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Numerical Modelling of the 22nd December 2018 Volcanic Landslide Tsunami at the Anak Krakatau Island (Indonesia)

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ABSTRACT

The volcano at the Anak Krakatau Island in the Sunda Strait of Indonesia is an active and dominant tsunamigenic volcano. The Krakatau Island volcano is known for its destructive eruption in 1883 which left a submarine caldera that developed the Anak Krakatau (Child of Krakatau) Island. The volcano again erupted on 22nd December 2018 (after 135 years) which caused the collapse of the south-west flank of Anak Krakatau triggering a tsunami. The tsunami caused a death toll of 426 people with 14,059 reported injured and 24 missing.Royal Haskoning DHV (hereafter RHDHV) has set up a regional tidal hydrodynamic model covering the Bay of Bengal and its surroundings including Indonesia to simulate tsunamis in the region. Numerical modelling of the 22nd December 2018 tsunami generated at Anak Krakatau has been carried out in the present study. The initial tsunami waves have been generated based on previous studies found in the literature search. The MIKE21 Flow Model FM of DHI has been used in the study to simulate thetsunami. Sample results from the tsunami modelling study are presented in this paper for illustration purposes. Recommended design considerations and tsunami (including mudslides and landslides) risk reduction measures are also highlighted. The model could beused to simulate any tsunami generated within the Bay of Bengal and its surroundings. The methodology described in this paper for modelling the 22nd December 2018 tsunami at Anak Krakatau Island could also be applied to simulate this type of events at other sites around the world.

Key words: Tsunami, Volcano, Natural Hazards, Anak Krakatau, Krakatau Island, Bay of Bengal, Numerical Modelling, Port Development, RHDHV

INTRODUCTION

The Krakatau Island is situated inside the Sunda Strait in Indonesia. The island lies within the Pacific Ring of Fire which is a major area in the basin of the Pacific Ocean where many earthquakes and volcanic eruptions occur generating major tsunamis. The mega tsunami in 1883 by the explosive volcanic eruption at the Krakatau Island destroyed the island. In 1927, Anak Krakatau (Child of Krakatau), emerged from the caldera formed in 1883. There has been sporadic eruptive activity at Anak Krakatau since the late 20th century. Cone collapse with tsunami generation was considered a potential hazard at Anak Krakatauimmediately prior to the 22nd December 2018 eruption. The size of the island was ~2.1km east-west and ~2.3 km north-south before the collapse. Scientists had modelled the possibility six years prior to the event and had identified the western flank as the section of the volcano most likely to fail.

Following the 22nd December 2018 eruptionat Anak Krakatau, it was believed that the south-west sector of the volcano, including the summit, had collapsed during the eruption. The large underwater collapse of the volcano caused a deadly tsunami on 22nd December 2018. On 23rd December 2018, this was confirmed by satellite data and helicopter footage, with the main conduit seen erupting from underwater, producing Surtseyan-style activity. The volcano lost over two-thirds of its volume due to this event, and its elevation above sea level was reduced from 338 m to 110 m. A volcanic cone standing 340 meters high was reduced to just 110m tall.

The volcanic eruption on 22nd December 2018 (after 135 years) caused the collapse of the south-west flank of the island triggering the tsunami. The deadly tsunami generated waves up to five meters in height. The tsunami affected more than 186 miles of coastline in Sumatra and Java. The 2018 tsunami caused a death toll of 426 people with 14,059 reported injured, 24 missingand 40,000 were displaced.This made the eruption the deadliest volcanic eruption of the 21st century so far.

Most of the above information was obtained from [1] and [2].

Literature search was carried out to determine the tsunami source(s) caused by the 22nd December 2018 eruption at the Anak Krakatau Island. The focus of this review is not the volcanic landslide process but on the initial tsunami waves. The dynamics of eruption and subsequent landslides in the first few seconds to a minute or so would require a special software involving non-hydrostatic modelling approach using a combination of soil and water. This was beyond the scope of this study. Therefore, the literature review was focused on finding the sources of the initial tsunami after it has evolved without taking the eruption process into account. A summary of the literature review is provided below.

Study by Grilli et al. (2019) [3]

They used three failure surfaces and resulting collapse geometry and volumes to initialize simulations with a three-dimensional (3D) slide and hydrodynamic model of tsunami generation and propagation using the NHWAVE (Non-Hydrostatic WAVE) model. For each of the three selected collapse volumes and corresponding geometry, the 3D model was used in the near-field (with 90m horizontal grid resolution and 5vertical layers) to simulate the lateral collapse landslide and the corresponding tsunami generation. They modelled the failure surface of the most likely 0.27km^3 volume scenario with associated uncertainty of two additional volumes [the upper and lower failure surfaces, with a 0.22km^3 (−20%) and 0.30km^3 (+10%) volume, respectively]. The slide direction was south-west (which was also suggested by the before and after pictures of Anak Krakatau Island).After the generation of the initial wave, the tsunami wave propagation at far-field was simulated using a hydrostatic software called FUNWAVE-TVD with a model grid resolution of 100mx100m. FUNWAVE-TVD is a fully nonlinear and dispersive 2D Boussinesq-type model used (and initialized) in their study to propagate the initial near-field tsunami generated with NHWAVE to the far-field.

University of Tokyo (2019) [4]

Numerical simulation was carried out using a two-layer shallow water model capable to investigate tsunamis generated by gravity currents (e.g. pyroclastic flows and landslides). The model is based on a non-linear long wave theory. It is solved using a finite difference method. Model grid size was 83.33m (= 250/3m) in close by areas and 250m for distant areas. Three different collapsed volumes were modelled (0.16km^3, 0.21km^3 and 0.26km^3). The direction of the collapse at the source was south-west. It was concluded that the collapsed volume during the 22nd December 2018 event was ~0.2km^3 or more.

Study by Giachetti, Paris, Kelfoun, & Ontowirjo (2012) [5]

This study calculated a hypothetical eruption event that could induce tsunami before the event of 2018 took place. Based on bathymetry and DEM data they estimated a south-westerly collapse of 0.28km^3 (with a width of approximately 1900m) in a single release event.The initial wave and tsunami propagation were modelled with a software called VolcFlow using a model grid resolution of 100mx100m (at the source area) and 200mx200m in the remaining area.

Study by Bachtiar, et al. (2017) [6]

This work is focused on tsunami heights at coastal areas in and around Jakarta. The simplified initial tsunami wave height and source dimensions, that has asymmetrical and cylindrical form, is set at one quarter of the 1883 event source that was modelled by the same authors in an earlier study [7]. The parameters applied are Radius = 28km, Depth = 30m and Height = 40m. The study did not mention the slide volumes associated with the initial wave source dimensions. The simulations were carried out using a VBM Boussinesq model with a (variable) model resolution of 200m.

The Present Study

Setting up a large tidal hydrodynamic model is essential to simulate propagation of a tsunami. Royal HaskoningDHV has set upa regional tidal hydrodynamic modelcovering the Bay of Bengal and its surroundings including Indonesia to support their work in the region. The model has been used on several occasions to assess tsunamis within this region particularly the mega tsunami generated by the December 2004 earthquake at the Sunda Trench in Indonesia.

The MIKE21 Flow Model FM of DHI [8] has been used in the present study. The initial tsunami conditions (changes in sea surface) were generated in the present study that matched the findings of other authors. Sample results of tsunami levels and arrival time from the modelling study are presented in this paper for illustration purposes only. Structural design considerations and tsunami (including mudslides and landslides) risk reduction measures are also discussed. The model could be used to simulate the passage of a tsunami anywhere within the Bay of Bengal and its surroundings including Indonesia. The methodology described in this paper for modelling the tsunami generated at the Anak Krakatau Island in the Sunda Strait could also be applied to simulate this type of events at other sites around the world. The flowchart in Figure 1 [adapted from (9)] illustrates the steps and the software used in the present study.

The general definition of tsunami level and wave height is illustrated in Figure 2 [10]. A tsunami wave height refers to the vertical distance from trough to peak of a tsunami wave. A tsunami level (also called amplitude) is referred to the height of the water column above the datum. Usually Mean Sea Level (MSL) or Chart Datum (CD) are used as datum in tsunami modelling. Mean Sea Level Datum was used in the present study and, therefore, any tsunami level (or tsunami amplitude) in this paper refers to a level above/below the Mean Sea Level.

