Scenario-Based Tsunami Hazard Assessment For Java (Sunda) Trench Using Monte Carlo Simulations

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ABSTRACT

Java (Sunda) trench lying along the eastern and southern coasts of Indonesia is one of the world's most active seismic zone. Java (Sunda) trench experienced devastating earthquakes and tsunamis throughout history. Despite the fact that about 14 years have passed since the 2004 Indian Ocean earthquake and tsunami, the seismic activity in this region is still intense. Thus, reliable estimation of the associated hazard of a possible large earthquake that can generate tsunami is vital for designing early warning systems, site selection of future critical infrastructures (CIs) and planning necessary mitigation measures for existing CIs and critical regions (CRs). Therefore, Scenario-based Tsunami Hazard Assessment (STHA) is performed for this region in this study. Historical earthquake data is compiled using ISC-GEM Global Instrumental Earthquake Catalogue for the region. Monte Carlo (MC) simulation method is used to generate random earthquake source parameters (i.e. magnitude, focal depth) along Java (Sunda) trench. The worst-case scenario among MC runs is selected and simulated using NAMI-DANCE tsunami simulation software. Critical Regions (CRs) and Critical Infrastructures (CIs) are identified and spatial distribution of the inundation levels along the eastern and southern coastline of Sumatra and Java Islands, focusing on these CRs and CIs is determined. It is observed that some of the CRs and CIs are vulnerable to potential high-risk tsunamis.

Keywords: Scenario-based tsunami hazard assessment; Monte Carlo; NAMI-DANCE; Critical regions; Critical Infrastructures

Monte Carlo Simülasyonu Kullanılarak Java (Sunda) Fay Hattı için Senaryo Bazlı Tsunami Tehlike Analizi

ÖZET

Endonezya'nın doğu ve güney kıyıları boyunca uzanan Java (Sunda) fay hattı dünyadaki en aktif sismik alanlardan biridir. Tarih boyunca Java (Sunda) fayında yıkıcı depremler ve tsunamiler oluşmuştur. 2004 Hint Okyanusu depremi ve tsunamisinin üzerinden 14 yıl geçmiş olmasına rağmen bu bölgedeki sismik aktivite hala yoğun bir şekilde devam etmektedir. Erken uyarı sistemlerinin yerleştirilmesi, gelecekteki yapıların lokasyonlarının belirlenmesi ve mevcut kritik yapılar ve bölgeler için risk azaltıcı önlemlerin alınması gibi konular için güvenilir bir tsunami tehlike analizi yapılması hayati önem taşımaktadır. Bu kriterler göz önüne alınarak bu çalışmada senaryo bazlı tsunami tehlike analizi (STHA) çalışılmıştır. Tarihsel deprem verisi ISC-GEM Küresel Deprem Kataloğundan derlenmiştir. Java (Sunda) fayı boyunca rastgele deprem verisi (magnitüt ve fokal derinlik) üretmek için Monte Carlo (MC) simulasyonu kullanılmıştır. Üretilen veriden en kötü senaryo seçilmiş ve NAMI-DANCE yazılımı kullanılarak tsunami simulasyonu yapılmıştır. Belirli kritik bölgeler ve altyapılar için tsunami dalga yükseklikleri belirlenmiş ve su altında kalan bölgeler ArcGIS programı kullanılarak gösterilmiştir. Bazı kritik bölge ve altyapıların yüksek seviyede risk potansiyeli taşıdığı belirlenmiştir.

Anahtar Kelimeler: Senaryo bazlı tsunami tehlike analizi, Monte Carlo, NAMI-DANCE, Kritik bölgeler, Kritik Altyapılar

1. INTRODUCTION

Tsunami hazard assessment (THA) has been a major concern in the scientific community over the last two decades (Yalciner et al., 2004; González et al., 2009; Knighton and Bastidas, 2015). THA provides information on potential places to be inundated by tsunami for a specified region. THA studies has been conducted on multiple levels including investigation of historical tsunami events, numerical modelling of the historical and probabilistic events with wide-ranging aspects, and worst case scenarios for different locations and sources. As an example, Strunz et al., (2011) performed an investigation about tsunami hazard assessment in the framework of the German Indonesian Tsunami Early Warning System (GITEWS). The method was applied for the coastal areas of Southern Sumatra, Java and Bali. A comprehensive people-centered tsunami hazard assessment and disaster risk reduction analysis were implemented to develop a scientific and technical approach for tsunami risk assessment. Following components was investigated to evaluate the risk.

