# Analysis of the Seismicity Pattern Change for Probabilistic Seismic Hazard Analysis (PSHA) and Mitigation: Mapping the Probability Difference Before Large Earthquake and Its implementation for PSHA & Mitigation around southern off the coast of Sumatra - West Java

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# Analysis of the Seismicity Pattern Change for Probabilistic Seismic Hazard Analysis (PSHA) and Mitigation: Mapping the Probability Difference Before Large Earthquake and Its implementation for PSHA & Mitigation around southern off the coast of Sumatra - West Java

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**Abstract**. The implementation of the Seismic Quiescence Index (SQI) into seismic hazard study and analysis mapped around the off southern coast of Sumatra - West Java. The 15 years of Region Time Length (RTL) were used in this study. To construct the SQI, first of all, we divided the period of the declustered shallow earthquake catalog of observation into two parts, i.e., a period of 1978 to 1992 and 1993 to June 2006. Two rate models were then developed to estimate the probability of a given magnitude and a specified time window. The result was then used to determine the probability difference between the two periods of observation and SQI estimation. The SQI then used better to understand the pattern of seismicity changes for PSHA. To construct the model for SHA is done by developing the seismicity rate model of the period 1978 to June 2006 and then weighted by the SQI index. Furthermore, the median Peak Ground Acceleration (PGA) of 10% probability exceedance level for 50 years is estimated and mapped. By incorporating an amplification factor, the PGA value on the surface can be determined. The amplification factor is calculated using the Horizontal-Vertical Spectral Ratio (HVSR) method. This result might be useful for better understand the future PSHA and mitigation before a large earthquake.
**Keywords**: SQI, Seismic Hazard Analysis, Peak Ground Acceleration, Amplification, Mitigation

## 1. Introduction

Based on the previous research results, the potential earthquake precursors can be characterized by changing seismicity patterns. In particular, space-time is found in the presence of a strong-correlation seismic quiescence phenomenon seismotectonic process before the large earthquake event (Wyss & Habermann, 1988). Interpretation and implementation of seismicity pattern change before large earthquake into seismic hazard study and analysis require careful analysis of the selected reference data and model to express the seismicity rate evolution. For the interpretation or the forecasting effort associated with the possible future hazard analysis or future mitigation, the pattern that probably represents a clustering model can be observed or extracted based on seismicity data (Michael 1997). One of the methods of approach that is often applied to obtain the clustering model is implementing the spatial smooth the past seismicity method so that it is possible to be used for potential future seismic hazard and mitigation model analysis. Some previous studies have implemented a seismicity smoothing using the Gaussian function approach, for example, (Frankel 1995, Petersen et al. 2008, Triyoso & Shimazaki, 2012, Triyoso et al. 2020a, Triyoso et al. 2020b).

Sukrungsri & Pailoplee (2016) and Triyoso et al. (2020b) conducted an evaluation of the model of the seismicity pattern change before the 2004 Aceh earthquake and the 2012 Indian Ocean earthquake and Andaman-Northern Sumatra before 2004 to 2010 Large Earthquake by implementing a Region-Time-Length (RTL) algorithm. The results obtained support the presence of seismic quiescence phenomenon, which is strongly correlated with the seismotectonic process before a major earthquake event. More detailed analysis results based on a dataset of catalogs with temporal variations and the inferred spatial distribution can reveal consistent characteristics in the change of seismicity patterns.