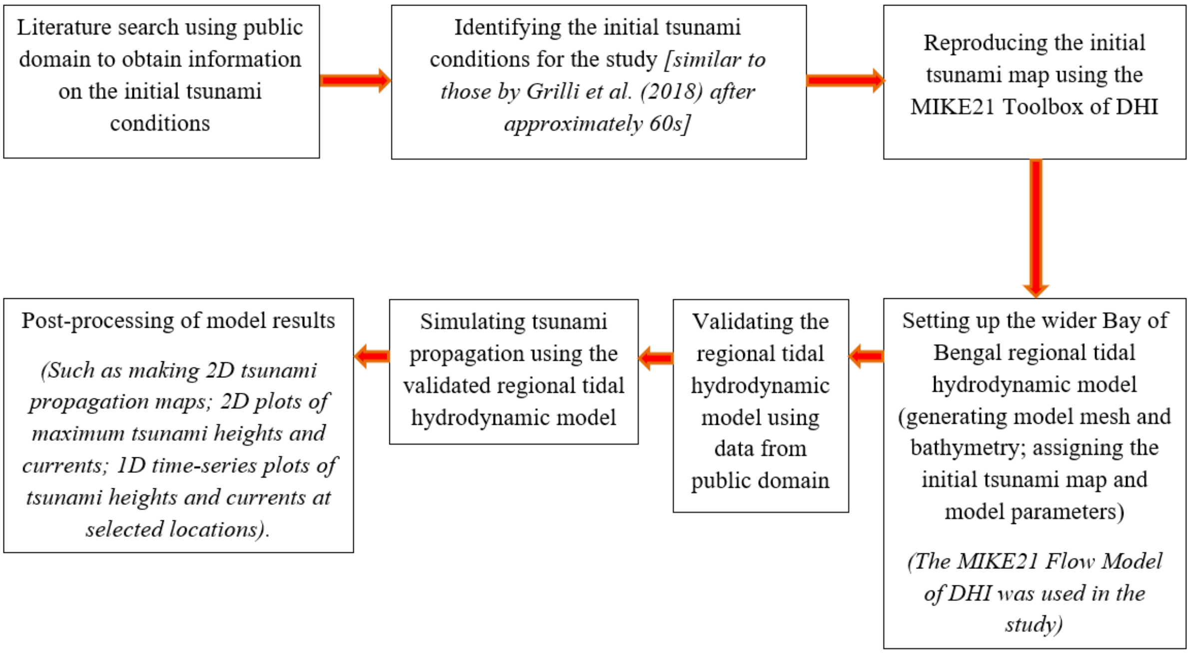


Fig. 1 Steps and software used in the tsunami modelling study [adapted from (9)]

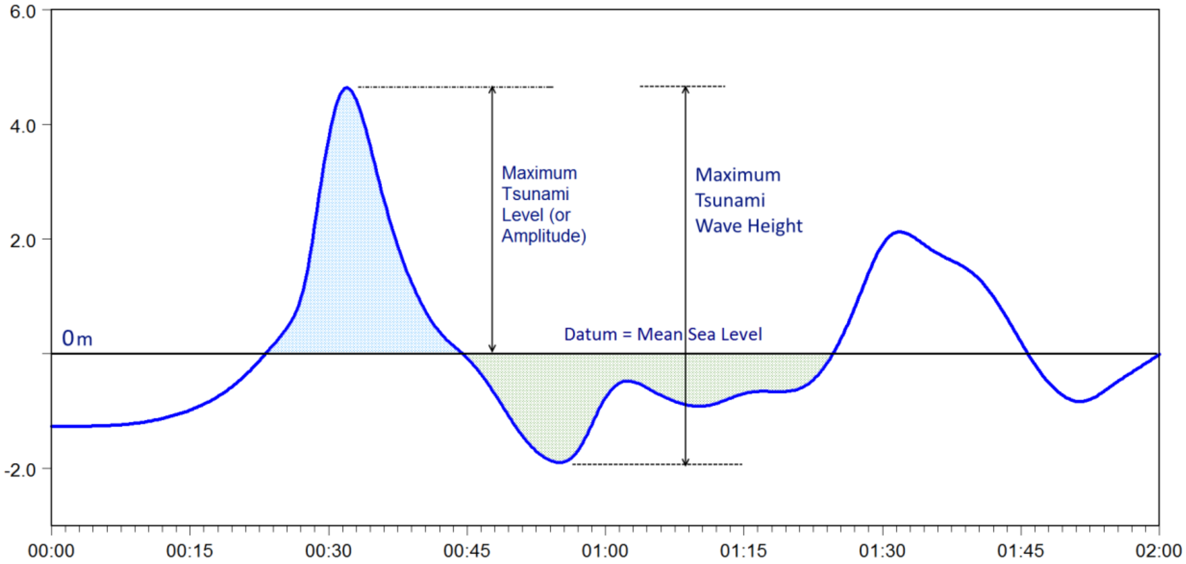


Fig. 2 General definition of tsunami level and tsunami wave height [10]

REGIONAL TIDAL MODEL SET UP BY ROYALHASKONINGDHV

Royal Haskoning DHV has set up a two-dimensional Regional Tidal Hydrodynamic Model for the Bay of Bengal and its surroundings using the MIKE21 Flow Model FM software of DHI [8]. The model is based on the numerical solution of the two/three-dimensional shallow water incompressible Reynolds averaged Navier-Stokes equations invoking the assumptions of Boussinesq and of hydrostatic pressure. Thus, the model consists of continuity, momentum, temperature, salinity and density equations.

The regional model covers the coastlines of six countries – India, Sri Lanka, Bangladesh, Myanmar, Malaysia and Indonesia (see Figure 3). An unstructured flexible (triangular) mesh (with variable cell sizes) was used in the study which allowed use of fine mesh at shallow areas where changes in physical processes occur quickly and over shorter distances. It also allowed to use fine mesh size at areas of importance (such as areas close to the tsunami source). The model bathymetry (as shown in Figure 3) was obtained from the C-Map Global Database [11]. This regional tidal model was used in the study to simulate the tsunami propagation.

