Development of Empirical Earthquake Fatality Model For Indonesia

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SUMMARY:
Human fatalities due to earthquakes have increased significantly due to many recent earthquake disasters in Indonesia. Currently available global models for Indonesia need to be verified with more comprehensive local data to be applicable for local fatality prediction. In this paper, the development of Indonesian fatality model is based on empirical data, as further development of global exponential model by Allen et al. (2009) and log-normal model by Jaiswal et al. (2009). The model is developed based on fatality data due to some recent large earthquakes in Indonesia. The fatality rates are correlated with MMI generated using ShakeMap software with appropriate ground motion predictive equations and ground motion intensity conversion equation. The local-site effect is developed through average shear wave velocity of the top 30m profile (V_{s30}) correlated from topographical slopes. Preliminary application of the developed model is made for fatality estimate of Indonesia.

Keywords: earthquake, fatality, MMI, ground-motion, empirical.

1. INTRODUCTION

Earthquake disasters have caused significant human fatalities due to the physical and social economic vulnerabilities of the people in the affected areas. Such conditions urge local government and community in the high risk areas to develop earthquake disaster risk-reduction and emergency response plans to increase preparedness. In order to develop these action plans from potential future disasters, it is necessary to conduct risk assessment based on hazard and vulnerability models specific to the local conditions. Fatality risk is one factor that needs to be considered in the earthquake disaster risk assessment process. The development of earthquake fatality model as a function of estimated Modified Mercally Intensity (MMI) that is supported by specific fatality-rate data from historical earthquakes will help the government and disaster managers to prioritize the earthquake vulnerability reduction programs to plan effective emergency response measures.

As a country that is prone to earthquake disasters, Indonesia has many earthquake historical records in the past decades. Previous and most recent seismic hazard mapping for Indonesia have identified many cities and urban areas are having high potential to relatively high earthquake shaking intensity that potential to cause many human fatalities. Therefore, there is an urgent need to develop fatality model to estimate human fatalities due to future potential earthquakes as part of earthquake disaster risk assessment. Currently, there have been several global fatality models developed based on global fatality data based mainly on empirical data. These global fatality models among others are by Allen et. al. (2009) and Jaiswal et al., (2009), and Porter et al., (2008) that are facilitating USGS PAGER (Prompt Assessment of Global Earthquake for Response-CAT). The models could be applied globally for fatality estimation as a function of MMI as first level prediction. Although these models have also been developed adopting Indonesian earthquake fatality data, it is considered that such models need to be more accurately calibrated by recorded local fatality data. Prior to application to local fatality prediction, the developed model is considered to be more accurate if the fatality-rate data be collected from previous earthquake disasters to relatively smallest identified unit of fatality-rate to MMI correlations.

The developed fatality model would be beneficial to the current real-time earthquake impact maps for Indonesia, which this would be part of the engine in the enhancement of the system for real-time products of loss models to be delivered to disaster management agency and the general public. The developed fatality model would be expected to improve earthquake vulnerability reduction program in the urban areas, which consists of strengthened buildings in the highest fatality area estimated by the model and improved method for earthquake disaster emergency response based on the near real-time prediction of fatality.

This paper presents process and analysis in the development of fatality model for Indonesia. The development is based on MMI distribution generation and fatality data collected from recent large earthquake disasters in Indonesia for the last decade. The paper also presents application of the developed fatality model for preliminary fatality estimate of whole Indonesia based on new 2010 seismic hazard map.

2. FATALITY MODELING

Fatality model for Indonesia in this study is developed based on empirical previously developed model by Allen, et al. (2009) and Jaiswal, et al. (2009). These models were developed in order to develop global loss models for rapid impact assessment of earthquakes using a catalog of global human population exposures, EXPO-CAT, data from recent historical earthquakes (since 1973-2007).

