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REAL-TIME TSUNAMI INUNDATION FORECASTING FOR MENTAWAI ISLANDS, INDONESIA

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ABSTRACT

This study evaluated the implementation of the Near-Field Tsunami Inundation Forecasting (NearTIF) method to enhance the operational capability of the tsunami early warning system in Mentawai Islands, Indonesia. This study focused on testing the method's reliability by conducting a retrospective test in forecasting the tsunami inundation during the 2010 Mentawai tsunami event.

The NearTIF method utilizes a pre-computed database containing pairs of inundation model and tsunami waveforms, an input fault model, and a NearTIF search engine. The pre-computed database was constructed using 462 unique fault scenarios. Linear and Non-Linear tsunami simulation was done to simulate tsunami propagation and inundation model. This study also utilized w-phase inversion to generate input fault models for the NearTIF method. A search engine was applied to choose the best inundation model for a specific site.

The NearTIF method's reliability was analyzed by comparing the simulated tsunami height from forecasting results and direct numerical forward modeling results (NFM) using input fault parameters with field observation data collected from another study. The computation speed to obtain each inundation model is also being compared. Analysis results in this study indicated that the NearTIF method is reliable and practical to be implemented in real-time tsunami early warning systems.

Keywords: Tsunami, Inundation, Early Warning System, Mentawai.

1. INTRODUCTION

The Mentawai islands are located above a seismically active megathrust zone and have experienced significant earthquakes and tsunamis. The deadliest event occurred in 2010 when an M7.8 earthquake struck the Island, triggering a big tsunami that caused over 700 people to die, 20,000 were displaced, and 4,000 households were affected (Ismoyo, 2010).

To mitigate the tsunami risk, the Indonesia Tsunami Early Warning System (InaTEWS) was established. The system provides crucial tsunami information to all affected communities, such as the tsunami's Estimated Time of Arrival (ETA) and Estimated Tsunami Height (ETH). However, the qualitative nature of the tsunami warning provided by InaTEWS does not currently provide detailed information about tsunami-affected areas on land.

This study aims to evaluate the implementation of the Near-field tsunami inundation forecasting (NearTIF) method. This method was developed by Gusman et al. (2014), which allows the generation of a detailed forecast of tsunami inundation, offering valuable information about the potential areas that may be affected by the tsunami's inundation. By integrating this forecasting method into the existing warning system, we aim to enhance the reliability of tsunami warnings in the Mentawai islands region.

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2. DATA

2.1. Bathymetry and topography

This study used BATNAS 6 arc-seconds bathymetry dataset and interpolation results of elevation contour lines from a 1:50,000 m Mentawai islands topography map with 12.5 m interval as a topography grid dataset. Both datasets were obtained from the Indonesia Geospatial Agency (BIG).

2.2. Broadband seismic waveform

This study utilized the vertical component of IRIS broadband stations with an epicentral distance between 5^o to 50^o to conduct the W-phase inversion to obtain the fault parameter. The broadband seismic data used in the W-phase inversion were divided into several datasets, which are 10 min, 20 min, and 30 min recording data after the origin time.

2.3. Tsunami field study

This study validated the simulation results from numerical forward modeling and the forecasted results from the NearTIF method with the 2010 Mentawai tsunami field study data collected by Satake et al. (2012). The data was collected from 27 observation points in 6 different areas in Mentawai islands.

3. METHODOLOGY

3.1. NearTIF method

This method was developed based on the idea that if different earthquakes generate the same tsunami waveform at nearshore locations, the resulting tsunami inundation in the coastal areas from those tsunamis will exhibit similar characteristics. Therefore, the inundation model at a specific site can be forecasted without requiring a precise earthquake source model for a given event. The NearTIF method relies on three components to work: (1) database containing pairs of pre-computed inundation scenarios and pre-computed tsunami waveforms at nearshore locations, (2) an input fault or tsunami source model, and (3) a “best-scenario” search engine.

3.2. Tsunami simulation

Non-linear tsunami simulation was performed to compute the inundation extent and tsunami height inland. This simulation used seven computational layers assigned to four-level nested grid domains (Table 1). Inundation models were computed in the finest layers (Domains 4A to 4D). On the other hand, linear tsunami simulation was done to simulate tsunami waveforms in specific observation points for forecasting processes. Linear tsunami simulation only incorporated one coarsest layer assigned to the largest domain (Domain 1) to generate tsunami waveform simulation results rapidly and efficiently.

