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Development of Risk Coefficient for Input to New Indonesian Seismic Building Codes

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Abstract. In 2010 a national team (Team 9) developed the hazard curve and maximum considered earthquake (MCE) for the whole Indonesian area. The results were further applied in this study. Risk-targeted ground motions (RTGM) with 1% probability of building collapse in 50 years were developed by integrating the hazard curve with the structural capacity distribution. Parametric study on various variables that affect the log-normal standard deviation suggests a value of 0.7. In the effort to obtain the RTGM for the whole Indonesian region, integration was carried out using definite integration in which the curves are split into thin vertical strips and the areas below each curve are multiplied and summed. Detailed procedures and verification are given in this paper. An example of RTGM calculation was carried out for Jakarta City and then applied to the whole Indonesian region. Risk coefficients defining the ratio between RTGM and MCE were eventually developed and mapped. Risk coefficient development was generated for two periods of interest, i.e. a short time period (T = 0.2 seconds) and a 1-second period, respectively. Based on the results, for the period of 1.0 seconds 55% of Indonesian cities/districts have a risk coefficient in the range of 0.9 to 1.1 and about 37% in the range of 0.7 to 0.9, with only 5% in the range of 1.1 to 1.25.

Keywords: *ground motion; hazard curve; log-normal standard deviation; risk coefficient; risk-targeted.*

1 Introduction

Indonesia is located between the intersection of two significant earthquake lanes, i.e. the circum-Pacific and circum-Mediterranean at the Sunda Strait. A consequence of this is a high earthquake frequency with events occurring almost every day. Many recent catastrophic earthquakes have hit Indonesia during the last decade, causing significant fatalities, damages and losses. These conditions demand comprehensive and systematic efforts in earthquake disaster risk reduction. A number of major earthquakes that occurred during the last decade have emphasized that earthquake demands in Indonesia must become an

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important factor to be addressed in structure design. Improving regulations reflecting the state of the art of structure design under earthquake load is a subject that can potentially save millions of people and reduce major risks for the country. A significant effort aimed at regulation is the completion of the seismic design map of Indonesia by using the most current methodology and up-to-date data.

The previous seismic design code SNI-1726-2002 [1] was outdated after several major earthquakes had hit Indonesia over the last decade. The code provided peak ground acceleration (PGA) for a 10% probability of being exceeded in 50 years, or a return period of 500 years. In addition, the calculation of PGA was based on seismic hazard only. Formal efforts to improve the seismic hazard map of Indonesia have been conducted since 2006. These efforts were initiated by the Department of Public Works and supported by Institut Teknologi Bandung (ITB), the Geological Research Center (PSDG) and the United States Geological Survey (USGS). Eventually, the previous code was successfully replaced by SNI-1726-2012 [2], providing ground motion values with a 2% probability of being exceeded in 50 years, in other words they have a spectral acceleration for a return period of 2475 years. In the same way as the previous code, the new one was computed by probabilistic seismic hazard analysis (PSHA). By following ASCE-SEI-7-10 [3], three seismic design maps are given in the new Indonesian code: for spectral acceleration at $T = 0$ s (PGA), short ($T = 0.2$ s), and long ($T = 1$ s) periods. Significant improvements in this updated code are not only changing the return period but also the uncertainty accounting of the collapse capacity of structures. Before this issue recently became known, the seismic design code of Indonesia was based on the assumption that the capacity against the collapse of structures was equal to the corresponding mapped value at the location of those structures.

Luco, *et al.* [4] stated two reasons why the collapse capacity of structures is uncertain. Firstly, because the spectral acceleration associated with the ground motion that a structure can resist without collapsing typically depends on the characteristics of the ground motion. The other reason is that the spectral acceleration associated with collapse depends on the construction details of the structure, such as construction quality, material properties, nonstructural components, and other characteristics of the structure that are relevant to collapse.

In fact, structure resistance during earthquakes is a random variable influenced by a number of factors, such as:

1. Concrete compression strength showing random behavior that follows normal or log-normal distribution. The variance coefficient of concrete

(Ω_{f_c}) varies in the range 0.10 to 0.20, depending of the contractor's experience and the degree of material cleanness.
2. Steel tension strength showing random variable behavior. Several researches have shown that steel tensile strength follows a log-normal distribution with a variance coefficient (Ω_{f_s}) and maximum of 0.10.
3. Earthquake energy content and frequency resulting in different responses to the structure.
4. Model of structural resistance.

