Jurnal Teknik Hidraulik
Vol. 11, No.1, Juni 2020

P -ISSN 2087 - 3611
E- ISSN 2580 - 8087
Terakreditasi Kemenristek Dikti
http://jurnalth.pusair-pu.go.id

A SIMPLE RUN-UP CALCULATION OF TSUNAMI KRAKATAU 1883 FOR THE EVALUATION OF NCICD SEAWALL DESIGN

PERHITUNGAN SEDERHANA RAYAPAN GELOMBANG TSUNAMI KRAKATAU 1883 UNTUK EVALUASI DESAIN TANGGUL LAUT PTPIN

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Diterima: 21 Januari 2020; Direvisi: 10 Februari 2020; Disetujui: 13 April 2020

ABSTRACT

NCICD (National Capital Integrated Coastal Development) Seawall is designed mainly to prevent coastal flooding due to sea level rise and land subsidence in North Jakarta. However, the seawall is not designed to countermeasure a tsunami impact. The purpose of this research is to calculate tsunami impact in term of run-up in five strategic locations such as Pelabuhan Muara Angke, Pelabuhan Nizam Zachman, Pantai Ancol, Pelabuhan Tanjung Priok dan Pantai Marunda. In this research, the seawall is evaluated for the worst-case tsunami scenario within the order of Tsunami Krakatau 1883. The source of tsunami is the initial condition from Maeno and Imamura (2011). The propagation from source to coastal area is conducted using the SWASH model. SWASH 2D model shows a good agreement with observation data. Compared to Maeno and Imamura's model, the numerical model shows a better agreement. Then. the verified model is then extracted and the time series is used as an input for the 1D model to calculate the tsunami run-up. The model result shows that Tanjung Priok and Pantai Marunda are the most vulnerable locations with tsunami run-up more than 4.5 m. With the addition of tidal factor, run up in Tanjung Priok and Pantai Marunda exceed the current seawall (with height of 4.8 m) about 0.2 m and 1.3 m respectively.

Keywords: *Seawall, Tsunami, run-up, SWASH model, PTPIN*

ABSTRAK

Dinding Laut PTPIN (Pengembangan Terpadu Pesisir Ibukota Nasional) didesain terutama untuk menanggulangi banjir rob yang diakibatkan oleh kenaikan muka air laut dan penurunan tanah di Jakarta Utara. Akan tetapi, desain tersebut belum mempertimbangkan penanggulangan dampak tsunami. Tujuan penelitian ini adalah untuk menghitung dampak tsunami dalam bentuk rayapan gelombang di beberapa lokasi strategis yaitu Pelabuhan Muara Angke, Pelabuhan Nizam Zachman, Pantai Ancol, Pelabuhan Tanjung Priok dan Pantai Marunda. Dalam penelitian ini, dinding laut didesain untuk skenario terburuk yaitu Tsunami Krakatau 1883. Sumber tsunami yang digunakan adalah kondisi inisial dari Maeno dan Imamura (2011). Penjalaran tsunami dari sumbernya menuju area pantai disimulasikan menggunakan model SWASH. Model ini menunjukkan hasil verifikasi yang baik terhadap data observasi dan menujukkan kemiripan yang lebih baik dibandingkan hasil model Maeno dan Imamura (2011). Model yang sudah terverifikasi kemudian diekstrak dan timeseries yang diperoleh digunakan sebagai input model 1D untuk menghitung rayapan tsunami. Hasil model menunjukkan bahwa Tanjung Priok dan Pantai Marunda merupakan lokasi yang paling rentan dengan rayapan lebih dari 4,5 m. Dengan tambahan faktor pasang surut, rayapan di Tanjung Priok dan Pantai Marunda lebih tinggi sekitar 0,2 m dan 1,3 m secara berturut-turut dari dinding laut yang tingginya 4,8 m.

Kata Kunci: *Dinding laut, tsunami, rayapan, model SWASH, PTPIN*

DOI https://doi.org/10.32679/jth.v11i1.633

INTRODUCTION

Tsunami is the scientific term for a physical phenomenon known as "seaquake", "high-tide wave" and "seismic sea wave" in the past. In the ancient literature, it is mentioned as "zeebeben" or "maremoto". However, the term "tsunami" is derived from Japanese words that means "harbour wave". This term is now widely accepted in scientific community to define a wave or series of waves in wave train generated by the sudden, vertical displacement a column of water (Bryant,2008). Furthermore, tsunami is commonly characterized by wave celerity, C = 200 m/s and wave length, L = 1000 km which is more than 4 km, the typical depth in World Ocean (Levin and Nosov,2009).

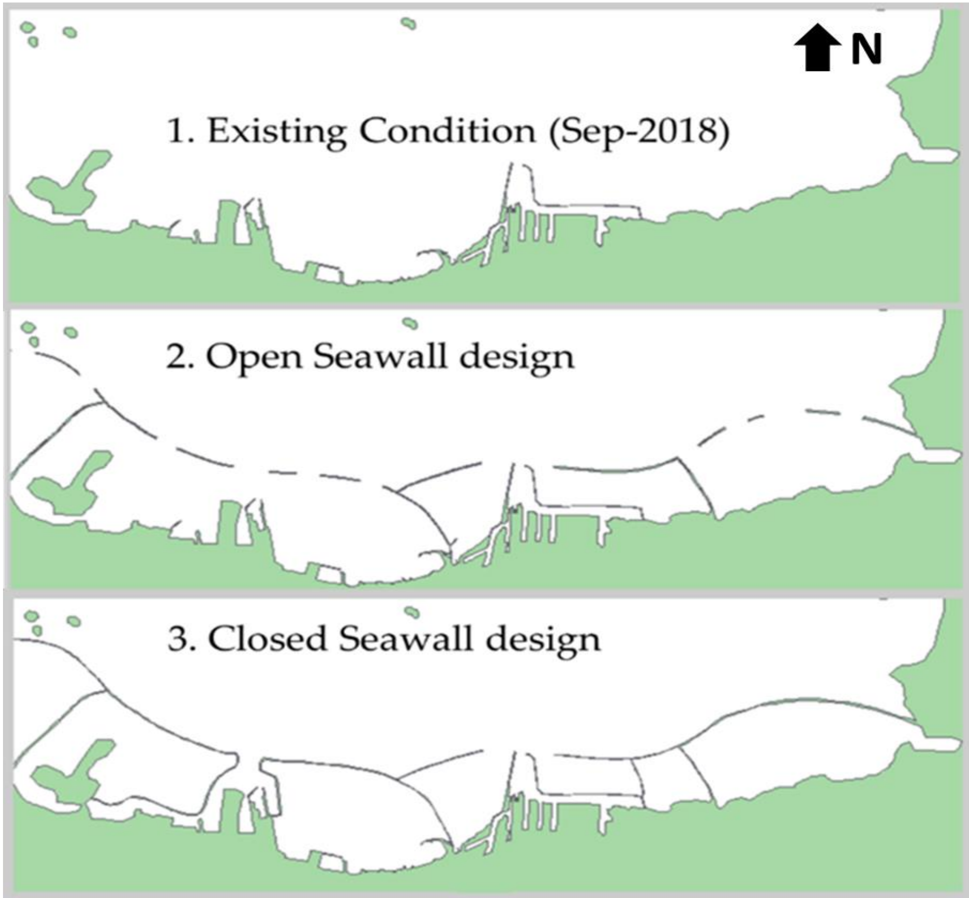
The generation of tsunami can be categorized into four mechanism. First, seismic-related activities such as landslides and earthquakes. The example is Tsunami Aceh in 2004. Second, the volcanogenic mechanism due to the eruption of above or under water mount. This is the case for Tsunami Krakatau 1883. The last two mechanisms are meteorological and cosmogenic source. Tsunami due to these two mechanisms is not common but has been actively discussed considering its possible catastrophic impacts.