Table 1. Computational domains for the nested grid configuration in tsunami simulation.

Dom.	Lon. Min (º)	Lon. Max (º)	Lat. Min (º)	Lat. Max (º)	Grid size (')	Grid size (m)
1	96.17	103.41	-6.86	0.38	1	1847.5
2	98.41	102.00	-4.85	-1.24	0.25	461.9
3	99.83	100.73	-3.33	-2.43	0.083	154.0
4A	99.95	100.01	-2.64	-2.58	0.016	30.9

4B	100.02	100.09	-2.86	-2.79	0.016	30.9
4C	100.17	100.24	-3.09	-3.02	0.016	30.9
4D	100.30	100.37	-3.24	-3.17	0.016	30.9

3.3. Fault model scenarios and virtual observation points

The inundation database in this study was created from 462 rectangular fault scenarios, accommodating three types of earthquakes: (1) megathrust, (2) tsunami earthquake, and (3) outer rise. Figure 1 shows the location of fault scenarios included in the database.

Twelve virtual observation points were employed, at which tsunami waveforms were simulated for the input fault model and every fault scenario in the pre-computed database. Each observation point is associated with a computation domain (Figure 2). Waveforms from the input model will be compared to waveforms from the database at the same observation points, and the most similar waveform based on Root Mean Square Error (RMSE) analysis will be chosen as the forecasting result for that computational domain.

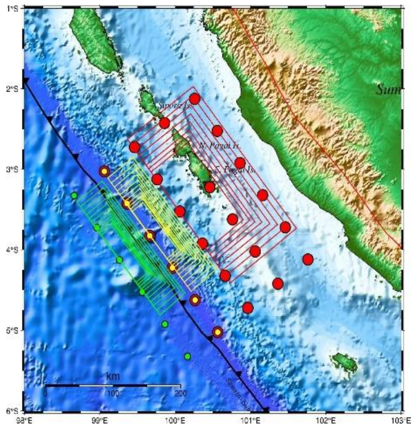


Figure 1. fault model scenarios location. Colored dots are the top center position of each fault.

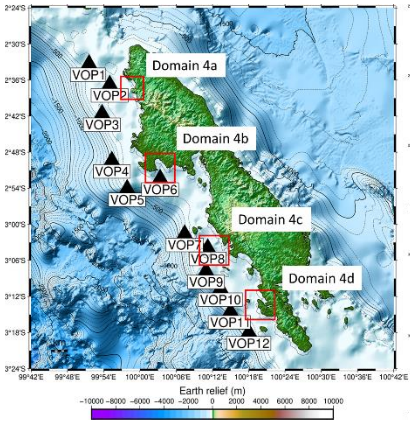


Figure 2. The location of virtual observation points assigned to each computation domain.

3.4. W-phase inversion

The w-phase inversion was utilized to obtain fault parameters of the 2010 Mentawai tsunami event. 10-min, 20-min, and 30-min broadband recording datasets were used to simulate earthquake and fault parameter determination during real-time tsunami monitoring and to test the quality of the inversion results for each elapsed time after the earthquake's origin time.

3.5. Model validation

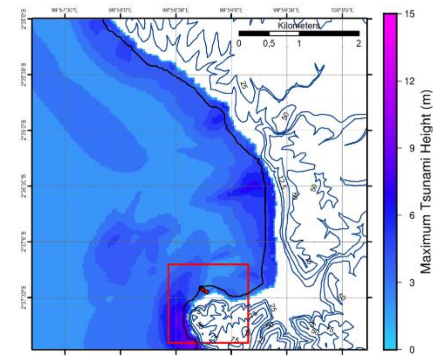
K and κ parameters by Aida (1978) were used in this study to validate the accuracy of tsunami height from the simulation results. This study considers the acceptable accuracy for simulated tsunami inundation height when the K parameter is between 0.6 – 1.4.

