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Sensitivity Analysis on Seismic Risk-Coefficients for Input to Indonesian Earthquake Resistance Building Code

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Abstract

New development in seismic design criteria of buildings is by adopting risk-targeted ground motions (RTGM)-based instead of previously adopted uniform hazard-based criteria. The RTGM adopts 1% probability of building collapse in 50 years, introducing a risk-coefficient. Risk-coefficient is defined as ratio of RTGM and maximum considered earthquake (MCE) hazard adopting 2% probability of exceedance in 50 years. The RTGM integrates hazard curve and building fragility, with a logarithmic standard deviation, β, value. This paper presents sensitivity analysis on hazard curves and β-values of six (6) specific sites in Indonesia. The hazard curves are represented by various seismic source conditions representing both subduction and shallow crystal zones with various level of intensities. This is obtained from recent probabilistic seismic hazard analysis conducted for revision of Indonesian seismic hazard maps. β-values are varied representing variation of building qualities. The sensitivity analysis is conducted for two spectral accelerations at periods of 0.2-second (short) and 1-second period. The analysis shows that there is about 7-14% deviation in risk coefficient values resulted from 0.6-0.8 variation in β-value and about 18-34% deviation resulted from 0.6-1.0 variation in β-value. Use of β value of 0.7 in the current Indonesian code is considered to be acceptable.

Keywords: Seismic; building code, spectral acceleration; ground-motion; fragility; risk-coefficient

1 Introduction

Indonesia has revised its seismic hazard map in 2010 by incorporating the most recent earthquake source zones, adopting relatively new ground motion predictive equations (GMPE) through probabilistic seismic hazard analysis (PSHA). The seismic hazard analysis and resulted map been elaborated and presented in Irsyam et al., (2010). As has been shown by many researchers that earthquake resistance structures subjected to a particular earthquake designed using equal hazard concept will not give value of equal risk (e.g. Liel et al. (2009); Luco et al. (2007); and Porter et al. (2007)). Considering these most current researches, in 2012, Indonesian seismic building codes (SNI-1726-2012) has been updated based on the new revised map, incorporating new concept of adopting risk-targeted ground motion (RTGM) derived from maximum considered earthquake (MCE) of the 2010 map as reference, representing 2% probability of exceedance (PE) in 50 years. In the previous building codes, the seismic design criteria is based on uniform hazard, without incorporating uncertainty in structural capacity (fragility) of the building. In the SNI-1726-2012, spectral accelerations at 0.2-second (S_s) and 1-second period (S_1) of the 2010 MCE map need to be multiplied by risk coefficients (C_{RS} ad C_{R1}), respectively, to new seismic criteria map of S_s and S_1 so called risk-targeted MCE (MCE_R).

The risk coefficients are obtained from RTGM of 1% probability of building collapse in 50 years, derived by integrating hazard curves of the 2010 PSHA with fragility curve of Indonesian buildings defined to have 10% probability of collapse and log-normal standard deviation, β. This follows new development in seismic design criteria developed for United States of America by Luco et al. (2007), that has been adopted in ASCE-SEI-7-10 and 2012 International Building Codes.

As RTGM is adopted, building fragility function with its logarithmic standard deviation value, β, need to be defined. General fragility function as adopted by Luco et al. (2007) and their previous related publications is adopted in RTGM derivation of Indonesian seismic codes. Uncertainties in the building fragility is considered mainly represented by the β-value. Sidi (2011) conducted study on hazard analysis and probability-based factor of safety representing tipical Indonesian building structures in general. Sidi recommends β-value of 0.7 for Indonesian RTGM calculation, as has been adapted in Sengara et al. (2012) for developing MCE_R maps for Indonesia. Recent research on collapse capacity (spectral acceleration that structure can resist without collpase) on sensitivity of of β-value (0.6-1.0) on resulting RTGMs for United States seismic design maps (in Luco et al., 2007 and NEHRP, 2009) are not significantly different. Most recent research by Liel et al. (2015) identifies that resulted RTGM would change if generic building fragility curve and hazard assessment were modified to account for seismic risk from subduction earthquakes and near-fault pulses. Nevertheless and aside from this recent researches, sensitivity analysis under various β-values on resulted RTGMs of Indonesian seismicity region is investigated and presented in the following sections to evaluate the recommended β-value of 0.7. The computed RTGMs under these various β-values are presented as C_R values. RTGMs are computed at two spectral periods of 0.2-second and 1-second with resulted C_{RS} ad C_{R1}, respectively. Six specific sites of Indonesia having different hazard curves and dominant controlling earthquakes potential, as resulted from de-aggregation analysis, covering two earthquake sources of subduction and shallow crustal fault respectively are investigated.