An effort to involve uncertainty in the new seismic design map was started in 2011 by adopting a proven methodology [4,5], the so-called risk integral. The risk integral requires two probability functions representing the annual probability of maximum ground motion and the probability of structural capacity against spectral acceleration. The structural capacity is defined as a log-normal distribution function whose shape is controlled by log-normal standard deviation (β) and risk-targeted ground motion (RTGM) as median. In risk-integral calculation, the RTGM is optimized to achieve 1% probability of building collapse in 50 years, following ASCE-SEI-7-10 [3]. In the new seismic design code, the RTGM values for all Indonesian grids are given as the risk coefficient showing a ratio of RTGM over MCE. Detailed methodology and computational procedures for generating the RTGM and coefficient risk (C_R) are presented in this paper.

The results of this research are in the form of risk coefficient maps as part of the seismic design criteria included in the Indonesian sesimic building codes. Once legally included in the building codes, the results can be applied to new designs of earthquake resistance buildings in Indonesia. This would mean a direct contribution to seismic disaster risk reduction in Indonesia.

2 Probabilistic Seismic Hazard Analysis (PSHA)

In general, an earthquake is a natural phenomenon that comprises uncertainty, and consequently it is a complex problem to predict when and where an earthquake will occur and with what strength, and also the effects of the earthquake at the location of a structure in the form of the ground acceleration that will exert inertia load on structures. Thus, it yields to the understanding that an earthquake and its load are random variables as well as its being a natural phenomenon.

PSHA has considered earthquake magnitude distribution, distance to earthquake source distribution and ground acceleration. Determination of ground acceleration depends on using ground motion prediction equations (GMPEs).

Since this method is based on a probabilistic approach, it is always good to review it on a yearly basis [6].

The following formulation shows the annual probability of maximum ground acceleration q_y due to earthquakes with magnitude M greater than the specific value of 'y' [7].

$$q_y = P(M > y) \tag{1}$$

The source of an earthquake can be a point source, a line source, or it can be spread over a zonal source, where each of these three kinds of sources has specific seismic characteristics. The greater value of 'y' implies that a lesser value of q_y and the expected return period T from this earthquake can be derived through the following equation:

$$T = \frac{1}{q_y} \tag{2}$$

The relationship between annual probability of exceedence, or return period, and ground acceleration can be graphically defined as the hazard curve. By plotting the interest return period (i.e. 500 years, 1000 years and 2475 years) on a hazard curve, the ground acceleration for each return period can be easily determined. The following Figure 1 shows a typical hazard curve.

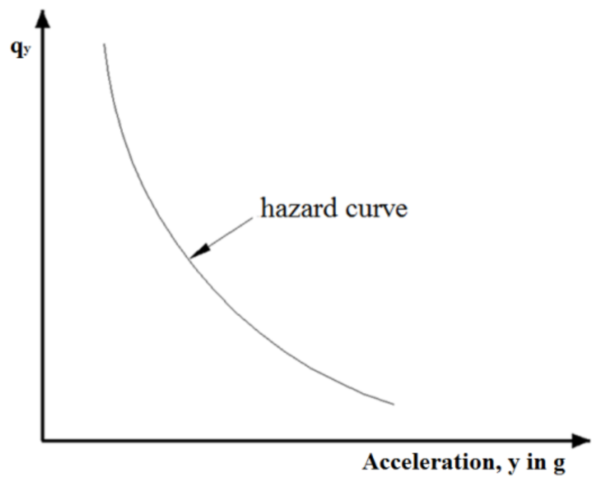


Figure 1 Correlation between ground acceleration and annual probability of exceedence.

Hazard curves for all Indonesian cell grids were developed in 2010 by a national team (called Team 9) in order to update the national standard code. The hazard curves were digitally stored in a database for computing the RTGM.

Detailed methodology and procedures for calculating the RTGM can be found in the next section.