Allen et al. (2009) proposed fatality-rate is in an exponential form correlating fatality rate, R, as a function of MMI, I, as formulated in Eqn. 2.1. The shaking intensity data, I, for development of the model is based on Atlas of ShakeMap (Allen et al. 2008). This model was derived for all global data using the Nelder–Mead technique. This model is derived from global fatality data so that applicable for global fatality-rate R(I) estimate with parameters a = 1.03 and b = 10.75.

$$R(I) = 10^{(aI-b)} \qquad (2.1)$$

where,

I : shaking intensity
a and b : parameters of exponential function

Another empirical model has been developed by Jaiswal et.al (2009b). Jaiswal proposed that fatality-rate is a function of fatality distribution parameters and earthquake intensity, S, as formulated in Eqn. 2.2. This model has been developed based on PAGER-CAT and EXPO-CAT global catalogs. Further, this global model was developed using fatality data specific for Indonesia by Jaiswal et al., 2009a, with specific parameter β = 0.14 and parameter θ = 14.05.

$$v[S_j] = \Phi\left[\frac{1}{\beta}\ln\left(\frac{S_j}{\theta}\right)\right] \qquad (2.2)$$

where,

v(Sj) : fatality-rate
Φ : standard cumulative distribution function
β and θ : log-normal distribution parameters

Fatality model developed in this study is a modification of the above two global models by correlating MMI distribution generated from ShakeMap and fatality data collected to discrete sub-districts level. The fatality data is collected from recent relatively large earthquake events in Indonesia that consist of Nias in 2005 (M_w=8.7), Yogyakarta in 2006 (M_w=6.3), West Sumatra in 2009 (M_w=7.6), and West Java in 2009 (M_w=7.0). The fatality modeling requires a set of data points that correlate fatality-rate associated with MMI value. Therefore, for each of this earthquake event, we require fatality data with corresponding MMI at the smallest identified unit area possible to capture the fatality characteristics that correspond to ground shaking intensity.

3. MMI DISTRIBUTION MAPPING

Fatality model requires correlation of fatality data for particular ground shaking intensity (MMI), I. In this process, MMI distribution map is needed for a particular earthquake event under consideration that has caused a certain number of fatality. MMI distribution of particular event under consideration was generated by using ShakeMap software (Allen et al., 2008 and Allen, 2011) with options on some ground motion predictive equations (GMPEs) to estimate peak ground acceleration (PGA) at reference subsurface rock, with seismic amplification factor calculated from average shear wave velocity of the top 30m profile (V_{s30}) correlated from topographical slopes that is built-in the ShakeMap to obtain PGA at ground surface. In addition, ShakeMap also support ground motion to intensity conversion equations (GMICEs) to correlate PGA at ground surface to MMI.

For generation of MMI distribution in this study, we adopt Zhao et al., (2006) for subduction interface and intra-plate earthquake sources. For shallow crustal fault earthquake sources, Zhao et al. (2006) and Chiou and Youngs 2008 (in Stewart et al., 2008) Next Generation Attenuation (NGA) function are used. For PGA to MMI correlation, GMICE developed by Wald et al. (1999) has been adopted. The Wald et al. (1999) GMICE is formulated as in Eqn. 4.1.

$$\text{MMI} = 3.66 \log(\text{PGA}) - 1.66 \quad (3.1)$$

For development of PGA and MMI distribution map for historical earthquakes needed for fatality model development, we adopt earthquake source models from recently published research for each of the historical earthquake event under consideration. The data source of the historical earthquakes and references used for MMI distribution mapping in this study are shown in **Table 3.1**. MMI distribution along with its finite source model for each of the earthquake event is presented in **Figure 3.1**.