- Hazard Assessment – provides information about the geographical extent of inundation and the probabilities that these areas are likely to be affected.
- Vulnerability Assessment – provides information about the losses and damages with respect to social, economic and environmental aspects.
- Preparedness Assessment – characterizes possible limitations which inhibit the community to respond adequately and efficiently.

Another study was performed by Hancilar (2012) to investigate the social and physical aspects of the risk for a possible tsunami for Istanbul. Probabilistic tsunami hazard assessment (PTHA) was carried out for the city to identify the physical and social elements at risk. For this purpose, tsunamigenic seismic sources were investigated for the North Anatolian Fault branch lying under the Marmara Sea. Tsunamigenic seismic zone maps and geographical information for both Turkey and Marmara Sea region were presented. PTHAs were conducted based on the results of the project entitled "Simulation and Vulnerability Analysis of Tsunamis Affecting the Istanbul Coasts" performed by OYO Co. (2007) for Istanbul Metropolitan Municipality. For this project, 42 tsunami simulations were performed to generate $>M_w 7$ earthquake. Built environment was classified depending on building attributes (e.g. construction material, number of storey, and usage type). Critical infrastructures like piers, ports, oil stations etc. were also taken into account to define elements at risk along the coastline. After conducting number of PTHAs for Istanbul, it was concluded that western coasts are less risky than the eastern coastlines.

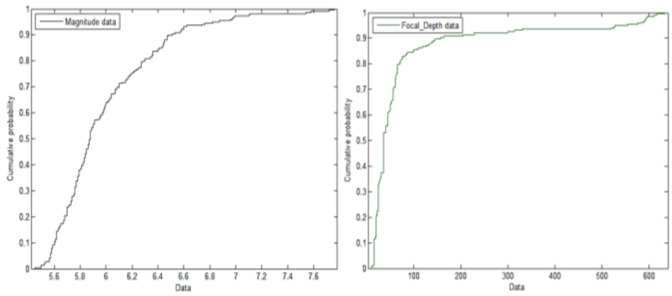
In this study, STHA is conducted for southern coasts of Indonesia (i.e. Java, Bali, and Lombok Islands). Random data is generated considering the independent parameters of earthquake (i.e. moment magnitude, focal depth) using Monte Carlo simulation method. The worst-case scenario is identified and simulated for the study area and inundation levels for 14 different locations which contains Critical Regions, CRs, and Critical Infrastructures, CIs, are mapped.

2. MATERIAL and METHOD

2.1 Monte Carlo Simulation Method

Monte Carlo Simulation method is used to generate random data for the independent parameters (i.e. magnitude and focal depth) of the earthquake source. The application of the simulation is based on the following steps:

1. 219 historical earthquakes are selected for the study area (i.e. Sunda Trench) from ISC-GEM earthquake catalogue which contains more than 20000 earthquakes observed within 110 years for the period of 1900 – 2009 (Storchak et al., 2013).
2. Cumulative Distribution Functions, CDFs, of the independent data (i.e. magnitude and focal depth) are determined (see Figure 1).



(a) (b)

Figure 1. CDF of the historical data for (a) magnitude and (b) focal depth

1. Kolmogorov-Smirnov goodness-of-fit test is applied for different type of distributions.
2. The best distribution is fitted for the historical data.

Random data is generated from the assigned distributions for moment magnitude and focal depth.

2.2 Earthquake Source Generation

Generation of earthquake source is one of the significant stages for spatial analysis of inundation in the study area. Earthquake source parameters are listed in Table 1.