4. RESULTS AND DISCUSSION

4.1. Comparison of the forecasted tsunami inundation scenarios with each input fault model

4.1.1. Case 1: Input fault model from 10-min W-Phase solution

The solution from the 10-min broadband dataset provided a fault model with a seismic moment of 5.95 x 10^{20} Nm or equivalent to an M_w 7.78 earthquake. The fault has an area of 104.7 x 34.9 km^2, thrust mechanism (i.e., strike = 336°, dip = 7°, rake = 110°), centroid location of 98.81° E and 3.51° S, depth of 25.5 km, and slip amount of 8.06 m. Figure 3 illustrates the inundation model (NFM) and the scenario forecasted using the NearTIF method. NearTIF search engine chose Scenario 290 for this domain.



This scenario has a magnitude of M_w 7.9, an area of 116.1 x 38.7 km^2, thrust mechanism (i.e., strike = 320°, dip = 10°, rake = 90°), centroid location of 99.66°E and 3.82°S, depth of 10 km, and slip amount of 19.84 m.

Both models show similar inundation characteristics at most locations. The maximum inundation distance is 266 m for the simulation result using NFM and 268 m for the forecasted result from the NearTIF method. Tsunami heights from both models generally agree with each other in most areas. However, the maximum tsunami height simulated by both models is somewhat different. Maximum tsunami height is 10.1 m for the NFM result and 12.1 m for the chosen scenario model.

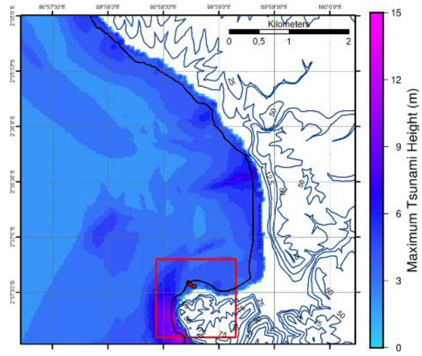


Figure 3. Tsunami inundation model for Domain 4A. (top) NFM results, (bottom) forecasted model.

Figure 4 compares the tsunami waveform from NFM (red) and chosen scenario from the NearTIF database (blue) for Domain 4A in this case. Both waveforms are relatively similar, as indicated by low RMSE.

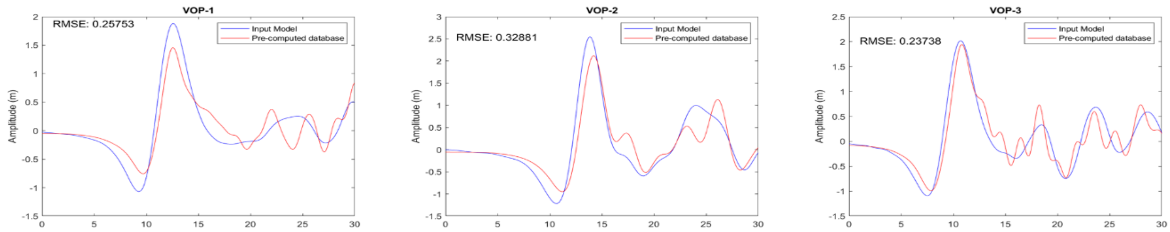


Figure 4. Comparison between tsunami waveform simulated from input model in Case 1 (blue) and from best site-specific scenario selected by NearTIF search engine (red).

4.1.2. Case 2: Input fault model from 20-min W-Phase solution

The solution using the 20-min broadband dataset provided a fault model with a seismic moment equivalent to an M_w 7.85 earthquake. The fault has an area of 106.5 x 35.5 km^2, thrust mechanism (i.e., strike = 341°, dip = 7.1°, rake = 125°), centroid location of 98.72°E and 3.51°S, hypocenter of 25.5 km depth, and a slip amount of 9.58 m.

Figure 5 depicts the inundation model for Domain 4B. Scenario 266 was selected by the NearTIF search engine for this domain. This scenario has a magnitude of M_w 7.7, an area of 97.7 x 32.6 km^2, thrust mechanism (i.e., strike = 320°, dip = 10°, rake = 90°), centroid location of 99.06°E and 3.02°S, hypocenter at 10 km depth, and a slip amount of 14.04 m.