The probabilistic maximum considered earthquake (MCE) is a predicted maximum acceleration based on PSHA by defining ground motions as having a 2% probability of being exceeded in 50 years (return period of 2475 years). The most recent GMPEs for different kinds of earthquake mechanisms have been considered. Youngs, *et al.* [8], Atkinson and Boore [9] and Zhao, *et al.* [10] were used to predict the acceleration for the subduction mechanism, while Boore and Atkinson [11], Campbell and Bozorgnia [12], and Chiou and Youngs [13] were used for the shallow crustal mechanism. A new method to accommodate random seismic data outside both the subduction and shallow crustal zones, known as gridded seismicity [14], was adopted as well. Detailed analyses of the Indonesian PSHA and development of the hazard curve are presented in Asrurifak [15] and Irsyam, *et al.* [16].

3 Risk-Targeted Ground Motion (RTGM)

The RTGM can be defined as a severe ground motion that achieves a collapse probability of 1% in 50 years. To calculate the RTGM of Indonesia, a risk-integral methodology as mentioned in Luco, *et al.* [3] and Luco [4] can be directly adopted. This section presents the basics of the risk integral, for which the hazard curve and structural capacity against spectral acceleration are required. This section also explicates how to formulate the structural capacity curve and determine the log-normal standard deviation as part of forming the curve shape.

3.1 Risk Integral

In general, the probability of failure from a structure caused by an earthquake or the risk from an earthquake can be stated as follows:

$$\text{Risk, } P_f = P\,(R < E_m) \tag{3}$$

where R is the structural resistance due to the earthquake load and E_m is the earthquake load that is applied to the structure. If R and E_m are random variables and the probability density function of each is $f_R(a)$ and $f_{E_m}[SA > a]$ respectively, the risk can be formulated as:

$$\text{Risk, } P_f = \int_0^\infty f_R\,(a)\, f_{E_m}(SA > a)\,\mathrm{d}a \tag{4}$$

$f_{E_m}(a)$ is commonly known as the hazard curve and $f_R(a)$ as the structural capacity against earthquake load. The two distribution functions can be seen in Figure 2.

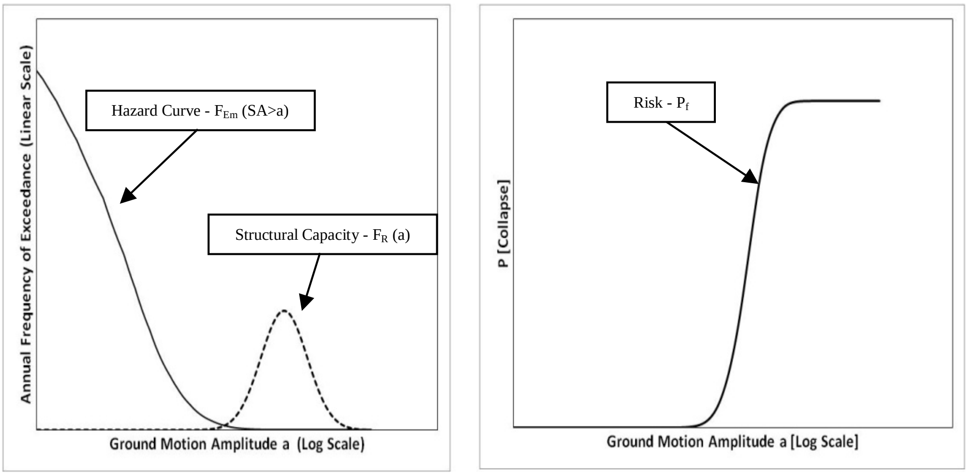


Figure 2 Risk integral and its forming components.

3.2 Structural Capacity Probability Curve

According to Figure 2 above, the earthquake distribution is quite hard to determine in Indonesia. This is because Indonesia has only few earthquake strong-motion recording tools that can directly record earthquake acceleration happening at any location for a certain time duration. The extreme static analysis needs to be generated for finding f_R*(a).*

Structural capacity can simply be formulated as follows:

$$f_R(a) \; = \frac{1}{a\beta\sqrt{2\pi}} \exp\left[-\frac{(\ln a-(\ln(\mathrm{RTGM})+1.28\beta))^2}{2\beta^2}\right] \quad (5)$$

Basically, Eq. (5) above can be probabistically written as:

$$f_R = \Phi\left[\frac{\ln\frac{\mu_r}{u_e}-0.5\{\xi_r^2+\xi_e^2\}}{\sqrt{\xi_r^2+\xi_e^2}}\right] \quad (6)$$

where μ_r is the average resistance value, μ_e is the average earthquake load value along structure life time, while ξ_r and ξ_e are the log-normal distribution parameters describing the variance about the values of μ_r and μ_e, respectively. ξ_r and ξ_e are formulated as follows:

$$\xi_r^2 = \ln(1+\Omega_r^2) \quad (7)$$

and

$$\xi_e^2 = \ln(1+\Omega_e^2) \quad (8)$$

where both Ω_r and Ω_e are variance coefficients of *R* and E_m.

