A study on the potential of tsunamigenic earthquakes in Java Subduction Zones

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Abstract. Subduction zone is a source of tectonic earthquakes that has potential to cause a tsunami. The study aims to obtain the estimation of earthquake parameter as a tsunami generator. Earthquake parameters were analyzed by using the scaling law theory for thrust fault type in the subduction zone. This study employed three magnitude scenarios, namely 8.9, 9.0 and 9.2 taken from the National Earthquake Study Center (Pusgen) of Indonesia and Blaser’s Equation. The results of model design in a vertical displacement indicated that deformation occurred on the seafloor. The results of source modeling illustrated the variations in maximum vertical displacement values for all three scenarios, namely 4,123; 5,309 and 4,831 meters based on the Blaser’s equation and 3,517; 3,183 and 4,526 meters based on the Pusgen’s data. The results of the study indicated that the value of vertical displacement can provide an estimate of the tsunami wave height at sea level.

1. Introduction

Java subduction zone stretches from Sumatra island to the southern sea of East Java with a length of ± 1,100 Km. Colliding with the Eurasian plate in the southern sea Java, the Indo-Australian plate protects moves at 68 mm/year [1]. Studies on plate movements in the Java subduction zone were conducted by Hanifah et al. [2], who examined the movement of the West Java segment, while Koulali et al. [3] examined plate movements in the East Java segment. The results of GPS measurement were used to study the pattern and speed of changes of coordinates from measurement points. The results of these studies would be very useful for mapping segmentation in the Java subduction zone. This research is the application of previous research results through the utilization of segmentation map to search for the source parameter tsunami-earthquake in the subduction zone of Java.

The Java subduction zone is a potential source for tectonic earthquakes. Earthquakes occur due to the rupture or uplift of rocks in the friction area between plates. Earthquake magnitude is highly depended on the fault width and the size of elastic rebound. The wider the fault is ruptured, the greater the elastic rebound of the subduction zone and the greater the magnitude will be. An earthquake that
occurs at a subduction zone can cause seafloor vertical deformation (reverse fault or normal fault) and become a tsunami-generating source [4].

Based on the Wichmann catalog of earthquakes and tsunami and Tsunami catalog and zones in Indonesia, it is suspected that the southern coast of Java was once hit by a large tsunami with an affected area of more than 500 km [5]. Local tsunamis were also recorded in 1840 and 1859, both of which hit the southern coast of Java between Kebumen and Pacitan. The southern coast of Java island between Pangandaran and Parangtritis Beach was also hit by a tsunami in 1921. These records mentioned that such earthquakes only caused a small tsunami (<30 cm). This statement is also supported by Harris and Major [6], stating that large and shallow earthquakes (Magnitude ≥ 8) have not occurred in the past 160 years in the southsea of Java. The potential for a large earthquake in the southsea of Java was released by Pusgen [1] through the 2017 Earthquake Source and Hazard Maps of Indonesia. It is stated in the book that if all Java subduction zones are ruptured in a single event (length ± 1050 km and width ± 200 km), it can result in a great earthquake of magnitude 9.2.

The study of the earthquake magnitude potential based on fault geometry and focal mechanism is very closely related to scaling laws. Scaling laws are a comparison/proportion of earthquake-triggering parameters. Scaling laws are used to predict earthquake source models such as width and length of faults as well as earthquake magnitude [7]. The geometry of rupture dimensions such as width, length, etc., will be used as input needed by the earthquake source model as initial conditions in numerical modeling of tsunami [8]. The tsunami source area is considered to follow deformation plane, seafloor vertical fault in the form of vertical reverse fault or normal fault symbolized by dip-slip components. Seafloor reverse fault or normal fault results in raising and lowering sea water starting from the ocean floor to the sea level. The tsunami-generating source area is considered following changes in the fault plane that occurs at the seafloor. Changes in this fault area will interfere with the concentration of seawater, so that seawater will respond by raising and lowering seawater quickly and propagating. This study aims to assess the vertical deformation value of several earthquake magnitude scenarios in relation to fault geometry and fault parameters. It is expected that the results of this study can describe a tsunami height at the earthquake source and can be used as the initial conditions in tsunami modeling.