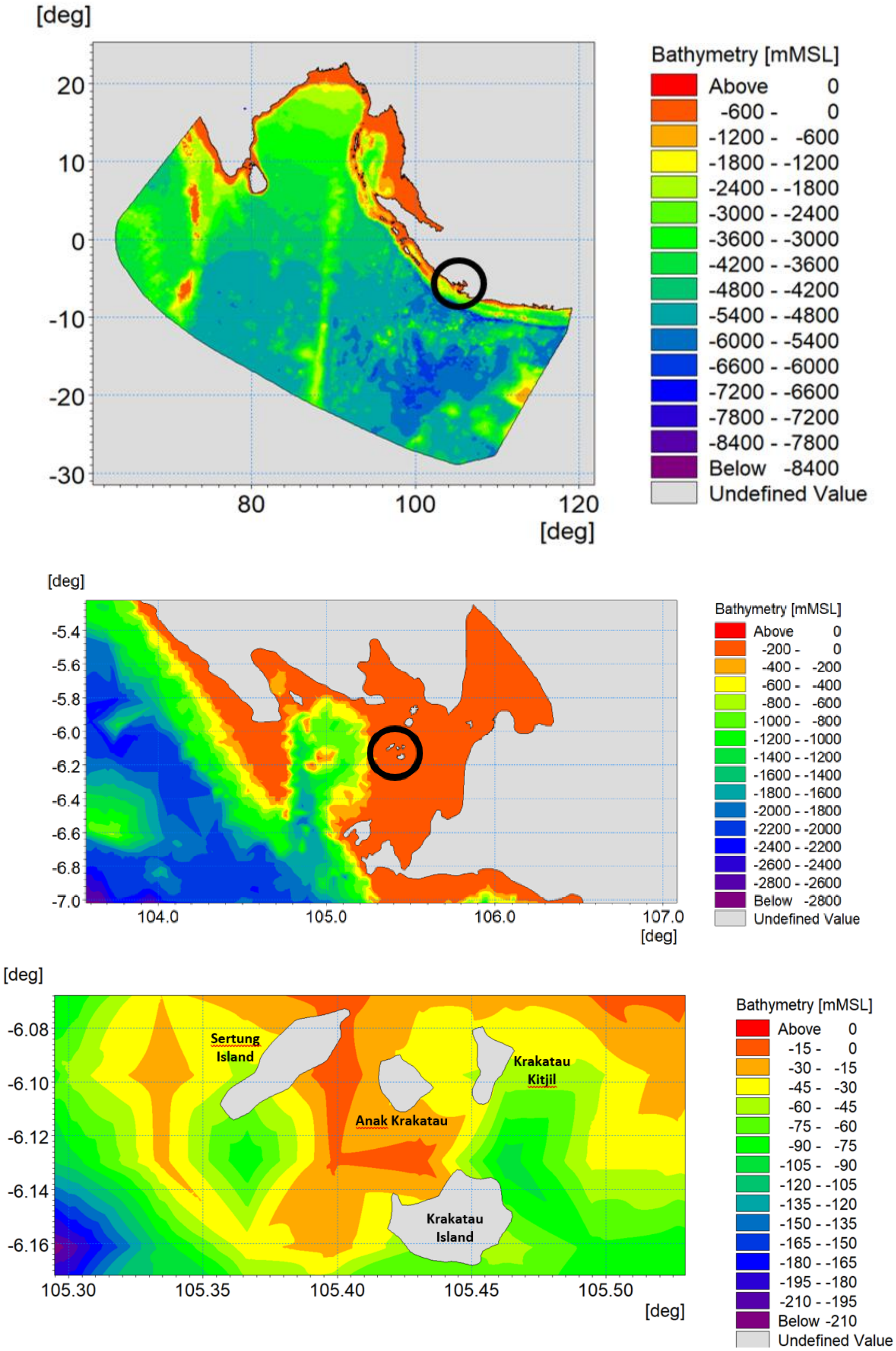


Fig. 3 The regional model domain and bathymetry [with zoomed-in views]

The order of the numerical schemes that are used in the numerical calculations for time integration and for space discretization can be specified in the MIKE21 Flow Model to control the simulation time and accuracy. A lower order scheme (first order) is faster but less accurate whereas a higher order scheme is slower but in general produces results that are significantly more accurate than the lower order scheme. Therefore, the higher order numerical scheme was used in the study for both time integration and space discretization.

“Flooding and Drying” were included in the model for treatment of the moving boundaries (flooding and drying fronts). Barotropic density and the Smagorinsky formulation for eddy viscosity were used in the model. Bed resistance was included in the model in the form of Manning’s number. Varying Coriolis forces were applied to the model.

MODEL MESH AND BATHYMETRY

Royal HaskoningDHV has set up a Regional Tidal Model covering the Bay of Bengal and its surroundings using the MIKE21 Flow Model FM. This model was used in the study to hindcast the 2018 tsunami. A flexible (triangular) mesh was used with variable mesh size distribution to obtain accuracy in the model results. Attention was given to the shallow areas and inside the Sunda Strait particularly around the Krakatau Island.

Typically, 20-30 grids (ideally 40 grids) per wave length are required to correctly resolve the physical processes of tsunami propagation. Shallower waters have shorter wave lengths. Therefore, smaller grid sizes are required for shallower waters.

The mesh size distribution was generally as below:

- 50m grid size at 1m depth
- 150m grid size at 10m depth
- 500m grid size at 100m depth
- 1500m grid size at 1000m depth
- 3000m grid size for the remaining deeper areas

The bathymetry of the model domain was obtained from the C-Map Database [11]. Figure 3 shows the model domain and bathymetry.

MODEL PARAMETERS

Some other major model parameters are given below:

- Minimum time step = 0.01s
- Maximum time step = 15s
- Critical Courant-Friedrich-Lévy (CFL) number = 0.8
- Run duration = 3 hours
- Higher order numerical scheme used
- Coriolis force = varying in domain

The MIKE21 Flow Model uses a variable time step between the minimum and maximum time steps assigned in the model. The time step interval must be selected so that the CFL number is less than 1 in order to secure the stability of the numerical scheme using an explicit scheme in the MIKE21 Flow Model. However, the calculation of the CFL number is only an estimate and, therefore, a reduced value of 0.8 was assigned in the model.

INITIAL TSUNAMI LEVELS

The process of landslide from the 22nd December 2018 volcanic eruption was not simulated in the present study. Rather the initial tsunami conditions (changes in sea surface) were generated that matched the findings of other authors such as [3] who carried out the landslide modelling. A slide direction of 245^0N was assumed in the present study which is consistent with the estimated direction by other authors such as [3], [4] and [5]. Epicentre of the slide was assumed at 105.42^0E, 6.1057^0S. The previous authors who modelled the landslide process considered a collapse volume of $0.16km^3$ to $0.30km^3$. The initial tsunami conditions generated for the present study matched the landslide volume of approximately $0.28km^3$.

The initial tsunami condition used in the present study was at the time when the tsunami wave had developed (i.e. ~50 seconds to 1 minute after the event) for input to the hydrostatic model. The initial tsunami wave length was approximately 2.2km and the initial tsunami wave period was approximately 63s in view of the hydrostatic modelling approach used in the present study. The initial tsunami wave height was approximately 75m. The depth at the location of the origins (generation point) of the selected initial tsunami wave is approximately 120m which is 1/18th of the wave length and, therefore, the initial tsunami wave can be considered nearly a long wave. The methodology used in the present study is commonly adopted in engineering studies. The initial tsunami waves of the 2018 event were reproduced using the MIKE21 Toolbox by DHI [12] and are shown in Figure 4. The pattern of the initial and/or maximum tsunami wave was similar to those in [3], [4] and [5] which confirms the realiability of the initial tsunmai conditions used in the present study.

MODEL CALIBRATION

The modelled tsunami levels and arrival time were extracted at selected locations. These locations are shown in Figure 5. Observed tsunami level at Carita during the 22nd December 2018 event was obtained from [13] as reported in [14]. Observed tsunami level and arrival time at Marina Jumbo were obtained from [15].The modelled tsunami levels and arrival time are compared in Table 1 with the observed values where available.

Table -1 Modelled and observed tsunami levels and arrival time

Ciwandan Port (6.016°S,105.954°E)		Marina Jumbu (6.19°S,105.82°E)		Carita (6.263°S,105.8°E)	
Modelled Tsunami	Observed Tsunami	Modelled Tsunami	Observed Tsunami	Modelled Tsunami	Observed Tsunami
0.7 to 1.6m (51 minutes)	- (50 minutes)	0.8 to 1.3m (36 minutes)	0.9m (29 minutes)	1.4-2.2m (34 minutes)	2.0m -

A good agreement was found both in the modelled and observed tsunami levels and arrival time at various locations within the Sunda Strait. Therefore, it is concluded that the present model can predict the tsunami levels and arrival timeanywhere within the model domain with an acceptable level of confidence.

MODEL RESULTS AND DISCUSSIONS

The propagation of tsunami waves over time was extracted from the model results as shown in Figure 6. The model results suggest that the neighbouring islands (Sertung Island, Krakatau Kitjil Island and Krakatau Island) were quickly affected (within 5 minutes) due to the proximity to the source. The Sebesi Island, Legundi Island and the southern part of the Pesawaran Regency (all situated north of the source) were also affected relatively quickly (within 20 minutes). The Panaitan Island at south-west and the Sawangbalak Island at north-east were affected within 21 minutes. The south-east end of the West Lampung Regency was affected within 22 minutes. The Sebuku Island at north and the Tanjung Lesung at south-east were affected within 28 minutes. The tsunami took 34 minutes to reach the western part of the Pandeglang Regency situated south of the source. It took about 40 minutes for the tsunami to reach the Sangiang Island situated north-east of the source. The tsunami took about one hour to reach the Java Sea at north-east whereas it took only 20 minutes to reach the Indian Ocean at south-west. The tsunami arrival time at key locations are shown in Figure 7 and are summarized in Table 2. These locations are shown in Figure 5.

Figure 8 illustrates the maximum tsunami levels during the entire passage of the tsunami. The maximum tsunami level at the source (south-west segment of Anak Krakatau) was about 84m. The maximum tsunami level at the Sertung Island was 40m. The maximum tsunami level at the Krakatau Kitjil was 11m. The maximum tsunami levels at Sebisi Island was 5.5m at its southern coastline whereas the maximum tsunami levels at the Sebuku Island was 2.5m at its western coastline. A tsunami level of up to 2.4m was found at the Sangiang Island at its western coastline. A tsunami level of up to 2.9m was found at the eastern coastline of the Panaitan Island. Up to 0.8m tsunami level was found at the eastern coastline of the Sawangbalak Island. The maximum tsunami levels at key locations shown in Figure 7 and are summarized in Table 2. These locations are shown in Figure 5.

