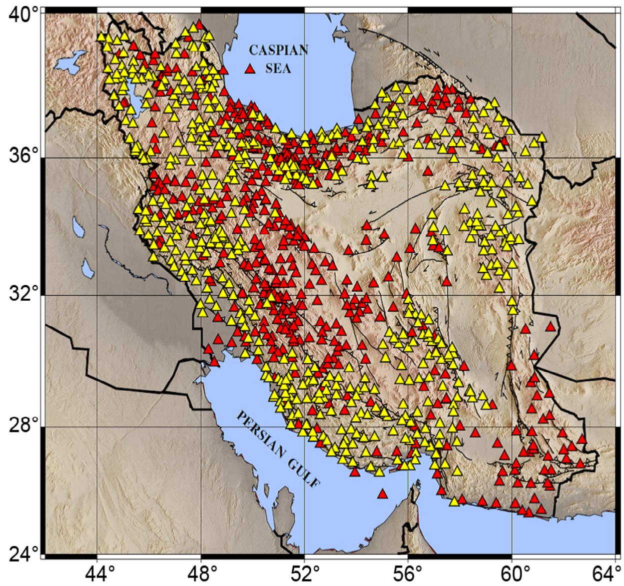

Figure 5. Distribution of strong ground motion of the ISMN in Iran (the V_{S30} is only available in yellow triangle).

Table 3. The success rate of the proposed approach of Wald and Allen [2] in determining the site classes for the measured data-base of V_{S30} of the ISMN.

Soil Class	V_{S30} Range	Total No of Station with Corresponding Soil Type	No of Success	Percent of Success (%)
A/B	>760 m/s	168	14	8.3
C	360-760 m/s	274	115	41.9
D	180-360 m/s	71	27	38.0
E	<180 m/s	5	1	20.0

Table 4. The amplification factor in short period (0.1-0.5 second) and long period (0.4-2.0 second) proposed by Borchert [1].

Class		Short-Period (PGA)				Mid-Period (PGV)			
PGA	V_{S30}	<150	150	250	350	<150	150	250	350
B	686	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C	464	1.15	1.10	1.04	0.98	1.29	1.26	1.23	1.19
D	301	1.33	1.23	1.09	0.96	1.71	1.64	1.55	1.45
E	163	1.65	1.43	1.15	0.93	2.55	2.37	2.14	1.91

For quantifying the amplification factor from the average shear velocity (V_{S30}) the procedure represented by Borcherdt [1] is employed. This approach used ground motion value and V_{S30} for estimation of short period (0.1-0.5 second) and long period (0.4-2.0 second) amplification factors. In Table (4), the corresponding amplification factor proposed by Borcherdt [1] for short and long period has been presented.

5. Application of the Proposed Procedure for the Earthquake of Sarpol-e Zahab (7.3 Mw)

The earthquake of Sarpol-e Zahab (M7.3) occurred in November 12, 2017 near the Iran-Iraq border in north-west of Iran. The event is a result of oblique-thrust faulting at the mid-crustal depth (~20 Km). Preliminary focal mechanism solution for the event indicates rupture occurred on a shallow dipping fault [31]. In Table (5), the focal parameters of the earthquake is presented. The event is recorded by 102 stations of ISMN, eight of which record PGA more than 0.1 g. In Table (6), the list of stations with PGA more than 0.1 g with their main characteristics including the station name, code, location, V_{S30} and the recorded acceleration has been represented. The highest acceleration (near to 0.7 g) is recorded in the Sarpol-e Zahab station, which is the closet station to epicenter (approximately 48 km from the epicenter). Figure (6a) plots the recorded ground motion values in seismic stations versus the predicted values given by GMPEs. Note that the figure suffers

Table 5. The focal parameter of the Sarpol-e Zahab earthquake (7.3 Mw).

Date	17/11/207
Time	18:18 (GMT)
Epicenter	(45.941 E, 34.886 N)
Depth	~19 (km)
M_w	7.3
Dip	10
Rake	
Strike	351

Table 6. The list of station with acceleration more than 0.1 g that records the earthquake of Sarpol-e Zahab, Iran (7.3 Mw).