Table 3.1. Historical Earthquakes Reference Used in This Study

No.	Earthquake	Date	Moment Magnitude	Epicenter Longitude (degree)	Epicenter Latitude (degree)	Depth (km)	Reference of Finite Source Model
1	West Sumatra	30-Sep-09	7.6	99.856	-0.7254	81	A. Sladen, Tectonic Observatory California Institute of Technology, 2009
2	Nias	28-Mar-05	8.7	97.013	2.0764	30	O. Konca, Tectonic Observatory California Institute of Technology,m 2007
3	Yogyakarta	26-May-06	6.3	110.43	-7.995	17	Tsuji, T. et al., 2009
4	West Java	2-Sep-09	7.0	107.259	-7.8088	46	Madlazim et al., ITS, 2010

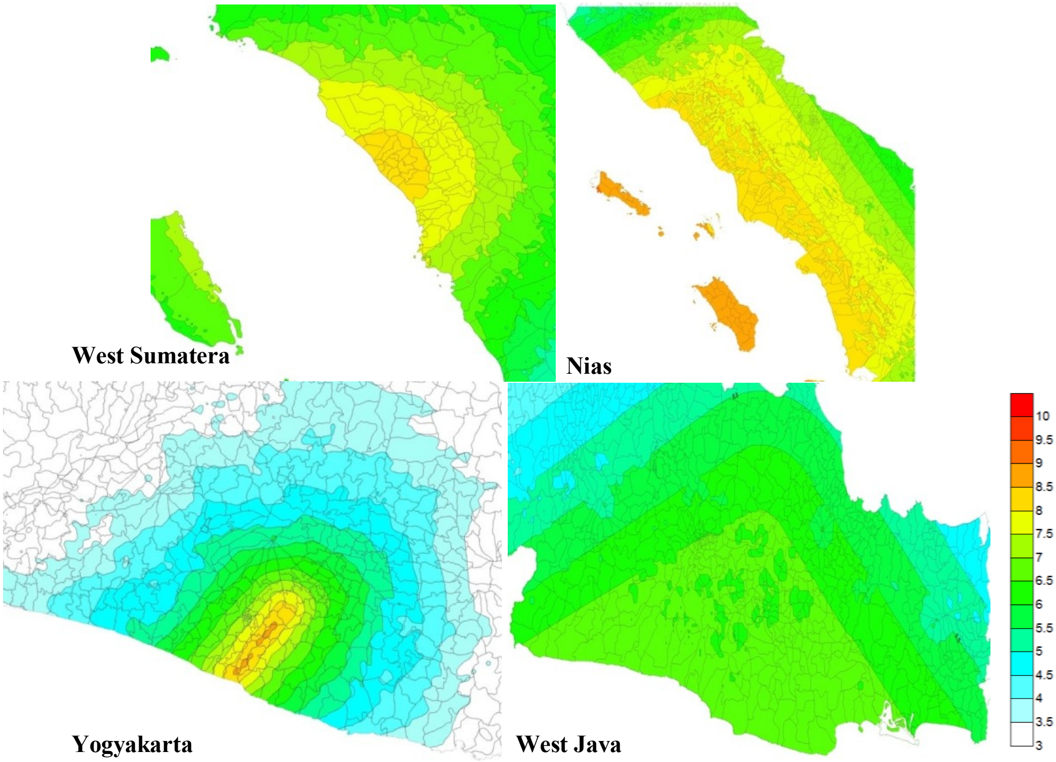

Figure 3.1 Estimated MMI Distribution at Ground Surface for Earthquake Events Considered in the Study

4. FATALITY DATA COLLECTION

Empirical fatality model requires fatality data and population exposure at district and sub-district levels for all the earthquake events under consideration. Fatality and population exposure data was collected from the statistic office and disaster management and other agencies at national and local levels. In this study, data collection to sub-district level unit was conducted to obtain more accurate fatality to MMI correlation. **Table 4.1** shows the fatality data for several sub-district levels for each earthquake event and number of fatality.