In this study, we proposed incorporating the SQI (Triyoso et al., 2020b) into seismic hazard study and analysis around the south off the coast of Sumatra - West Java. The smoothed seismicity rate model is constructed based on seismicity smoothing algorithms with Gaussian kernel models using the shallow earthquake catalog data from 1978 to June 2006 (PUSGEN 2017, Triyoso et al. 2020a). Combined with the geological rate of the large earthquake (Billham et al. 2005), used to quantify the long-term seismicity rate background model. The 75 km radius correlation distance is used to construct the model based on the declustered earthquake catalog of the two different periods. They are the period from 1978 to 1992 and 1993 to June 2006. To construct the model for SHA is done by developing the seismicity rate model of the period 1978 to June 2006 and then weighted by the SQI index. Furthermore, the PGA of a 10% probability exceedance level for 50 years is estimated and mapped. An amplification factor is then evaluated for several locations and then incorporate into the PGA estimated. This is done by multiplying the PGA and amplification factor for the purpose as one of the inputs for seismic disaster mitigation. The amplification factor is calculated using the Horizontal-Vertical Spectral Ratio (HVSR) method of the BMKG data.

## 2. Data and Methodology

This study's seismicity data is based on the previous study (PUSGEN, 2017; Triyoso et al., 2020a). We select the earthquakes data with a magnitude $M_w \geq 5.0$ and a maximum depth of 50 km around Sumatra - West Java. Furthermore, we choose the b-value ~1.0. The earthquake catalog is then declustered to get the independent earthquake events, using ZMAP software (Wiemer, 2001). The long-term geological rate is based on Billham et al. (2005), in which around 100 to 400 years of return period is used to quantify the background model around the study area. Two different periods of the seismicity model are constructed based on the declustered catalog data with the correlation distance of 75 km. They are the period from 1978 to 1992 and 1993 to June 2006. To develop an integrated model, we combine the seismicity smoothing rate with a large earthquake's geological rate. The two-rate models are then set to estimate the probability of a given magnitude and a specified time window. The result is then used to estimate the probability difference between the two periods of observation, and then the SQI is calculated based on that probability difference (Triyoso et al.,2020b). The new model is then constructed for SHA, which is the SQI incorporated. It is done by developing the seismicity rate model from 1978 to June 2006 and then weighted by the SQI index. Furthermore, the PGA of a 10% probability exceedance level for 50 years is estimated based on the new model and mapped.

To better understand the possible seismic disaster mitigation, an amplification factor is incorporated to estimate the PGA value on the surface. The amplification factor is calculated using the Horizontal-Vertical Spectral Ratio (HVSR) method of several BMKG data accelerogram stations. The amplification factor was calculated based on accelerogram recorded data at about 3 BMKG stations. They are Bengkulu Fatmawati, Liwa, and Kota Agung-Lampung.

### *2.1. Seismicity Smoothing*

In this study, results of some previous studies of seismic hazard assessment based on a seismicity smoothing using the Gaussian function approach, for example, (Frankel 1995, Petersen et al. 2008, Triyoso & Shimazaki, 2012, Triyoso et al. 2020a, Triyoso et al. 2020b) is implemented. First of all, gridding is done on the area to be studied, then the number ($n_i$) of earthquake events with magnitude equal to or greater than the reference ($M_{ref}$) is estimated in each grid. The value of $n_i$ express as the maximum likelihood estimate of $10^a$ for earthquakes above $M_{ref}$ in the cell (Bender, 1983). The grid of $n_i$ values is then smoothed spatially by using a Gaussian function with correlation distance $c$. For each cell $i$, the smoothed value is obtained from:

$$\tilde{n}_i = \frac{\sum_j n_i e^{-\Delta^2{}_{ij}/c^2}}{\sum_j e^{-\Delta^2{}_{ij}/c^2}} \tag{1}$$

in which $\tilde{n}_i$ is the normalized value to preserve the total number of events, $\Delta_{ij}$ is the distance between the *i*-th and *j*-th cells, and *c* is the correlation distance. In equation (1), the sum is taken over cell *j* within a distance of 3c from cell *i*.