The model correctly reproduced the tsunami phenomena observed on site with the sea level rising and receding leaving a drying beach and foreshore followed by a rapid rise in the level of the sea. The nearby islands, headlands and coastlines were worst affected due to its proximity. The highest level of 84m was found at south-west coast of Anak Krakatau immediately after the event.

A relatively higher rise in sea surface elevation was found in the shallower water depths. Rise in water level at shallow waters is higher than that in deeper waters as expected due to shoaling effects.

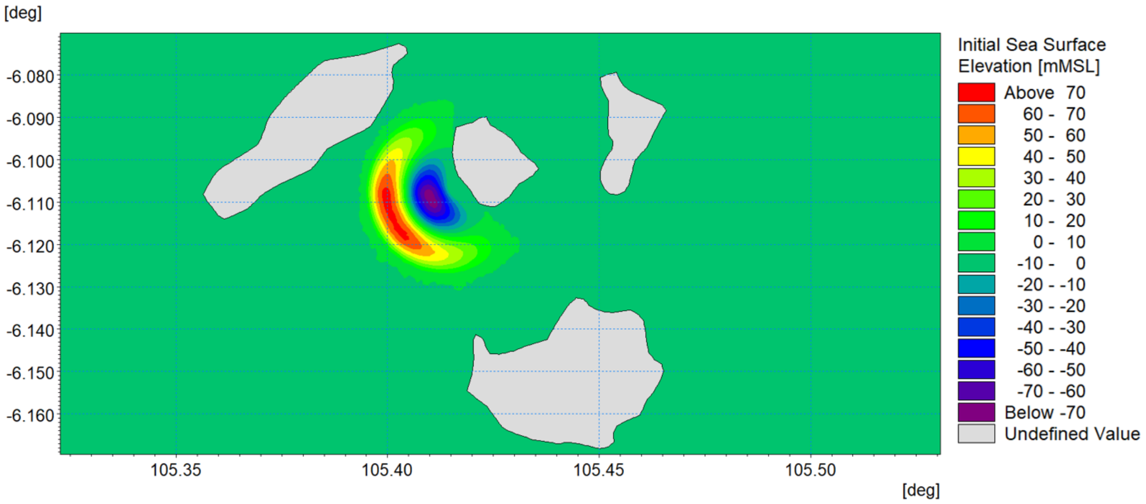
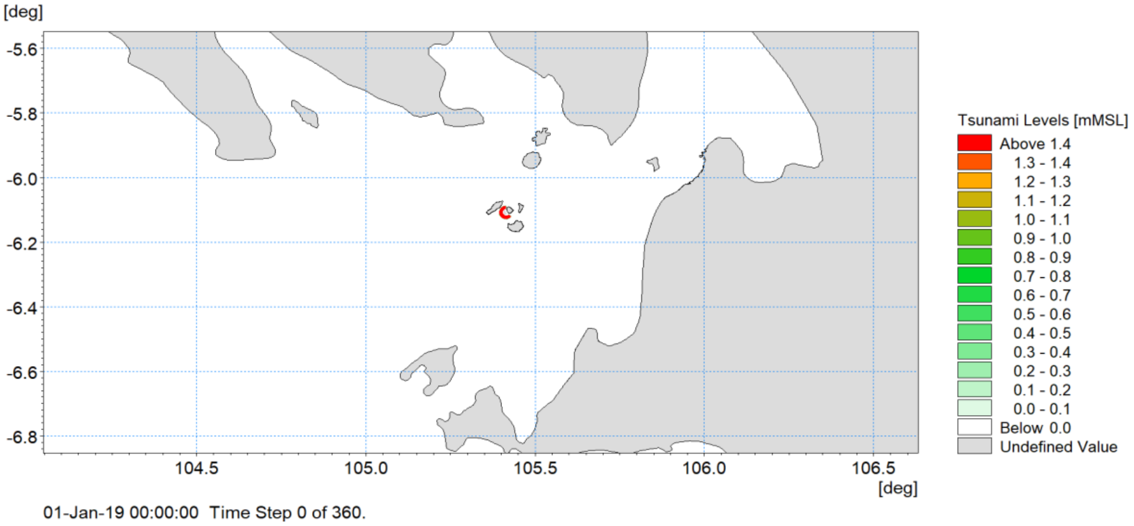
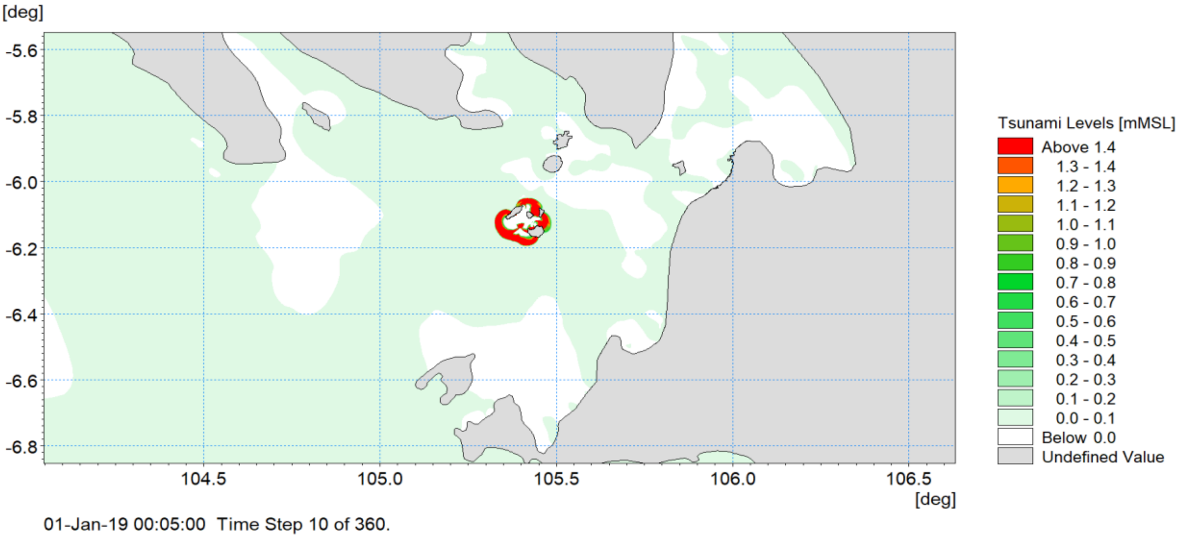


Fig. 4 Initial tsunami levels [22nd December 2018 event]

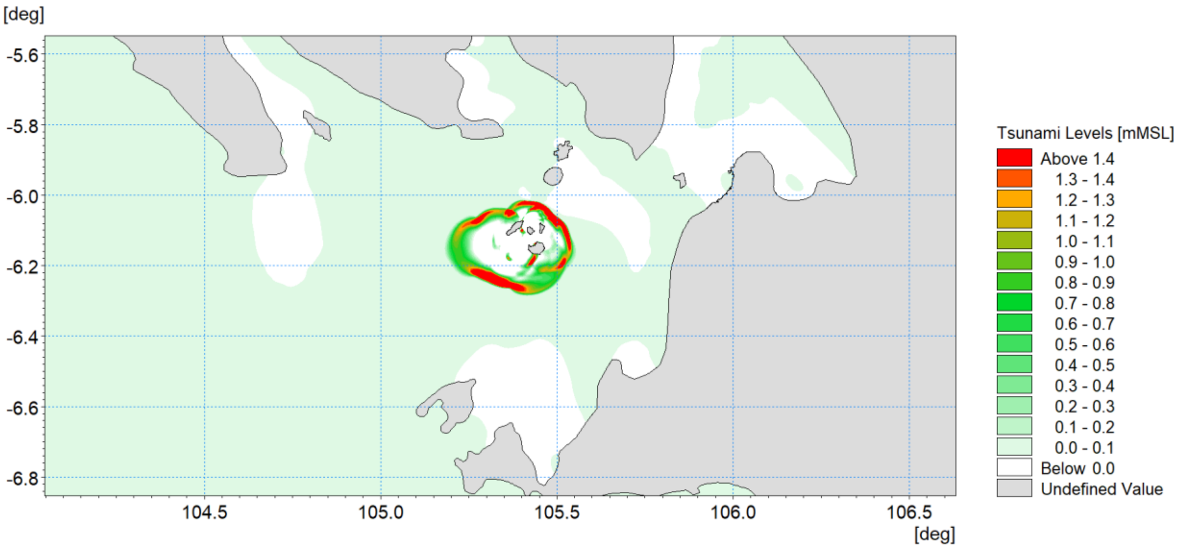
Fig. 5 Selected output locations [Image source – Google Earth]



