Analysis of Tsunami Disaster Risk for a Petroleum Refinery Plant at Tsunami Prone Area

D C Istiyanto
d, W Kongko2, T Priambodo1, M Wibowo2, S Nugroho1, C Murtiaji2, H Azis2, E Kustiyanto2, M Irfani2

1 Center of Technology for Maritime Industrial Engineering, Agency for the Assessment and Application of Technology, Tech. Bldg#2 PUSPIPTEK, Setu Tangerang Selatan 15314 - Indonesia
2 Port Infrastructures and Coastal Dynamic Technology Laboratory, Agency for the Assessment and Application of Technology, Jl Grafika 2 Sekip, Yogyakarta 55281 - Indonesia
Corresponding author: dinar.catur@bppt.go.id

Abstract. A Petroleum Refinery Plant is located in the tsunami prone area at the southern coast of Central Java, Indonesia. The potential mega thrust earthquake, along subduction zone of southern coast of Java, has been identified to have moment magnitude as maximum as Mw = 8.7. The worst scenario due to this earthquake will potentially generate 5.3m to 8.6m tsunami height along the coast within 30 minutes and will inundate one to two kilometres inland of the refinery area. In this regard, a comprehensive investigation on potential tsunami hazard, level of vulnerability, and tsunami risk potential were carried out. The investigation includes collection and analysis data of detailed topography, bathymetry, land covering and land use, availability of protective structure as well as disaster contingency plan, field ground check data verification, awareness questionnaire, etc. The investigation output includes numerical tsunami inundation simulation, tsunami hazard index, vulnerability index, capacity index, and tsunami risk index for all area of refinery unit. It is concluded that: 1) the main location of refinery complex with considerable numbers of tanks is vulnerable to high tsunami hazard index, and 2) the capacity index in all area are mostly between low to mid-level.

1. Introduction
A Petroleum Refinery Plant is located in the tsunami prone area at the southern coast of Central Java, Indonesia. The potential mega thrust earthquake, along subduction zone of southern coast of Java, has been identified to have moment magnitude as maximum as Mw = 8.7[1]. The worst scenario due to this earthquake will potentially generate 5.3m to 8.6m tsunami height along the coast within 30 minutes and will inundate one to two kilometres inland of the refinery area. In the above regard, a comprehensive investigation on potential tsunami hazard, level of vulnerability, and tsunami risk potential were carried out. The investigation includes collection and analysis data of detailed topography, bathymetry, land covering and land use, availability of protective structure as well as disaster contingency plan, field ground check data verification, awareness questionnaire, etc. The investigation output includes numerical tsunami inundation simulation, tsunami hazard index, vulnerability index, capacity index, and tsunami risk index for all area of refinery unit. Figure 1 shows the location map of the Petroleum Refinery Plant and the potential tsunami inundation map on the related area [2].
2. Tsunami risk assessment

The assessment of potential tsunami disaster risk is calculated based on hazard factors, vulnerability factors and capacity factors as follows [3, 4]:

\[ R \approx H \times \frac{V}{C} \] (1)

where \( R \) is disaster risk, \( H \) is hazard threat, i.e. the frequency (probability) of a certain hazard tends to occur with a certain intensity at a certain location, \( V \) is vulnerability, i.e. the expected loss (impact) in a certain area in the case of a particular disaster occurs with a certain intensity, and \( C \) is adaptive capacity, i.e. the available capacity to escape and recover from certain disaster.

The hazard threat component is compiled based on the intensity and probability of occurrence parameters. The vulnerability components are arranged based on socio-cultural, economic, physical and environmental parameters. The capacity component is prepared based on the parameters of regulatory capacity, institutions, warning systems, skills training education, mitigation and preparedness systems.

For the generation of a tsunami risk map, it needs to modify equation (1) to be in the form of equation (2) based on practical considerations of application. Multiplication with an inverse capacity \((1 - C)\) is performed rather than division by \( C \) to avoid high values in the extreme case of low \( C \) values or errors in the case of empty \( C \) values. Further, correction is applied to the result of the multiplication index by using the powers of \( 1/n \) to retrieve its original dimension, e.g. \((0.25 \times 0.25 \times 0.25 = 0.015625,\) corrected to be: \(0.015625^{1/3} = 0.25\)). Accordingly, the equation become:

\[ R = \sqrt[3]{H \times V \times (1 - C)} \] (2)

The Disaster Risk Map development flowchart is illustrated in figure 2 [4]. As shown in figure 2, the Tsunami Risk Map is an overlay of the Hazard Map, Vulnerability Map and Capacity Map. These maps are generated based on the calculation of various relevant indices data which will be described in the following related sections.