Table 4.1 Summary of Fatality Data Collected from Sub-District Levels for each Earthquake Event

No	Earthquake Event	Data Collection Level
1	West Java Earthquake	Sub-district: 5 sub-districts with fatalities in Ciamis District and 1 sub-district with fatalities in Bandung District.
2	Yogyakarta Earthquake	Sub-district: 17 sub-districts with fatalities in Bantul District, Yogyakarta Province and 21 sub-districts with fatalities in Klaten District, Central Java Province
3	West Sumatera Earthquake	Sub-district: 11 sub-districts with fatalities in Padang City and 17 sub-districts with fatalities in Padang Pariaman District
4	Nias Earthquake	Sub-district: 19 sub-districts with fatalities in Nias District

Each of the sub-district fatality data was then assigned particular corresponding MMI in accordance with the generated MMI distribution due to associated earthquake event. **Figure 4.1** shows frequency on number of sub-district fatality data points with corresponding MMI for the four earthquake events under consideration. It is indicated that with the four earthquake events under consideration, there is fatality data available that represent various MMI level from as low as 5 to as high as 9. Even though the number of fatality data for each MMI is not well distributed for each earthquake event, the combination of all the four earthquakes events provide relatively good distribution of fatality data with various MMI. Yogyakarta 2006 earthquake event provides fatality data with various MMI from 5 to 9. West Sumatra earthquake event provides fatality data mostly at MMI 8. Whereas, Nias earthquake event provides fatality data for high intensity 8.5-9.

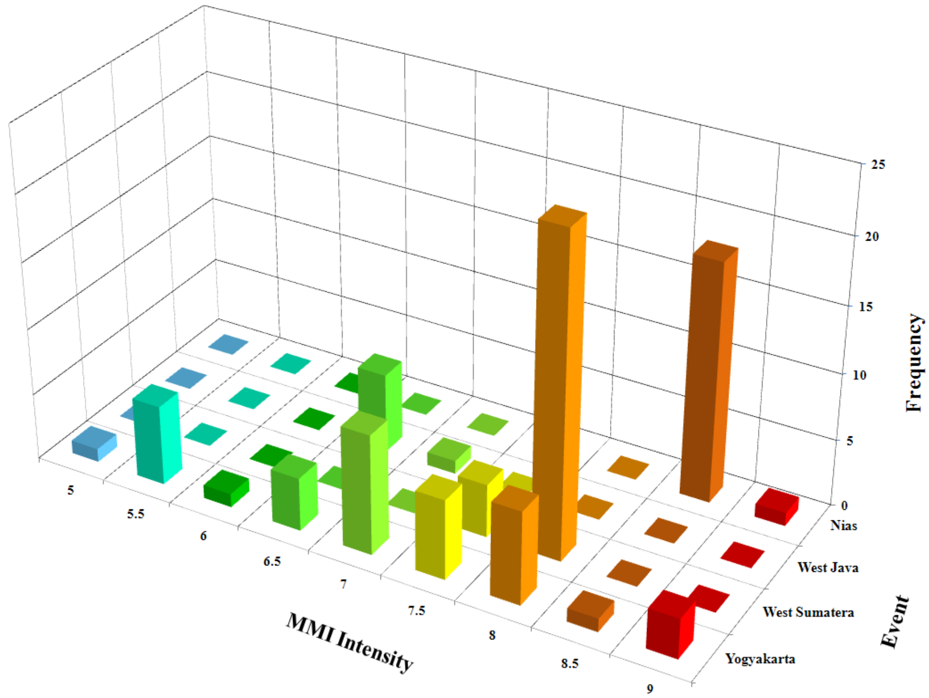

Figure 4.1 Frequency on number of sub-district fatality data points with corresponding MMI for earthquake events under consideration

Data analysis was also made by classifying several sub-districts fatality data that have the same MMI to the unit rounded to 0.5 unit MMI scale. **Table 4.2** shows summary of aggregated fatality data having the same MMI. There are total of 14 data points of fatality-rate data to develop earthquake empirical fatality model. Fatality rate is defined as ratio of number of fatality to total number of exposed population within the considered area having particular MMI.