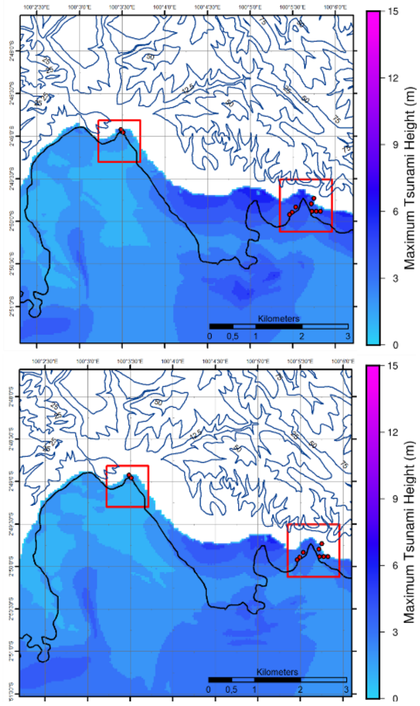


Figure 5. Tsunami inundation model for Domain 4B. (top) NFM results, (bottom) forecasted model.

Both models from NFM and the chosen scenario exhibit similar inundation characteristics at most locations. The maximum inundation distance is 1.393 m for the NFM simulation and 1.362 m for the forecasted result. Tsunami heights from both models generally agree in most areas, although the maximum tsunami height differs slightly: 7.58 m for the NFM result and 7.05 m for the chosen scenario model.

Figure 6 compares tsunami waveforms from the NFM result, and the chosen NearTIF scenario result for Domain 4B. Both waveforms are relatively similar, indicated by the small RMSE value.

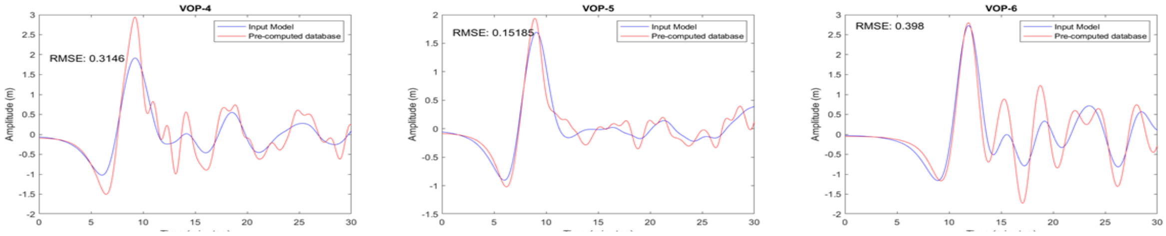


Figure 6. Comparison between tsunami waveform simulated from input model in Case 2 (blue), and from best site-specific scenario selected by NearTIF search engine (red).

1.3. Case 3: Input fault model from 30-min W-Phase solution

The solution using the 30-min broadband dataset provided a fault model with a seismic moment equivalent to an M_w 7.91 earthquake. The fault has an area of 106.5 x 35.5 km^2, thrust mechanism (i.e., strike = 321^o, dip = 5.1^o, rake = 82.7^o), centroid location of 99.52^{o}E and 4.01^{o}S, hypocenter of 25.5 km depth, and a slip amount of 10.81 m.

Figure 7 compares the inundation model between the input model for this case with the forecasted model. Scenario 298 was selected as the best site-specific inundation model for domain 4d. This scenario has a magnitude of M_w 7.6, an area of 89.6 x 29.9 km^2, thrust mechanism (i.e., strike = 320^o, dip = 10^o, rake = 90^o), centroid location of 99.966^{o}E and 4.22^{o}S, hypocenter of 10 km depth, and a slip amount of 11.82 m.

Both models show similarities to each other in terms of inundation extent and tsunami height. Both models have a maximum inundation distance of 179 m in the same location. Tsunami heights from both models are matched in most areas, although the maximum tsunami height differs slightly. The maximum tsunami height for the current domain is 9.29 m for the input model and 10.31 m for the best-forecasted model.

Figure 8 illustrates the comparison between tsunami waveforms from the NFM result and the forecasted scenario model by the NearTIF method for Domain 4D.