2.1. Tsunami hazard analysis

The magnitude of tsunami hazard is determined based on the agreed scenario. The scenario is based on historical data of earthquakes and tsunamis events in the southern coast of Java, the magnitude of potential earthquake and tsunami sources, various types of tsunami generation mechanisms and analysis results from earthquake and tsunami experts.

2.1.1. Earthquake magnitude and parameters for tsunami generation

Determination of the earthquake magnitude refers to the recent study [1] which indicates the accumulation of energy due to locks in the two colliding plates (Australia - Java). If the energy accumulates over 300 years, the energy released will be equivalent to Mw 8.7, which can either be
released gradually or become a big earthquake at the same time. Figure 3(a) shows the plate movements recorded in cGPS for 3 years (2008 - 2010) [1].

Earthquake parameters data include the position of epicenter, depth, angles of the earthquake mechanism (angle of strike, dip, slip/rake), length and width of the fault and dislocation. The slab data from the USGS (United States Geological Survey) is used to determine the angles of the earthquake mechanism. A presentation image of strike, dip, slip data from the USGS slab data for the southern location of Java Island is presented in figure 3(b) [5]. Based on this analysis, the southern zone of Java has a potential earthquake moment magnitude of Mw = 8.7.

Determination of the fault length and width parameters as well as the magnitude of earthquake dislocation is based on the theory and formulas (scaling law) from Wells and Coppersmith [6] for Mw = 8.7. Based on the analysis results, twelve earthquake scenarios were setup, i.e. 6 scenarios with a depth of 30 km and 6 scenarios with a depth of 40 km as listed in Table 1. The location points of these scenarios is shown in figure 4(a). Numerical deformation model were then run to get initial conditions for the rise and fall of the water level as shown for example in figures 4(b) and 4(c) for Scenario-3 and Scenario-9 respectively.

**Table 1. Twelve tsunami modelling scenarios in the present study**

| Scenario | Lon (°E) | Lat (°S) | Depth (Km) | Strike (Deg) | Dip (Deg) | Slip (Deg) | L (Km) | W (Km) | D (m) |
|---------|---------|---------|------------|-------------|-----------|------------|-------|-------|-------|
| 1       | 108.538416 | -8.513342 | 40         | 295.318     | -18.528   | 90         | 420   | 90    | 12.3  |
| 2       | 108.684372 | -8.553634 | 40         | 290.913     | -18.335   | 90         | 420   | 90    | 12.3  |
| 3       | 108.802832 | -8.588166 | 40         | 291.652     | -18.502   | 90         | 420   | 90    | 12.3  |
| 4       | 108.915078 | -8.631722 | 40         | 292.244     | -18.558   | 90         | 420   | 90    | 12.3  |
| 5       | 109.036514 | -8.675137 | 40         | 292.763     | -19.269   | 90         | 420   | 90    | 12.3  |
| 6       | 109.175137 | -8.736158 | 40         | 293.941     | -19.719   | 90         | 420   | 90    | 12.3  |
| 7       | 108.325064 | -8.820086 | 30         | 292.373     | -12.005   | 90         | 420   | 90    | 12.3  |
| 8       | 108.476072 | -8.884924 | 30         | 291.988     | -11.869   | 90         | 420   | 90    | 12.3  |
| 9       | 108.637152 | -8.926214 | 30         | 291.027     | -12.239   | 90         | 420   | 90    | 12.3  |
| 10      | 108.795930 | -8.975810 | 30         | 290.286     | -12.591   | 90         | 420   | 90    | 12.3  |
| 11      | 108.952117 | -9.012558 | 30         | 289.915     | -12.93    | 90         | 420   | 90    | 12.3  |
| 12      | 109.130262 | -9.038909 | 30         | 289.234     | -14.15    | 90         | 420   | 90    | 12.3  |

Comparison of simulation results of tsunami height along the coast revealed that Scenario-3 (representing the 40 km depth) and Scenario-9 (representing the 30 km depth) are representing the two worst-case scenarios among twelve. In the further discussion, Scenario-3 and Scenario-9 will be referred as Scenario-1 and Scenario-2, respectively.

The initial deformation models for both scenarios are derived from preliminary calculations which show that the fault length is 420 km. By considering the subduction line in South Java, the continuous
fault length of 420 km is not naturally suitable. Therefore, the adjustment approach is carried out by dividing the fault path of each scenario into 3 segments to naturally fit the subduction path. Table 2 and table 3 show the earthquake parameters of the two generation scenarios with 3 fault segments each.