2 Risk-Targeted Maximum Considered Earthquake (MCE_R) of Indonesia

As has been described earlier, risk-targeted ground-motion (RTGM), MCE_R in this case, is defined as MCE hazard multiplied by risk coefficient, C_R. RTGM calculation is conducted by using a software that is specifically developed for obtaining C_R values as has been presented in detail in Sengara et al. (2012 and 2015). The RTGM is obtained by multiplication of site-specific hazard curve $F_{Em}(SA > a)$ and building fragility curve $f_R(a)$. The hazard curves of Indonesia are made available from new 2010 PSHA of Indonesia conducted by Team-9 (Irsyam *et al.* (2010). This new PSHA of Indonesia was developed by considering the most recent seismicity data, seismo-tectonic source zones considering tomographical cross section of subduction zones, and most recent GMPEs. PSHA results also provide Maximum Considered Earthquake (MCE) at 0.2 second (short period) and 1.0 second with 5% critical damping for reference site Class-B.

The hazard curve, fragility curve, and result of their multiplication is illustrated in Figure 1. Risk as a measure of probability of building collapse is formulated by the following formula:

$$\text{Risk, } P_f = \int_0^\infty f_R\,(a)\; f_{E_m}(SA>a)\;\mathrm{d}a \qquad (1)$$

where the fragility curve is given by general fragility function as:

$$f_R(a) \;= \frac{1}{a\beta\sqrt{2\pi}}\exp\left[-\frac{(\ln a-(\ln(\mathrm{RTGM})+1.28\beta))^2}{2\beta^2}\right] \qquad (2)$$

with two parameters: log normal standard deviation β and 10-percentile collapse probability with coefficient of 1.28.

The fragility curve would contribute in collapse capacity of building and there are uncertainties involved in this collapse capacity. Record to record variability would also involved in these uncertainties. Providing spectral acceleration is known, collapse capacity is also uncertain due to characteristics of building among others are building construction quality (Luco et al., 2007 and Liel et al., 2015). Parameter β would essentially represents these uncertainties. Since Indonesia has minimum strong-motion records and also the fact that not many earthquake building damage associated with different ground-motion characteristics (shallow crustal or subduction source), then it is complicated to accurately represent β-value based on probabilistic data. Nevertheless, a recommendation on representative β-value of Indonesia has been exercised by Sidi (2011). The study identified uncertainty of material strength, simplification of actual field condition, and human errors for the Indonesian conditions. It is concluded that β-value for Indonesia would vary between 0.65 and 0.70. For the current C_R seismic map, β-value of 0.7 was applied. Furthermore detail study and brief discussion regarding development of MCE_R of Indonesia can be found in Sengara *et al*. (2015) and Sengara *et al*. (2012). To further evaluate variation of β-value to RTGM or C_R values, sensitivity analysis through parametric study has been conducted to investigate its deviation to C_R values and to justify the current β-value adopted in the Indonesian C_R map.