Table 1. Earthquake Source parameters

Moment magnitude, M_w	: (Dimensionless)
Focal Depth	: (km)
Seismic moment, M_0	: Nm (or Dyne-cm)
Shear modulus of the crust, μ	: ($3 * 10^{11}$ dyne/cm^2)
Fault length, L	: (km)
Fault width, W	: (km)
Displacement, D	: (m)
Strike Angle	: (In degree)
Dip Angle	: (In degree)
Rake Angle	: (In degree)
Longitude	: (In degree)
Latitude	: (In degree)

Moment magnitude,M_w and focal depth are independent parameters of the source. Seismic moment is a function of the shear modulus of the crust, fault length, fault width and displacement. The angles are directly dependent on the fault attributes.
Earthquakes also were classified depending on whether they occured within an active plate margin or a stable continental region. Hanks and Kanamori (1979) mentioned that seismic moment, M_0 demonstrates the relationship between the source parameters and earthquake size. For crustal faults, seismic moment can be formulated as (Hanks and Kanamori, 1979):

$$M_0 = \mu LWD \quad (1)$$

There is also a physically meaningful relationship between the seismic moment and the moment magnitude of an earthquake and it is formulated (Hanks and Kanamori, 1979) as:

$$M_w = {}^{2}/_{3} * \log(M_0) - 10.7 \quad (2)$$

In the literature, it is known that earthquake magnitude is correlated with the rupture length. Lower bound of the moment magnitude, M_w, was set at 4.7 to refrain from the aftershocks for the regressions on surface rupture length and rupture area (Wells and Coppersmith, 1994). Wells and Coppersmith (1994) compared the rupture length values with the measured ones by inspecting the maps and figures. As the magnitude of the earthquake increases, surface rupture length is more reliable than the subsurface rupture length. The earthquakes for regression analyses depending on the surface rupture lengths if the following criteria are satisfied (Wells and Coppersmith, 1994):

- Rupture length uncertainity should not exceed 20% of the average total length.
- There should be at least one estimation about the surface displacement.
- Rupture length of multiple earthquakes should be known.

Displacement is generally poorly documented for many earthquakes contrary to the available information on surface rupture length. However, field researches and theorotical investigations of seismic moment show that there should be close correlation between the magnitude and displacement along the ruptured fault. To generate a regression analyses related to displacement, major sources of uncertainities and assessment of some criteria on historical data was investigated in detail.

Wells and Coppersmith (1994) performed some studies on empirical relationships among the compiled earthquake source parameters like seismic moment, M_0, moment magnitude, M_w, fault length, L, fault width, W, and average surface displacement, D, for global historical earthquakes. Historical earthquake data was inspected and divided as reliable and unreliable by Wells and Coppersmith (1994). 244 historical earthquakes which have reliable data for all source parameters from a data base were inspected in order to develop some empirical relationships among different source parameters. The following empirical relationships were generated by Wells and Coppersmith, (1994), and obtained from the regression analyses of the real data examined in detail and used to calculate the source parameters which will be performed to generate simulations of the earthquakes in this study. Equation 3 shows the regression of fault length, L, on magnitude M_w (Wells and Coppersmith, 1994).

$$M_w = 4.38 + 1.49 * \log(L) \quad (3)$$

Equation 4 shows the regression of fault width, W, on magnitude M_w (Wells and Coppersmith, 1994).

$$M_w = 4.06 + 2.25 * \log(W) \quad (4)$$

In this study, M_w and focal depth are randomly selected from the data generated with Monte Carlo Simulation method. L , W, and D is calculated using the empirical equations provided in the literature. Longitude, latitude, strike angle, dip angle, and rake angle are randomly selected from historical earthquake database compiled for Java (Sunda) trench.

2.3 Inundation Computations

Different numerical models have been generated for tsunami simulations since 1960's. Some of the most commonly used Tsunami modelling software are TUNAMI N1 (Imamura, 1995), MOST (Titov, 1999), NAMI DANCE (Zaytsev and Yalçıner, 2006) and SIFT (NOAA, 2015). In this study, NAMI-DANCE is used to simulate tsunamis originating in the selected area. NAMI-DANCE uses finite difference method to solve non-linear shallow water wave equations to analyze and compute generation, propagation and amplification of selected tsunamis depending on the source parameters using seismic source characteristics. The model computes all components of tsunamis in shallow waters and the inundation zones in specified region.

NAMI-DANCE runs the shallow water equations which are bounded with sea surface and the bottom topography. Shallow water equations precisely describe the tsunami propagation with long wave assumption (Segur, 2007). The long wave assumption can be described as a wavelength, L_w, sufficiently long as compared with the water depth, h_w : $L_w >> h_w$.