In this paper, the discussion will be focused on the Tsunami Krakatau 1883. This volcanogenic tsunami has been studied extensively for more than a century following the event. The Tsunami is originally reported by Verbeek (1884) and his team based on their field observation. An extensive and illustrated report edited by Symons (1888) is then published to give a complete account of Tsunami Krakatau 1883 from the perspective of geology, geophysics (terrestrial magnetism and electricity) and meteorology including special chapter for air-sea wave interactions. The report described that the Tsunami preceded by the explosion of the Mount Poerbawatan, Mount Danan and Mount Rakata subsequently. The explosion of the first two mounts only cause minor tsunamis while the third mountain generated a tsunami known as The Principal Tsunami which is the biggest of all.

The source of the Principal Tsunami is debated among scientist. According to Latter (1981), there are ten possible sources for a volcanogenic tsunami as summarized by Bryant (2008) in Table 1. According to Maeno and Imammura (2011), the number of possible tsunami sources is reduced to four. First, the caldera formation based on the research of Verbeek (1884) and Francis (1985). Second, the submarine explosion. This hypothesis is supported by the work of Yokoyama (1981, 1987) and Nomanbhoy and Satake (1995). Pyroclastic flow is also considered as the generating mechanism (Latter,1981; Self and Rampino,1981). The last mechanism, lateral blast or basal surge is also proposed. However, Francis (1985) suggests that the mechanism is not efficient. Hence, only the first three hypotheses are possible to generate the Principal Tsunami. Maeno and Imamura (2011) reproduces the tsunami with the three sources and compare the result. The numerical model shows that the result with pyroclastic flow sources agree with the observation data better than the other two sources.

In this research, the propagation of the tsunami from the source is simulated using pyroclastic flow as the generating mechanism as suggested by Maeno and Imammura (2011). The wave propagation is simulated using the SWASH model developed by TU Delft. This numerical model is based on non-shallow water equation. The focus of this research is the propagation of the tsunami in Jakarta Bay where Project NCICD (National Capital Integrated Coastal Development) or PTPIN (Pengembangan Terpadu Pesisir Ibukota Nasional) is being conducted. The giant seawall is mainly constructed to prevent the seawater flooding into the North Jakarta area (Figure 1). A general overview of the project is provided by Putuhena (2016). However, the seawall is designed without taking tsunami into account. A previous attempt to address this problem is already made by Bachtiar et al. (2017). The urgency is heightened with the event of Tsunami Sunda Strait 2018 caused by the volcanic activity of Mount Anak Krakatau. Badriana et al. (2017) attempt to calculate the tsunami run-up on NCICD seawall from hypothetical source of Mount Anak Krakatau. Reliable calculation of the tsunami run-up is made in this research in two aspects. First, the source of tsunami represents the physical process of pyroclastic material-seawater interaction. This is compared to mathematical inverse function used in the previous research. Second, the numerical model is verified with observation data as opposed to a research for a hypothetical condition. In addition, Tsunami Krakatau 1883 is one of the tsunami events with various and complete data made possible especially from early observation by Verbeek (1884). The calculation for NCICD seawall is argued still valid with the assumption that the tsunami wave height of Anak Krakatau will not be higher than that of the Krakatau 1883 event. So, the seawall is designed for the worst-case scenario of tsunami within an order of Krakatau 1883 magnitude.

The novelty of this research is the calculation of the tsunami run-up in several strategic points in Jakarta Bay such as Pelabuhan Muara Angke, Pelabuhan Nizam Zachman, Pantai Ancol, Pelabuhan Tanjung Priok dan Pantai Marunda. The run-up calculation will be considered as important parameter in designing the NCICD. The design aspect is about whether the current design is sufficient enough to deal with an extreme case such as Tsunami Krakatau 1883 in term of wave run-up.



Sumber: Bachtiar et al. ,2017

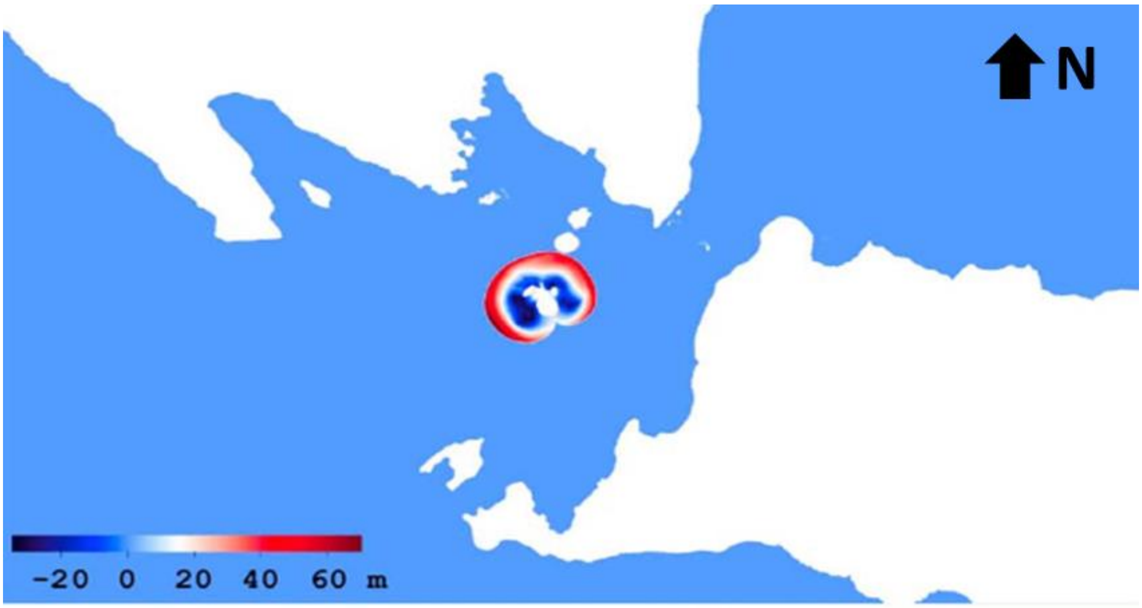
Figure 1 Design of The NCICD Seawall

Table 1 The source of volcanogenic tsunami according to Latter (1981) in Bryant (2008)