There are two controlling parameters of the structural capacity function that are assumed through log-normal distribution, i.e. μ and β with which the median value of the distribution is formed.

$$\ln (X_m) = \ln \mu - \frac{1}{2}\beta^2 \text{ or} \tag{9}$$

with β can be determined through this equation:

$$\beta^2 = \ln (1 + \Omega^2) \tag{10}$$

Parameter β can also be determined by gathering the number (X) of data that are sampled through the calculation of the dynamic nonlinear time-history analysis under several values of scaled earthquake events at any location. The value of X data can also be calculated using joint/section angle rotation or interstory drift [17].

Analysis and recommendations on representative β values of Indonesian buildings have been conducted through hazard analysis and probability-based safety factors by Sidi [18]. The analysis identified inherent variability of concrete compressive strength and steel reinforcement tension capacity, simplification of actual field conditions representing random phenomena in the design formulation, and random human errors through reliability analysis in the derivation of the fragility function that is considered to be representative for the Indonesian condition. The analysis suggests that β values for Indonesia vary between 0.65 and 0.7. For development of the RTGM for Indonesia, a relatively high value of $\beta = 0.7$ was adopted, which yields a higher RTGM.

3.3 Risk Coefficient

Kicher [19] found that a structure can collapse in any direction due to the effect of bi-axial movement. The direction of collapse is governed by the maximum component of the ground motion. This is known as the directivity factor. FEMA [20] and Whittaker [21] suggested applying a factor of 1.1 for short periods and 1.3 for long periods. In this study, directivity factors of 1.05 and 1.15 for short and long periods respectively were used.

The risk coefficient is the ratio between RTGM and MCE, corrected by the directivity factor. It is formulated as follows:

$$C_{RT} = \frac{RTGM_T}{MCE_T * DF_T} \tag{11}$$

where DF is the directivity factor and T denotes the observed spectral period.

4 Computation of Risk Integral

Although the RTGM was developed in 2007, Indonesia only applied this concept in 2011 through a national program for developing a new national standard code. The work was first conducted by the geotechnical division of Institut Teknologi Bandung through the IMHERE project. For the full research report see Sengara, *et al.* [22]. This section discusses an explanation of how to enhance the concept of generating risk coefficient maps for the whole Indonesian area at two spectral values (T = 0.2 s and T = 1.0 s).

The RTGM can be easily computed by the following equation derived from Eq. (4):

$$P_F = \int_0^{\sim} \gamma(a) \frac{1}{a\beta\sqrt{2\pi}} \exp\left[-\frac{(\ln a-(\ln(\mathrm{RTGM})+1.28\beta))^2}{2\beta^2}\right] \mathrm{d}a \tag{12}$$

where $\gamma(a)$ is the site-specific hazard curve from PSHA, corrected by the directivity factor.

The equation above can be solved by using a definite integration in which the areas below the curves are split into thin vertical strips and treated as rectangular shapes. The width of the spectral acceleration (δa) must be defined as small as possible. The smaller the value of δa, the more accurate the approximation will be. The area of the rectangular shape is determined as the multiplication of the width of the spectral acceleration (δa) with the function value for each curve.

A multiplication of the area under the hazard curve and the area under the structural capacity for each δa needs to be carried out. The results of the multiplication of the number of splits are then added up to define the risk integral. This process can be represented by deriving Eq. (12) as follows:

$$P_F = \lim_{\delta\mathrm{a}\to 0} \sum_0^{\mathrm{n}} \left(\gamma(a) \frac{1}{a\beta\sqrt{2\pi}} \exp\left[-\frac{(\ln a-(\ln(\mathrm{RTGM})+1.28\beta))^2}{2\beta^2}\right] (\delta a)^2\right) \tag{13}$$

where n is the total number of splitted areas.