In order to derive the shallow water equations, global conservation of mass should be considered. Continuity equation should be satisfied for all conditions.

$$\frac{\partial \eta}{\partial t} + \frac{\partial \eta u}{\partial x} + \frac{\partial \eta v}{\partial y} = 0 \tag{5}$$

where η is the vertical free surface displacement, t is time and u, v are the velocity components.

Assuming that there is no vertical velocity variations and vertical pressure gradients are nearly hydrostatic, the momentum equations and continuity equation of shallow water condition can be written as (Segur, 2007):

$$\frac{\partial \eta u}{\partial t} + \frac{\partial}{\partial x}\left(\eta u^2 + \frac{1}{2} g \eta^2\right) + \frac{\partial \eta u v}{\partial y} = 0 \tag{6}$$

$$\frac{\partial \eta v}{\partial t} + \frac{\partial \eta u v}{\partial x} + \frac{\partial}{\partial y}\left(\eta v + \frac{1}{2} g \eta^2\right) += 0 \tag{7}$$

Both of these equations together generate the parts of the shallow water equations in case of no coriolis, frictional or viscous forces.

2.4 Calculation of Run-up Levels

It is too difficult to estimate the run-up levels and inundated areas in such a large and course bathymetry. Therefore, 14 gauges are digitized at 50 m water depth offshore to determine the nonbreaking tsunami waves. Green's Law is used to carry tsunami wave heights recorded at the gauges implemented at 50 m water depth offshore to the coast. A similar approach was used by Lovholt et al.,, (2012) and Lovholt et al.,, (2014) and it was concluded that reliable results were obtained according to their investigations. Synolakis (1991) revealed Green's law equation as follows:

$$\frac{H_1}{H_{50}} = \left(\frac{d_{50}}{d_1}\right)^{\frac{1}{4}} \tag{8}$$

where H_{50} and H_1 are the tsunami wave heights at 50 m and 1 m water depths, respectively and d_{50} and d_1 are 50 m and 1 m water depths, respectively.
Definitions of the solitary wave run-up equation components can be seen in Figure 2.

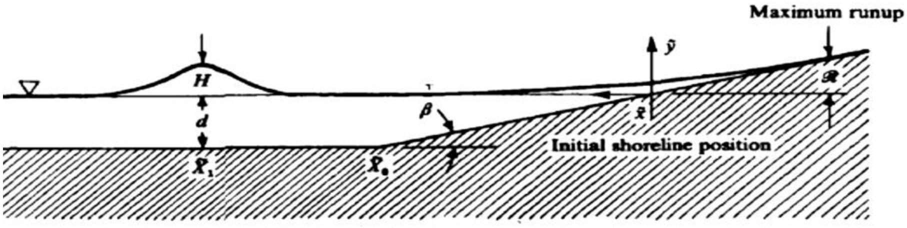


Figure 2. Definition sketch of the solitary wave equation components (Synolakis, 1991)

3. STUDY AREA

3.1 Generation of the Bathymetry of the Study area

Accurate bathymetry and reliable source parameters are needed to generate a coastal tsunami and conduct hazard mapping of the selected region. In this study, a bathymetry of 312x312 m^2 grid size is generated using GEBCO dataset (see Figure 3).

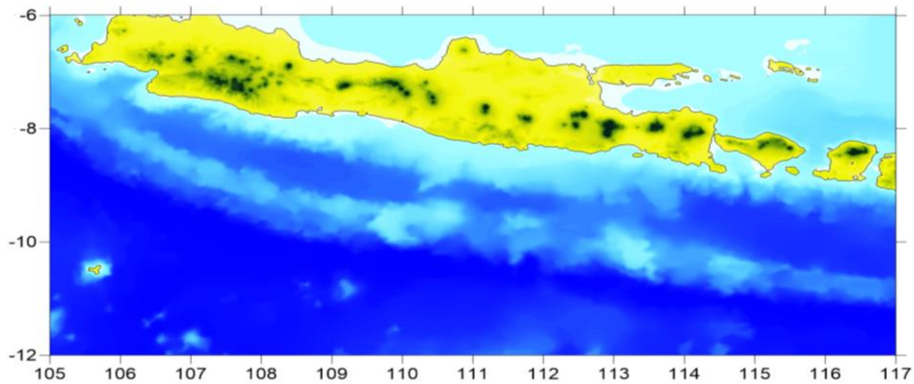


Figure 3. Bathymetry of the selected region

3.2 Computational Grids

Digital elevation maps (DEM) with 30 m resolution of the selected locations are retrieved from Shuttle Radar Topography Mission, SRTM (Available at: https://www2.jpl.nasa.gov/srtm/), and digitized in ArcGIS (see Figure 4).