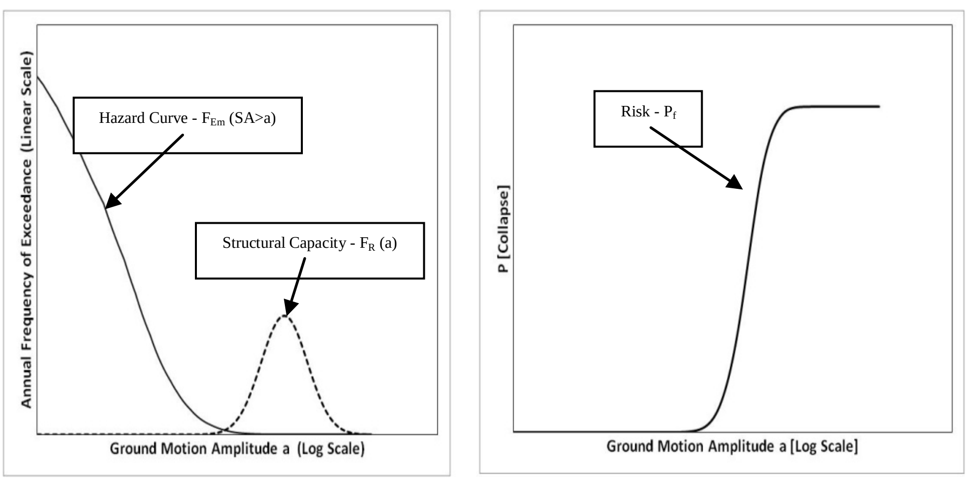


Figure 1 - Risk integral and its components of hazard and structural capacity curves

3 Site-specific Sensitivity Study on Risk-Targeted Ground Motion within Indonesia

In general, there are two mechanisms of earthquake sources contribute to seismic hazard of specific site within the Indonesian region. The two sources are subduction and shallow crustal mechanisms. Each mechanism would generate different ground-motion characteristics in both frequency content and duration. RTGM computation will involve these characteristics through its site-specific hazard curve resulted from the PSHA along fragilities of the buildings. It has been identified by many researchers that duration of the ground-motion is highly sensitive to different collapse fragility between subduction and crustal records. Raghunandan *et al* (2014) identified the average duration of subduction and shallow crustal are 44.3 seconds and 13.9 seconds, respectively. In addition Campion and Liel (2012) mentions that U.S seismic maps do not consider the impact of forward directivity in hazard curve and fragility for the condition near-active fault, as a result, risk are identified to be underestimated at some sites.

The sensitivity analysis of β-value to RTGM or C_R-value for several sites of interest in Indonesia based on the both mechanisms is investigated and presented herein. There are six (6) site locations that have been selected to represent both mechanisms. The location of the sites are provided and shown spatially in Figure 2. Each site location represents specific dominant controlling earthquake (either shallow crustal or subduction), resulted from de-aggregation analysis of the PSHA. All sites with shallow crustal controlling earthquakes are relatively close to the fault (Sianok-SFZ, Bandung-Lembang, and Yogyakarta-Opak), whereas for sites with subduction controlling earthquakes are relatively far but the closest on land to the subduction source (Padang and Denpasar-Bali cities). One more site is Jakarta city with relatively far distance but still dominantly controlled by Megathrust subduction south of Java island.