Table 4.2. Summary of aggregated fatality data having the same MMI

Data Aggregate per MMI Level			
Event	**Population**	**Fatalities**	**MMI**
West Java	204557	3	7
	4452310	8	6.5
Yogya	141970	1656	9
	32556	422	8.5
	547774	2472	8
	80159	57	7.5
	467693	456	7
	37606	9	6.5
	537428	89	6
	264904	6	5
West Sumatra	1197007	760	8
	44552	20	7.5
Nias	379224	274	9
	154725	576	8.5

5. ANALYSIS RESULTS

The fatality data associated with the corresponding MMI data in Table 4.1 is the basis for both exponential and log-normal cumulative distribution function (CDF) modeling. Optimizations process are performed by the iteration of the equation parameters (in this case is exponential and log-normal CDF) in order to obtain minimum value of objective functions. This iteration process makes use of the Nelder-Mead technique to find the optimized equation parameters. There are several commonly used objective functions as shown in Eqn. 5.1 to Eqn. 5.4.

$$\varepsilon_1 = \sum_{i=1}^{N} |(E_i - O_i)| \qquad \text{L1 norm} \qquad (5.1)$$

$$\varepsilon_2 = \sum_{i=1}^{N} (E_i - O_i)^2 \qquad \text{L2 norm} \qquad (5.2)$$

$$\varepsilon_3 = \sum_{i=1}^{N} \left[ln\left(\frac{E_i}{O_i}\right)\right]^2 \qquad \text{G norm} \qquad (5.3)$$

$$\varepsilon_4 = ln\left(\sqrt{\frac{1}{N}\sum_{i=1}^{N}(E_i - O_i)^2}\right) + \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[ln\left(\frac{E_i}{O_i}\right)\right]^2} \qquad \text{L2G norm} \qquad (5.4)$$

where: ε : Residual error

E_i : Estimated fatality of event i

O_i : Number of recorded fatality of event i

In this optimization, Eqn. 5.4 (L2G norm) is used as objective function because this norm provides a better accuracy both for low and high fatality rates. **Figure 5.1** below shows the comparison between these objective functions for the exponential form model.

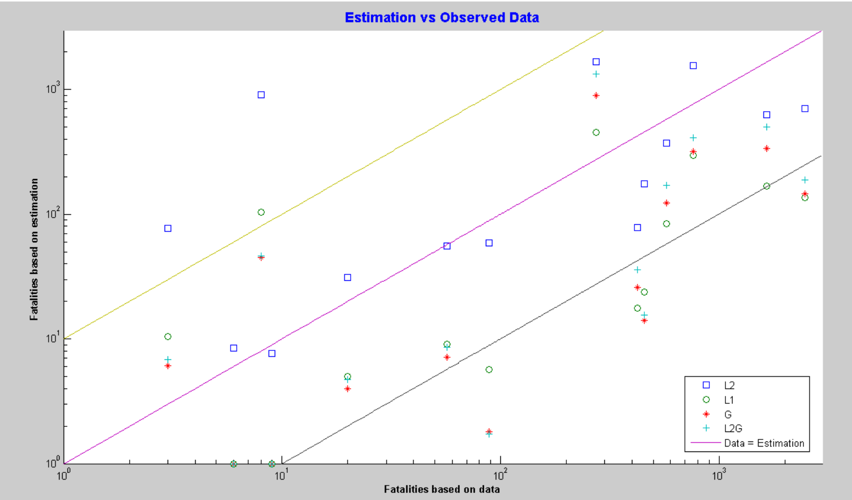

Figure 5.1. Estimated versus Recorded Fatalities using 4 Objective Functions for Exponential Form Model