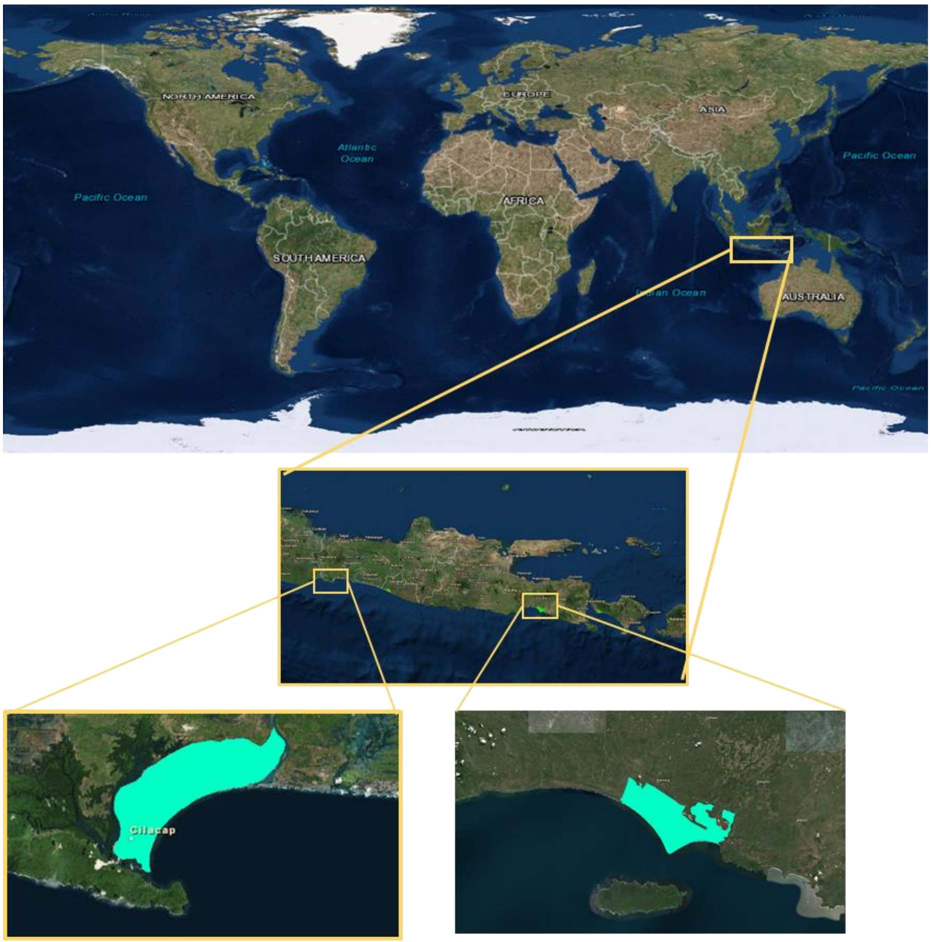


Figure 4. DEMs of the selected sample locations (i.e. Cilacap_City_Center and Kencong_plain) in the study area

4. RESULTS and DISCUSSION

4.1 Application of Monte Carlo Simulation

CDFs of the moment magnitude and focal depth are determined. In order to check goodness of fit test Kolmogorov-Smirnov goodness of fit test is applied and the results of the test are given in Table 2.

Table 2. Results of the goodness of fit test

Parameter	Distribution	Components	p-value	Alpha-value
Magnitude	Normal	mu = 6.0026, sigma = 0.415666	1.31E-04	0.01 - 0.05
	Lognormal	mu = 1.78996, sigma = 0.0659772	1.69E-04	0.01 - 0.05
	Weibull	a =6.21294, b = 11.5857	3.18E-09	0.01 - 0.05
Focal Depth	Lognormal	mu = 3.81231, sigma = 0.938139	6.23E-05	0.01 - 0.05
	Gamma	a = 0.944899, b = 88.5887	1.64E-12	0.01 - 0.05

Depending on the p-values for 5% confidence interval, Weibull distribution and Gamma distribution are fitted to moment magnitude and focal depth, respectively.
After the completion of distribution fitting stage, 5000 random data are generated using the following script in Matlab (see Table 3). The probability of the worst-case scenario is $\frac{1}{5000}$. This means that the selected return period of the worst-case scenario is 5000 years in this study.