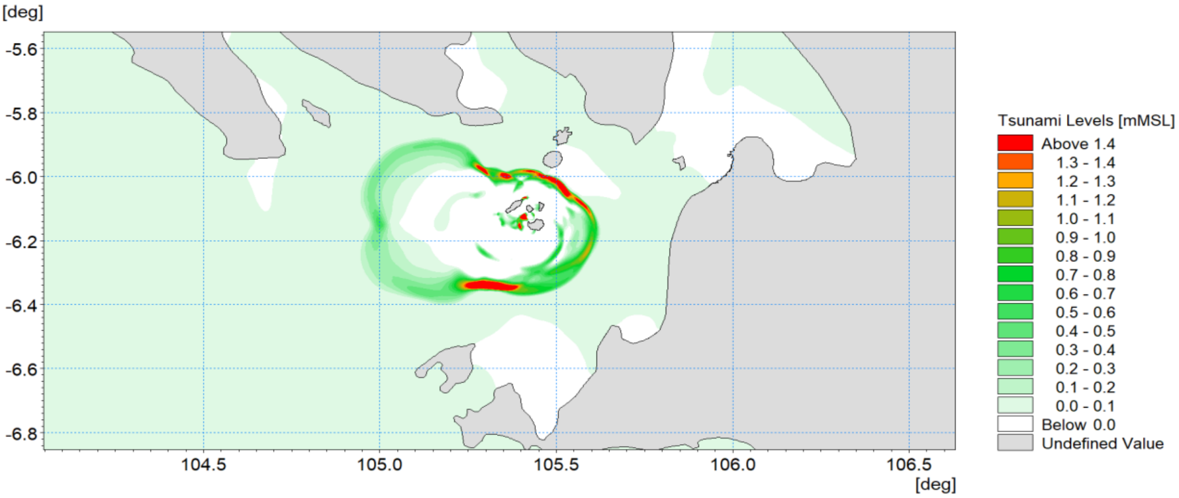
(a) Tsunami waves at t = 0 minutes



(b) Tsunami waves at t = 5 minutes

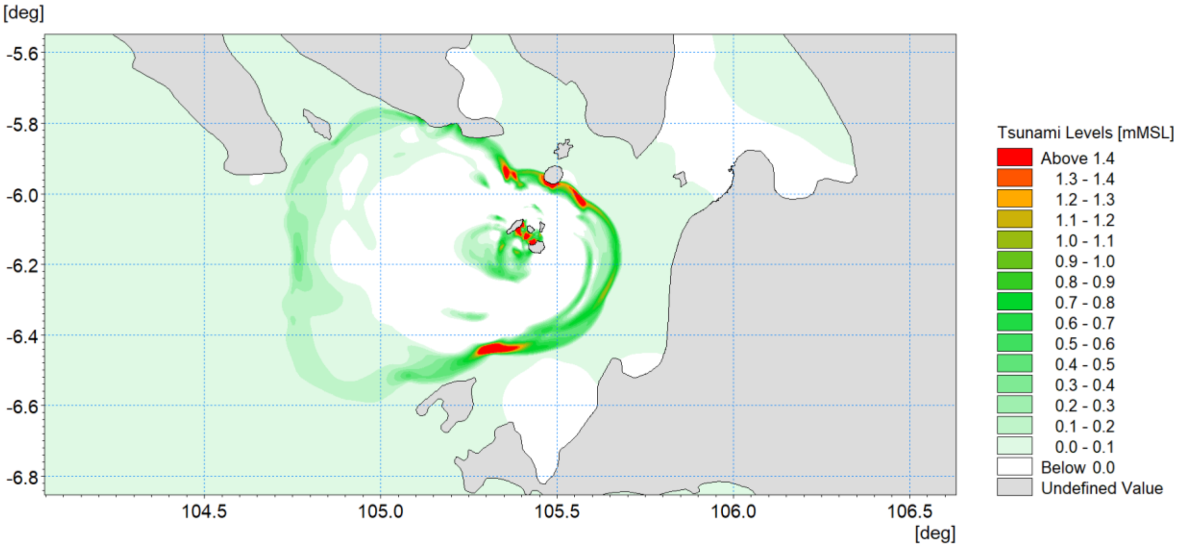


(c) Tsunami waves at t = 10minutes



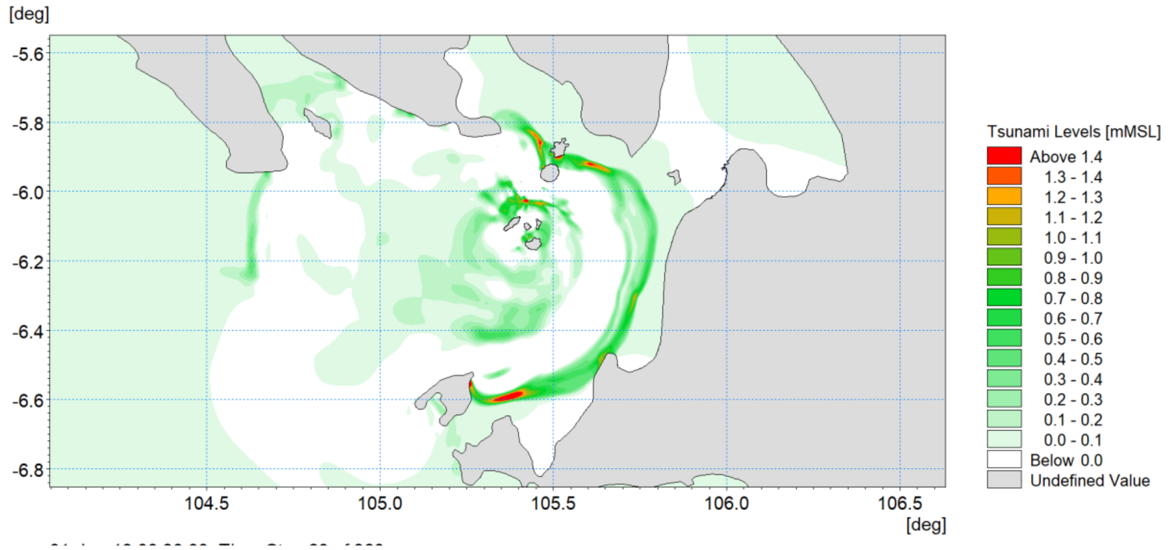
01-Jan-19 00:15:00 Time Step 30 of 360.

(d) Tsunami waves at t = 15 minutes

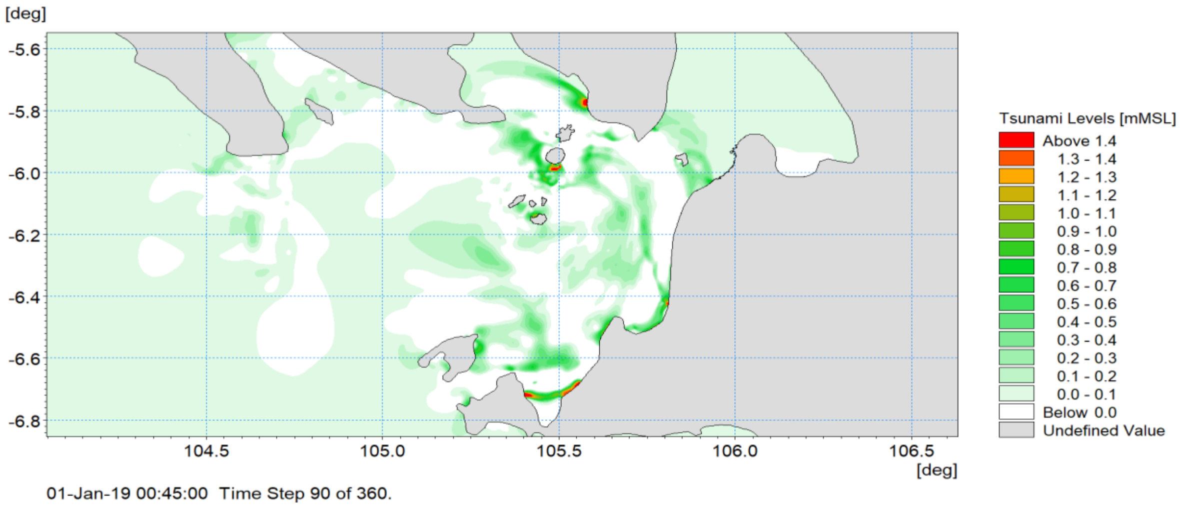


01-Jan-19 00:20:00 Time Step 40 of 360.