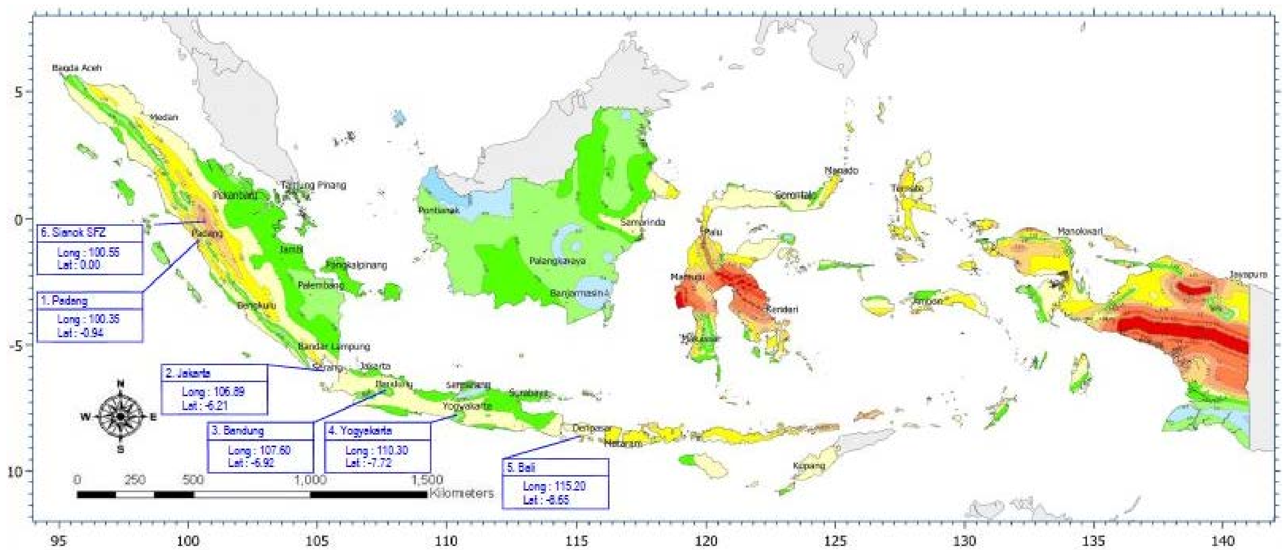


Figure 2 - Six selected locations representing specific subduction or shallow crustal earthquake source

Site-spesific characteristic of the sites of interest in this sensitivity analysis is represented by its hazard curve correlating annual frequency of exceedance and ground motion amplitude, A, for period of interest. In this case, hazard curve for each site under investigation consists of two periods, that is 0.2-second and 1-second, respectively. These hazard curves for all the sites of interest are shown in Figure 3. It is indicated in Figure 3 that there is significant difference in annual frequency of exceedance for particular ground-motion amplitudes, both for short and 1-second period motions. Specific characteristics of each site is next to be elaborated.

a. Subduction Source

For this study, there are three selected sites representing subduction mechanism. Since subduction sources in Indonesia are mostly located at western coast of Sumatra Island and southern coast of Java island. The sites are distributed within Western and Central Indonesia. The sites representing subduction earthquake source are: (a) Padang, located in Sumatera Island (latitude: 100.35, longitude: -0.94), is dominantly controlled by Sumatra Megathrust (Interface) and Benioff (Intra-plate); (b) Jakarta, located in Java Island (latitude: 106.84, longitude: -6.21), is potentially controlled by of Java Megathrust (Interface) and Benioff (Intra-plate) seismic sources; (c) Denpasar, located in Bali Island (latitude; 115.20 longitude; -8.65), is potentially occurring from Java Megathrust and Sumba Megathrust seismic sources. The sensitivity analyses of C_R through variation of β-value from 0.6 to 1.0 has been conducted for the three sites of interest.