No.	Station Name	Station Code	PGA (g)	Longitude	Latitude	Epicenter Distance (Km)	V_{S30} (cm/s)
1	Ravansar	RVN	0.122	46.65	34.65	69	267
2	Kerend	KRD	0.266	46.24	34.28	72	800
3	Eslamabadqarb	ELA	0.125	46.53	34.11	101	266
4	Goorsefid	GRS	0.315	45.85	34.22	74	403
5	Sarpolezahab	SPZ	0.697	45.87	34.46	47	619
6	Loomar	LUM	0.142	46.82	33.57	167	413
7	Javanrood	JAV	0.211	46.49	34.81	50	298
8	Kermanshah2	KRM2	0.126	47.12	34.36	122	-

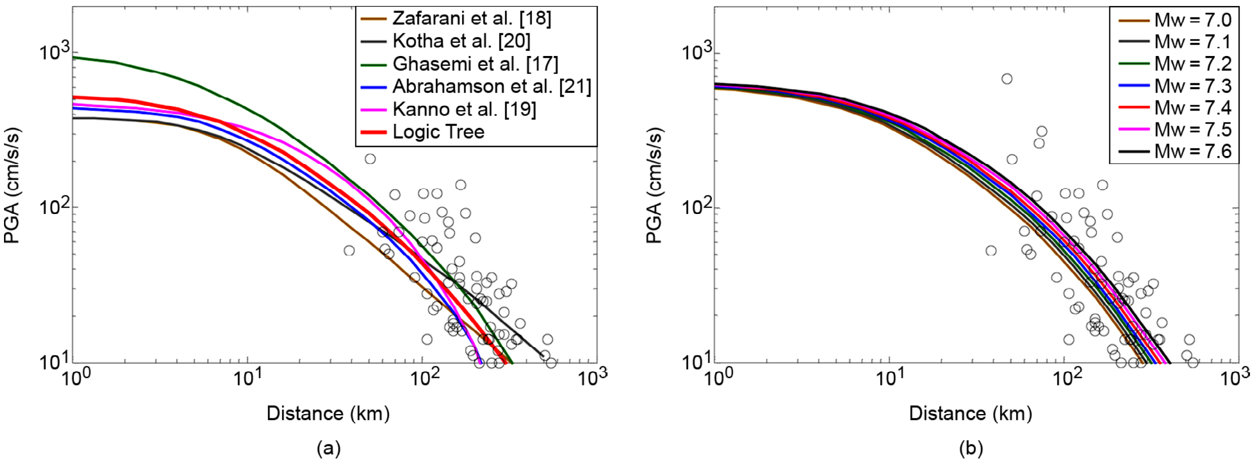

Table 6. The observed ground motion values versus the estimated values given by GMPEs; b) the estimated values GPMEs by considering different magnitude (bias correction); (the circles represent the recorded ground motion value).

