Citation: Putra Y. M. K., Y. Fujii (2022), Slip distribution of the 2006 West Java earthquake by inversion of tide gauge data using phase-corrected Green's functions, Synopsis of IISEE-GRIPS Master's Thesis.

# SLIP DISTRIBUTION OF THE 2006 WEST JAVA EARTHQUAKE BY INVERSION OF TIDE GAUGE DATA USING PHASE-CORRECTED GREEN'S FUNCTIONS

**Yogha Mahardikha Kuncoro Putra**[1] **Supervisor: Yushiro FUJII**[2]
**MEE21721**

**ABSTRACT**

The 2006 West Java earthquake was one of the devastated tsunami events in Indonesia. In this study, we re-estimated the slip distribution of the 2006 earthquake by tsunami waveform inversions of tide gauge data using phase-corrected Green's functions. Then, to evaluate our slip models, we performed tsunami inundation simulations and computed the K and $\kappa$ numbers.

The slip distribution obtained with an assumed rupture velocity of 1.25 km/s shows that the maximum slip was around 5.9 to 11.8 m in the shallower part near the trench. The total source length was 300 km, while the seismic moment calculated from this source was 6.4 x $10^{20}$ Nm (Mw = 7.8). The dominant shallow slips in our slip models support the previous study that classified the 2006 earthquake as a tsunami earthquake event.

We successfully updated the source model based on the previous study, although we found that the K and $\kappa$ numbers of our slip models were unsatisfied with recommended standard values. We also found that the tsunami inundation simulation results were still underestimated around the Pangandaran, Cilacap, and Binangun. One possible reason for the underestimation at some survey points may be local (near coasts) bathymetry effects. Furthermore, we tried to assess the possible locations of the landslide source in front of the Permisan region. We found that a near-coast landslide source looks better to reproduce the extreme tsunami heights in the Permisan region. However, a landslide source far from the coastline was preferable to reproduce the tsunami heights for the western and eastern sides. Nevertheless, further studies are needed to determine more accurate landslide sources.

**Keywords:** 2006 West Java earthquake, Tsunami waveform inversion, Tsunami inundation simulation.

## 1. INTRODUCTION

Indonesia is a country that has quite complex tectonic conditions and lies on the boundaries of major tectonic plates; at least five large tectonic plates interact and drive seismotectonic activity around Indonesian territory. One Indonesia region with a historical record of big earthquakes and tsunamis is Java Island. According to the BMKG tsunami catalog, in the last 30 years, there have been four earthquake events that caused tsunamis around Java Island. Among the four tsunami events, the one that caused the most casualties was the 17 July 2006 West Java earthquake and tsunami. According to the United States Geological Survey (USGS) catalog, the epicenter of the 2006 earthquake was located at 9.284$^{o}$ S and 107.419$^{o}$ E, and the depth was 20 km. After this earthquake and tsunami event, Fritz et al. (2007) and Tsuji et al. (2021) conducted field surveys by interviewing local people along 200 km of coast northeast of the epicenter, and they reported that the residents felt slight or no shaking. The large tsunami having slight, or no ground shaking was typical of a tsunami earthquake. Using six tide gauge

[1] Indonesian Agency for Meteorology, Climatology, and Geophysics-BMKG.
[2] International Institute of Seismology and Earthquake Engineering (IISEE), Building Research Institute (BRI).

data, Fujii and Satake (2006) estimated the slip distributions on the faults of the 2006 event. However, their slip distribution was underestimated to reproduce the measured tsunami heights.

There was a systematic delay in travel times and the polarity reversals of the first waves between the observed tsunami waveforms and simulation results at far-field stations since the case of the 1960 Chile earthquake. Watada et al. (2014) noticed that the effects of solid earth's elasticity, seawater compressibility, and potential gravitation variation associated with mass motion during the tsunami propagation caused these problems. They proposed a phase-correction method for Green’s functions to solve the problems. After this study, there was an improvement to this method by adding the effects of ocean density stratification and actual ray path (Ho et al., 2017). This phase correction method has been applied to conduct tsunami waveform inversions using far-field data to construct source models. In this study, we re-estimate the source of the 2006 earthquake by tsunami waveform inversions of tide gauge data including far-field stations using the phase-corrected Green’s functions.