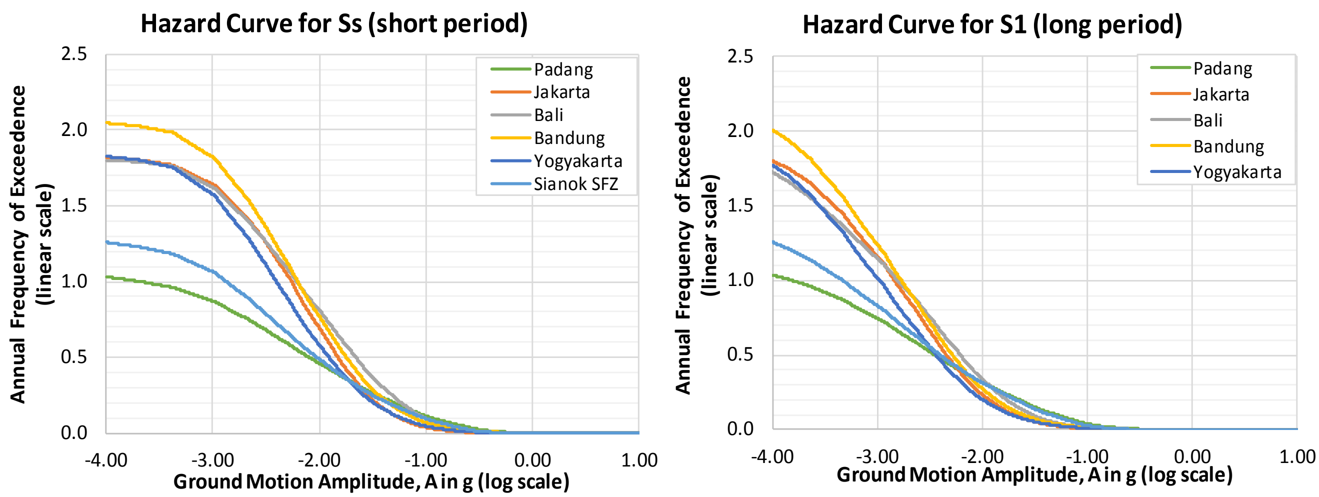


Figure 3 - Hazard curves of sites of interest for short and 1-second period

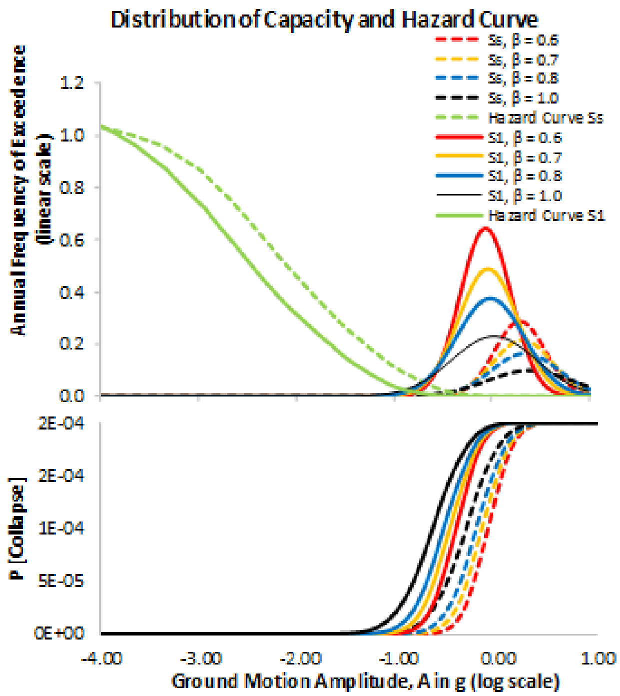
b. Shallow Crustal Source

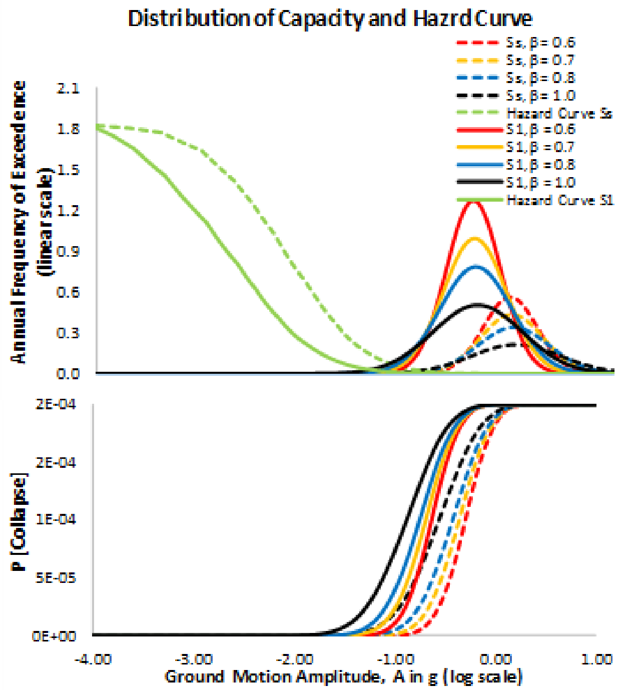
Large potential shallow crustal in Indonesia may occur along Sumatra Island, so-called Sumatra Fault Zone (SFZ). SFZ is segmental end it is extending along Sumatra Island from Aceh to Lampung, and then many small single source throughout Java Island. Some of earthquakes occupancy within this SFZ segments has occurred in the last two decades. Some potential shallow crustal sources in Java Island have also been identified since the last decade. In this paper, three sites of interest representing shallow crustal source in Indonesia are selected. The sites are; (a) Bandung (latitude; 107.6, longitude; -6.92) influenced by Lembang Fault; (b) Yogyakarta (latitude; 110.3 longitude; -7.70) influenced by Opak Fault; (c) Sianok (latitude; 100.55 longitude; 0.00) influenced by SFZ.