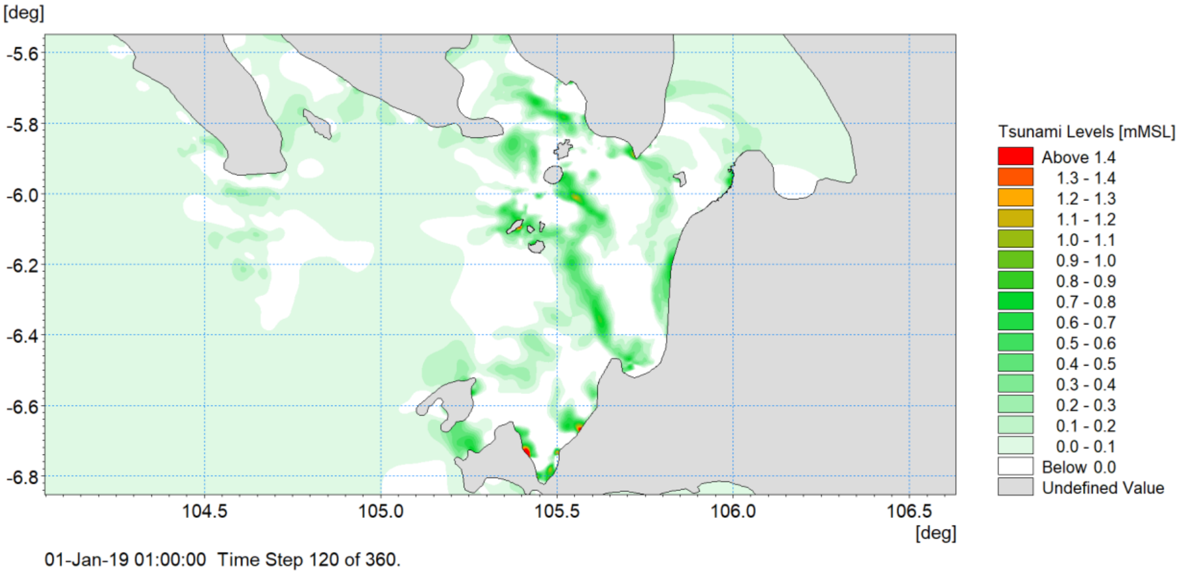
(e) Tsunami waves at t = 20 minutes



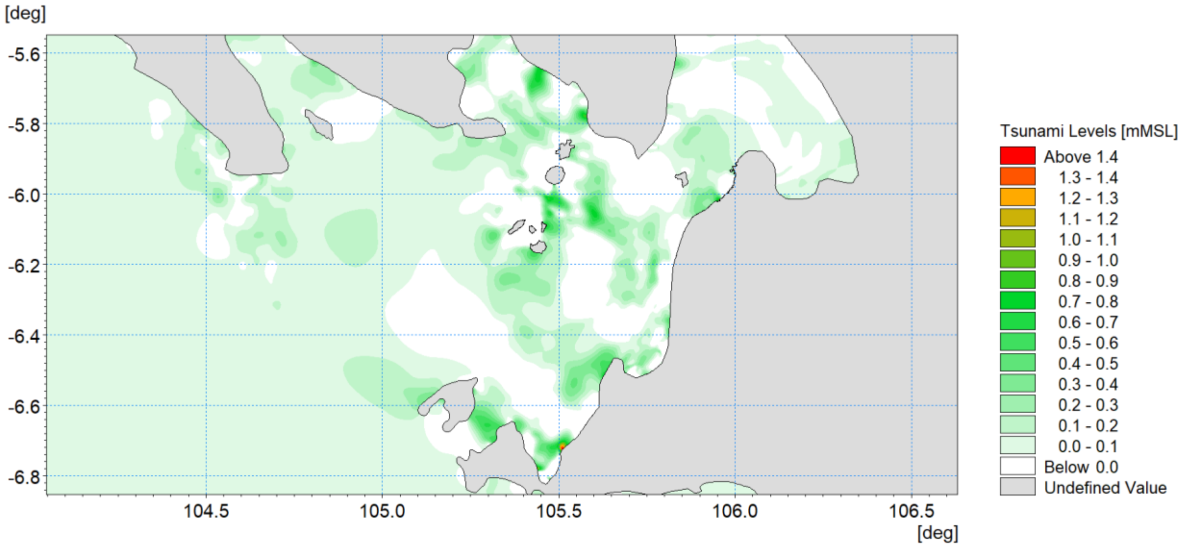
(f) Tsunami waves at t = 30 minutes



(g) Tsunami waves at t = 45 minutes

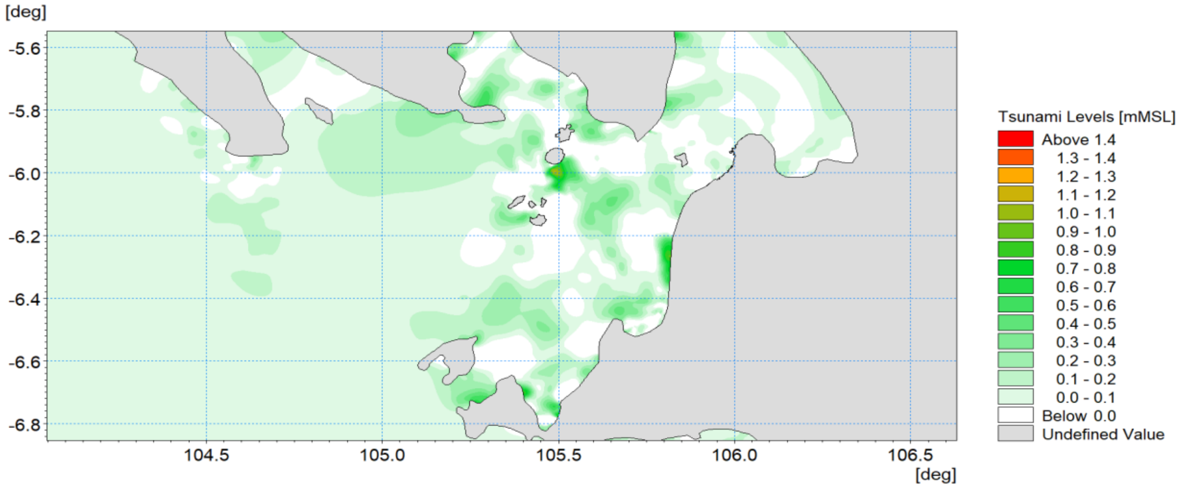


(h) Tsunami waves at t = 1 hour



01-Jan-19 01:30:00 Time Step 180 of 360.

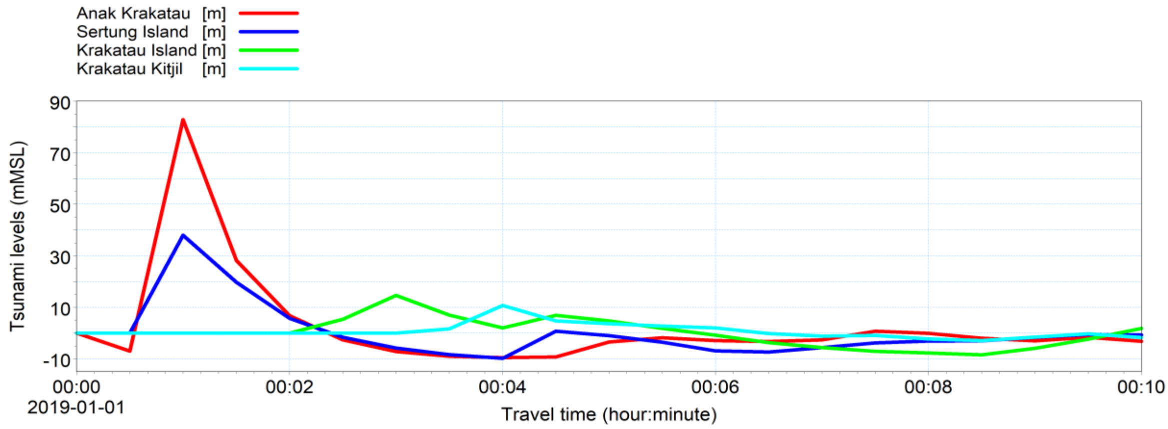
(i) Tsunami waves at t = 1 hour 30 minutes



01-Jan-19 02:00:00 Time Step 240 of 360.

