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Numerical Simulation of the 2010 Mentawai Tsunami: Interpretation of the Field Survey in Pagai Island

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Abstract: There was an M 7.7 Mentawai-Indonesia earthquake on October 25th 2010 at 14.42 (Western Indonesia Time), and a tsunami was detected. The paper aims to compare the tsunami numerical model to a field report of the undertaken by a BMKG Team a few days after the occurrence of a tsunami invading the western coast of Mentawai (Indonesia). The tsunami caused severe damage and claimed many victims in some coastal villages. The field survey was to measure the inundation and the run-up values as well as to ascertain the possible morphological changes caused by the wave attacks. We did a numerical model using TUNAMI-N2 and divided four regions with Pagai Utara islands as the main focus on the modeling. Most places were hit by three significant waves with documented wave height often exceeding 5 m. The maximum run-up value (17.00 m) was on-site measured at North Pagai, where also the most impressive erosion phenomena could be found.

Keywords: mentawai; tsunami earthquake; slow-slip

This paper recalls the Pagai Mentawai Tsunami on October 25, 2010 at 21.42 WIB, triggered by a shallow earthquake in the Mw7.7 Mentawai megathrust zone, which claimed the lives of 414 people. The talk about potential megathrust earthquakes in the Sunda Strait and Mentawai-Siberut is not new. From 2010 October 30th to November 1st, an on-site post-event survey team organized by the Indonesia Agency for Meteorology Climatology and Geophysics (BMKG) did post near-field survey investigated the effects of the affected area of Mentawai Earthquake and tsunami in the near epicenter. During a 2024 research mission conducted and facilitated by OceanX, samples were collected aboard the R/V OceanXplorer in the Mentawai island straits.

1. INTRODUCTION

Fifteen years ago, on October 25, 2010 at 21:42:20 Western Indonesia Time, a slow-slip earthquake of magnitude Mw 7.7 occurred off the south-western coast of Mentawai Island, Indonesia at 21h 41m. The epicenter was at 3.61 S; 99.93 E (by BMKG) about 79 km from the nearest coast. Some of the people of the Mentawai Islands had gone to rest when they were

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suddenly shocked by an earthquake. According to the people living in Mentawai, the earthquake did not feel very strong [1].

Less than five minutes later, at 21:47:06 WIB, BMKG released information about an earthquake with a magnitude of 7.2 M with a depth of 10 km, centered 78 km southwest of South Pagai, Mentawai Islands, and at the same time BMKG issued a tsunami early warning.

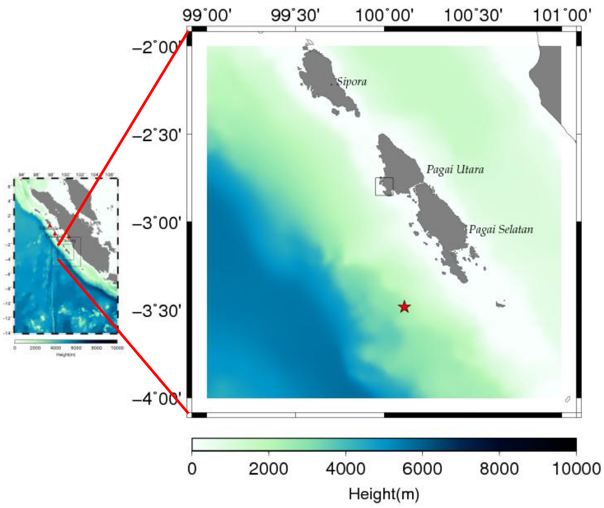

Figure 1. The Mentawai October 25, 2010 Earthquake Epicenter
Source: BMKG

This tsunami early warning information was sent via Digital Video Broadcasting (DVB)/ Warning Receiver System (WRS) throughout Indonesia, one of which is located at the Local Disaster Management Office of Mentawai Islands Regency in Tuapejat [2]. About 7 minutes after the main shock, a sizable tsunami hit the coast, inflicting heavy damage on several coastal villages in the North and South of Pagai regencies of West Sumatra Province.

We organized a team and surveyed the west coasts of Mentawai Islands from October 30th to November 1st 2010. We conducted interviews at damaged villages, searched for traces of inundation of sea water, and measured heights of sea-water inundation with reference to mean sea level elevation at the time of the survey. Correction for the astronomical tide was applied later to obtain our estimates of tsunami heights referenced to mean sea level. In this paper, we report the distributions of the seismic intensities, the distributions of tsunami heights, and human and building damages due to the tsunami [3].