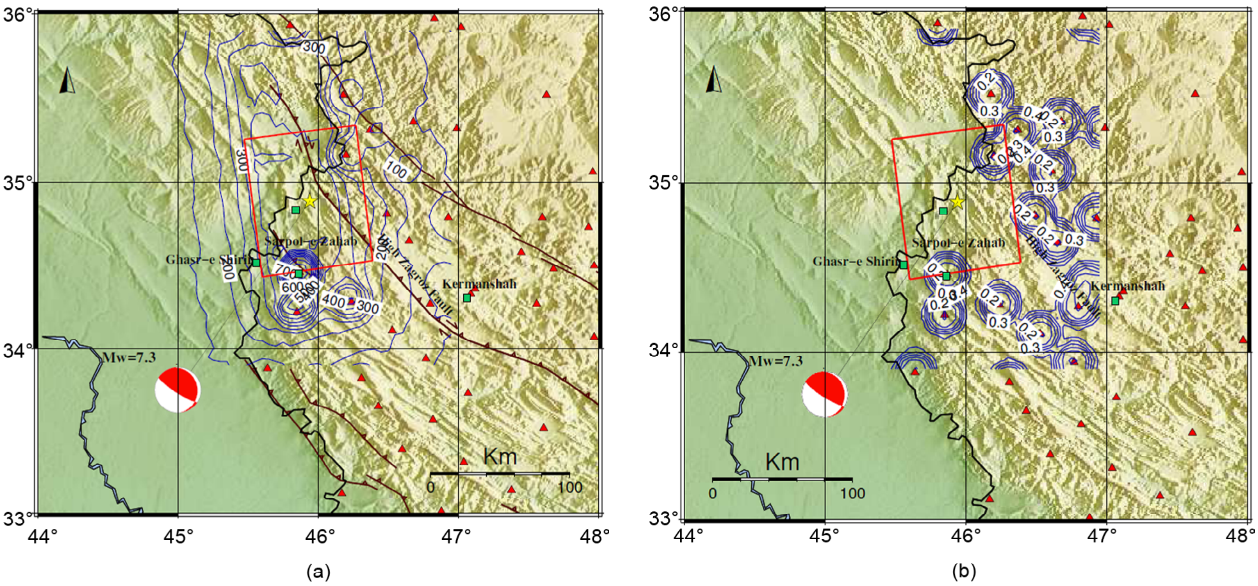

Table 7. The ground motion shaking map of PGA, and b) its corresponding uncertainty in Sarpol-e Zahab, Iran earthquake (red line and red triangles respectively presents fault plane and accelerometer stations; the fault plane adopted from the http://www.gsi.go.jp/cais/topic171115-index-e.html).

from the inconsistent definition of distance metric of various GMPEs. It should be remarked that the approach developed by Worden et al. [5] incorporates the bias correction. When enough stations record the event (here is considered as at least six stations), the magnitude of the event adjust in such a way that provides the minimum misfit. The definition of the misfit is configurable, here, the absolute difference of the recorded and estimated values (i.e. the L1 norm) is used. This correction has been introduced to account for various factors such as error in magnitude, inter-event and intra-event variability, etc. [8]. It should be noted that in the process of computing the bias, the outlier are removed; in fact, this is done in an iterative process. In the present study, the outliers are considered as the recorded value, which exceeds or lessens than the median value given by GMPE plus/minus four standard deviations. In Figure (6b) the effect of the bias correction is presented. By considering the bias correction, M 7.5 is considered as the appropriate magnitude for generating the ground motion shaking map. This issue indicates that the adopted GMPEs underestimate the actual ground motion values for the earthquake of Sarpol-e Zahab, Iran (2017). Thus, the correction attempts by increasing the magnitude to reduce the bias in GMPEs.

In Figure (7), the distribution of ground motion values in term of PGA for the Sarpol-e Zahab, Iran earthquake in a uniform grid of sites

(0.0086°×0.0086°) is presented. As illustrated, the highest estimated acceleration is approximately 0.7 g, which is attributed the value recorded in Sarpol-e Zahab station in (45.87 E, 34.46 N). In addition, the estimated uncertainty is reduced near the seismic stations whose real values are recorded (Figure 7b). It should be noted, when enough station records the earthquake (here at least six stations, this corresponds to the number of stations to implement to bias correction), in estimation of uncertainty, the inter-event variability is set aside and just the intra-event uncertainty, which is related to the viability from one location to another is considered in analysis. The reduced uncertainty will have a negligible impact on the relative contribution of the predictions of GMPEs in the averaging process; however, it will reduce the uncertainty for every output point in the map [5].

Controlling the ground motion shaking map developed by the recorded PGA in other seismic stations can be considered as an appropriate approach to test the calibrated model. To this end, the authors use the strong ground motion station installed in the Hirvi dam. The location of station is clarified by yellow triangle in Figure (7) (46.23 E, 35.12 N). The recorded PGA in the Hirvi station is 58 cm/s^2; while the ground motion shaking map presents the 78 cm/s^2. As it is clear, there is no significant difference among the observed value in Hirvi station and the value obtained from the calibrated weighted-average approach.