Mechanism	Percentage of Events	Examples	Date	Height (m)
Volcanic earthquakes	22.0	New Hebrides	January 10, 1878	17
Pyroclastic flows	20.0	Ruang, Indonesia Krakatau, Indonesia	March 5, 1871 August 26-27, 1883	25 >10
Submarine explosions	19.0	Krakatau, Indonesia Sakurajima, Japan	August 26-27, 1883 September 9, 1780	42 6
Caldera formation	9.0	Ritter Island Krakatau, Indonesia	March 13, 1888 August 26-27, 1883	12-15 2-10
Landslides	7.0	Unzen Volcano, Japan	May 21, 1792	6-9
Basal surges	7.0	Taal Volcano, Philippines	Numerous	?
Avalanches of hot rock	6.0	Stromboli, Italy	Numerous	?
Lahars	4.5	Mt. Pelee, Martinique	May 5, 1902	4.5
Atmospheric pressure wave	4.5	Krakatau, Indonesia	August 26-27, 1883	<0.5
Lava	1.0	Matavanu Volcano, Samoa	1906-1907	3.0-3.6

METHODOLOGY

In general, there are three sequence of tsunami research. First, the source. Second, the propagation. Last, the effect in the coastal area. The source of Tsunami Krakatau 1883 is debated among scientist but Maeno and Imammura (2011) shows that the pyroclastic flow mechanism lead to a better agreement with observation data. In this research, the initial condition for the pyroclastic flow is reproduced from Maeno and Imammura (2011). Figure 2 shows the water elevation resulted from the pyroclastic flow to the vicinity of Krakatau seawater. The figure is digitized to acquire the water elevation data.



Sumber: Maeno and Imammura,2011

Figure 2 Water elevation resulted from the flowing of pyroclastic material of Mount Krakatau

SWASH is used as the numerical model to simulate the propagation of the tsunami. Bathymetric data is from BATNAS (Batimetri Nasional) which has data resolution, 185 m x 185 m. The modelling scheme can be divided into two phases. Phase 1 is 2D modelling from the source to Jakarta Bay. The general parameter for the model set up is shown in Table 2. It is important to note here that SWASH is not spesifically designed to simulate tsunami wave. So, there are adjustments for initial condition and boundary condition. To generate the tsunami, there are no special feature in the model. Tsunami initial condition is defined as water level which, in this case, is taken from Maeno and Imammura (2011). Open boundary condition is defined as weakly reflective. Moreover, each open boundary in the model is equipped with numerical layer to absorb the reflection using SPONGE feature. To have a better outlook of the model settings can be accessed in the user manual SWASH (2019). The 2D model is then verified with observation data and also compared to the Maeno and Imammura (2011). The purpose is to understand the model capacity to represent the physical process of the tsunami propagation. If the model result is considered good enough, modelling is continued to phase 2.

Table 2 Model Set up for SWASH 2D Model

Grid	400 m x 400 m
Time Step	0.05 second
Running Time	6 hours
Boundary Condition	Weakly Reflective
Sponge Layer	0.2 deg (22.264km)
Bottom Friction (Manning)	0.025

Phase 2 is 1D modelling of the tsunami propagation from source point outside Jakarta Bay to the five strategic points. The model set-up is shown in Table 3. The modelling goal is to calculate the effect of tsunami in Jakarta Bay coastal area. In this case, the effect to be studied is the tsunami wave run-up. Figure 3.a shows the illustration for 1D propagation of the tsunami wave. Timeseries data from the 2D model is extracted and to be the tsunami source for 1D model. The water level from the source is defined as the west boundary in the model. Bathymetric data in 1D model is a cross section data from the source point to the determined strategic locations which are Pelabuhan Muara Angke, Pelabuhan Nizam Zachman, Pantai Ancol, Pelabuhan Tanjung Priok dan Pantai Marunda. The general parameter for the 1D model is overall the same with that of 2D model except for the grid size and the bottom roughness. Grid size in the model is 200 m. The manning coefficient for sea bottom is 0.025 while varying coefficient from 0.03 to 0.3 is used to represent the dryland. It is important to note here that the dryland is only represented by the manning coefficient. Since this is only a simple calculation of run-up, the land topography and building distribution parameter is not taken into account. There are three observation of run-up in the dryland. Point A is located in the coastline or 0 m from the coastline. Both Point B dan C is 2000 m and 4000 m respectively from coastline (Figure 3.b)

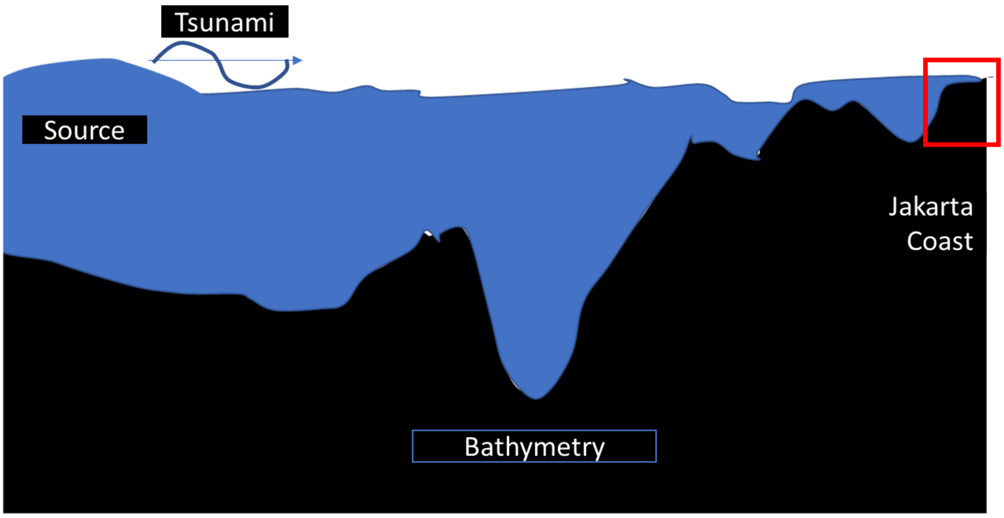
Table 3 Model Set up for SWASH 1D Model

Grid	200 m
Time Step	0.05 second
Running Time	6 hours
Boundary Condition	Weakly Reflective (West) Radiation (East)
Bottom Friction (Manning)	0.025 (wet) 0.03 to 0.3 (dry)

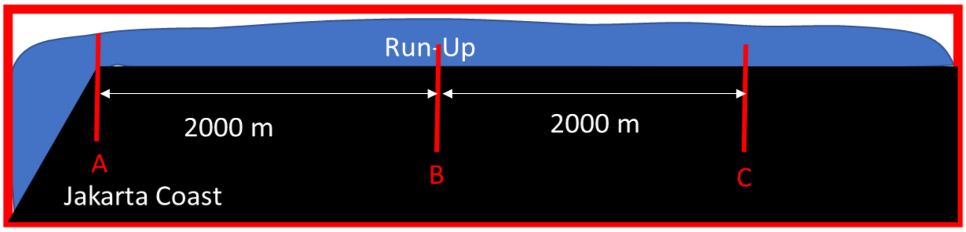
RESULTS AND DISCUSSION

The initial condition provided by Maeno and Imamura (2011) gives a good input for the numerical in order to obtain a realistic representation of the real Tsunami Krakatau 1883. The source is considered good since the initial water elevation resulted from a geophysical process of interaction between the pyroclastic flow and seawater.