Figures 4. (a) Location points of twelve earthquake scenarios; (b) initial rise and fall of the water level for scenario-3; (c) initial rise and fall of the water level for scenario-9

| Fault | Epicentre Lat | depth (km) | Strike (deg) | Dip (deg) | Slip (deg) | L (km) | W (km) | D (m) |
|-------|---------------|------------|--------------|-----------|------------|--------|--------|-------|
| 1     | 107.472       | 30.087     | 298          | 13.4      | 90         | 140    | 90     | 12    |
| 2     | 108.669       | 27.815     | 291          | 11.8      | 90         | 140    | 90     | 12    |
| 3     | 109.957       | 27.342     | 280          | 19.2      | 90         | 140    | 90     | 12    |

| Fault | Epicentre Lat | depth (km) | Strike (deg) | Dip (deg) | Slip (deg) | L (km) | W (km) | D (m) |
|-------|---------------|------------|--------------|-----------|------------|--------|--------|-------|
| 1     | 107.561       | 43.11      | 295.7        | 20.8      | 90         | 140    | 90     | 12    |
| 2     | 108.772       | 40.95      | 291.2        | 18.7      | 90         | 140    | 90     | 12    |
| 3     | 110.045       | 47.45      | 285.5        | 26.5      | 90         | 140    | 90     | 12    |

2.1.2. Simulation and inundation map of tsunami

The earthquake parameter data in table 3 and table 4 were input for calculating the sea floor deformation which will generate sea level rise and fall. The method used in this calculation is the method of Mansinha and Smylie [7]. The results of this calculation were used as the initial conditions for wave propagation simulation using the TUNAMI software.

The present tsunami hazard simulation assumed the worst scenario in which tsunami occurs when the tidal conditions at the highest elevation and the highest wave (wave setup). In accordance with this assumption, a constant of 1.5 m is added to the initial height of the generating tsunami. Figure 5 shows the initial sea level conditions due to earthquake parameters in Scenario-1 and Scenario-2.

Figure 5. The initial sea level conditions due to earthquake parameters in (a) Scenario-1 and (b) Scenario-2
For the purposes of a tsunami hazard assessment, tsunami inundation depth data are required and displayed in the form of tsunami inundation map. This tsunami inundation map informs the tsunami elevation above the ground level. The inundation map of Scenario-1 and Scenario-2 are presented in figure 6(a) and 6(b) respectively. It appears that Scenario-2 generated greater area and depth of inundation and accordingly this is used as the basis for the development of Tsunami Hazard Map and Risk Map. The detail tsunami inundation map of Scenario-2 is shown in figure 6(c).

![Figure 6](image)

**Figure 6.** Tsunami inundation map based on (a) Scenario-1 and (b) Scenario-2; (c) detail tsunami inundation map of Scenario-2 around the Petroleum Refinery Plant area

### 2.1.3. Tsunami Hazard Index and Tsunami Hazard Map

Tsunami Hazard Index is determined related to the tsunami inundation map according to the classification available in [4]. The classification of tsunami hazard index is shown in table 4. The Tsunami Hazard Map is drawn based on the tsunami inundation map and classification of the tsunami hazard index. Figures 7 shows tsunami hazard maps of the Petroleum Refinery area which consists of Area 70 and Lomanis area.

| Hazard | Component/Indicator | Index Classification | Total Weight | References |
|--------|---------------------|----------------------|--------------|------------|
| Tsunami | Tsunami Inundation Map/ Tsunami Hazard Map | (< 1m) (1-3 m) (>3m) | 100% | Guideline from Badan Geologi Nasional-ESDM and BMKG |

![Table 4](table)

**Table 4.** Tsunami Hazard Index [4]

![Figure 7](image)

**Figure 7.** Tsunami Hazard Map of Area 70 Plant (left) and Lomanis Area Plant

### 2.2. Vulnerability analysis

Vulnerability is dependent on social, economic, physical and ecological factors or processes that resulted in the level of potential losses under the hazard [8]. It is defined as the product of exposure factor and sensitivity factor (=Exposure×Sensitivity). The exposed assets include human life (social vulnerability), economic area, physical structure and ecological areas. Each asset has its own sensitivity, which varies
per disaster (and intensity of disaster). The indicator used in the vulnerability analysis is mainly exposure information. In case of two or more information are available, the weighting factors are applied to compose the sensitivity factor. See figure 8.