The RTGM of Indonesia is calculated as the ground motion's spectral value (a) resulting in a 1% probability of failure P_f in 50 years through numerical integration and an iterative process with a log-normal standard deviation (β) of 0.7 as described in Section 3.2. An optimization procedure for getting the RTGM is the Newton-Rhapson method. The reasons for using this iterative method in this study were that it has very fast convergence and is easy to program.

The following points describe the detailed procedure of computing the RTGM for the whole Indonesian area. Figure 3 presents a flowchart of the procedure.

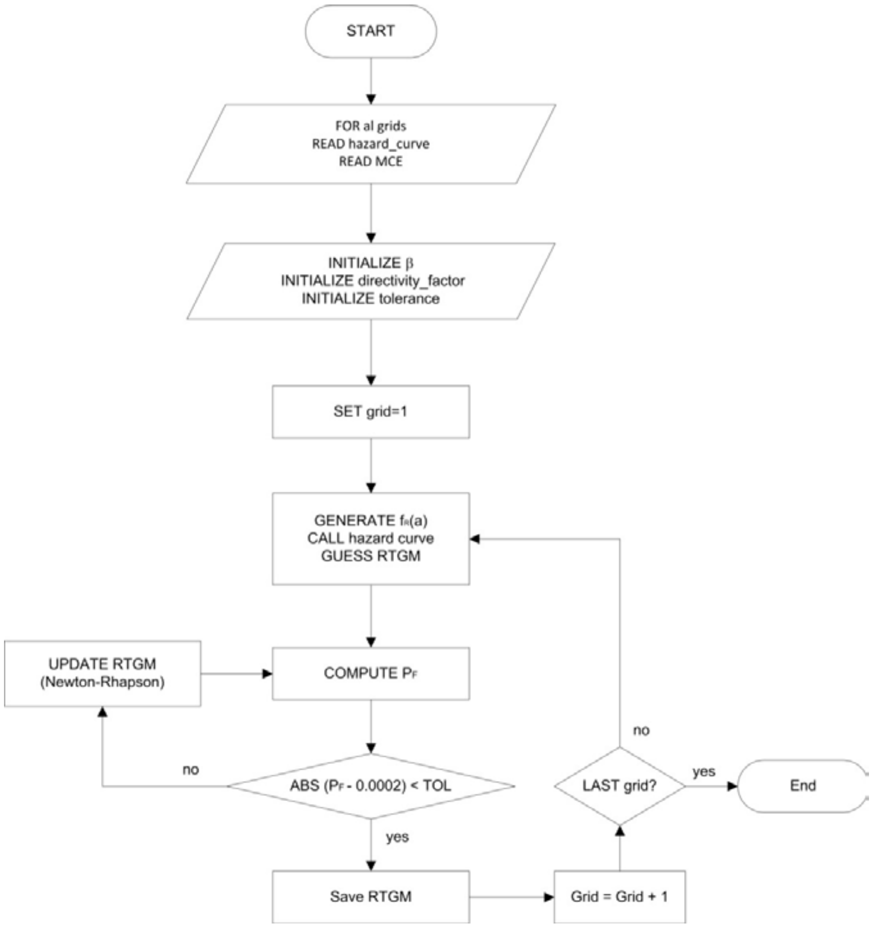


Figure 3 Flowchart of computing the RTGM.

1. Initialize a grid size of 0.1° x 0.1°; the total number of cells for the whole Indonesian area is about 96,600.
2. Select the period of interest.
3. Initialize the logarithmic standard deviation (β) and directivity factor for the selected period.
4. For each grid conduct the following steps:
   a. get the hazard curve from the results of PSHA 2010 [16] in accordance with the selected period;
   b. multiply the hazard curve with the directivity factor;

c. set the default for the RTGM and develop the structural capacity distribution using Eq. (5);
d. do risk integral using definite integration to solve Eq. (13);
e. carry out the iteration process of the Newton-Rhapson method for optimizing the RTGM in which the risk integral has to achieve 1% probability of building collapse in 50 years;
f. save the RTGM resulting from the risk integral for 1% probability of building collapse in 50 years;
g. compute C_R using Eq. (11) for the selected period;
h. digitally store C_R for the interest period into the database.

5 Finish.Verification

Table 1 The procedure mentioned in the previous section was verified by Earthquake-RTGM-Calculator adopting the computation method of Luco [3]. Earthquake-RTGM-Calculator is a web-based application for calculating risk-targeted ground motions and risk coefficients from given hazard curves [23]. The calculator is copyrighted by USGS. RTGM verification at both short and long periods.