*2.2. The Rate of Occurrence Rate*

The theoretical earthquake occurrence rate function for a particular cell, $v_i$ ($\geq M_{ref}$), is given by

$$v_i(\geq M_{ref}) \approx \frac{N_i}{T} \tag{2}$$

Ni represents the number of earthquakes with magnitude $\geq M_{ref}$ in cell *i,* and *T* is the record length. $v_i$ means the $10^a$ of the earthquake with magnitude equal to or greater than $M_{ref}$. The $M_{ref}$ is determined based on the result of the magnitude completeness analysis. It implies that applying the Gaussian function to smooth the seismicity accepts the $10^a$ by equation (2). Furthermore, substituting $10^a$ of equation (2) in equation (1), we may write the following equation,

$$v_i(\geq m) \approx \frac{\tilde{n}_i(\geq M_{ref})}{T.b\ln(10)} 10^{-bm}(1-10^{b(m-M\max)}) \tag{3}$$

$v_i$ ($\geq M_{ref}$) results from smoothed seismicity for grid *i* of the earthquakes above the $M_{ref}$ during the time interval *T.* The *b* is the uniform *b*-value. $M_{max} \sim 9.0$ is used in this study.

*2.3. Probability of Occurrence*

The probability of occurrence of a given earthquake magnitude larger than or equal to m at a particular cell k during time interval T under the Poisson distribution is given by:

$$p(\geq m) = 1 - \exp(-v_i) \tag{4}$$

in which $p(\geq m)$ is the probability of occurrence the smoothed value for cell i of the number of earthquakes above reference magnitude.

*2.4. Probability Difference: Seismic Quiescence Index.*

The decrease in earthquake activity may occur within a part or all of the subsequent mainshock's source volume. This decreasing trend may continue to the mainshock time or may be separated from it by a relatively short period of an increasing trend in earthquake activity. Since quiescence duration depends strongly on the tectonic structure and probably on the loading rate, the earthquake activity rate measurement may be essential to understand the possible future earthquake potential. These types of parameters have been used in many seismicity studies for different parts of the world and also Andaman-Northern Sumatra (e.g., Katsumata and Kasahara, 1999, Cao and Gao, 2002, Tsapanos et al. 2014; 2016, Sukrungsri & Pailoplee, 2016, Triyoso et al., 2020b). Referring to Wyss and Habermann's (1988) definition and the result of Triyoso et al. (2020b), we propose using the SQI better to understand the changes of seismicity pattern seismic hazard analysis. To construct the model for SHA with SQI incorporated is done by developing a combined seismicity rate model of period 1978 to June 2006 with the long-term geological rate and then weighted by the SQI index to estimate Seismic Hazard Function (SHF).

*2.5. The Probability of Exceedance (PE)*

The annual PE of peak horizontal ground motion (PGA or PGV) u at a site due to events at a particular cell k under the Poisson distribution is given by:

$$P(u \geq u_0) = P_k(m \geq m(u_0, D_k)) = 1 - e^{(-v_i(\geq m(u_0, D_k)))} \quad (5)$$

The $P_k$ ($m \geq m$ ($u_o$, $D_k$)) is the annual of the probability of occurrence of an earthquake with magnitude *m*. The m ($u_o$, $D_k$) in the $k^{th}$ source grid that would produce a peak ground motion (PGA or PGV) of $u_o$ or larger at the site. And $D_k$ is the distance between the site and the source grid. The function m ($u_o$, $D_k$) is the attenuation relation or Ground Motion Prediction Equation (GMPE). The PE of PGA or PGV at the site was determined by integrating the influences of the surrounding source cells, i.e.

$$P(u \geq u_0) = 1 - \prod (1 - P_k(u \geq u_0)) \quad (6)$$

By substituting the GMPE, we could obtain

$$P(u \geq u_0) = 1 - \prod e^{(-v_i(\geq m(u_0, D_k)))} = 1 - e^{-\sum v_i(\geq m(u_0, D_k))} \quad (7)$$

which gives the annual PE of a particular PGA or PGV. For specific time duration *T,* the probability of exceedance is given by

$$P(u \geq u_0) = 1 - (1 - P(u \geq u_0))^T = 1 - e^{(-T \sum v_i(\geq m(u_0, D_k)))} \quad (8)$$

The yearly PE of specified ground motions is calculated by applying equation (7) for each grid. For a specified time duration, the probability of exceeding specified ground motions is computed using equation (8).