Figure 4 shows comparison of the model result after 30 minutes between Maeno and Imamura (3.a) and 2D SWASH model (3.b). A visual comparison between the two model give obvious similarity and distinction. The red circles mark several areas which have the same resemblance with Maeno and Imamura (2011) model. It means that the SWASH model has the same travelling time. On the other hand, the vanilla circle means there is a different propagation in that area. This is perhaps due to the higher coastal reflection in the SWASH model.



(a)



(b)

Figure 3 Illustration of (a) Propagation of tsunami from source point outside Jakarta Bay and (b) tsunami run-up in Jakarta coast

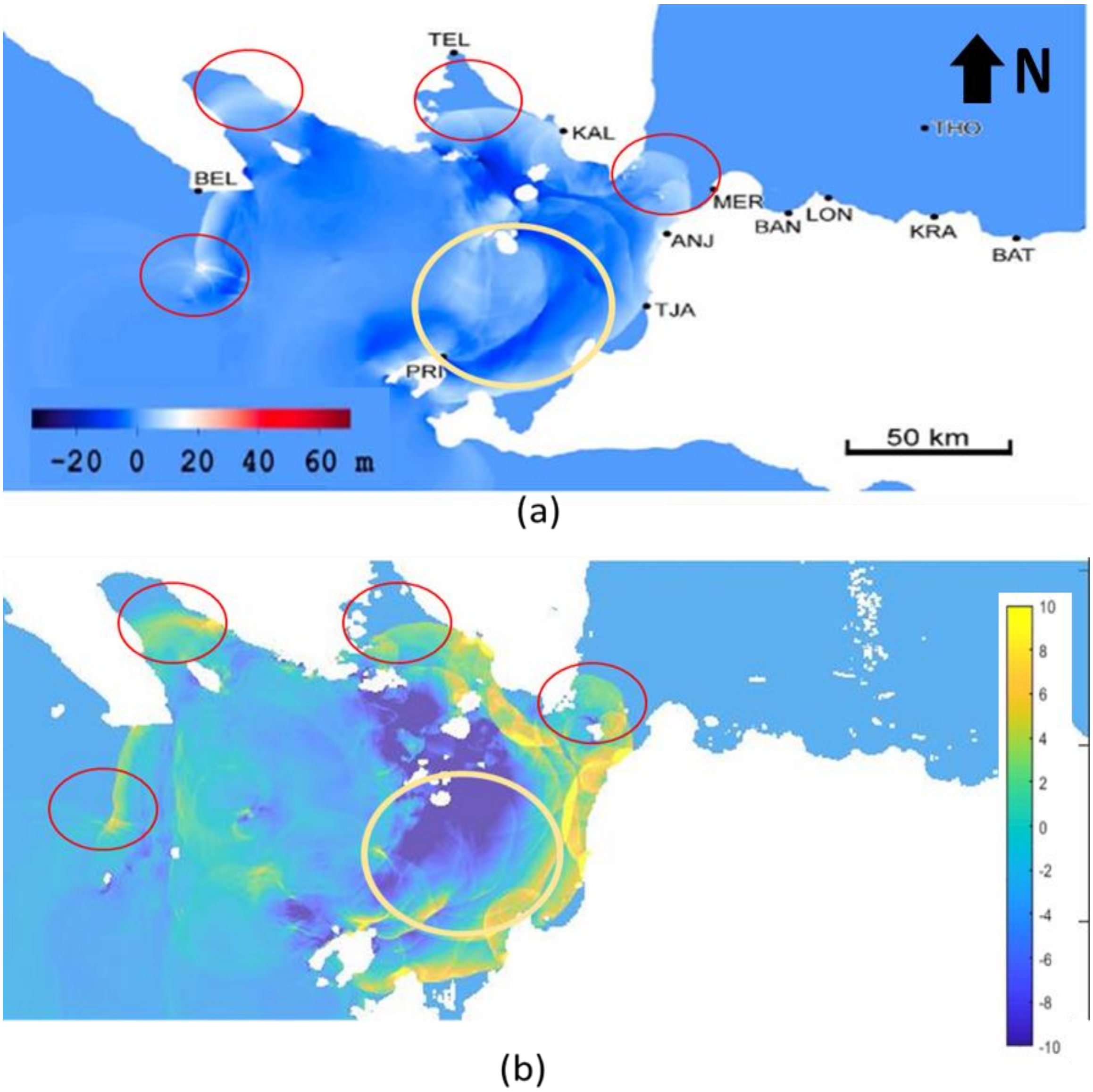


Figure 4 Comparison Propagation after 30 minutes in (a) Maeno and Imammura 's model; (b) SWASH mode

The robustness of the SWASH model is then assessed further by verifying the model result with the observation data. There are two data used to be a comparison: data by Verbeek (1884) and tide gauge. Both observation data are in Tanjung Priok. However, there is no detailed coordinate of the observation point. Figure 5 shows the comparison between the numerical result and the observation data. The comparison is summarized in Table 4.

Supplementary 3 is provided to have better understanding of the table. The first parameter to assess the figure is the wave amplitude. There are two observation data. So, data with more resemblance to model result will be used as comparison. First, the wave crest of the first tsunami wave. Compared to Verbeek (1884), SWASH overestimate the amplitude 0.23 m while the value is underestimated 0.13 m by Maeno and Imammura (2011). In this case, SWASH is only about 5 % less accurate. For the wave through, both models have more than 20 % error for the amplitude. The amplitude for wave crest is 0.89 m. SWASH underestimates the result with 6 % error while Maeno and Imamura (2011) has 4 % error.