2. Methods

Subduction zone segmentation in this study was analyzed based on the calculation of seismicity which refers to the earthquake magnitude. Deformation that occurred was represented as the slip that could be calculated from seismic moments. A seismic moment is a quantity measured directly that shows the amount of energy released during an earthquake [9]. The stages to determine the deformation of the potential earthquake that may occur in the Java subduction zone are described as follows:

2.1 Study Area

The Java subduction zone is divided into three segments, namely Banten Sunda Strait (BSS) segment, West Java (WJ) segment and Central Java-East Java (CE) segment. The BSS segment is ± 280 kilometers long, while the WJ segment is ± 320 kilometers long, which was the location of the Pangandaran earthquake on July 17, 2006. The CE segment is located in the south of Central Java and Yogyakarta to East Java with a segment of ± 440 kilometers long, which was the source of the Banyuwangi Earthquake on June 3, 1994 [1]. Of the three segments, the WJ and CE segments have released their energy in large earthquakes accompanied by tsunamis. Based on the Seismicity Map in the CE segment, there are areas that earthquakes rarely occur, namely the southern region of Central Java and Yogyakarta (figure 1). An area in the subduction zone that rarely experiences tectonic earthquakes is called Seismic Gap. Such area is suspected of being storing energy, which will later be released in a huge earthquake.

2.2 Fault Parameters
In order to obtain the magnitude value of each segment, input was needed in the form of fault parameters and the width of the fault plane. The earthquake magnitude was determined based on the equations given by Kanamori and Anderson [9] and Hanks and Kanamori[10] (equations (1) and (2))

\[ M_0 = \mu A D \]  
\[ M_w = \frac{2}{3} \log M_0 - 10.7 \]

where \( M_0 \) = seismic moment, \( \mu \) = rock rigidity (Nm²), \( A \) = Area of fault plane (m²), and \( D \) = deformation/ dislocation (m), \( M_w \) = Magnitude.

The correlation of scales with lengths and widths of fault plane for strike-slip, thrust and reverse fault types was developed and updated by [11]. This study sought the correlation of scale to obtain the length and width of fault plane by analyzing 283 earthquakes in the world. The relationship of scale was analyzed through statistics using linear least squares method and orthogonal regression. The relationship between the fault plane and the magnitude at the subduction zone for the thrust fault type can be seen in the following equation [11]:

\[ \log L = 0.62 M_w - 2.81 \]  
\[ \log W = 0.45 M_w - 1.79 \]

2.3 Initial Model Scenarios

Scenarios for tsunami source modeling require data input in the form of lengths and widths of faults in the subduction zone boundary lines. The fault area in equation (1) can be adjusted according to the slip parameter (m), so that the relationship between the area of fault plane and slip is directly proportional and does not affect the seismic moment value. The parameters of tsunami source in this study use three magnitude scenarios, namely 8.9 Mw, 9.0 Mw, and 9.2 Mw with the area of fault plane based on Pusgen [1] and Blaser et al. [11].

The magnitude scenario employed calculation data from Pusgen for CE and BSS-CE segmentation, while WJ-CE segmentation was modified based on the existing data. The vertical deformation modeling employed a multifault system by dividing the fault into 3, 5 and 7 fault planes. The multifault model used fault planes which were divided into small fault planes in order to describe the entire fault planes. The epicenter of each fault plane was determined as the midpoint of the fault.
plane made. The determination of parameter values was calculated by using the scaling law table and the 2017 earthquake book using a square area. The use of a square area represents the area of the fault plane in the subduction zone. In its application, the area of the fault plane could be divided into smaller square areas or multifaults. Vertical deformation was modeled using a multifault model developed by Kongko and Schlurmann [8], which was also applied by Basit et al. [12] to model tsunami waves around the southern sea of Java. The fault parameters in this study consisted of epicenter coordinates, length, width of fault, depth, rigidity, strike, slip, dip and Du for each scenario. The results of the determination of fault parameters from each magnitude scenario were then inputted into the multi_deform program.