![Figure 8](image)

**Figure 8.** (a) The graphic diagram of vulnerability components and its related weighing factor [4]; (b) the classification score for each main component of vulnerability [8]

### 2.2.1. Exposed population

The indicators used for exposed population include population density, sex ratio, poverty ratio, disability ratio and age group ratio. The exposed population vulnerability index is the product of the average population density weight (60%) and the vulnerable group (40%) which consists of sex ratio (10%), poverty ratio (10%), disability ratio (10%) and age group (10%). The index conversion parameters are shown in table 5 [4].

| Parameter                | Weighting (%) | Rank (population/km2) | Score         |
|--------------------------|---------------|------------------------|---------------|
| Population Density       | 60            | < 500                  | 0.4           |
| Gender ratio (10%)       | 40            | < 20%                  | 0.1           |
| Poverty ratio (10%)      |               | 20 - 40%               | 0.2           |
| Disability ratio (10%)   |               | > 40%                  | 0.3           |
| Age group ratio (10%)    |               |                        |               |

The exposed population index is calculated by using the following formula [4]:

\[
Exp. Pop. Index = 0.6 \times \frac{\log(Pop_{/0.01})}{\log(100_{/0.01})} + (0.1 \times Gen) + (0.1 \times Pov) + (0.1 \times Dif) + (0.1 \times Age)
\]

### 2.2.2. Economic losses component

The indicators for economic losses analysis include the value of productive land (e.g. rice fields, plantations, agricultural land and ponds) and Gross Regional Domestic Product (GRDP) value. Economic losses index conversion parameters related to tsunami disaster are shown in table 6[4].
The economic losses index is calculated by using the following formula:

\[
Economic \, losses \, index = (0.6 \times \text{Prod land score}) + (0.4 \times \text{GRDP score})
\]  

(4)

2.2.3. Structural component
The indicators used for structure index analysis include average density of house (permanent, semi-permanent and non-permanent), public buildings / facilities and vital facilities. The density is obtained by division of the built-up area by village or land total area (in ha). The economic value of structure component is then multiplied by the relevant unit price. The structure index conversion parameters for the tsunami hazard are shown in table 7.

| Parameter         | Weighting (%) | Classification (million) | Score         |
|-------------------|---------------|--------------------------|---------------|
| Residential Bld.  | 40            | < 400 million            | 400–800 million | > 800 million | Rank score/Rank max score |
| Public Facilities | 30            | < 500 million            | 500–1000 million | > 1000 million | score/Rank max score |
| Vital Facilities  | 30            | < 500 million            | 500–1000 million | > 1000 million | max score |

The Structural Index is calculated by using the following formula:

\[
Struct. \, Index = (0.4 \times \text{Resd Bld score}) + (0.3 \times \text{Pub Fac score}) + (0.3 \times \text{Vital Fac score})
\]  

(5)

2.2.4. Ecological damage component
The indicators used for ecological damage index analysis include land cover (e.g. sanctuary forest, natural forest, mangrove forest, swamps and shrubs). The ecological damage index is obtained from the average density of land cover. The conversion parameters of the ecological damage index are combined through the weighting factors shown in table 8.

| Parameter     | Weighting (%) | Classification (Ha) | Score         |
|---------------|---------------|---------------------|---------------|
| Sanctuary Forest | 30            | < 20                | 20 -50        | > 50          | Rank score/Rank max score |
| Natural Forest  | 30            | < 25                | 25 -75        | > 75          | score/Rank max score |
| Mangrove Forest | 40            | < 10                | 10 – 30       | > 30          | max score |

The Ecological Damage Index is calculated by using the following formula:

\[
Ecol \, Dmg \, index = (0.3 \times \text{Sanct score}) + (0.3 \times \text{Nat Frs score}) + (0.4 \times \text{Mangr Frs score})
\]  

(6)

2.2.5. Total Vulnerability Index
Total vulnerability index is the product of social (exposed population), economic (economic losses), physical (structural) and environmental (ecological damage) indices. Total vulnerability index is calculated by using the following formula:

\[
Total \, Vulnerability \, Index = (0.4 \times \text{Population Exposure}) + (0.25 \times \text{Economical Losses}) + (0.25 \times \text{Structure Damage}) + (0.1 \times \text{Ecological Damage})
\]  

(7)
The calculation results of total vulnerability score are classified into 3 levels as shown in table 9.