Risk-integral calculations of hazard curve and building capacity curve using equation 1 have been made for each site varying β-value of 0.6-1.0. Iterative process to calculate ground-motion amplitude, to result in risk-integral of 1% probability of building collapse in 50 years (RTGM) is obtained. Results of the calculation for β-value variation of 0.6-1.0 for S_S and S_1 spectral periods, are plotted in Figure 4 and Figure 5, representing subduction and shallow crustal sites, respectively. It is indicated that there is a range of deviation on resulted RTGM risk-integral for each site location, as β-value is varied.

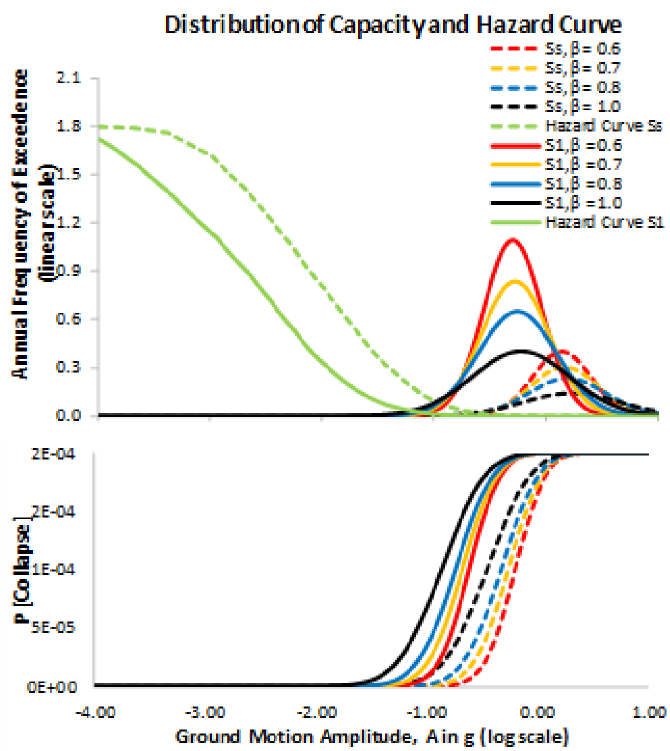
4 Results of Analysis

Table 1 summarizes RTGM and C_R values for thsix (6) sites of interest with variation of β-value. RTGM and C_R value for β-value of 0.7 is highlighted, as the one currently adopted in Indonesian C_R map. It can be clearly observed that variation in β-value of 0.6-0.8 does not significantly affect the RTGM and C_R values for almost all cases (the range is 7-17%). However, relatively high deviation is identified for β-value variation from 0.6 to 1.0, reaching 20-30% for all cases.



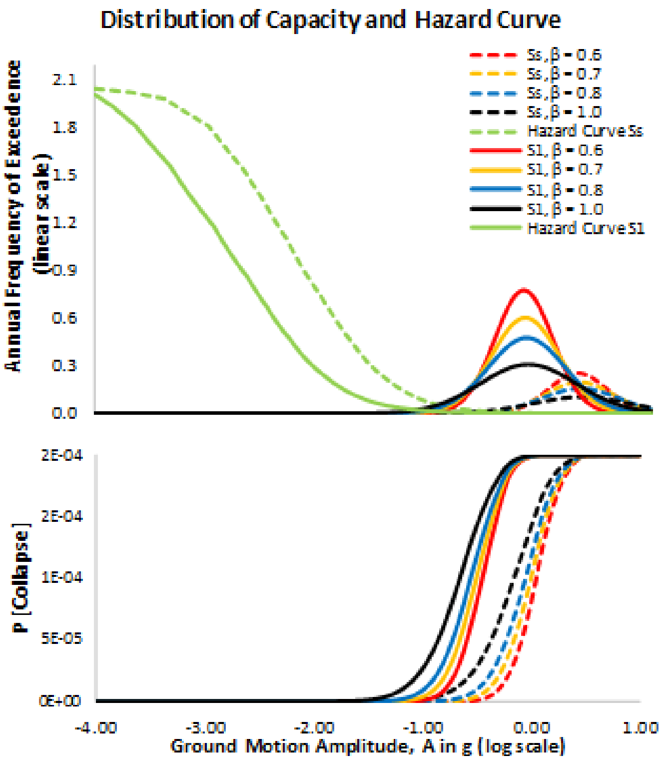


(a) (b)