(j) Tsunami waves at t = 2 hours

Fig. 6 Propagation of 22nd December 2018 tsunami waves



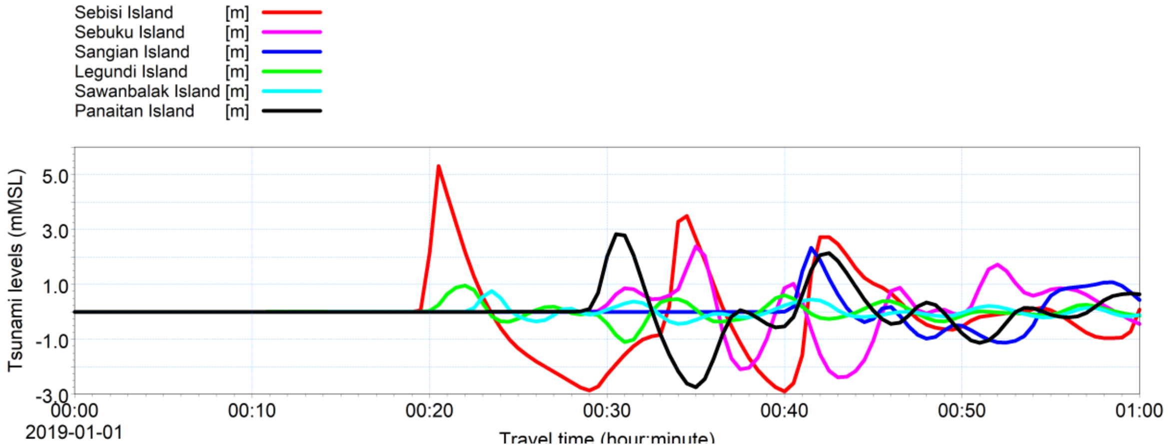
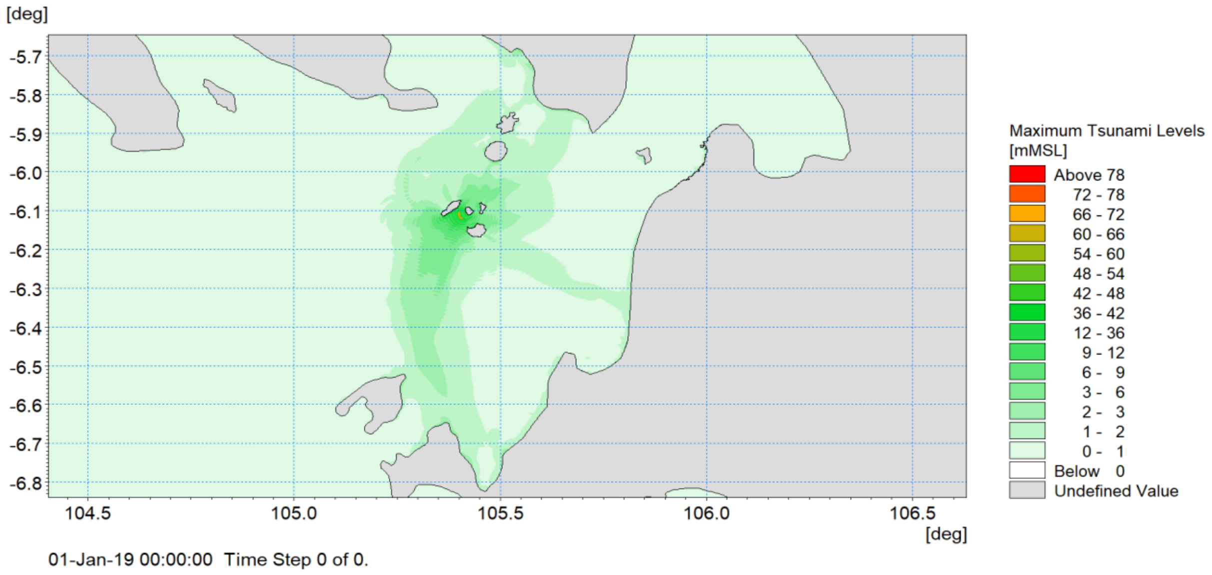
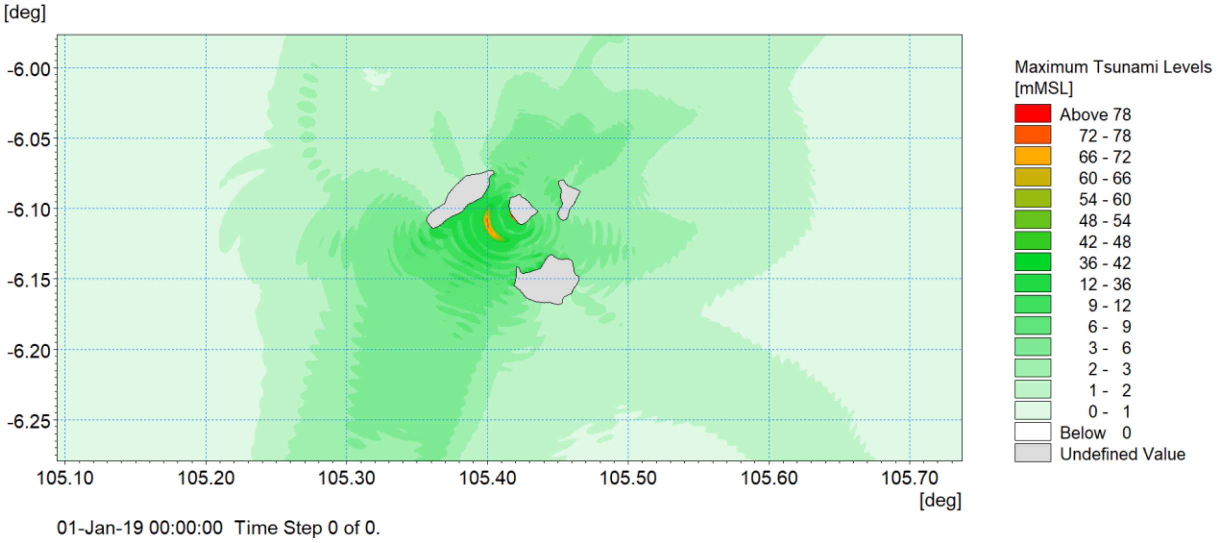


Fig. 7 Time-series of tsunami levels at selected locations





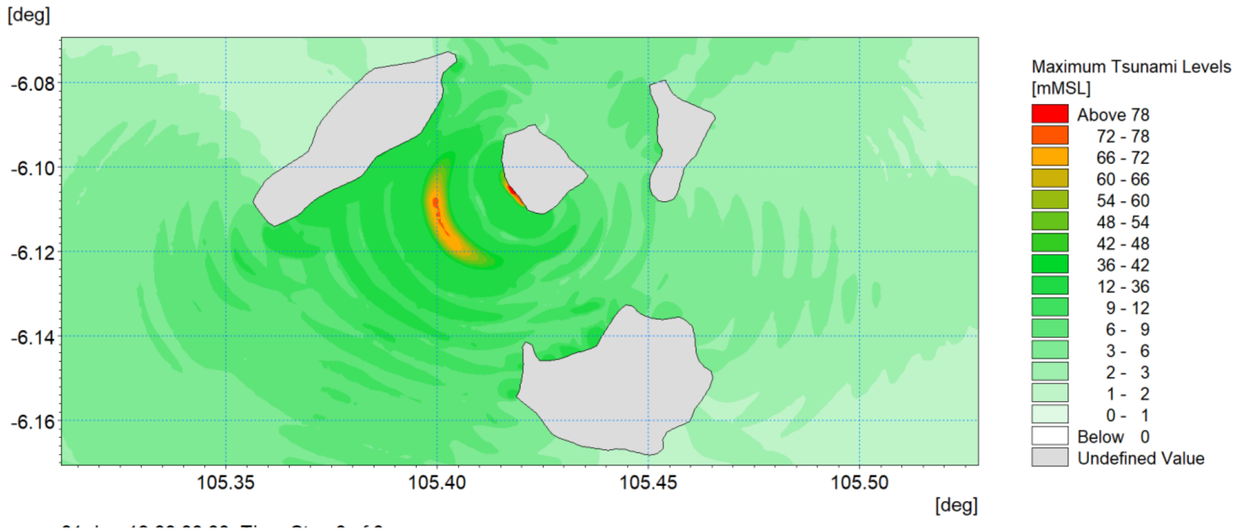


Fig. 8 Maximum tsunami levels (with zoomed-in views)