Table 4 Summary of Model and Observation Verification and Comparison

Observation Data / Model	First Wave				Second Wave	
	Wave Crest		Wave Through		Wave Crest	
	Amplitude	Arrival Time	Amplitude	Arrival Time	Amplitude	Arrival Time
Tide Gauge	0.89 m	02h17m	0.92 m	02h54m	0.89 m	04h10m
Verbeek (1884)	1.58 m	02h17m	3.56 m	02h54m	1.27 m	04h10m
SWASH Model	1.81 m	02h01m	1.45 m	03h07m	0.83 m	04h40m
Maeno and Imamura (2011)	1.45m	02h30m	1.17 m	02h59m	0.93 m	03h48m

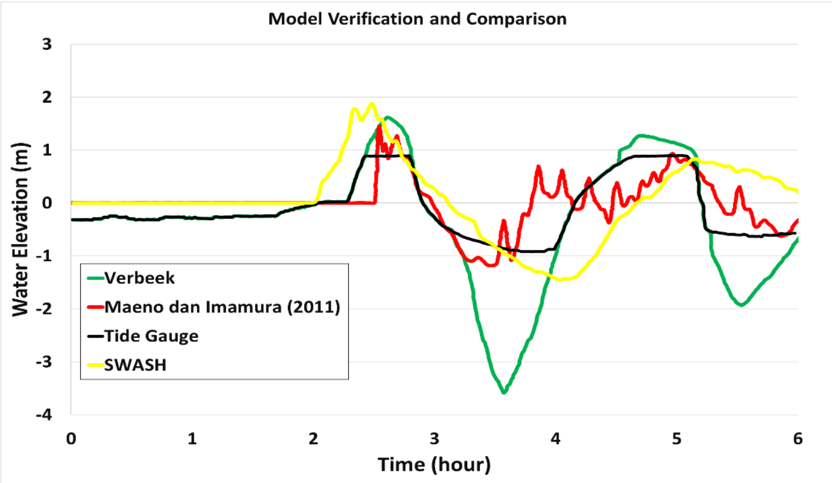


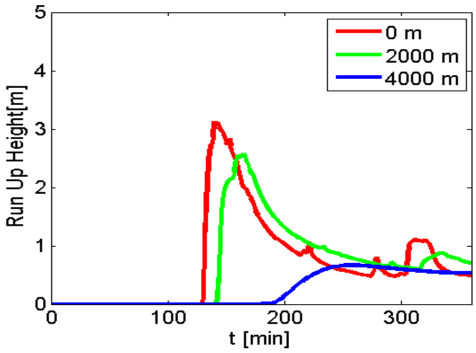
Figure 5 SWASH 2D model verification

Another parameter to be analysed is the arrival time. Both Verbeek data and tide gauge data has the same arrival time. For the wave crest of the first tsunami wave, the time is 02 hour and 17 minutes. SWASH prediction shows earlier arrival time about 16 minutes while there is 13 minutes lag time for Maeno and Imamura (2011). The arrival time for wave through is lagged about 13 minutes and 8 minutes for SWASH and Maeno and Imamura (2011) respectively. The wave crest of the second wave I is predicted by Maeno and Imamura 22 minutes earlier than the observation while there is 30 minutes lag for SWASH.

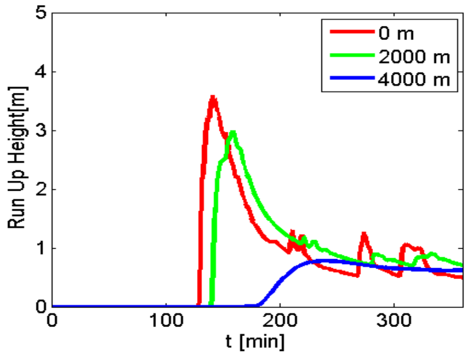
The capability SWASH model to simulate the tsunami can be inferred from the analysis of the two parameters. SWASH can predict the wave amplitude as good as Maeno and Imamura (2011). The prediction is only about 5 % less accurate with the exception for the wave through. As for arrival time, the estimation by SWASH has error about 8 minutes. In general, the difference between the two models is most obvious for the tsunami wave through. The result of Maeno and Imamura (2011) is disturbed with significant noise while SWASH has a significant longer period for the wave through. This difference is possible due to two reason. First, the bathymetric data used is different. Second, the model set-up especially tuning parameter such as bottom roughness can give a different end-result.

Differences between the two models also can be analysed further using Root Mean Square Error (RMSE). With respect to data from tide gauge, SWASH model and Maeno and Imamura (2011) have RMSE 0.4456 and 0.6943 respectively. On the other hand, the RMSE value is higher if the Verbeek data is used. The error for Maeno and Imamura (2011) is 0.9491 while it is 1.1013 for SWASH model. From this, it can be inferred that SWASH can still give a good simulation with slighty higher error than that of Maeno and Imamura (2011).

Timeseries is extracted from the verified SWASH 2D as an input for the 1D model. This model is specifically set up for run-up calculation. The wave run up for five strategic locations in Jakarta Bay is described in Figure 6. The red line describes tsunami run-up in coastline (Point A). The green line represents Point B which is located 2000 m from coastline while Point C (blue line) shows run up for a point with distance of 4000 m from coastline.



(a)



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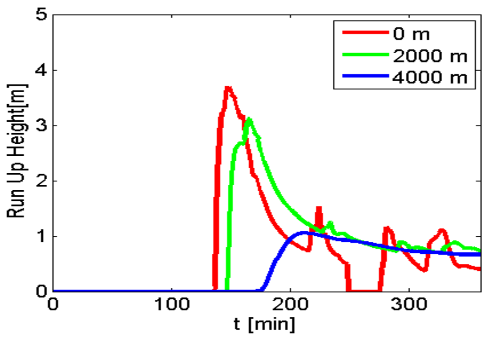

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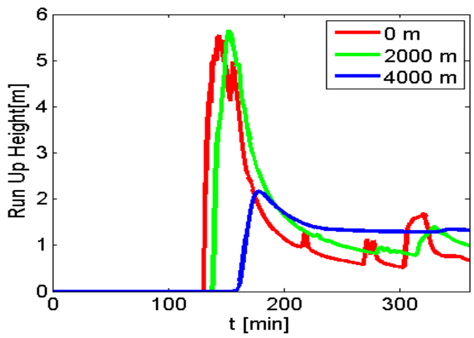

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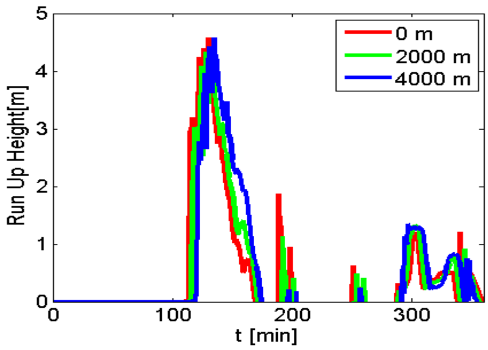

(e)

Figure 6 Tsunami wave run up as a function of time in (a) Muara Angke;(b) Nizam Zachman; (c) Pantai Ancol; (d) Tanjung Priok; (e) Pantai Marunda

In general, the run up has distinguishable pattern. Point A has the highest tsunami run up. Point B is observation point with the second highest run-up height while the run-up for point C is the lowest. However, this is only true for Muara Angke, Nizam Zachman and Pantai Ancol. The pattern is different for Tanjung Priok and Pantai Marunda. The former has nearly the same run up height in observation point, A and B while the run-up height for Pantai Marunda is nearly the same for all observation point.