*2.6. Ground Motion Prediction Equation (GMPE)*

In constructing the seismic hazard map expressed by PGA or PGV, we need an attenuation relationship (Ground Motion Prediction Equation), in terms of PGA or PGV as a function of magnitude and distance. In this study, since the focus is to evaluate the potential hazard, in which the source is the megathrust or subduction zones, then we refer to the result of Triyoso et al. (2020a) and select GMPE that is based on Atkinson et al. (2006).

*2.7. Horizontal-to-Vertical Spectral Ratio (HVSR or H/V)*

The Horizontal-to-Vertical Spectral Ratio (HVSR or H/V) method is one method for obtaining the bottom-surface information of a single station measurement on the earth's surface initially used to examine the risk of the earthquake in Japan. The acquisition of data on this method requires a 3-component station that performs a spectrum comparison of the Fourier horizontal and vertical components. The assumption used in this HVSR method is the H/V ratio value in bedrock equals one. Furthermore, the amplitude of the waves that propagate towards the vertical and horizontal direction are of equal value so that the HVSR formula can be written in the equation,

$$H/V = A_H/A_V \quad (9)$$

$A_H$ is the Fourier spectrum of the horizontal component of accelerogram data. $A_V$ is Fourier the spectrum of the vertical component of accelerogram data.

Mucciarelli and Galipolli (2004) conducted a comparative review of HVSR methods using Rayleigh waves and noise. The analysis was performed to 500 and more HVSR results for three stations being in sediment and one station in the base rock. The conclusion of the review of HVSR analysis by using noise and earthquake waves shows the same results. Other studies conducted in the Los Angeles Basin use Rayleigh waves and body waves. The study results showed Rayleigh's waves gave better amplification information in the sedimentary basin area compared to using only the body wave (Bowden and Tsai, 2017). In this study, amplification is calculated based on the frequency band of 0.3 – 0.7 Hz. The use of this frequency range is based on Bowden and Tsai (2017). To incorporate the amplification into PGA is done by multiply the SHF with the amplification factor. This implies that the PGA estimated at the base rock is converted to the PGA at the surface.

## 3. Results and Discussion

Figure 1 shows the result of the annual rate of earthquake occurrence models of the south off the coast of Sumatra - West Java with magnitude larger than or equal to 5.0 derived based on the period of 1978-1992 and period of 1993-June 2006. The long-term geological rate is combined with the smoothed seismicity rate of $M_w \geq 5.0$ with a correlation distance of 75 km to estimate the seismicity rate. Furthermore, the probability difference between the two different models is calculated, and the Seismic Quiescence Index is then evaluated by calculating the normalized of maximum value that probability difference subtracted by the result of that probability difference of the two different models. Furthermore, the new model is then constructed for SHA with the SQI is incorporated. It is done by developing the seismicity rate model from 1978 to June 2006 and then weighted by the SQI index. Figure 2 shows the Seismic Quiescence Index map and the model's annual rate in which the SQI is incorporated. It is done by developing the seismicity rate model from 1978 to June 2006 and then weighted by the SQI index. The results show that the high Seismic Quiescence Index and the high annual rate of earthquake occurrence are consistent with the large earthquake of the year 2006-2010. The earthquake hazard potential curve was obtained by plotting the probability exceedance value of earthquake events versus PGA values. The total probability of selected sources around the study area's subduction zone is estimated for the earthquake with a magnitude range of 6.0 to 9.0. The calculation is based on Triyoso et al. (2020a), in which the influences parameter are the changes in the magnitude and distance of earthquakes. The focal depth value is estimated from the half of seismogenic depth at 10 km and the starting locking depth at 5 km. Thus, the focal depth used is 15 km. Therefore, using equations 8 and GMPE (Triyoso et al., 2020a), we calculate the median value of PGA of the 10% probability of exceedance for 50 years. The PGA map of the 10% probability exceedance for 50 years of the model in which the SQI is incorporated. Figure 3 shows that some SHF evaluation with and without site amplification for the three BMKG stations (Bengkulu Fatmawati, Liwa, and Kota Agung-Lampung).