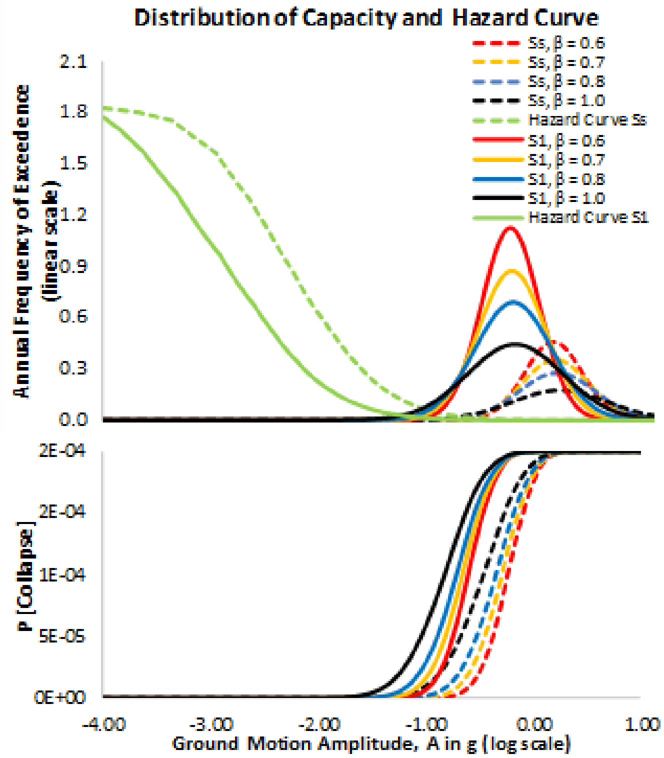


(c)

Figure 4 - Risk-targeted ground-motion for subduction sources with variation of β-values for S_S and S_1 spectral periods, consisting of three (3) sites of interest: (a) Padang, (b) Jakarta, and (c) Denpasar-Bali



(a)



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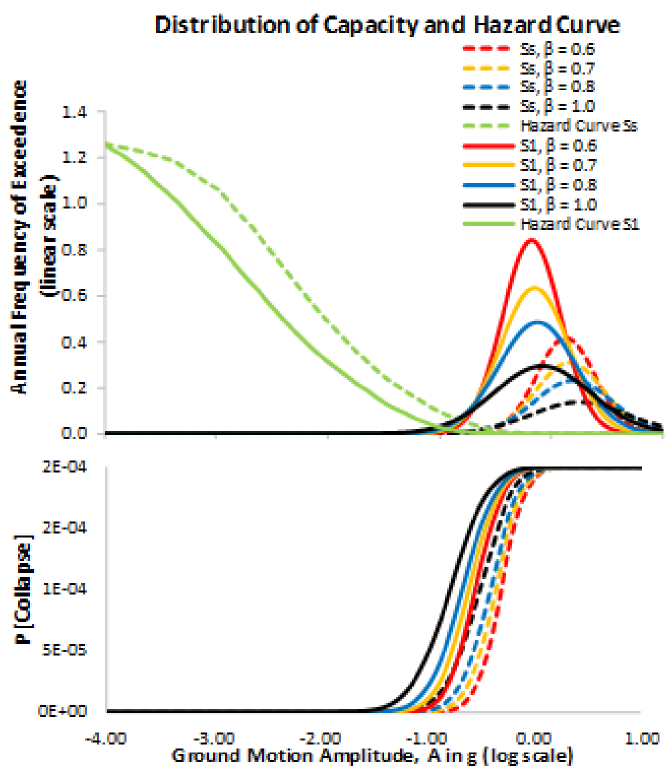

(c)

Figure 5 - Risk-targeted ground-motion for <u>shallow-crustal</u> sources with variation of β-values for S_S and S_1 spectral periods, consisting of three (3) sites of interest: (a) Bandung, and (b) Yogyakarta (c) Sianok SFZ