Table **5** is provided to better understand this pattern. The maximum tsunami run-up height for the first three strategic locations is ranged from 3.1 to 3.6 m in observation point A. The height is about 0.5 to 0.6 m lower in point B. Point C has run-up height about 1 m or lower. Tanjung Priok has the highest run up height of all the locations. It is about 5.5 m but the run-up height for point B in the location is higher than that of point A. For point C, the run-up is about 2 m which is twice the run up of point C in Muara Angke, Nizam Zachman and Pantai Ancol. The tsunami run-up for Pantai Marunda is the second highest, range from 4.4 to 4.5 m. However, the height is nearly similar in point A, B and C. Bathymetry may be the cause for the high run up in Tanjung Priok and Pantai Marunda.

Overall, the analysis of run up shows the strategic locations can be defined as two categories. The tsunami run-up for Muara Angke, Nizam Zachman and Pantai Ancol is lower than 3.7 m. On the other hand, Tanjung Priok and Pantai Marunda have run up higher than 4.5 m. The current height design for the seawall is 4.8 m. From this, the first three locations can be defined as less vulnerable locations or blue area while the other two are categorized as highly vulnerable area or red area. Both Tanjung Priok and Pantai Marunda are vital for economic activity either for trade or tourism. In addition, research of Lee and Shimoyama (2016) suggests that tsunami-tide interaction can cause 0.5 increase in tsunami wave height. Therefore, the run-up can be higher 0.5 m at maximum. The tidal factor increases the vulnerability of Tanjung Priok and Pantai Marunda against tsunami.

This calculation can be served as important parameter for NCICD seawall design. With addition of the tidal factor, the maximum wave run up for the blue are is maximum about 4.2 m. The current seawall still can anticipate this. On the other hand, the tidal factor makes the run up even higher for the red area. The tsunami run-up exceeds the seawall about 0.2 m and 1.3 m for Pantai Marunda and Tanjung Priok respectively. Extra countermeasure is needed to secure this red area. Further research is needed to detail the run-up calculation with considering the land topography and building distribution. In addition, tsunami propagation in coastal area such as Jakarta Bay is complex physical processes. Bathymetric data with higher resolution is needed to obtain model result with higher accuracy. Another important aspect to be considered is the high traffic of ship navigation and complicated reclamation. Tsunami interaction with these two aspects need to be studied furthermore.

Table 5 Maximum wave run-up height based on SWASH 1D model

Strategic Locations	Maximum Wave Run-up Height (m)		
	Point A (0 m from coastline)	Point B (2000 m from coastline)	Point C (4000 m from coastline)
Muara Angke	3.124 m	2.574 m	0.667 m
Nizam Zachman	3.589 m	2.988 m	0.778 m
Pantai Ancol	3.695 m	3.109 m	1.056 m
Tanjung Priok	5.543 m	5.656 m	2.161 m
Pantai Marunda	4.570 m	4.420 m	4.574 m

CONCLUSION

Tsunami Krakatau 1883 is simulated with the initial condition from Maeno and Imammura (2011). The SWASH model still has considerable agreement with observation data. Compared to Maeno and Imamura (2011), the wave amplitude is predicted by SWASH with less accuracy of 5 % while the time arrival is simulated with 8 minutes error. Different result between the model maybe due to different bathymetric data and model set up. Time series data is extracted from the verified model to be an input for the 1D model to calculate the tsunami run-up. The run-up analysis shows that Muara Angke, Nizam Zachman and Pantai Ancol as less vulnerable to tsunami or categorized as blue area with run-up height lower than 3.7 m. On the other hand, Tanjung Priok and Pantai Marunda, defined as red area are highly vulnerable with run up more than 4.5 m. The NCICD seawall with height of 4.8 m can safely secure the blue area while extra countermeasure is needed to defend the red area. The tidal factor may increase the vulnerability of the area with the addition of 0.5 m of tsunami height. This study may provide overestimated tsunami run up in the strategic locations due several limitations. Factor such as land topography, building distribution and detailed physical processed between tsunami and harbour are not taken into account and may lead to lower estimation. Even so, the crucial importance is that Tanjung Priok and Pantai Marunda are more vulnerable than other locations due the bathymetric feature. Further study that consider detailed run up processes is needed to estimate more accurate run up.

ACKNOWLEDGEMENT

The author wishes to acknowledge the the principal scientist in The Experimental Station of Coastal Engineering, Research Center for Water Resources, Ministry of Public Works and Housing, Republic of Indonesia for their supervision during this research.

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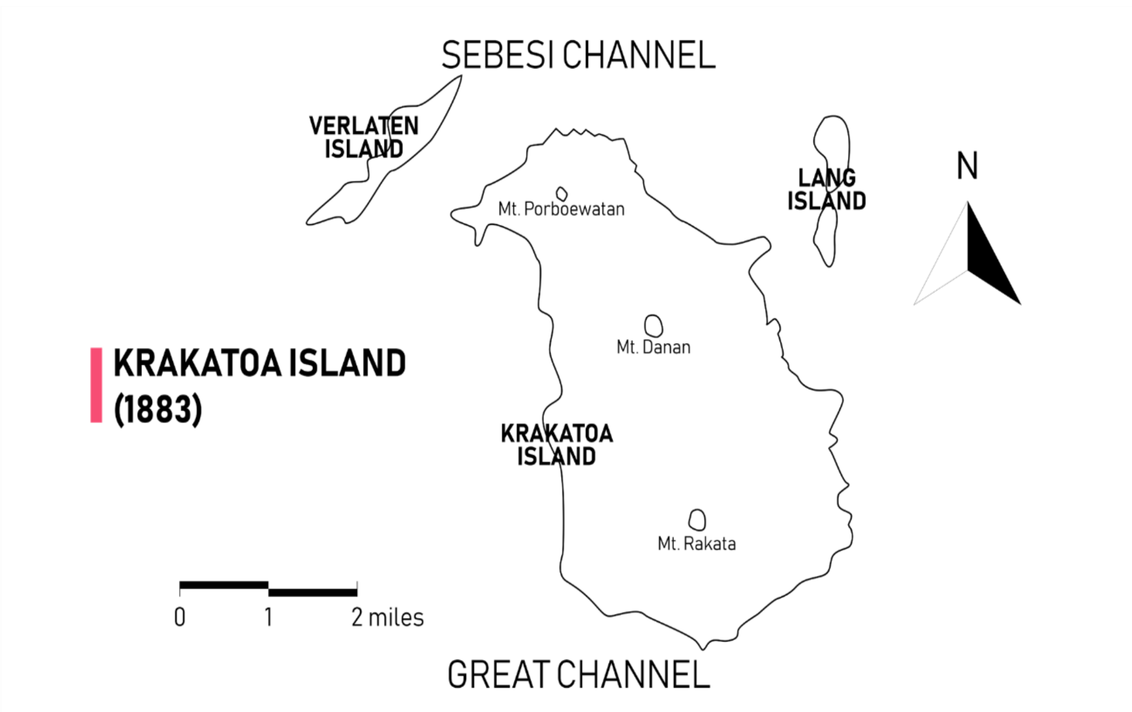
Supplementary 1: Krakatau 1883 Chronology