Table -2 Maximum tsunami levelsand arrival time at selected locations

Locations	Position with respect to the source	Tsunami arrival time (minutes)	Tsunami levels (mMSL)
Anak Krakatau	Source	0	84.00
Sertung Island	West	1	40.00
Krakatau Island	South-east	2	15.00
Krakatau Kitjil	East	3	11.00
Sebesi Island	North-east	18	5.50
Sebuku Island	North-east	28	2.50
Legundi Island	North-west	19	1.00
Siuntjal Island	North-west	22	0.75
Sangiang Island	North-east	40	2.40
Sawangbalak Island	North-west	21	0.90
Panaitan Island	South-west	21	2.90
Java Sea	North-east	60	0.80
Indian Ocean	South-west	20	0.50

APPLICATIONS OF MODELLING RESULTS

The results from the tsunami model provide valuable information at all stages of a project including planning, design, environmental impact assessment, construction, operation, and de-commissioning. The model results can also be used in emergency planning and decision-making to estimate potential loss of life, damage to properties and marine facilities and to develop mitigation measures and plan clean-up operations.

The tsunami model is a key tool for deriving robust design conditions for coastal and marine structures and facilities. The models can also provide input conditions to scale physical models for testing structural stability and overtopping rates and input to coastal flood studies.

UNCERTAINTIES IN MODELLING RESULTS

An unstructured flexible mesh was used in the modelwhich fits better with a curved coastline. It also allowed smaller grids in the areas of higher importance to obtain better accuracy in model results. A variable mesh size distribution as required was maintained with smooth transition between two mesh sizes to obtain accuracy in model results.

Bathymetry is a major input parameter to the model which was obtained from the C-Map Database. The accuracy of this data is the same as if extracted directly from Admiralty Chart data at the various scales available. Admiralty Chart data is based on surveys carried out in the past and some changes in the seabed particularly at shallow waters are expected over time. Therefore, there are uncertainties in model results in shallow waters due to expected seabed changes over time.

However, the model results were extracted at relatively deep waters and hence no major effect of discrepancy in bathymetry data is expected.

On the tidal modelling, it is important that the regional circulations are understood so that these are captured within the model. Including the effect of the Coriolis force into a tidal model is also important.

A numerical model is developed based on various assumptions. Although the MIKE21 Flow Model developer (DHI) carried out calibration and validation as part of the development process, local site-specific calibration and validation are required before applying the model. Good quality measured data are required for model calibration and validation. Limited observed data were available on tsunami wave heights on some Sunda Strait coasts. These limited observed data were used along with some numerical model prediction obtained from published literature to validate the present model.

Model results presented in this paper are for illustration purposes only. These should not be used for any practical project work for which use of local survey bathymetry data and detailed local calibration are essential.

Although there are various uncertainties, numerical models are considered useful tools by researchers and practitioners globally.

RECOMMENDED DESIGN CONSIDERATIONS

The potential impact of a tsunami event on the design of coastal and marine facilities may be summarised as follows:

1) Shoaling results in an increase in water levels and stronger currents inshore and the measures will be required to protect structures from scouring of the foreshore and sea bed and limit damage to the crest if heavy overtopping occurs;
2) The foreshore will be subjected to flooding as the tsunami waves and surge approach; and
3) Facilities located on the landward slope are at risk from tsunami wave run-up and surge.

TSUNAMI RISK REDUCTION MEASURES

Damage due to a tsunami depends on its strength and proximity as well as local bathymetry and topography and location of people, structures and facilities.

It is almost impossible to fully protect people and settlements from major tsunami events. However, various soft and hard measures (independently or in combination) could be adopted to reduce fatalities and damage to key infrastructure.

Some potential measures to reduce the risk of fatalities and damage from major tsunami events are highlighted below:

1) Detection, early warning systems and real-time observation systems are of great importance to save lives and reduce damage;
2) Appropriate awareness and understanding among the general public will reduce death toll;
3) Mitigation plans and evacuation and rescue preparedness by responsible authorities will reduce damage and death toll;
4) Tsunami risk assessment, flood risk and inundation hazard maps;
5) Tsunami shelters are of great use for people to flee;
6) Developing artificial forest such as mangroves and casuarinas of appropriate width behind the shoreline will reduce tsunami wave energy;
7) Maintaining natural sand dunes;
8) Regulations for development in the coastal zone;
9) Saline embankments to prevent salt-water entering fertile lands;
10) Raising ground levels of important structures and facilities such as warehouses, terminals and quays will reduce risk to these being flooded; and
11) Constructing tsunami defence structures such seawalls, dykes, gates, nearshore breakwaters and offshore barriers will reduce risk and damage. However, these structures are huge and are very expensive.

For major coastal infrastructure, the adoption of appropriate design parameters, a proper assessment of structural loads, forces and stability in combination with a detailed understanding of tsunami processes will reduce the level of damage resulting from these events. Furthermore, physical modelling of major coastal and marine structures and mooring systems to investigate their stability under severe conditions will be helpful to reduce damage due to tsunamis.

RISK REDUCTION FROM MUDSLIDES AND LANDSLIDES

High tides during a tsunami may cause floods and submergence of low-lying areas and can lead to mudslides and landslides in mountainous areas causing loss of life and property. Landslides and mudslides are downhill earth movements that can move slowly and cause damage gradually. These can also move rapidly destroying property and taking lives suddenly and unexpectedly. They typically carry heavy debris like trees and boulders which can cause severe damage along with injury or death. Faster movement of mudslides makes these deadly.

There is nothing one can do to prevent a mudslide or a landslide. However, one can always be prepared and take necessary steps to lessen the impact of a mudslide or prevent one altogether. Some guidelines are briefly mentioned below:

1) Carrying out risk assessment;

2) Creating public awareness and practicing an evacuation plan**;**
3) Staying up-to-date on warnings during times of increased risk;
4) Watching for any visible signs such as cracks on land, debris flows or trees tilting or boulders knocking**;**
5) Staying alert and awake;
6) Moving out of the path of the landslide or debris flow; and
7) Some erosion control measures might be helpful (such as installing barrier walls, improving drainage system and planting trees with deep and extensive root systems).

SUMMARY OF FINDINGS

Numerical modelling of the tsunami generated by the volcanic landslide at Anak Krakatau on 22nd December 2018 was carried out in this study. This paper illustrates how a tidal hydrodynamic modelcan be used to simulate the impacts of a tsunami on coastal developments, facilities and communities.

Findings from the tsunami modelling study are summarised below:

a) The volcanic landslide at Anak Krakatau resulted to a maximum tsunami level of about 84m at its south-western coastline.
b) The three neighbouring islands (Sertung Island, Krakatau Island and Krakatau Kitjil Island) were affected the most due to their proximity.
c) The maximum tsunami level at the nearest island (Sertung Island) was 40m and it took only one minute for the tsunami to reach its eastern coastline.
d) The maximum tsunami level at the nearby Krakatau Island was 15m and it took only two minutes for the tsunami to reach its north-eastern coastline.
e) The maximum tsunami level at the nearby Krakatau Kitjil Island was 11m and it took only three minutes for the tsunami to reach its western coastline.
f) The maximum tsunami level at the Sebisi Island was 5.5m and it took 18 minutes for the tsunami to reach its southern coastline.
g) The maximum tsunami level at the Sebuku Island was 2.5m and it took 28 minutes for the tsunami to reach its south-western coastline.
h) The maximum tsunami level at the Panaitan Island was 2.9m and it took 21 minutes for the tsunami to reach its north-western coastline.
i) The maximum tsunami level at the Sangiang Island was 2.4m and it took 40 minutes for the tsunami to reach its north-western coastline.

The methodology described in this paper for modelling the 22nd December 2018 volcanic tsunami at Anak Krakatau Island could also be applied to other sites around the world that are affected by this type of events.

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