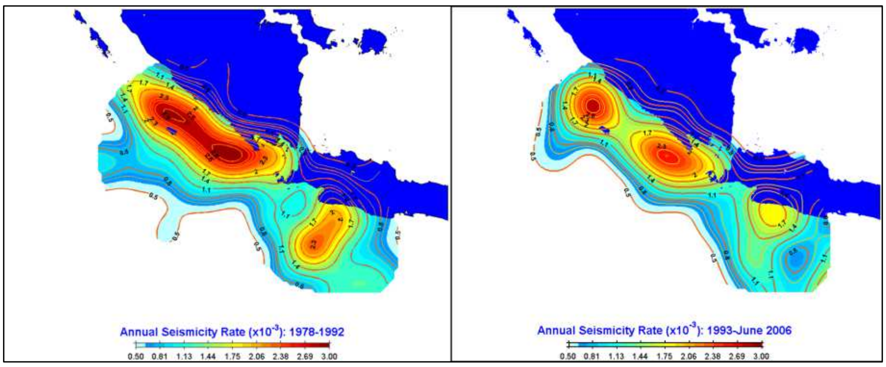


**Figure 1.** The result of the annual rate of earthquake occurrence models of the south off the coast of Sumatra - West Java with magnitude larger than or equal to 5.0 derived based on the period of 1978-1992 and 1993-June 2006. The long-term geological rate is combined with the smoothed seismicity rate of $M_w \geq 5.0$ with a correlation distance of 75 km to estimate the seismicity rate.

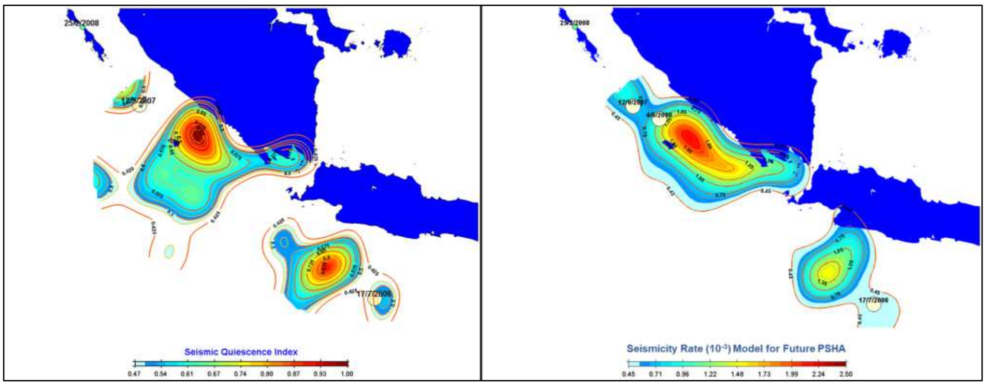


**Figure 2.** The Seismic Quiescence Index map of the off southern coast of Sumatra - West Java and the annual rate of the model in which the SQI is incorporated. It is done by developing the seismicity rate model from 1978 to June 2006 and then weighted by the SQI index. The results show that the high Seismic Quiescence Index and the high annual rate of earthquake occurrence are consistent with the large earthquake of the year 2006-2010.