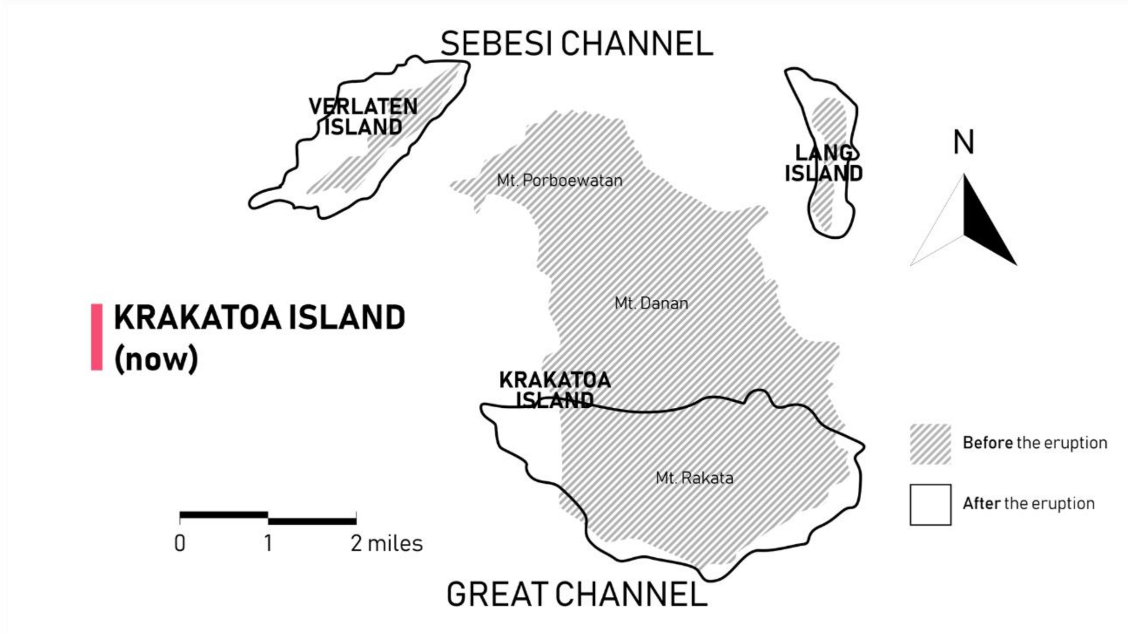
The illustrated view of Krakatau Island before the eruption

The map sketch of Krakatau Island before eruption



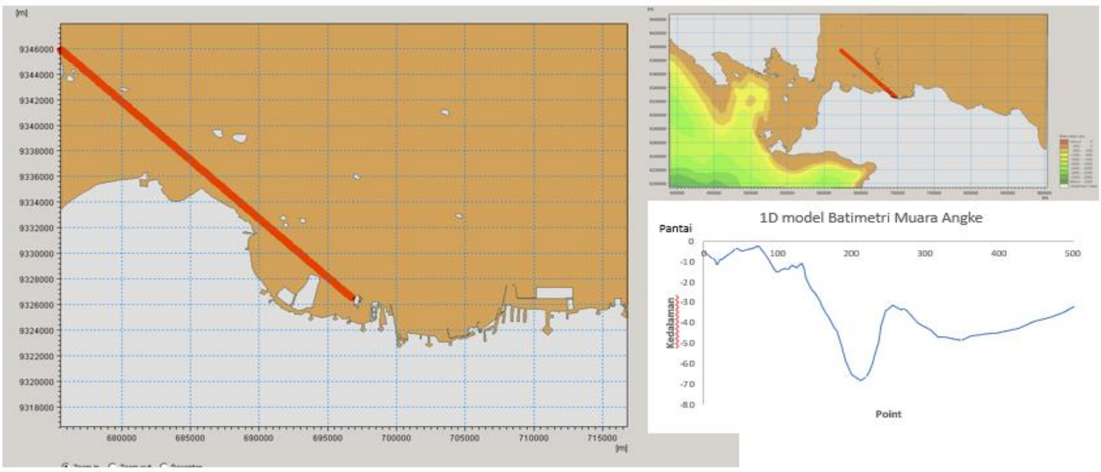
According to Verbeek, the Krakatau 1883 event chronology is
- May 1883: Mount Krakatau became active
- 26 Agustus 1883: Huge explosion occurred and volcanic cloud formed
- 27 Agustus 1883 05.28: Mount Poerbawatan destroyed
- 27 Agustus 1883 06.36: Mount Danan exploded
- 27 Agustus 1883 09.58: Mount Rakata destroyed an caused The Principal Tsunami
- 27 Agustus 1883 12:30: The tsunami arrived in Jakarta Bay