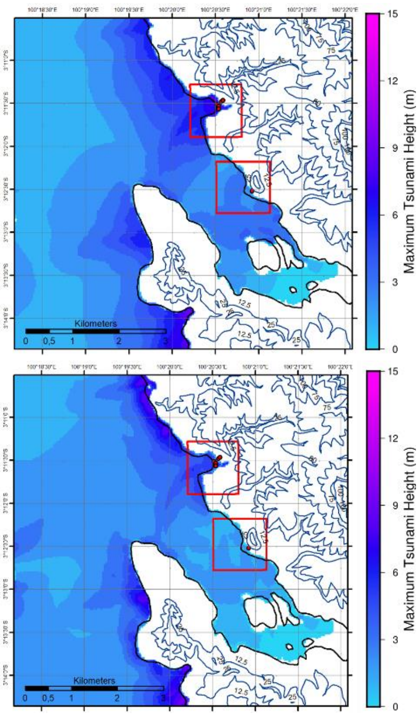


Figure 7. Tsunami inundation model for Domain 4D. (top) NFM results, (bottom) forecasted model.

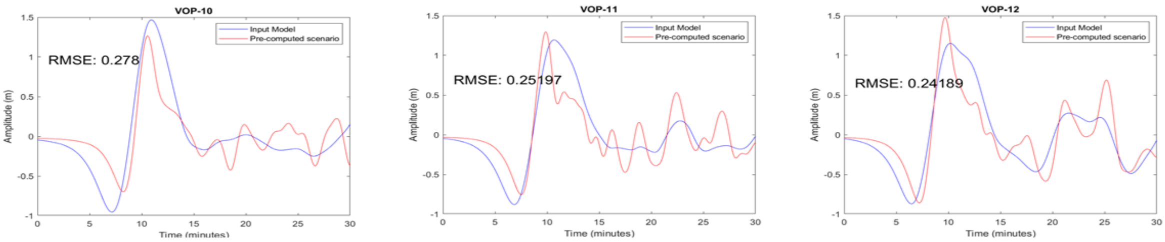


Figure 8. Comparison between tsunami waveform simulated from input model in Case 3 (blue), and from best site-specific scenario selected by NearTIF search engine (red).

4.2. Model validation with tsunami field observation data

The calculation results of K and κ parameters for all input model cases in 6 field study areas are shown in Figure 9. Results from Cases 1 and 2 show that simulated tsunami height from both models has acceptable accuracy in most areas, except the Sabeu area in Domain 4B. This is probably because the fault solution from the 10- or 20-min broadband data still contains errors. The results are better for Case 3. However, the overestimated tsunami height might be due to an inappropriate assumed rigidity value for estimating the slip amount.

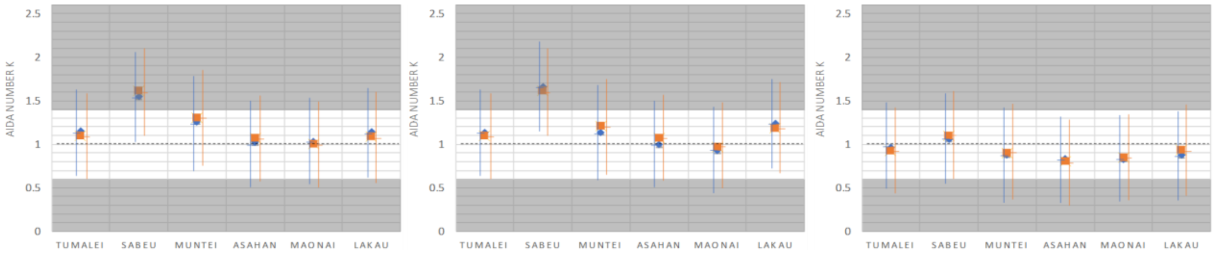


Figure 9. K and κ parameters for Case 1 (left), 2 (middle), and 3 (right). Blue diamonds and lines are for the input model, and orange ones are for the forecasted model.

4.3. Computation Speed

On average, it required at least 44 min to obtain the inundation model for four domains in this study by using the NFM method. As for the NearTIF method, the average run time was merely 48 seconds. Therefore, by utilizing the NearTIF method and w-phase inversion, a reliable inundation model forecast for Mentawai islands can be obtained within 11 minutes after the earthquake happened (10 minutes to obtain inversion results and less than 1 minute to forecast the inundation model).

5. CONCLUSIONS

This study successfully evaluated the reliability and the practical aspect of the NearTIF method application in tsunami early warning systems. The results indicated that if an appropriate fault or tsunami source model can be obtained, the NearTIF method can forecast reliable inundation models with high accuracy within a very efficient run-time. Therefore, the NearTIF method is very practical to be implemented to enhance the tsunami early warning system.

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