## 2. DATA

We collected the tide gauge data at 19 stations around the Indian Ocean. We obtained the data by sending requests and downloading the data from the website. The locations of tide gauge stations are shown in Figure 1. The tide gauge records contain tsunami signals and ocean tides. In this study, to prepare the observed tsunami waveforms we used a fitted polynomial function to estimate the effects of ocean tide and then remove them from the original waveform.

To prepare the bathymetry data for tsunami simulations, we used bathymetry data from GEBCO 2021 with a spatial resolution of 15 arc-sec, about 0.463 km and another bathymetry data from BATNAS with a resolution of 6 arc-sec, about 180 m. We also used topography data from FABDEM with a resolution of 1 arc-sec, about 30 m. In order to perform numerical simulations, we need to convert bathymetry data to grid files using GMT software. However, the processed bathymetry grid data from GMT coastline database could not reproduce the actual coastline's shape well. Because of that, we slightly modified the bathymetry grid values to express the shoreline's shape for obtaining more accurate locations of the tide gauges, referring to Prototype Global Shoreline Data from the National Oceanic and Atmospheric Administration (NOAA) and Google Satellite Data.

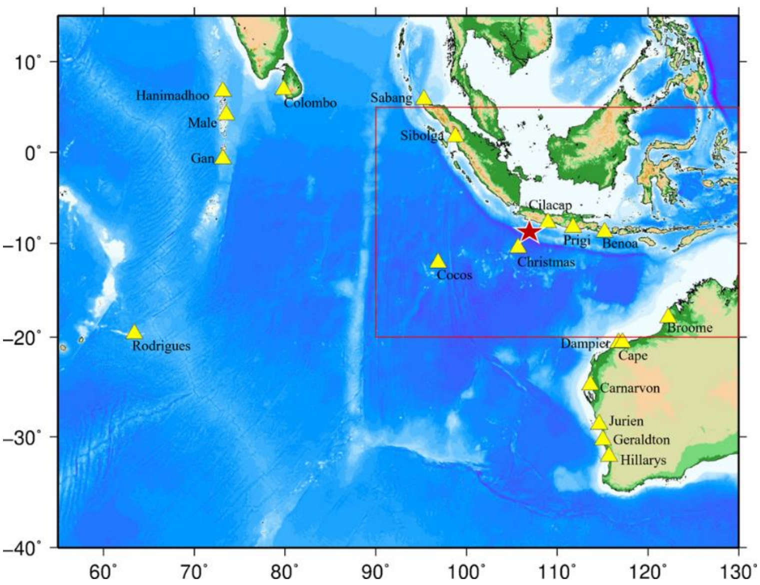


Figure 1. Computation area used to calculate Green’s functions and location of tide gauge stations (yellow triangles). The black outline and red line show the areas that we used GEBCO 2021 and BATNAS data, respectively.

We also used field survey data to validate the source model obtained from this study. We referred to four different results of field survey data (Fritz et al., 2007; Kato et al., 2007; Indonesia Survey Team; and Tsuji et al., 2021) and combined those data. According to Fritz et al. (2007), there were extreme run up heights recorded up to 21 m around the Permisan region, Nusa Kambangan Island.

## 3. METHODOLOGY

In this study, to estimate the slip distribution on the fault of the 2006 West Java earthquake, we used the fault model from Fujii and Satake (2006) as a base model. Then, we modified the fault model by halving the width of the shallow sub faults and extending the fault to the east (a length of 300 km and a width of 100 km). We divided the fault plane into 18 subfaults with the length and width equal to 50 km each for the deeper part and 50 km x 25 km for the shallower part (Figure 2a). Then, by referring to Slab2 model, we determined the depths and the dip angles of the subfaults. For the shallow subfaults, we used the top depths of 3 km and 4.9 km, shown by odd numbers, while for the deep subfaults, we used 7.6 km, shown by even numbers. For the focal mechanism, we used the dip values of 4.4°, 6.2°, and 9.5° from shallow to deep subfaults. For the value of strike and rake angles, we used 289° and 95°, respectively.

Then, we calculated the tsunami propagation from each subfault to the tide gauge stations to obtain Green’s functions. The computation area ranges 40°S - 15°N and 55°E - 130°E as shown in Figure 1. For the bathymetry data, we merged the GEBCO 2021 and BATNAS data and resampled it to 24 arc-sec. We performed the numerical simulation using the GPGPU code from Satake et al. (2017), which is based on linear long wave equations in a spherical coordinate system. The computation time was about 6 hours for the tsunami propagation of 10 hours.