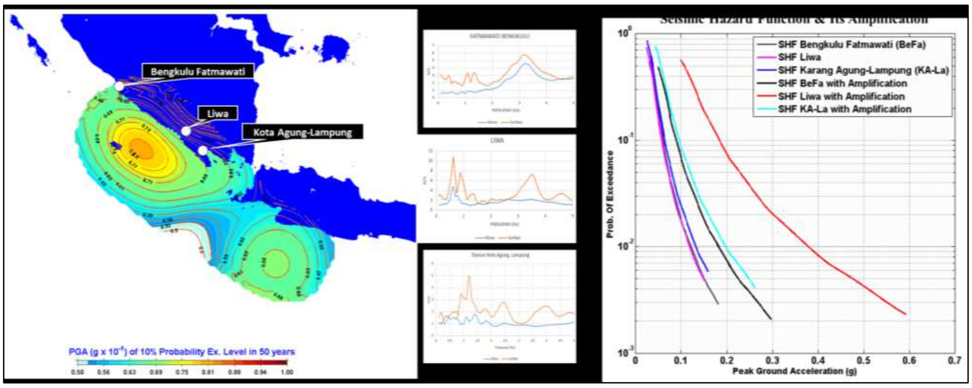


**Figure 3.** The PGA of 10% probability of exceedance for 50 years. The PGA map of 10% probability exceedance for 50 years of the model in which the SQI is incorporated and some evaluation of SHF with and without site amplification for the three BMKG stations (Bengkulu Fatmawati, Liwa, and Kota Agung-Lampung).

**4. Conclusions**

In this study, the probability difference between the two different models is calculated, and the Seismic Quiescence Index is then estimated around the study area of the south off the coast of Sumatra - West Java. The SQI is then incorporated for Seismic Hazard and Mitigation Analysis by developing the seismicity rate model from 1978 to June 2006 and then weighted by the SQI index. The results show that the high Seismic Quiescence Index and the high annual rate of earthquake occurrence are consistent with the large earthquake of the year 2006-2010. In this study, the SHF over the entire study area is estimated. The PGA map of 10% probability exceedance for 50 years of the model is constructed in which the SQI is incorporated. The site amplification is evaluated based on the HVSR method, and some evaluation of SHF with amplification is done for the three BMKG stations (Bengkulu Fatmawati, Liwa, and Kota Agung-Lampung). This result might help better understand the future seismic hazard study and mitigation before large earthquake analysis.

**Conflict of Interest**

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

**Authors' contributions**
WT developed the method, did the analysis, and prepared the figures and the manuscript. AS and AA helped in the manuscript preparation and discussion.