Both exponential form and log-normal CDF form provide a similar value of residual error. Residual error from iteration process is 8.2576 for exponential equation and is 8.2916 for log-normal CDF equation. **Figure 5.1** shows the fatality models of both exponential and log-normal CDF relative to the fatality data used for the modeling. For exponential model, the parameters of the model are a= 0.622 and b=8.033, so that the resulted equation is:

$$R(I) = 10^{(.622I-8.033)} \tag{5.5}$$

In addition to the exponential and log-normal CDF models resulted in this study, the Allen et al., 2009 and Jaiswal et al., 2009 models are also plotted for comparison. It is indicated that the fatality-rate resulted from this study is relatively much lower compared to Allen et al., 2009 global model particularly for MMI higher than 7.0. Comparing the developed models in this study, Jaiswal et al. 2009 model using Expo-CAT data specific for Indonesia, on the other hand, predict lower fatality-rate from low MMI to MMI as high as 8.5 and then predict higher fatality-rate for high MMI greater than 8.5.

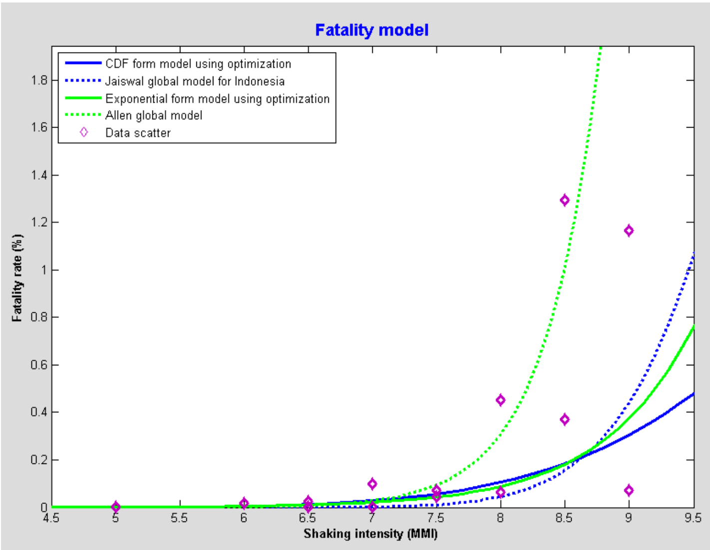

Figure 5.2 Result of developed fatality models in this study in comparison to Jaiswal et al., 2009 and Allen et al., 2009 model

Expo-CAT data from USGS website is also used to give a comparison between exponential and log-normal CDF forms. Expo-CAT data contains a wide range of recording events of natural disasters around the world. Overall, there were 78 recorded disasters that occurred in Indonesia, including deaths due to fires, tsunamis, liquefaction and landslides. These data are not all taken into account, only the events that have more than 10 casualties and caused by the earthquake are included. In this data, there are also populations at each level of earthquake intensity and the total number of fatalities caused by an earthquake event. The Expo-CAT data representing observed fatalities is compared with the developed exponential and log-normal CDF models. **Figure 5.3** show these comparisons along with Jaiswal et al., 2009 model. It is indicated that most of the Expo-CAT data fall within the lower and upper bound of the developed models in this study. It is also indicated that exponential form provides a better accuracy compared to log-normal CDF form as also identified from the smaller residual error resulted from this Expo-CAT data. Therefore, the developed exponential model in this study is recommended for fatality estimates of Indonesia.