Table 1 - Summary of C_R calculation for six (6) sites of interest in Indonesia

No	Location / Mechanism	Coordinate	Period (Sec)	*β*-value	RTGM (g)	MCE (g)	C_R	Deviation of C_R (%) range β-value (0.6 - 0.8)	Deviation of C_R (%) range β-value (0.6 - 1.0)
1	**Padang** (Megathrust M1 Sumatera)	longitude: 100.35 latitude: -0.94	0.2	0.6	1.285		1.02	14	30
				0.7	1.377	1.198	1.09		
				0.8	1.497		1.19		
				1.0	1.837		1.46		
			1.0	0.6	0.440		1.02	14	29
				0.7	0.469	0.375	1.09		
				0.8	0.509		1.18		
				1.0	0.624		1.45		
2	**Jakarta** (Megathrust Java and Benioff)	longitude: 106.84 latitude: -6.21	0.2	0.6	0.656		0.95	9	23
				0.7	0.683	0.655	0.99		
				0.8	0.724		1.05		
				1.0	0.855		1.24		
			1.0	0.6	0.290		0.94	8	20
				0.7	0.299	0.269	0.97		
				0.8	0.314		1.02		
				1.0	0.363		1.18		
3	**Denpasar-Bali** (Megathrust Java and Sumba)	longitude: 115.20 latitude: -8.65	0.2	0.6	0.922		0.99	13	28
				0.7	0.978	0.886	1.05		
				0.8	1.056		1.14		
				1.0	1.289		1.39		
			1.0	0.6	0.338		0.99	11	26
				0.7	0.355	0.298	1.04		
				0.8	0.380		1.11		
				1.0	0.454		1.33		
4	**Bandung** (Shallow Crustal/Lembang Fault)	longitude: 107.6 latitude: -6.92	0.2	0.6	1.456		0.94	7	18
				0.7	1.502	1.469	0.97		
				0.8	1.571		1.02		
				1.0	1.786		1.16		
			1.0	0.6	0.476		0.91	8	20
				0.7	0.493	0.456	0.94		
				0.8	0.518		0.99		
				1.0	0.593		1.13		
5	**Yogyakarta** (Shallow Crustal/Opak Fault)	longitude: 110.3 latitude: -7.70	0.2	0.6	0.807		0.96	10	23
				0.7	0.843	0.797	1.01		
				0.8	0.895		1.07		
				1.0	1.053		1.26		
			1.0	0.6	0.329		0.96	8	20
				0.7	0.340	0.299	0.99		
				0.8	0.358		1.04		
				1.0	0.413		1.20		
6	**Sianok SFZ** (Shallow Crustal/ Sumatera Fault Zone)	longitude: 100.55 latitude: 0.00	0.2	0.6	0.887		1.11	17	34
				0.7	0.965	0.759	1.21		
				0.8	1.064		1.33		
				1.0	1.336		1.68		
			1.0	0.6	0.440		1.02	14	29
				0.7	0.469	0.375	1.09		
				0.8	0.509		1.18		
				1.0	0.624		1.45		

5 Conclusions

Seismic design criteria in new 2012 Indonesian seismic building codes has shifted from uniform hazard-based criteria to risk-targeted ground-motion (RTGM) criteria, employing 1% probability of building collapse in 50 years. Generic building fragility curves represented by log-normal standard deviation, β-value, has been applied in combination with hazard curve to develop the RTGM. Log-normal standard deviation, β-value of 0.7 has been adopted for the risk-coefficient (C_R) to adjust the MCE hazard map. Sensitivity analysis on the β-value to C_R,has been conducted in this paper. The analysis has been made for two spectral periods of 0.2-second (S_S) and 1-second (S_1). β-values are varied between 0.6 to 1.0, considering variation in building fragilities. Six (6) specific sites dominantly controlled by either subduction or shallow crustal fault earthquake source, respectively, have been investigated.

The analysis was conducted for two ranges of β-value to identify ranges of deviation in C_R-values. The analysis shows that there is about 7-14% deviation C_R-values resulted from 0.6-0.8 variation in β-value, and about 18-34% deviation in C_R-values resulted from 0.6-1.0 variation in β-value, respectively. Results of the analysis suggest that use of β value of 0.7 in the current Indonesian seismic building code is considered to be acceptable. Future research on improving and enhancing seismic hazard map and fragility functions, considering specific motion to motion variability is recommendation.

6 Acknowledgment

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