City	RTGM at T=0.2s, in g			RTGM at T=1.0s, in g		
	RTGM Calc	Computed	Deviation (%)	RTGM Calc	Computed	Deviation (%)
Aceh	1.448	1.456	0.568	0.592	0.594	0.302
Medan	0.548	0.549	0.198	0.321	0.322	0.275
Padang	1.361	1.364	0.213	0.556	0.558	0.253
Bengkulu	1.293	1.298	0.433	0.518	0.519	0.300
Lampung	0.745	0.747	0.269	0.272	0.273	0.300
Jakarta	0.689	0.691	0.290	0.271	0.272	0.301
Bandung	1.063	1.066	0.352	0.334	0.335	0.292
Semarang	0.872	0.874	0.181	0.267	0.267	0.115
Yogyakarta	1.067	1.070	0.302	0.353	0.355	0.639
Surabaya	0.633	0.635	0.279	0.207	0.208	0.514
Denpasar	0.965	0.968	0.232	0.313	0.313	0.223
Mataram	0.965	0.967	0.215	0.339	0.340	0.223
Kupang	1.104	1.107	0.268	0.257	0.258	0.281
Makassar	0.360	0.361	0.214	0.137	0.137	0.216
Manado	0.947	0.949	0.195	0.362	0.363	0.169
Ambon	1.291	1.293	0.164	0.395	0.396	0.201
Manokwari	1.767	1.767	0.009	0.672	0.674	0.269

City	RTGM at *T*=0.2s, in g			RTGM at *T*=1.0s, in g		
	RTGM Calc	**Computed**	**Deviation (%)**	**RTGM Calc**	**Computed**	**Deviation (%)**
Jayapura	2.057	2.059	0.122	0.833	0.835	0.168
Samarinda	0.106	0.106	0.302	0.036	0.036	0.370

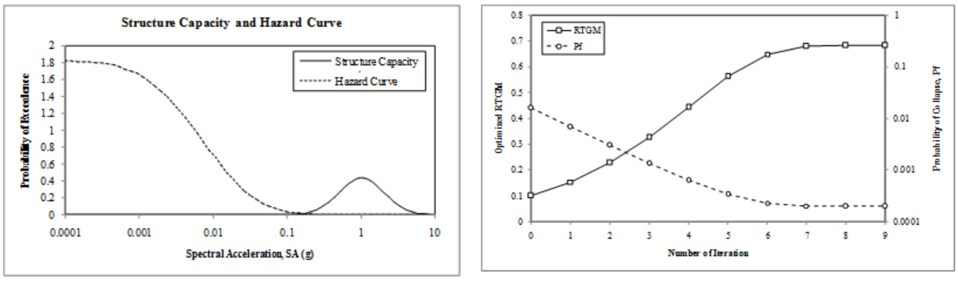
Verification was carried out for 19 big cities in Indonesia with β = 0.8 and directivity factor = 1.0. By following the procedures mentioned in Section 4, the computed RTGM values for both the short and the long periods agree with those from Earthquake-RTGM-Calculator, see Table 1. Deviations between both computations for all cities were smaller than 1%.

6 Results

In this section, the RTGM calculation for Jakarta City is presented as an example. The final result of this study, i.e. risk coefficient maps for Indonesia, is discussed herein as well.

6.1 Example of RTGM Calculation for Jakarta City

As an example, the RTGM calculation for a long period (*T*= 0.2 s) was conducted for Jakarta City. A directivity factor of 1.05 and *β* of 0.7 were assigned into the calculation procedure as described in Section 4. The RTGM result for Jakarta City was 0.683g for which the targeted probability of collapse was met.



(a) (b)

Figure 4 (a) Plotting of hazard curve and structural capacity distribution at last iteration of RTGM optimization; (b) convergence of RTGM calculation.

Figure 4(a) graphically represents the structural capacity distribution and hazard curve when the risk integral achieves 1% probability of collapse in 50 years. Meanwhile, Figure 4(b) represents the total number of iterations needed to converge. By starting from a RTGM of 0.1g, only nine iterations were needed to achieve the target.