Table 3. Scripts used to generate random data for moment magnitude and focal depth

```
pd=fitdist(Magnitude,'Weibull')

Random_Magnitude_Weibull=wblrnd(6.21294,11.5857,[5000,1]);

[h,p,ks2stat] = kstest2(Magnitude,Random_Magnitude_Weibull)
```

```
pd=fitdist(Historical_Focal_Depth,'Gamma')

Random_Focal_Depth=gamrnd(1.34612,24.6262,[5000,1])

[h,p,ks2stat] = kstest2(Historical_Focal_Depth,Random_Focal_Depth)
```

4.2 Generation of Earthquake Source

Since the goal is to simulate the worst-case scenario that is generated using the historical earthquake records for the study area along Java (Sunda) Trench, the maximum moment magnitude (i.e. $M_w 7.7$) is selected from Monte Carlo simulation results. Related source parameters of the worst-case scenario are given in Table 4.

Table 4. Simulated earthquake source parameters for the worst-case scenario

Simulated Earthquake Source Parameters				
Moment Magnitude	**Focal Depth (km)**	**Fault Length (km)**	**Fault Width (km)**	**Displacement (m)**
7.7	25	174	42	1.93
Latitude	**Longitude**	**Strike Angle**	**Dip Angle**	**Rake Angle**
-9.328	107.323	54	10	110

Tsunami simulation of the earthquake is conducted using NAMI-DANCE software. The duration of the simulation is selected 18000 seconds (5 hours). The source location and the propagation of the tsunami wave at t=2460 seconds are shown in Figure 5 and Figure 6, respectively.

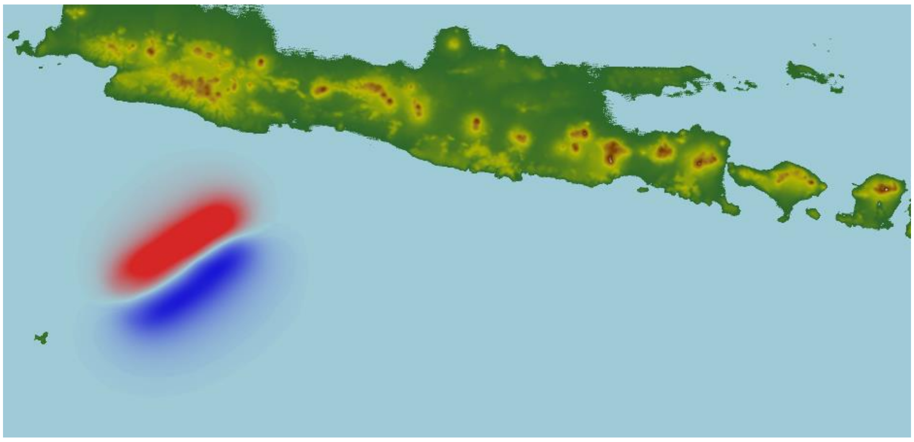


Figure 5. Source location of the simulated earthquake

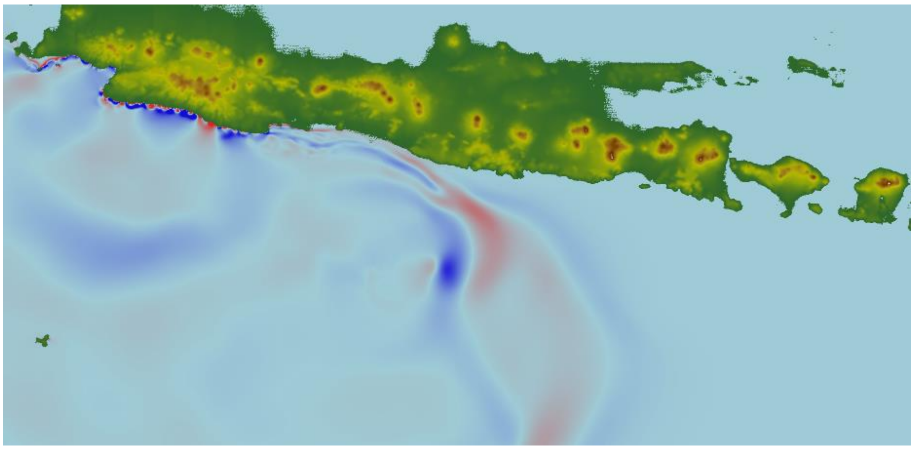


Figure 6. Tsunami wave propagation of the earthquake (t= 2460 s)