3. Results and Discussion
Numerical modeling of tsunami was used to reveal the effect of fault parameters on the propagation of tsunami waves from the earthquake source to the mainland. The parameters in the tsunami model represented factors that had a significant correlation with the phenomenon of tsunami wave propagation. The numerical tsunami model applies the theory of non-linear wave propagation in deep waters and shallow waters to seek flow velocities in the x and y (horizontal) direction, by taking the seafloor friction into consideration. The input parameters required for the source modeling of tsunami were in the form of rupture areas which were obtained through empirical calculations using Blaser’s equation [11] and seismic moments using Hank and Kanomari’s equation [9]. Data were processed using multi_deform which produced output in the form of vertical displacement values. This deformation modeling used two fault plane sources. The first source referred to the fault plane resulted from the Blaser’s equation and the second source referred to the fault plane resulted from the Pusgen’s calculation. The input parameters used in the two scenarios were based on equations (1) and (2). The output from the results of processing multi_deform could be used as an initial model in the tsunami propagation modeling. The initial model was used to determine the position of the earthquake source and the parameter values of tsunami-generating earthquake source. The initial model was determined by using six earthquake source scenarios which were a combination of Pusgen [1] and Blaser et al. [11]. The value of vertical deformation and the direction of fault plane in the area studied could be found out from the results of vertical deformation modeling. The calculation results of the initial model can be seen in table 1 and table 2.

| Magnitude | Epicenter (deg.) | Mag. (Mw) | Depth (km) | Strike | Dip | Slip | Dimension L (km) | Dimension W (km) | Diolc (m) | Rigidity (Gpa) |
|-----------|-----------------|-----------|------------|--------|-----|------|-----------------|-----------------|-----------|--------------|
| Mw. 8.9   | 107.4595        | -8.5854   | 8.5        | 26     | 293 | 12   | 90              | 120             | 180       | 11           | 30           |
|           | 108.6261        | -8.9549   | 8.5        | 28     | 290 | 12   | 90              | 120             | 180       | 11           | 33           |
| M 9.0     | 109.7821        | -9.1293   | 8.6        | 34     | 286 | 20   | 90              | 120             | 180       | 11           | 42           |
|           | 110.7014        | -9.2556   | 8.6        | 34     | 266 | 21   | 90              | 120             | 180       | 11           | 42           |
|           | 112.3113        | -9.3457   | 8.5        | 29     | 284 | 16   | 90              | 120             | 180       | 11           | 34           |
| Mw 9.2    | 106.6588        | -7.9494   | 8.6        | 31     | 304 | 13   | 90              | 112             | 220       | 10           | 37           |
|           | 107.6809        | -8.4531   | 8.6        | 32     | 294 | 14   | 90              | 112             | 220       | 10           | 39           |
|           | 108.6845        | -8.8141   | 8.6        | 32     | 291 | 14   | 90              | 112             | 220       | 10           | 39           |
|           | 109.7957        | -8.9898   | 8.7        | 41     | 288 | 23   | 90              | 112             | 220       | 10           | 53           |
|           | 111.0863        | -9.1512   | 8.7        | 40     | 265 | 23   | 90              | 112             | 220       | 10           | 52           |
Table 2. Source parameter tsunami-earthquake with fault dimensions from Pusgen

| Magnitude | Lon. | Lat. | Mag. (Mw) | Depth (km) | Strike | Dip | Slip | L(km) | W(km) | Disloc (m) | Rigidty (Gpa) |
|-----------|-----|-----|----------|-----------|--------|-----|------|-------|-------|------------|--------------|
| Mw 8.9    | 108.4177 | -8.8284 | 8.6 | 30 | 287 | 12 | 90 | 150 | 200 | 8 | 36 |
|           | 109.8489 | -9.0914 | 8.6 | 37 | 280 | 22 | 90 | 150 | 200 | 8 | 47 |
|           | 111.2394 | -9.3045 | 8.6 | 33 | 278 | 20 | 90 | 150 | 200 | 8 | 40 |
| Mw 9.0    | 107.1007 | -8.3867 | 8.5 | 27 | 291 | 12 | 90 | 150 | 200 | 7 | 31 |
|           | 108.4177 | -8.8284 | 8.5 | 30 | 287 | 12 | 90 | 150 | 200 | 7 | 36 |
|           | 109.8489 | -9.0914 | 8.6 | 36 | 280 | 22 | 90 | 150 | 200 | 7 | 45 |
|           | 111.2394 | -9.3045 | 8.5 | 32 | 278 | 20 | 90 | 150 | 200 | 7 | 39 |
|           | 112.6464 | -9.4927 | 8.5 | 29 | 282 | 17 | 90 | 150 | 200 | 7 | 34 |
| Mw 9.2    | 105.8247 | -7.6900 | 8.6 | 25 | 298 | 14 | 90 | 150 | 200 | 10 | 29 |
|           | 107.1007 | -8.3867 | 8.6 | 27 | 291 | 12 | 90 | 150 | 200 | 10 | 31 |
|           | 108.4177 | -8.8284 | 8.6 | 30 | 287 | 12 | 90 | 150 | 200 | 10 | 36 |
|           | 109.8489 | -9.0914 | 8.7 | 37 | 280 | 22 | 90 | 150 | 200 | 10 | 47 |
|           | 111.2394 | -9.3045 | 8.6 | 32 | 278 | 20 | 90 | 150 | 200 | 10 | 39 |
|           | 112.6464 | -9.4927 | 8.6 | 29 | 282 | 17 | 90 | 150 | 200 | 10 | 35 |
|           | 114.0083 | -9.7271 | 8.6 | 31 | 281 | 20 | 90 | 150 | 200 | 10 | 37 |