In Figure (8), the ground motion shaking map of the region by just using the GMPEs is presented. This is done to provide a comparison between the ground motion shaking map using GMPEs alone and the weighted-average approach. As it is clear, the map developed by GMPEs is more smoothed. Besides, there is a significant difference in the highest acceleration with respect to the weighted-average approach. This discrepancy between the results is due to incorporating the observed values in the weighted-average approach, which provide a more realistic distribution of shaking. This argument validates by a number of statistical tests performed by Worden et al. [5]. They compile a high quality database of California earthquakes and provide a comparison among the predicted values given by GMPEs, bias GMPEs and the weighted-average approach. Their result indicates that the weighted-average approach improved the predictions.

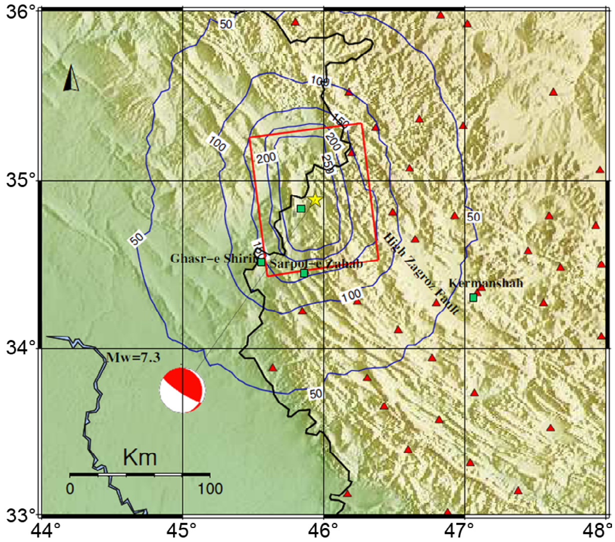

Table 7. The ground motion shaking map of PGA for the earthquake of Sarpol-e Zahab, Iran earthquake by just using GMPEs.

6. Conclusion

In the present study, the standard procedure adopted by USGS ShakeMap is calibrated to implement in Iran for generating near real time ground motion shaking map. The ground motion predictions equation and identification the local site condition are two critical parameters that should be properly modeled to provide a reliable ground motion shaking map. The epistemic and aleatory uncertainties of GMPEs are respectively considered in analysis by employing a logic tree and random sampling of inter-event and intra-event uncertainties. Here, a set of local, regional and global GMPEs were selected, including the relation of Ghasemi et al. [17], Zafarani et al. [18], Kanno et al. [19], Kotha et al. [20] and Abrahamson et al. [21]. The aleatory uncertainties of GMPEs are also considered in analysis by random sampling of the intra-event uncertainty. To provide a more realistic result, the random coefficients are drawn from a spatial correlation function developed by Jayaram and Baker [24]. The local site condition is considered in analysis through the approach developed by Borcherdt [1]. That approach uses the PGA and the V_{S30} to determine the amplification factors in short and long period. The VS30 for the whole country is exploited from the procedure developed by Wald and Allen [2]. That procedure uses the gradient to estimate the shear velocity in the upper 30 meter of the surface. To evaluate the accuracy of the approach in estimation of V_{S30}, a statistical analysis based on measured V_{S30} in ISMN is performed. The result indicates that the proposed model does better than selecting the soil class by chance.

The aforementioned calibrated model is employed to generate the ground motion shaking map of the earthquake of Sarpol-e Zahab, Iran (2017). The result shows that the weighted-average approach performs better than the simple implementation of GMPEs alone. This issue reflected in the highest predicted acceleration and distribution of PGA, which are more compatible with the reality (the observed ground motion values).

It should be noted that the aforementioned calibrated model is associated with uncertainties. In term of hardware, providing a highly dense seismic station network, which transfers the real time information can significantly improve the accuracy of ground motion shaking map, especially in a highly populated region where a substantial exposure is at risk. From the theoretical point of view, developing more appropriate GMPEs that are compatible with local seismic characteristic of the region or properly modelling the local site condition will enhance the quality of the ground motion shaking map.

The outcome of this study can be used to generate the database of ground motion shaking map of past earthquakes in Iran, which is an important requirement to develop the empirical fragility or vulnerability model.

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