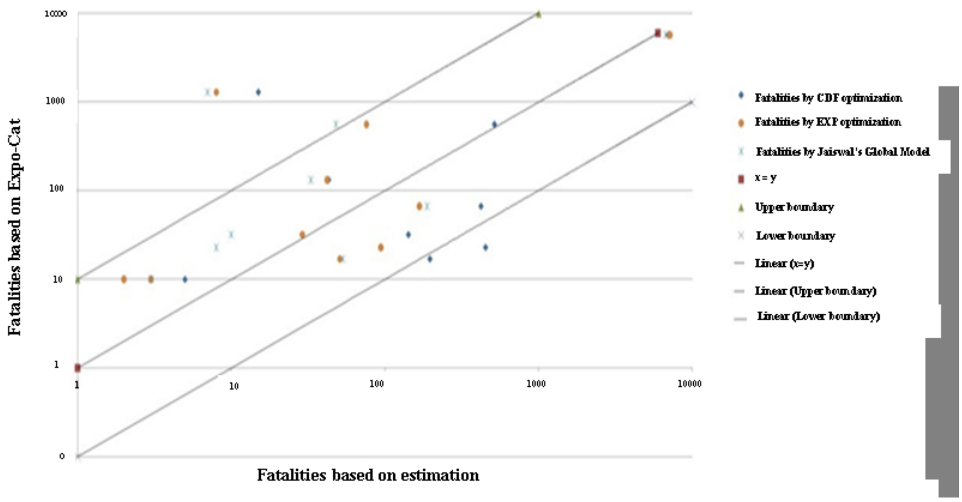

Figure 5.3. Comparison of the Fatality Model Estimate per Event with Expo-CAT Data

6. FATALITY PREDICTION FOR INDONESIA

Preliminary fatality estimate has been made herein for whole Indonesia employing the developed fatality model in this study. This prediction is revision of the previous estimate made in Sengara et al., 2011b adopting Allen et al., 2009 fatality model. MMI of whole Indonesia is generated with reference to Sengara et al., 2011b, Irsyam et al., 2010, and Wald et al.,1999. Population density data is with reference to World Bank Report, 2009 and the statistical data obtained in 2011. Based on the developed earthquake fatality model in this study, that is the developed exponential form model, number of fatality/km^2 can be estimated for Indonesia, as shown in **Figure 6.1**. The estimates in Figure 6.1 suggest that high number of fatality could be associated with high potential of earthquake intensities and high population density with its vulnerabilities. For example, Java and Bali Islands (orange color) are relatively highly populated areas and relatively medium to high earthquake intensity corresponds to relatively high fatality number. In other islands where relatively less population are found, such as Eastern Sumatra and Kalimantan Islands, the fatality number gradually decreases. In more detailed we can also look that at some areas in Java Island, the rate is around 1-10/km^2 and some cities with 10-100/km^2, while most of areas in Java are around 0.1-1/km^2. In Sumatra Island, we can find that the rate is between 0.01-0.1/km^2 since the population density is less than in Java. The rest of the islands indicate relatively low fatality-rates due to lower earthquake intensities and less number of population.

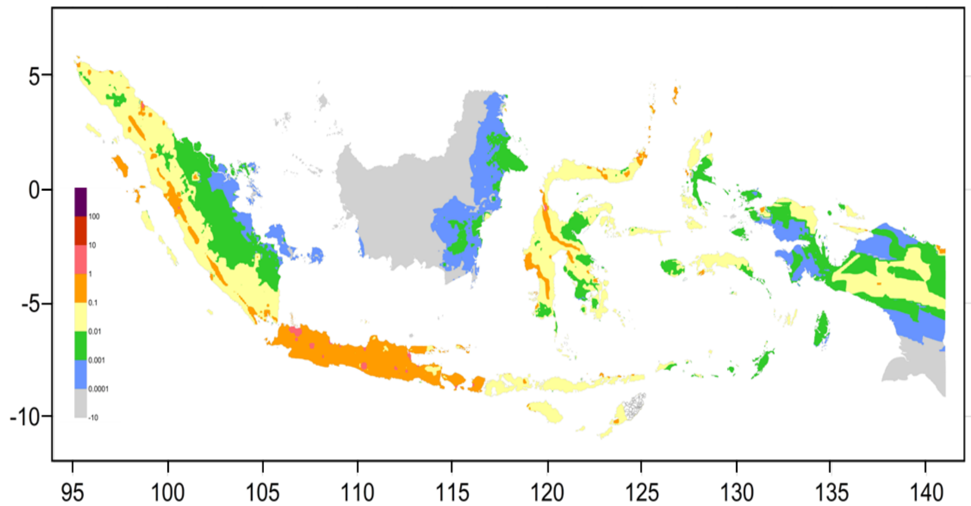

Figure 6.1. Fatality Prediction Map of Indonesia in Number of People Killed per km^2
(10% PE in 50 years earthquake scenario)