Source: Results of Analysis (2019)

All faults in tables 1 and 2 are located on the South of Java. The magnitudes in this study consisted of three variations, namely 8.9 Mw, 9.0 Mw and 9.2 Mw. The multifault system was used in determining the magnitude scenario. Epicenter was determined as the midpoint in the middle of the fault and in the subduction zone. The fault shape and location were visualized by using epicenter coordinates, rupture angles and dimensions. The visual description of making an initial model can be seen in Figure 2.
Figure 2. The visualization of rupture dimensions of six magnitude scenarios using multi_deform.

The results of deformation modeling are shown in Figure 3, which illustrates variations in the maximum and minimum values of vertical deformation of the six magnitude scenarios. Deformation movements occurring on the ocean floor will be followed by sea level movements. This means that the vertical deformation value reflects the water level at the beginning of the earthquake. The deformation value provides information that seawater around the earthquake source will rise as high as the maximum value above sea level and fall as low as the minimum value below sea level.
Figure 3. The cross-sectional rupture shape and position of a tsunami wave

Tsunami height at the sources is based on six scenarios as shown in figure 3, with a range of -2,154 m to 5,039 m. In detail, the results of tsunami height at the sources of the six scenarios can be seen in table 3. The highest scenario of sea level movement in the earthquake source area occurred during an earthquake with magnitude 9.0 with a fault area of 600 km x 180 km, with a range of values -2,074 m to 5,039 m. In this study, the highest maximum value was 5,039 m which was obtained from
the magnitude 9.0 Mw scenario based on the Blaser’s equation. Meanwhile, the lowest minimum value was -2.154 m which was obtained from the magnitude 9.2 scenario based on the Pusgen’s data. The tsunami height at the earthquake source would have an impact on the tsunami wave height on land because the tsunami height depends on bathymetry. According to Fauzi [13], the tsunami wave height of 5 meters in the deep sea (earthquake source) could develop to tens of meters on the coastline.

### Table 3. Comparison of Deformation Values between Blaser and Pusgen

| Mw | L  | W  | Depth | Deformation Value | Remarks |
|----|----|----|-------|-------------------|---------|
|    |    |    |       | Maximum | Minimum |           |
| 8.9| 510 | 160 | 31    | 4.123    | -1.908  | Blaser   |
|    | 450 | 200 | 37    | 3.517    | -1.426  | Pusgen   |
| 9  | 600 | 180 | 34    | 5.309    | -2.074  | Blaser   |
|    | 750 | 200 | 36    | 3.183    | -1.446  | Pusgen   |
| 9.2| 784 | 220 | 41    | 4.831    | -1.867  | Blaser   |
|    | 1050| 200 | 37    | 4.526    | -2.154  | Pusgen   |

Source: Results of Analysis (2019)

The maximum value of vertical deformation indicates the vertical movements of the rising ocean floor, while the minimum value of vertical deformation indicates the vertical movement of the falling ocean floor. The movement of the ocean floor deformation on the seafloor will be followed by sea level movements that follow the deformation of fault plane. This occurs because the vertical movement of the ocean floor results in changes in the mass of water above the moving ocean floor. If the ocean floor rises or falls rapidly in response to an earthquake, it will raise and lower sea water on a large scale, starting from the ocean floor to the surface.