4.3 Run-up Levels at the selected CRs and CIs

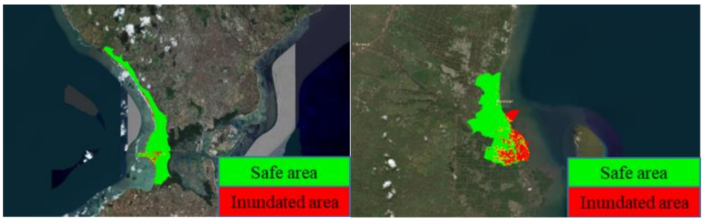
List of the selected locations and maximum run-up levels calculated using Eq. 8 proposed by Synolakis (1987), can be seen in Table 5.

Table 5. List of the selected locations and maximum run-up levels

Name of gauge pt.	Maximum(+)ve amp.(m)	Maximum(-)ve amp.(m)	Run_up_levels
Kuta_City_Center_Bali	0.075655	-0.0779599	1.62
Mataram_City_Center	0.0474563	-0.0496888	0.44
Negara_Pulukan_Coastline	0.0765944	-0.061612	0.67
Banyuwangi	0.0348108	-0.0301499	0.58
Muntjar	0.0348108	-0.0301499	0.58
Kesilir_Agricultural_Area	0.150288	-0.161984	3.72
Kencong_Plain	0.134081	-0.137799	1.47
Pantai_Tambakrejo	0.223742	-0.247893	3.81
Pantai_Sidem	0.194702	-0.208337	3.79
Panggul	0.27241	-0.197617	5.48

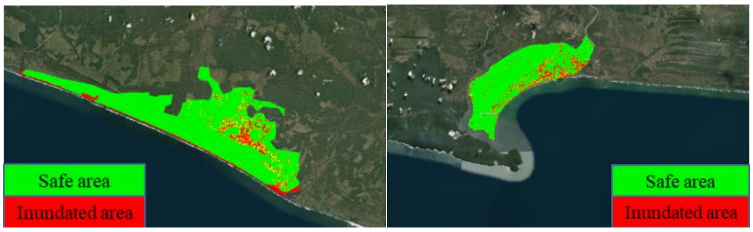
Pacitan	0.189631	-0.216572	4.34
Wates_Coastal_District	0.0849766	-0.125502	2.03
Petanahan_Coastal_District	0.0452637	-0.0541443	1.15
Cilacap_City_Center	0.100479	-0.100082	2.67
Cikangkung_Coastal_District	0.14801	-0.105887	2.15

Calculated run-up levels as the result of the selected worst case earthquake are used to generate tsunami hazard map for the aeras that contain CRs and CIs. Sample tsunami hazard maps for Kuta city center and Muntjar city center are given in Figure 7 and for Wates costal district and Cilacap city cetner in Figure 8.



(a) **(b)**

Figure 7. Scenario-based tsunami hazard map for **(a)** Kuta city center (not to scale) and **(b)** Muntjar city center (not to scale)



(a) **(b)**

Figure 8. Scenario-based tsunami hazard map for **(a)** Wates coastal district (not to scale) and **(b)** Cilacap city center (not to scale)

5. CONCLUSION

In the present study, a probabilistic tsunami hazard assessment (PTHA) approach is conducted using Monte Carlo simulation method. Independent parameters of the earthquake are defined using Monte Carlo simulation technique and the worst case scenario is simulated using NAMI-DANCE software. A total of 14 different CR and CI locations along southern coasts of Indonesia covering Java, Bali, and Lombok islands are identified and hazard maps are generated for these areas. Run-up levels are calculated using the empirical equation proposed by Synolakis (1987). Inundated areas are depicted using the DEMs retrieved from SRTM with 30 m resolutions. Since the simulated area is restricted with the selected bathymetry and a total of 5000 MC simulations are used, higher run-up levels and inundations might be observed along these locations due to larger earthquakes (i.e. $>M_w7.7$). The hazard maps of the region will help to identify areas that need mitigation measures most and consequently reduce destructive effects of tsunamis that may happen due to earthquakes in the Indian Ocean.