We calculated the tsunami waveforms (Green's functions) based on the phase correction method proposed by Watada et al. (2014). The computation of phase-corrected Green's function is greatly simplified as follows: for applying the phase correction to the Green's functions from linear long wave simulations, we needed to use Fast Fourier Transform (FFT) which transforms the synthetic waveform from the time domain to Fourier spectra in the frequency domain. Then, we applied the phase differences correction using the table of Ho et al. (2017). Next, the spectra were converted to the time domain by conducting Inverse FFT.

In this study, we estimated the slip amount for each subfault and its error by using the non-negative least square method to avoid a negative slip and the delete-half jack knife method, respectively. We used different assumed rupture velocities such as instantaneous rupture, 1 km/s, 1.25 km/s, 1.5 km/s, and 2 km/s. We set five times larger weights to the Rodrigues station and we included the effects of rupture time delays in the tsunami waveform inversions.

After obtaining the slip distributions, we performed tsunami inundation simulations. We used the TUNAMI code by Yanagisawa (2022). The governing equations are based on the non-linear long wave theory with a spherical coordinate system. We used the merged data from FABDEM and BATNAS. We used nested grid systems which consist of three layers of 27 arc-sec, 9 arc-sec, and 3 arc-sec for numerical simulation.

To confirm the reliability of the obtained tsunami source models, we calculated the K and $\kappa$ numbers (Aida, 1978). K is the ratio between the measured tsunami heights and the simulated ones, while $\kappa$ is the standard deviation. The recommended values of K and $\kappa$ are $0.8 < K < 1.2$ and $\kappa < 1.45$, respectively.

## 4. RESULTS AND DISCUSSION

The slip distributions of the 2006 West Java earthquake by the tsunami waveform inversions of tide gauge data using phase-corrected Green’s functions are shown in Figure 2. We found that the larger slip located in shallow region of the slip models regardless of the assumed rupture velocities. Among those five slip model results, we preferred to choose the slip model with an assumed rupture velocity 1.25 km/s (Figure 2a.). The slip model shows that the large slip amount is 5.9 to 11.8 m located in the eastern part of the epicenter near the trench with the top depth of 4.9 km. The variance reduction is 0.56 from the comparison of the observed tsunami waveforms and the synthetic ones (Figure 3). The seismic moment calculated from the slip model is $6.4 \times 10^{20}$ Nm ($M_w = 7.8$), assuming a rigidity of $1.0 \times 10^{10}$ N/m$^2$. Our slip models are relatively consistent with other source models that were obtained by seismic waveform analyses such as Ammon et al. (2006), Yagi and Fukahata (2011), Bilek and Enghdal (2007), and the source model from a tsunami waveform inversion (Fujii and Satake, 2006).