The vertical value of the earthquake source deformation for each magnitude is different. Based on calculations for six earthquake scenarios, there was no correlation between magnitude, fault plane and vertical deformation value. In addition to the vertical deformation value, the direction of the fault plane occurs in the study area can also be seen that the direction of the fault plane in the Java subduction zone is moving to north-south. The data of direction of the fault plane at the time of the earthquake that has the potential for tsunami is a very useful information in the evacuation process of the tsunami disaster [4]. The fault surface can have different conditions and the movement can have different directions along the surface which is caused by vertically-experienced basic friction. The size of the strike value has a correlation with the fault direction. If this strike leads to an area with more shallow morphology, the value of the tsunami wave is higher. Meanwhile, if this strike direction leads to an area with deep seafloor morphology, the height of tsunami wave will be small.

### 4. Conclusion

The results of the fault plane calculation using an empirical approach can be used as input in the initial model for numerical modeling of tsunami. The calculation of vertical deformation values can indicate the movement of deformations on the ocean floor, and simultaneously reflects the sea level height around the earthquake source. The direction of the fault plane in the south sea of Java tends to move to the north-south, which is in line with the movement of the Indo-Australian plate that moves northward colliding with the Eurasian tectonic plate. In this study, the vertical deformation value is not correlated with the magnitude and area of the fault plane.
Acknowledgments

Authors would like to express their sincere gratitude to the Indonesia Endowment Fund for Education (LPDP), who have funded this study through the BUDI-DN scholarship scheme and the Laboratory for Harbor Infrastructure and Coastal Dynamics Technology, Agency for the Assessment and Application of Technology (BTIPDP-BPPT) which provided scaling law data and tsunami source modeling program.

References

[1] Pusgen 2017 *Peta sumber dan bahaya gempa bumi tahun 2017* (Bandung: Balitbang PUPR)
[2] Hanifah N R, Sagiya T, Kimata F, Efendi J, Abidin H Z and Meilano I 2014 Interplate coupling model off the southwestern coast of java, indonesia, based on continuous GPS data in 2008-2010 *Earth and Planetary Science Letters*.401 159
[3] KoulaLI A, McCluskyS, Susilo S, Leonard Y, CumminsP, Tregoning P, Meilanol, Efendi J and Wijanarto AB 2017 The kinematics of crustal deformation in java from GPS observations: implications for fault slip Partitioning *Earth and Planetary Science Letters*.458 69
[4] Khoiridah S and Santos B J 2014 Estimasi centroid moment tensor (CMT), bidang fault, durasi rupture, dan pemodelan deformasi vertikal sumber gempa bumi sebagai studi potensi bahaya tsunami di laut selatan java *J. Sains dan Seni Pomits*.3 2337
[5] Latief H, Puspito N TandI mamuraF 2000 Tsunami catalog and zones in indonesia, *J. of Natural Disaster Science*.22 25
[6] Harris R and Major J 2016 Waves of destruction in the east indies: the wichmann catalogue of earthquakes and tsunami in the indonesian region from 1538 to1877 *Geological Society*.4419
[7] Kase Y 2010 Slip-length scaling law for strike-slip multiple segment earthquakes based on dynamic rupture simulations *Bulletin of the Seismological Society of America*. 100473
[8] Kongko W and Schlurman T 2010 The java tsunami model: using highly-resolved data to model the past event and to estimate the future hazard *Proc.Int. Conf. on Coastal Engineering (Shanghai)* vol 32 p 1
[9] Kanamori H and Anderson DL 1975 Theoretical basis of someempirical relations in seismology *Bulletin of the Seismological Society of America*.65 1073
[10] Hanks T Cand Kanamori H 1979 Moment magnitude scale *J. of Geophysical Research*. 84 2348
[11] Blaser L, Krüger F, Ohrenberger M and Scherbaum F 2010 Scaling relations of earthquake source parameter estimates with special focus on subduction environment *Bulletin of the Seismological Society of America*.100 2914
[12] Basith A, Prakoso Y and Kongko W 2016 Model Validation and Error Estimation of Tsunami Runup Using High Resolution Data in Sadeng Port, Gunung Kidul, Yogyakarta *Proc. Int. Symp.on Earth and Disaster Mitigation (Bandung)* AIP-Publishing vol 1 p 090007-1
[13] Fauzi Y 2015 Aplikasi matematika dalam pemodelan risiko bencana tsunami *Proc. Seminar Nasional Matematika (Bandung): Unpar* vol10 p 32