The sketch map after the eruption

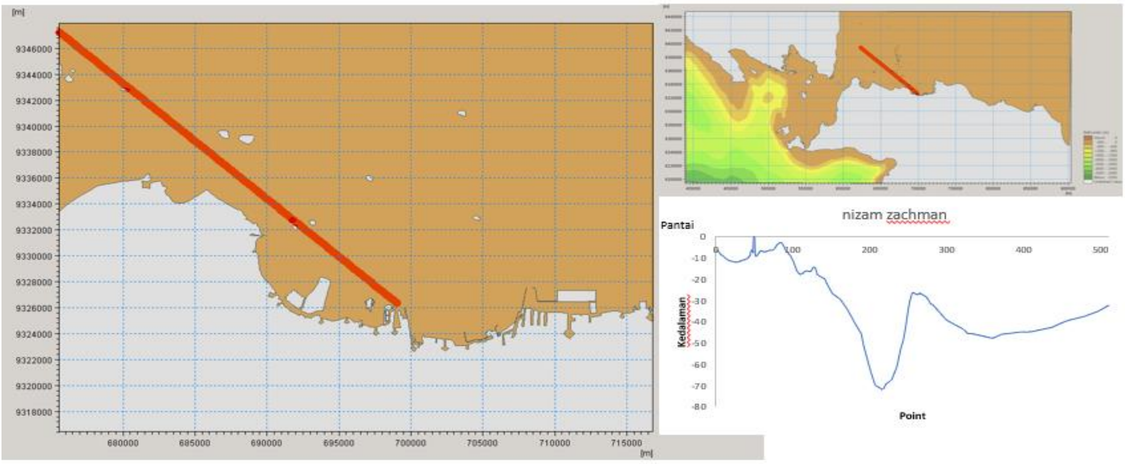


Supplementary 2: Bathymetric crossection for the five strategic locations

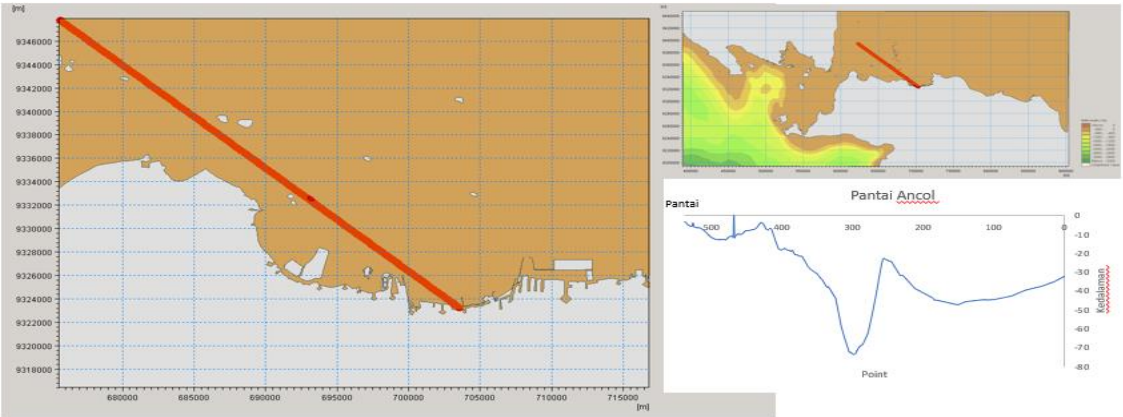
Muara Angke



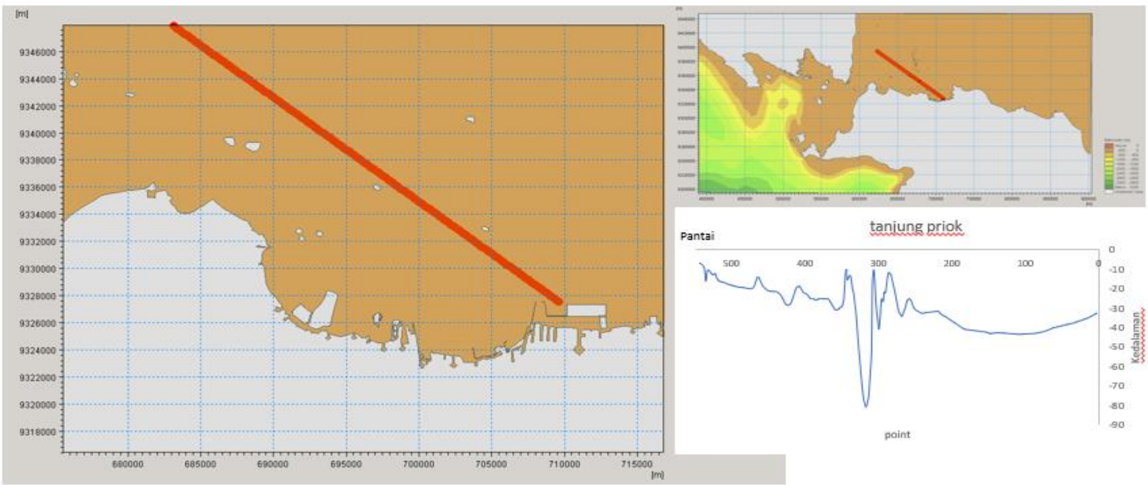
Pelabuhan Perikanan Samudera **Nizam Zachman**



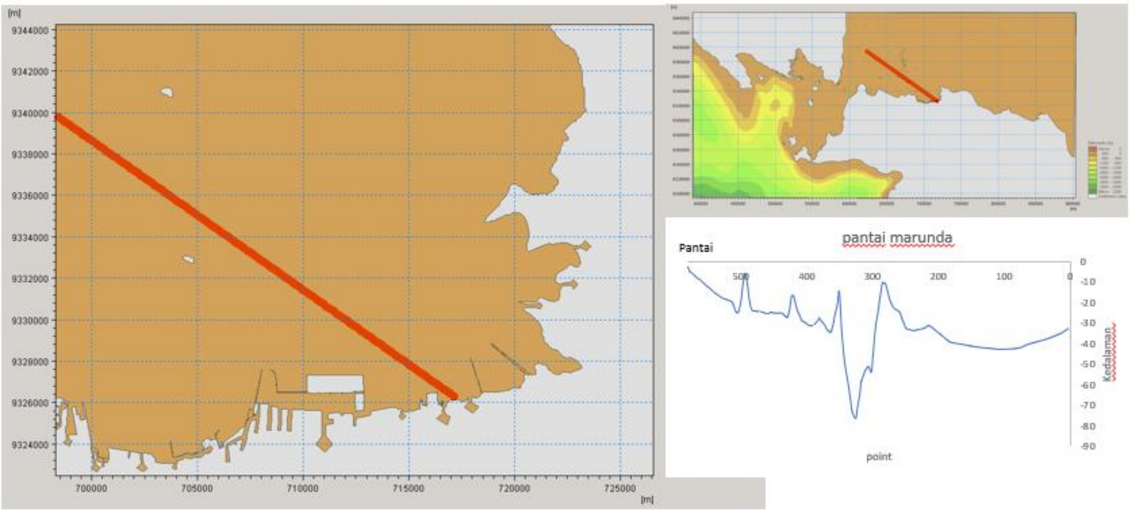
Pantai **Ancol**



Tanjung Priok



Pantai **Marunda**



Supplementary 3: Assessment of Amplitude and Arrival Time for Figure 5 Model Verification and Comparison

Tsunami Krakatau 1883 observed in Jakarta Bay is characteristically consists of two main waves. The first wave is a complete one (wave crest and wave through) while the second wave only has the wave crest. There are two parameters to compare each set of observation data/model result: The wave amplitude and arrival time. The figure below illustrates how both parameters is calculated to produce Table 4. I0n general, wave amplitude is calculated from the highest water elevation compared to Mean Sea Level (MSL. Arrival time is determined from the time when the water elevation begin to rise up or go down from MSL.
Box 1: Arrival time for wave crest of the first wave
Box 2: Wave amplitude for wave crest of the first wave
Box 3: Arrival time for wave through of the first wave
Box 4: Wave amplitude for wave through of the first wave
Box 5: Arrival time for wave crest of the second wave
Box 6: Wave amplitude for wave crest of the second wave