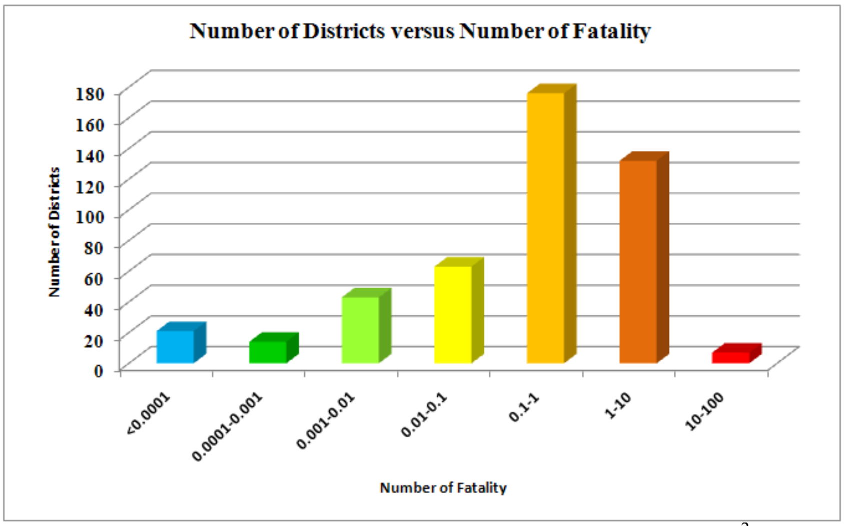

Figure 6.2. Number of Districts with Number of Fatality/km^2

Based on the estimation, around 30% of Indonesian districts and cities are having high to fatality of (1-10)/km^2 and 3% having very high fatality of (10-100)/km^2. The possibility of loss of life caused by earthquakes is quite high, likely due to structures that are not resistant to earthquakes.

7. CONCLUSIONS

Fatality model for Indonesia has been developed based on empirical data from most recent earthquakes with fatality rates data generated to sub-districts unit. The model development is a modification of previously developed global model employing more global fatality data. The fatality model for Indonesia is developed based on fatality data collected from recent earthquake events that represent sub-district levels that capture both vulnerability of buildings and population density. Fatality model that is based on exponential form provides best match with the fatality data considered in the study. Fatality-rate estimate resulted from the developed model specific for Indonesia in this study is relatively lower compared to those previously developed by global models. The developed exponential model also match well with the Expo-CAT data specific for Indonesia.

The developed fatality model could be used for the current real-time earthquake impact maps for Indonesia and could be applied for computing losses from scenario earthquakes for pre-disaster planning. The developed fatality model has been adopted for preliminary fatality analysis of whole Indonesia employing scenario earthquakes based on new 2010 seismic hazard map of 10% probability of exceedance in 50 years, for reference rock with local site-effect, V_{s30}, generated from topographical slopes estimate. The analysis has identified some districts and cities of approximately 33% with relatively high to very high fatality. The number of fatality information would be important for the districts and cities that have high to very high fatality need to develop appropriate structural and non-structural mitigation measures.

ACKNOWLEDGEMENT
The authors thankful to Trevor Allen, Hadi Ghasemi, and Hyeuk Ryu for reviewing and providing fruitful inputs through technical discussions during the development of the model. Supports by research assistants at Research Center for Disaster Mitigation-Institut Teknologi Bandung: InIn Wahdiny, Anin Utami, Bayu Novianto, Addifa Yulman, and particularly Aria Mariani, who has also assisted in editing the paper, are higly appreciated. The authors thank to *Australia-Indonesia Facility for Disaster Reduction (AIFDR)* and *Indonesian Disaster Management Agency (BNPB)* that has financially supported the study.

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