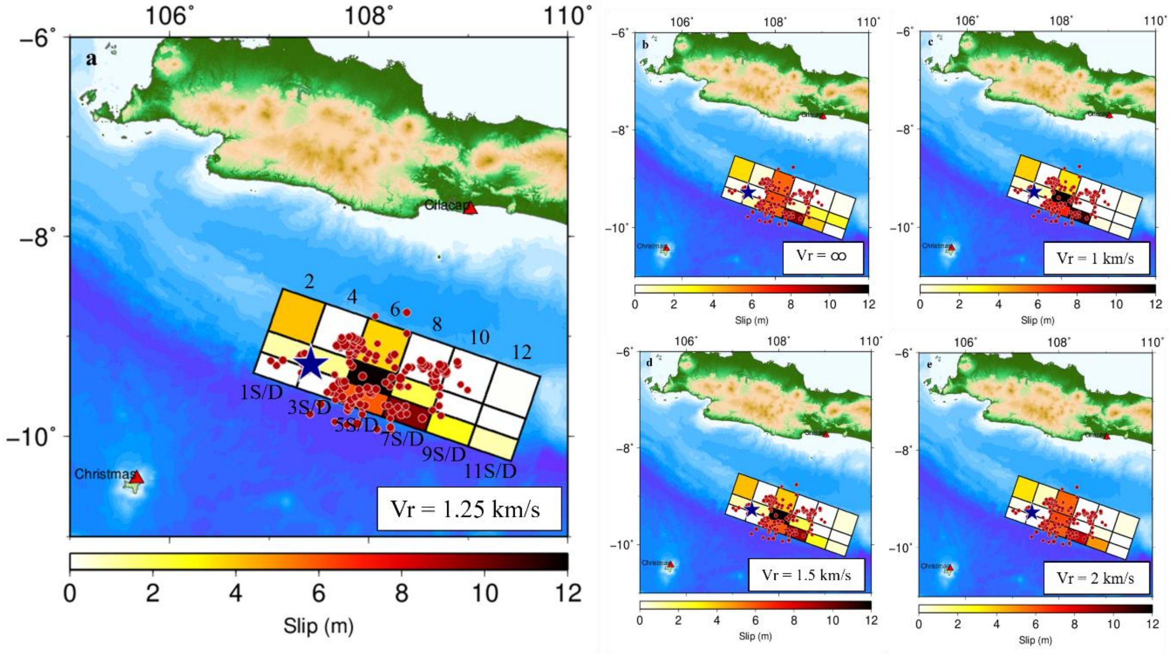


Figure 2. Slip distributions estimated for the 2006 West Java earthquake by tsunami waveform inversions with an assumed rupture velocity of (a) 1.25 km/s and different rupture velocities (b) instantaneous rupture, (c) 1.0 km/s, (d) 1.5 km/s, and (e) 2.0 km/s.

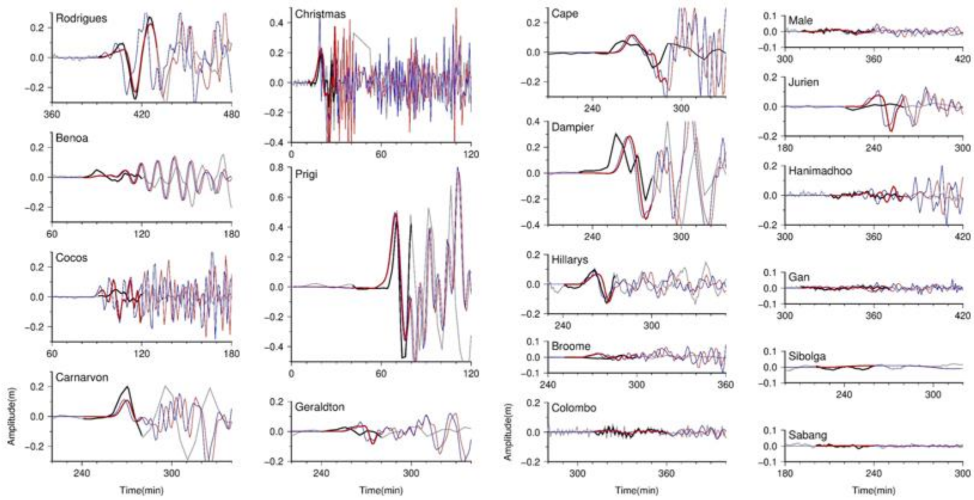


Figure 3. Observed tsunami waveforms (black) and synthetic ones with (red) and without (blue) phase correction in case of the rupture velocity 1.25 km/s.

We performed tsunami inundation simulations to evaluate our source models using three different slip models and computed K and $\kappa$ numbers. We used slip models with an assumed rupture velocity of 1.25 km/s, which were determined using the Green's functions with phase correction (our preferred model) and without phase correction, and the one from Fujii and Satake (2006). We removed the data in the Permisan region to calculate the K and $\kappa$ numbers. For our preferred slip model, we obtained the K number of 1.21, and the $\kappa$ number of 2.12, while for the slip model without phase correction, we found the K number of 1.46 and the $\kappa$ number of 2.37. For the source model from Fujii and Satake (2006), the K value is 2.14 while the $\kappa$ is 2.87. According to the results, we successfully updated the source model by providing a better ratio of measured tsunami heights and simulation results, and by providing a smaller value of geometric standard deviation. However, we found that the K and $\kappa$ numbers of our slip models were unsatisfied with the recommended standard values. The comparison of the measured tsunami height data and simulation results is shown in Figure 4. We also found that the simulation results were still underestimated around the Pangandaran, Cilacap, and Binangun. One possible reason for the underestimation at some survey points may be local (near coasts) bathymetry effects.