REFERENCES

Yalciner, A., Pelinovsky, E., Talipova, T., Kurkin, A., Kozelkov, A., & Zaitsev, A. (2004). Tsunamis in the Black Sea: comparison of the historical, instrumental, and numerical data. Journal of Geophysical Research: Oceans, 109(C12).

González, F. I., Geist, E. L., Jaffe, B., Kânoğlu, U., Mofjeld, H., Synolakis, C. E., ... & Horning, T. (2009). Probabilistic tsunami hazard assessment at seaside, Oregon, for near-and far-field seismic sources. Journal of Geophysical Research: Oceans, 114(C11).

GTZ-GITEWS (2010a) Tsunami evacuation plan for Kelurahan Kuta, Bali: a documentation of the process and results of tsunami evacuation planning. http://www.gitews.org/tsunami-kit/en/id_tsunami_evacuation_map_kuta.html

Knighton, J., & Bastidas, L. A. (2015). A proposed probabilistic seismic tsunami hazard analysis methodology. Natural Hazards, 78(1), 699-723.

Strunz, G., Post, J., Zosseder, K., Wegscheider, S., Mück, M., Riedlinger, T., ... & Harjono, H. (2011). Tsunami risk assessment in Indonesia. Natural Hazards and Earth System Sciences, (11), 67-82.

Hancilar, U. (2012). Identification of elements at risk for a credible tsunami event for Istanbul. Natural Hazards and Earth System Sciences, 12(1), 107.

OYO International Co.: Simulation and Vulnerability Analysis of Tsunamis Affecting the Istanbul Coasts, Final Report to Istanbul Metropolitan Municipality, Directorate of Earthquake and Ground Investigation, Istanbul, 2007.

Storchak, D. A., Di Giacomo, D., Bondár, I., Engdahl, E. R., Harris, J., Lee, W. H., ... & Bormann, P. (2013). Public release of the ISC–GEM global instrumental earthquake catalogue (1900–2009). Seismological Research Letters, 84(5), 810-815.

Hanks, T. C. and H. Kanamori (1979). A moment-magnitude scale, J. Geophys. Res. 84, 2348-2350.

Wells, D. L., & Coppersmith, K. J. (1994). New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. Bulletin of the seismological Society of America, 84(4), 974-1002.

Imamura, F. (1995). Tsunami numerical simulation with the staggered leap-frog scheme (numerical code of TUNAMI-N1 and N2). Disaster Control Research Center, Tohoku University, 33.

Titov, V. V., & Gonzalez, F. I. (1997). Implementation and testing of the method of splitting tsunami (MOST) model.

Yalciner, A. C., Pelinovsky, E., Zaytsev, A., Kurkin, A., Ozer, C., & Karakus, H. (2006). NAMI DANCE Manual. Middle East Technical University, Civil Engineering Department, Ocean Engineering Research Center, Ankara, Turkey, http://namidance. ce. metu.edu.tr/pdf/NAMIDANCE-version-5-9-manual. pdf.

Segur, H. (2007). Waves in shallow water, with emphasis on the tsunami of 2004. In Tsunami and nonlinear waves (pp. 3-29). Springer Berlin Heidelberg.

Løvholt, F., Glimsdal, S., Harbitz, C. B., Zamora, N., Nadim, F., Peduzzi, P., & Smebye, H. (2012). Tsunami hazard and exposure on the global scale. Earth-Science Reviews, 110(1-4), 58-73.

Løvholt, F., Glimsdal, S., Harbitz, C. B., Horspool, N., Smebye, H., De Bono, A., & Nadim, F. (2014). Global tsunami hazard and exposure due to large co-seismic slip. International journal of disaster risk reduction, 10, 406-418.

Synolakis, C. E. (1991). Green’s law and the evolution of solitary waves. Physics of Fluids A: Fluid Dynamics, 3(3), 490-491.