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# Figures

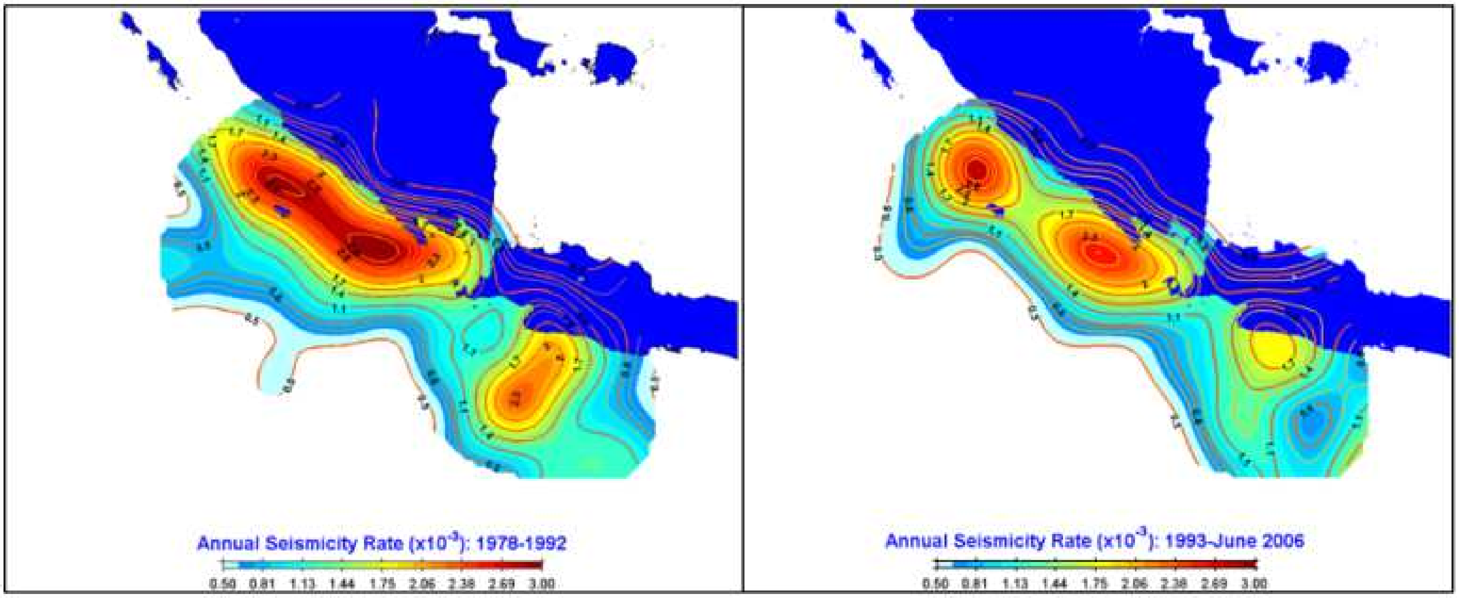


**Figure 1**

The result of the annual rate of earthquake occurrence models of the south off the coast of Sumatra - West Java with magnitude larger than or equal to 5.0 derived based on the period of 1978- 1992 and 1993-June 2006. The long-term geological rate is combined with the smoothed seismicity rate of Mw ≥ 5.0 with a correlation distance of 75 km to estimate the seismicity rate.