Furthermore, we also tried to assess the possible locations of the landslide source in front of the Permisan region, which had extreme runup heights. We assumed two candidates for the landslide source near and far from the coast (Figure 5a). We performed tsunami inundation simulations by combining our preferred source model with the two candidate locations of landslide sources. The results showed that the near-coast landslide source (Source 1) looks better to reproduce the extreme tsunami height in Permisan region than the far-coast landslide source (Source 2). However, a landslide source far from the coastline is preferable to increase the tsunami heights for the western and eastern sides (Figure 5b). In addition, we also computed K and $\kappa$ numbers using all the survey points, including the data in the Permisan region. We obtained the K number of 1.18 and the $\kappa$ number of 1.98 for the near-coast landslide source, and the K number of 1.19 and the $\kappa$ number of 2.10 for far-coast landslide source. The K number from using these two sources satisfied the recommended values. For the $\kappa$ number, our result is still unsatisfied with the recommended standard value.

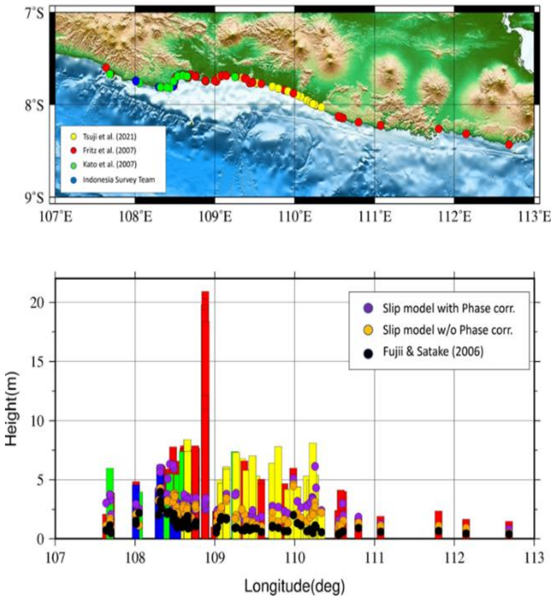


Figure 4. Comparison of measured tsunami height data from four different sources and tsunami inundation simulation results using the three different slip models.

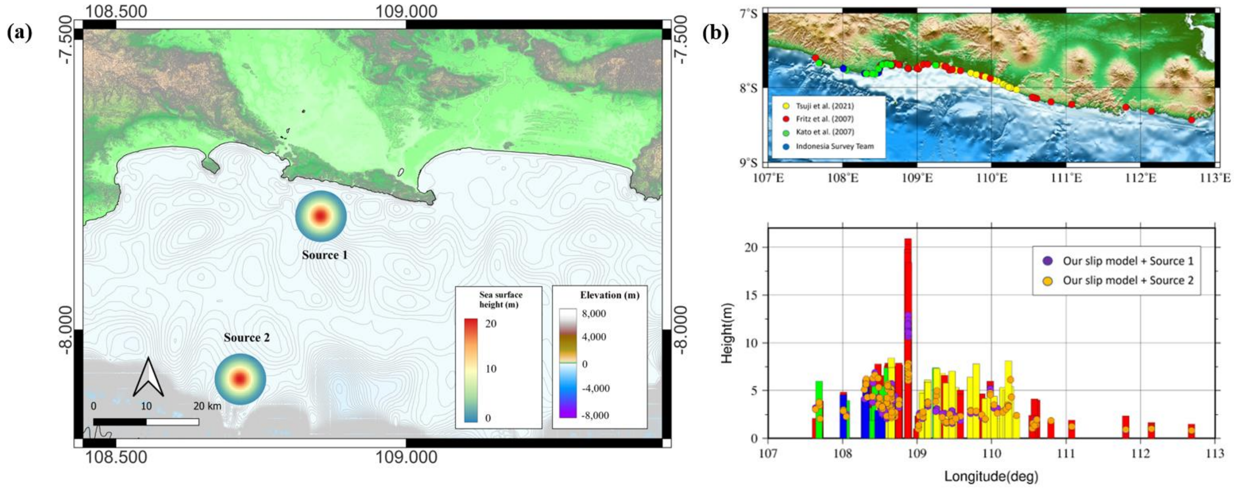


Figure 5. (a) Two candidate locations of landslide source in front of Permisan region. We assumed the two sources near the coast (Source 1) and far from coast (Source 2). (b) Comparison of measured tsunami heights and tsunami inundation simulation results by using combinations of the near-coast landslide source (Source 1) with our slip model and far-coast landslide source (Source 2) with our slip model.