6.2 Risk Coefficient Map for Indonesia

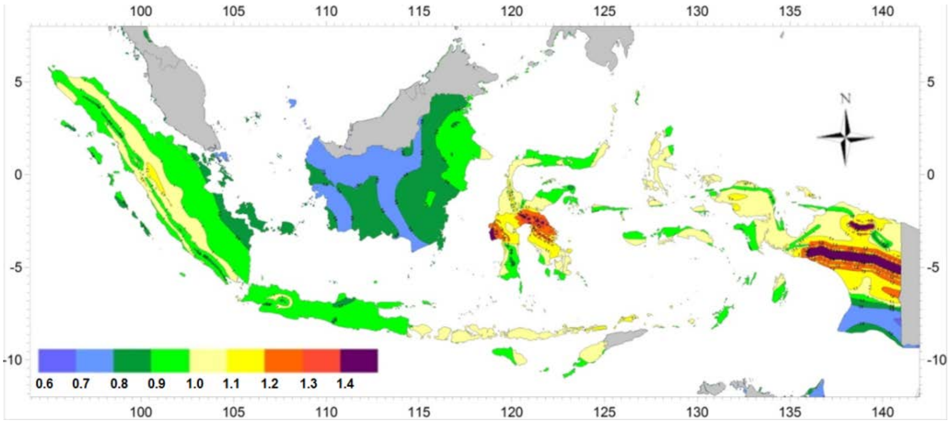
Calculation of the RTGM for the whole Indonesian region, consisting of approximately 96600 cells, for two spectral values at T = 0.2 s and T = 1.0 s, was conducted as described in Sengara, *et al.* [22]. The results of the RTGM are presented in the risk coefficient (C_R) definition as given by Eq. (11). Table 2 summarizes the RTGM and C_R values for 19 cities in Indonesia at a short period (C_{RS}) and a long period (C_{R1}). Figure 5 shows the distribution maps of the risk coefficients for both periods. These risk coefficient maps have been adopted in the new Indonesian seismic building code (SNI-1726-2012).

Table 2 RTGM and C_R values for 19 cities in Indonesia.

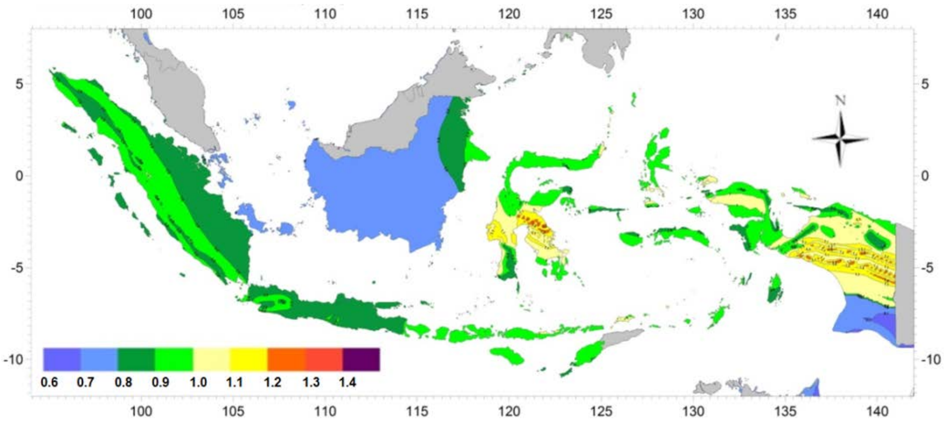
CITY	MCE (g)		RESULT			
	2475 years		*T*=0.2s		*T*=1.0s	
	T=0.2s	*T*=1.0s	RTGM (g)	C_{RS}	RTGM (g)	C_{R1}
Aceh	1.375	0.578	1.443	0.999	0.648	0.975
Medan	0.485	0.297	0.534	1.049	0.349	1.022
Padang	1.173	0.506	1.323	1.074	0.597	1.026
Bengkulu	1.211	0.505	1.284	1.010	0.567	0.976
Bandar Lampung	0.677	0.264	0.734	1.033	0.299	0.985
Jakarta	0.65	0.265	0.683	1.001	0.298	0.978
Bandung	1.083	0.322	1.064	0.936	0.366	0.988
Semarang	0.943	0.269	0.891	0.900	0.295	0.954
Yogyakarta	1.112	0.347	1.075	0.921	0.389	0.975
Surabaya	0.593	0.204	0.627	1.007	0.227	0.968
Denpasar	0.833	0.274	0.938	1.072	0.335	1.063
Mataram	0.823	0.298	0.936	1.083	0.364	1.062
Kupang	0.973	0.238	1.075	1.052	0.278	1.016
Makassar	0.315	0.118	0.354	1.070	0.147	1.083
Manado	0.791	0.306	0.914	1.100	0.386	1.097
Ambon	1.094	0.339	1.244	1.083	0.422	1.082
Manokwari	1.445	0.534	1.711	1.128	0.709	1.155
Jayapura	1.728	0.717	2.001	1.103	0.893	1.083
Samarinda	0.101	0.036	0.106	1.000	0.040	0.966