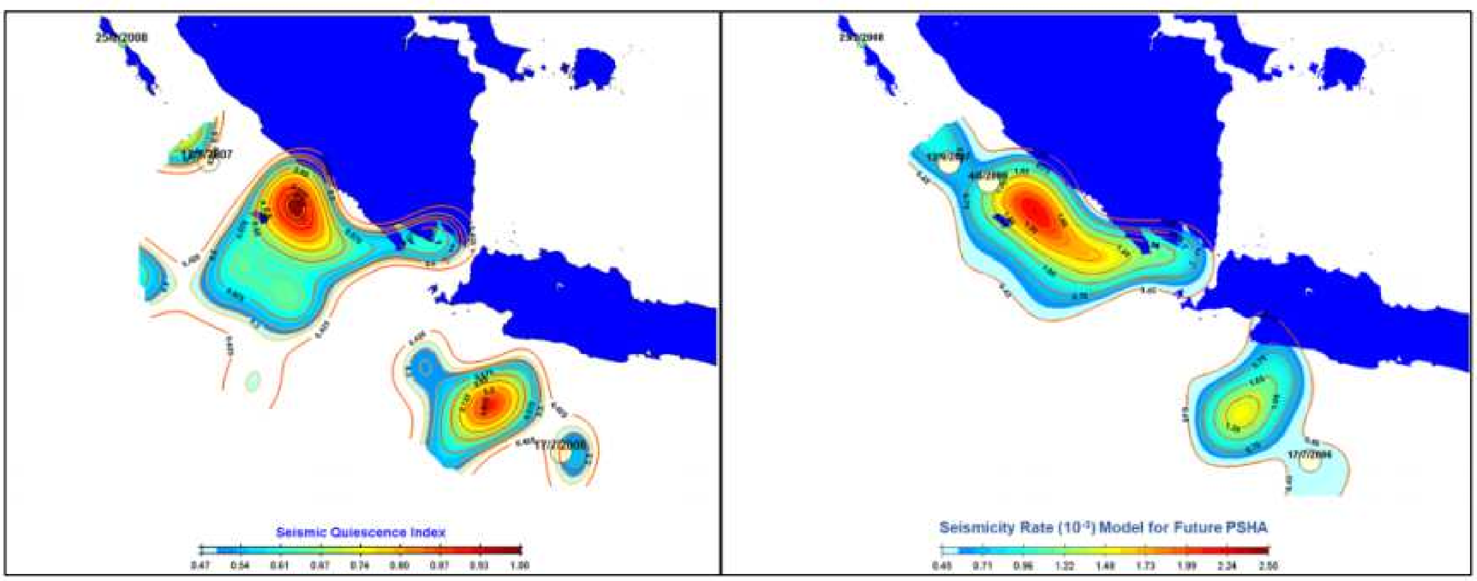


**Figure 2**

The Seismic Quiescence Index map of the off southern coast of Sumatra - West Java and the annual rate of the model in which the SQI is incorporated. It is done by developing the seismicity rate model from 1978 to June 2006 and then weighted by the SQI index. The results show that the high Seismic

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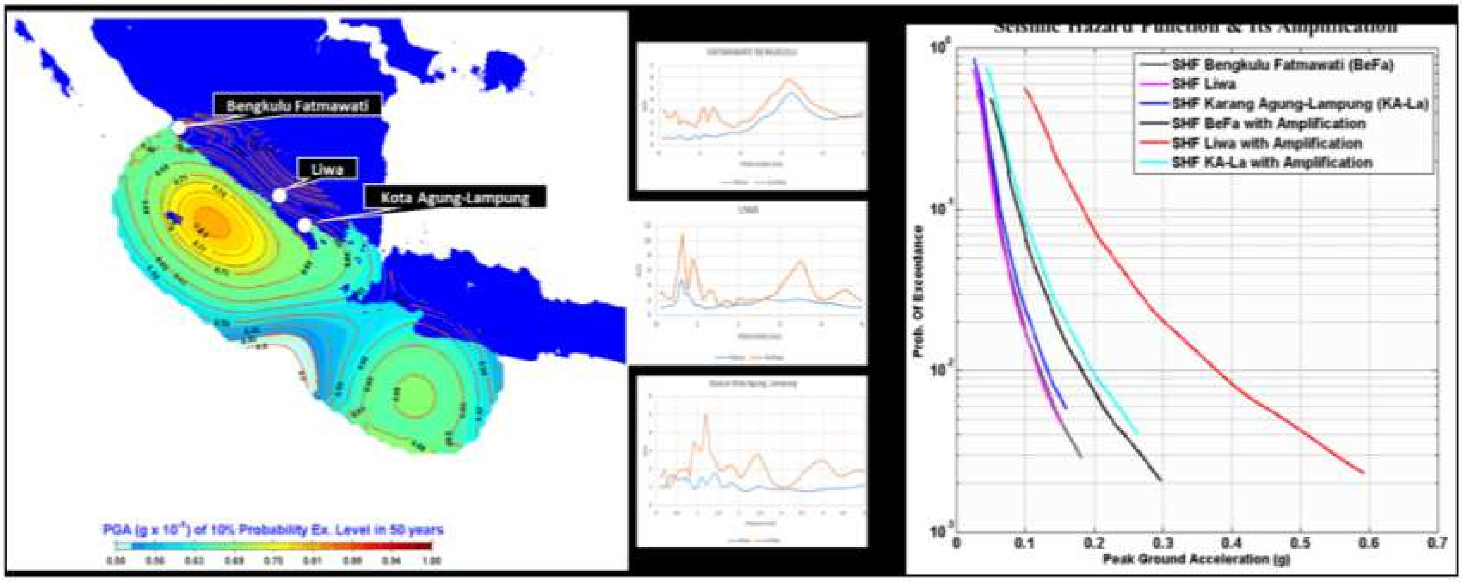


## Figure 3

The PGA of 10% probability of exceedance for 50 years. The PGA map of 10% probability exceedance for 50 years of the model in which the SQI is incorporated and some evaluation of SHF with and without site amplification for the three BMKG stations (Bengkulu Fatmawati, Liwa, and Kota Agung-Lampung).