## 5. CONCLUSIONS

We re-estimated the slip distribution of the 2006 West Java earthquake by tsunami waveform inversions of tide gauge data using phase-corrected Green's functions. The slip distribution obtained with an assumed rupture velocity of 1.25 km/s shows that the large slips were around 5.9 to 11.8 m in the shallower part near the trench. The total source length was 300 km, while the seismic moment calculated from this source was 6.4 x $10^{20}$ Nm (Mw = 7.8). The obtained slip distributions were relatively consistent with other source models. The dominant shallow slips in our slip models support the previous study that classified the 2006 West Java earthquake as a tsunami earthquake event.

We performed tsunami inundation simulations to evaluate our slip models and computed the K and $\kappa$ numbers. We compared the K and $\kappa$ numbers of the slip models with an assumed rupture velocity of 1.25 km/s which were constructed in this study using the Green's functions with phase correction and without phase correction, and the one from the previous study of a tsunami waveform inversion. The results showed that our preferred slip model provided better K and $\kappa$ numbers, although we found that the K and $\kappa$ numbers were unsatisfied with the recommended standard values. One possible reason for the underestimation at some survey points may be local (near coasts) bathymetry effects.

Furthermore, we also tried to assess the possible location of the landslide source in front of the Permisan region. The results showed that the near-coast landslide source looks better to reproduce the extreme tsunami heights in the Permisan region than the far-coast landslide source. However, a landslide source far from the coastline is preferable to increase the tsunami heights for the western and eastern sides. Nevertheless, further studies are needed to determine more accurate landslide sources.

## ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my supervisor Dr. Yushiro Fujii for his valuable advice and support which helped me to complete my research successfully, and to Prof. Kenji Satake for his valuable comments to improve this study.

## REFERENCES

Aida, I., 1978, Reliability of a tsunami source model derived from fault parameters, Journal of Physics of the Earth, 26(1), 57-73.

Ammon, C. J., et al., 2006, The 17 July 2006 java tsunami earthquake, Geophysical Research Letters, 33(24).

Bilek, S. L., and Engdahl, E. R., 2007, Rupture characterization and aftershock relocations for the 1994 and 2006 tsunami earthquakes in the Java subduction zone. Geophysical Research Letters, 34(20).

Fritz, H.M., et al., 2007, Extreme runup from the 17 July 2006 Java tsunami, Geophysical Research Letters, 34(12).

Fujii, Y., and Satake, K., 2006, Source of the July 2006 West Java tsunami estimated from tide gauge records, Geophysical Research Letters, 33(24).

Ho, T. C., et al., 2017, Improved phase corrections for transoceanic tsunami data in spatial and temporal source estimation: Application to the 2011 Tohoku earthquake, Journal of Geophysical Research: Solid Earth, 122(12), 10,155-110,175.

Kato, T., et al., 2007, Preliminary report on crustal deformation surveys and tsunami measurements caused by the July 17, 2006 South off Java Island Earthquake and Tsunami, Indonesia, Earth, planets and space, 59(9), 1055-1059.

Satake, K., et al., 2017, Different depths of near-trench slips of the 1896 Sanriku and 2011 Tohoku earthquakes, Geoscience Letters, 4(1), 1-10.

Tsuji, Y., et al., 2021, July 17, 2006 Tsunami survey results due to the earthquake off the southwest coast of Java Island, Research Report of Tsunami Engineering Vol.38, 45-68. (In Japanese)

Watada, S., et al., 2014, Traveltime delay and initial phase reversal of distant tsunamis coupled with the self-gravitating elastic Earth. Journal of Geophysical Research: Solid Earth, 119(5), 4287-4310.

Yagi, Y. and Fukahata, Y., 2011, Introduction of uncertainty of Green's function into waveform inversion for seismic source processes, Geophysical Journal International, 186(2), pp.711-720.

Yanagisawa, H., 2022, Numerical simulation of tsunami inundation and its application, IISEE Lecture Note 2021-2022.