The BMKG noted that about 46 aftershocks had shaken the region since 28 October 2010 to 31 October 2010 with the strongest measuring magnitude 5.1. The areas that were affected by the earthquake are Mentawai, Padang Pariaman and Bengkulu. The BMKG focal mechanism shows that the dominant mechanism of this earthquake was the reverse. The team conducted early identification of affected areas by using macro seismic observation, earthquake foreshock recorded, and loss-damages documentation.

At Pagai Selatan the intensity was recorded at VI-VII MMI scale, V MMI at Sipora island, IV MMI at Padang Pariaman and Siberut island, III MMI at Sungai Penuh, II MMI at Ketaun and Kepahiang (Bengkulu Province). In total, the death toll continues to rise and the latest official estimate is that at least 357 people died, 313 people were seriously injured, 409 people were missing, and up to thousands people have been left homeless.

The tsunami hit South Pagai Island and the maximum runup height reached 17 m above sea level on the small island in the western of South Pagai, namely Sibigau Island. Sibigau Island was completely swept out. The worst devastation was in North Pagai and the damage from this tsunami was widespread.

Figure 2. Damaged Houses in Purourougat, South Pagai
Source: BMKG (2010)

An estimated 648 houses have been destroyed and 6 mosques or churches were damaged, 5 bridges were devastated, 5 schools and educational institutions, 2 resort estates, 1 fisherman boat, and 2 ships were broken. The tsunami has disproportionately affected children and the elderly, as many were not able to move quickly enough to safety during the evening.

Because the limitation mode of communication to the community, the community around the epicenter of the earthquake, did not all receive the tsunami warning information, but some people on Pagai Island received information from national television broadcasts that the earthquake that had just been felt had the potential to cause a tsunami. Information that a tsunami had hit South Pagai Island was only known the next day, namely October 26, 2010, due to the difficulty of obtaining information on the impact of the earthquake around the epicenter due to limited communication facilities.

2. METHODS AND METHODOLOGY

The Mentawai Fault Zone is not a strike-slip fault, but it is actually a back-thrust system developed along the boundary between the retro accretionary wedge and the continental backstop [4]. This system was initiated by the translation and back-rotation of the closely spaced seaward-verging imbricated thrust, and developed through the continuous growth of the accretionary wedge [5]. The compressional-dominated phase, active since the early Pliocene, initiated the Mentawai back-thrust reactivation and deformed the basin fill sediments. Mentawai is a Fore-arc and is built by accretion prism [6]. The Mentawai Islands emerged due to an accretionary prism that experienced uplift due to the Indo-Australian subduction [7]. Frontal subduction can cause earthquakes that trigger tsunamis, called tsunami earthquakes, where the magnitude of the earthquake is not too large but triggers a tsunami that is larger than expected.

Numerical models use mathematical equations to describe physical processes [8]. For the purposes of tsunami warnings, numerical models estimate the expected tsunami wave height, run-up, and inundation based on the description of the tsunami source and modeling technique [9]. To get the best results, the model needs to have specific descriptions of the initial source location and the actual physical situation. Also, all models need to be validated with observed or historical data to ensure that the model will calculate reasonable values for future events [10].

Figure 3. Damaged Houses in Muntei Barubaru, North Pagai
Source: BMKG (2010)

This study uses TUNAMI-N2 with the Scaling Law and Tsunami Travel Time (TTT) methods to determine the inundation and wave run-up values. The inundation value is measured from the coastline to the land inundated by seawater [11]. The inundation area is marked by inundation due to tsunami waves measured horizontally, while the height of the tsunami run-up is measured vertically.

In this study, tsunami modeling was performed using GMT, TUNAMI-N2 (Tohoku University's Numerical Analysis Model for Investigation of Tsunami No.2), CYGWIN, GSVIEW, TTT (Tsunami Travel Time). TUNAMI N-2 (Tohoku University's Numerical Analysis Model for Investigation of Tsunami No.2), modified by Yanagisawa (2012). TUNAMI-N2 can calculate the maximum tsunami height and its arrival time at the coastal observation point by using Huygens Principle at each latitude and longitude coordinate of bathymetric points. The data used in the modeling is the Mentawai earthquake data on October 25, 2010, with its fault plane parameters obtained from Global CMT. Bathymetric data obtained from GEBCO. Wave height data obtained from ioc-sealevelmonitoring.org which records wave heights when the Mentawai tsunami occurred [12].

The series of steps in this study began with searching for earthquake parameter data obtained from Global CMT. The earthquake parameters were used in modeling with TUNAMI-N2. The earthquake magnitude data obtained was used in the calculation to find the fault plane as a tsunami generator. The area of the fault plane obtained from the calculation and the Mentawai earthquake parameter data were used as input in the modeling. Tide gauge data were used in the validation of wave height and arrival time.