**Table 9. Total Vulnerability Index Classification**

| No. | Vulnerability Level | Total Score |
|-----|---------------------|-------------|
| 1.  | Low                 | < 0.33      |
| 2.  | Mid                 | 0.33 – 0.66 |
| 3.  | High                | 0.66 – 1.00 |

2.2.6. *Vulnerability analysis result of the Petroleum Refinery Plant*

Under consultation and discussion with the Plant Management, the population density is classified into Low (< 5 people/ha), Medium (5-10 people/ha), and Height (> 10 people/ha). Further, the vulnerable group at work location is counted for 5% and the number of worker at the refinery plant are counted for 75% of total. Whereas, the contribution to GRDP in the Area 70 and Lomanis Area are far above Rp. 300,000,000. Related to structural component, the value/price per m² of residential buildings were calculated based on the building condition. Public facilities occupancy are assumed to be 10% of total area and priced at Rp. 500,000/m². Vital facilities include hospital buildings, plant area and petroleum tanks. Buildings in the plant area are priced at Rp. 6,000,000 per m², whereas the value of petroleum tanks were classified as Big tank (diameter > 60 m) = Rp. 40,000,000,000, Medium tank (diameter 30–60 m) = Rp. 25,000,000,000, and small tank (diameter < 30 m) = Rp. 15,000,000,000. The ecological damage was not considered in the present assessment since there are no sanctuaries, natural as well as mangrove forests in the Refinery Plant area. Figure 9 shows the result of vulnerability index map of Area 70 Plant, which is classified to be at mid vulnerability level, whereas figure 10 shows the vulnerability index map of Lomanis Area Plant which also classified at mid vulnerability level.

![Figure 9. Vulnerability index map of area 70 plant](image1)

![Figure 10. Vulnerability index map of Lomanis Area Plant](image2)
2.3. Capacity analysis
Capacity index was calculated based on the measurement of preparedness indicators quoted from the Hyogo Framework for Actions [9]. Based on the measurement of the preparedness indicators, the final assessment result will provide five qualification levels of preparedness, from the lowest Level#1 to the highest Level#5.

The measurement of preparedness indicators was carried out by using a set of Questionnaire [9] that totally contains 88 questions, which consist of 22 sections based on indicators of HFA achievement, each of which requires 4 questions to determine the level of achievement. The qualification of Capacity Index is shown in table 10.

2.3.1. Selection of respondent
Eight sampling respondents were selected from each plant location in consultation with the Plant management. These respondents represent various positions. In more detail, the respondent positions in each plant location are informed in table 11.

| Component/Indicators                                      | Classification | Total Weight |
|-----------------------------------------------------------|----------------|--------------|
| 1. Regulations and Institutions for Disaster Management   |                |              |
| 2. Early Warning and Disaster Risk Assessment             |                |              |
| 3. Disaster Education                                     |                |              |
| 4. Reduction of Basic Risk Factors                        |                |              |
| 5. Development of Preparedness on all fronts              |                |              |
| Preparedness Level 1 and Level 2                          |                |              |
| Preparedness Level 3                                      |                |              |
| Preparedness Level 4 and Level 5                          |                | 100%         |

2.3.2. Calculation of capacity index
Based on the Questionnaire result, all respondents’ score are summed for each location and divided by the number of respondents in the related location to get average score for this location. This average score is correlated to the predetermined range of score to get the relevant rank of Capacity Index [10]. The correlation of predetermined range of score with the rank of Capacity Index is depicted in table 12.
Table 12. Classification of Capacity Index [10]

| Score range | Capacity Index |
|-------------|----------------|
| 85.1 – 100  | 5              |
| 70.1 – 85   | 4              |
| 55.1 – 70   | 3              |
| 35.1 – 55   | 2              |
| ≤35         | 1              |

The calculation of capacity index resulted an average score of 69.46 for Lomanis Area and 69.83 for Area 70, means that both are classified in the Mid Preparedness Capacity Level.

2.4. Tsunami risk map

The Tsunami Risk Map in figure 11 is an overlay of the Hazard Map, Vulnerability Map and Capacity Map where the calculation of the combined risk value of the components of hazard, vulnerability and capacity is obtained from the calculation using the available formulation. Based on this Tsunami Risk Map it can be summarized that for the location of Area 70, all of their areas fall into the medium risk category, whereas the location of Lomanis Area is divided into two risk categories, namely no risk area and area with medium risk level.

Figure 11. Tsunami Risk Maps for Area 70 (left) and Lomanis Area (right).

3. Conclusion

The simulation results of tsunami wave propagation show that the tsunami waves begin to reach the coast in about 30 minutes and reach the highest peak of waves approximately 40 minutes after earthquake generation, with tsunami height along the coast ranging from 5m to by 9m. The present analysis concluded that for the case of worst scenario caused by an earthquake of Mw = 8.7 that occurred in the subduction zone of South Java, with a depth of 40 km and when the sea level is at the highest tide and during the wave setup, there is a potential medium tsunami risk to the Petroleum Refinery Plant under consideration.

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