According to Figure 5, typical values of C_R for both periods are high when the site locations are near a fault. Moreover, the C_R value near faults for sites located in the eastern part of Indonesia is higher compared to the western part of

Indonesia. In order to control the maximum number of C_R, a capping value of 1.4 was applied here.



(a)



(b)

Figure 5 (a) Map of C_{RS} (C_R value corresponding to spectral values at 0.2 second period) and (b) C_{R1} (C_R value corresponding to spectral values at 1.0 second period), Sengara, *et al.* [15].

By extracting the C_{R1} map, it can be identified that the C_{R1} values for most Indonesian cities and districts (55%, 249 from a total of 456) are in the range of 0.9 to 1.1; about 37% are in the range of 0.7 to 0.9; 5% are in the range of 1.1 to 1.25; and the rest higher than 1.25. The lowest value was identified in the Sambas District, West Kalimantan and the highest in Boven Digoel, Papua. The distribution of the C_{R1} values is shown in Figure 6. A similar distribution was also conducted for the C_{RS} values: 72% cities and districts have C_{RS} values in the range of 0.9 to 1.1; about 11% in the range of 0.7 to 0.9; 10% in the range of 1.1 to 1.25; and the rest higher than 1.25.

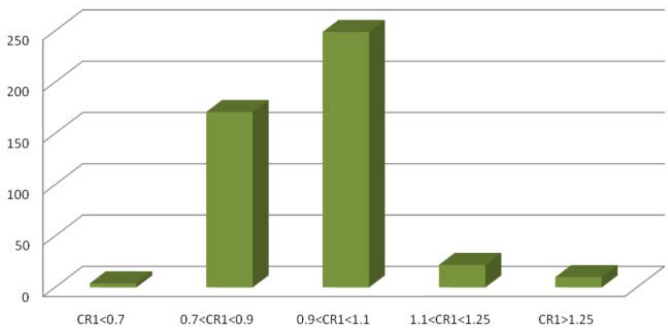


Figure 6 Distribution of CR1 values versus number of cities/districts.

7 Concluding Remarks

The risk-targeted ground motion in the form of a risk coefficient (C_R) for the whole Indonesian area was calculated and presented in this paper. The risk coefficients were adopted in the new Indonesian seismic building code maps at two spectral periods of interest (T = 0.2 s and T = 1 s). The RTGM was computed by optimizing the probability of failure until approximately achieving 1% probability in 50 years. The risk coefficient was simply defined as the ratio between RTGM and maximum considered earthquake. The assumption of a log-normal standard deviation (β) of 0.7 was taken to form the structural capacity curve shape. Directivity factors, which are due to the effect of bi-axial movement, of 0.05 for the short period (T = 0.2 s) and 1.15 for the long period (T = 1.0 s) were applied in this study.

Detailed RTGM calculation procedures for the Indonesian region were developed and presented in this paper. Verification was also done in this study. An example calculation of the RTGM for Jakarta City was given following the developed procedure. Furthermore, the proposed procedure was also used to obtain the RTGMs and risk coefficients for the whole Indonesian area.

The results show that more than 90% of Indonesian districts have risk coefficient values between 0.7 and 1.1 at a spectral period of 1.0 s. Specifically, almost all 19 big cities in Indonesia have C_R values ranging between 0.9 and 1.1, both at a spectral period of 0.2 s and of 1.0 s. In addition the resulted risk-coefficient maps for both periods of interest were adopted in the new Indonesian seismic building code (SNI-1726-2012).

Further research into determining the value of β needs to be carried out for some typical buildings. In addition, enhancing ground motion directivity factors is also important to be investigated in further research studies.

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