Wave arrival time was used in the TTT method. The results of modeling with Scaling Law and TTT will later be compared with tide gauge data [13].

At 2024 June 26 – July 04, surveys of Mentawai Straits were conducted during the Indonesia Ocean Expedition onboard the R/V OceanXplorer. R/V OceanXplorer was equipped with deep-sea vehicles, including a remotely operated vehicle (ROV) Chimera (Argus Mariner XL model) featuring 360-degree benthic cameras, as well as two Triton manned submersibles, Neptune (designed for scientific sampling operations) and Nadir (designed for media operations).

3. RESULTS

The Mentawai Islands are a group of islands on the west coast of Sumatra, a group of islands formed by the subduction of the front arc where the distance is relatively close to the subduction path of the Indo-Australian plate with the Eurasian plate. So that the sources of earthquakes are quite close to the Mentawai Islands and if the earthquake triggers a tsunami, the tsunami will hit the Mentawai Islands in a short time.

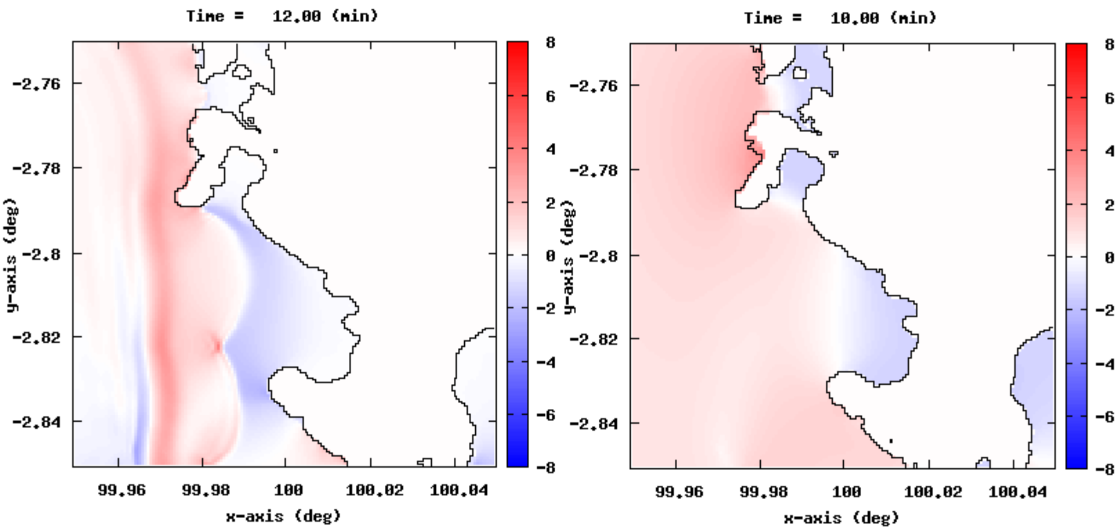

Figure 4. October 25, 2010 Tsunami Numerical Processing using Scaling Law (left) and TTT (right)

Based on the earthquake and tsunami in 2010 and the results of the tsunami wave propagation modelling simulation with the earthquake epicenter scenario around the Mentawai Islands, the tsunami wave arrival time is very fast, which is less than 10 minutes, even some places with the tsunami wave propagation modelling scenario, the tsunami arrival time is less than 5 minutes.

It can be concluded that the time to self-evacuate during the earthquake has the potential to hit Mentawai is only a matter of minutes after the earthquake occurs. The tsunami arrival time modelling simulation is certainly not one hundred percent accurate, but at least this can be used as an approach for consideration by local governments, disaster stakeholders and the community to take advantage of the golden time in carrying out evacuation to save themselves from the dangers of tsunamis.

This subduction earthquake occurred close to land. Based on tide gauge records located on Enggano Island, Bengkulu, the tsunami hit Enggano Island at 22:25:00 Western Indonesia Time or around 43 minutes after the earthquake with a tsunami height of 27 cm, while in Tanah Bala, South Nias the tsunami hit at 22:28:00 WIB or around 46 minutes after the earthquake with a height of 22 cm and in Padang the tsunami was recorded on the Bungus port tide gauge at 22:45:00 WIB or after 1 hour 3 minutes after the earthquake with a height of 33 cm.

Furthermore, after it was known that a tsunami had hit Mentawai, BMKG sent a survey team to several points in South Pagai, including; Malakopa Village; Purourougat and Muntei Baru-baru. The results of interviews with the community, the tsunami waves arrived approximately 5 to 7 minutes after the earthquake, or only 2 minutes after the BMKG tsunami warning had hit Pagai Island, in several places closer to the source of the earthquake in Purourougat, the tsunami hit the area at the same time as the BMKG warning was issued.

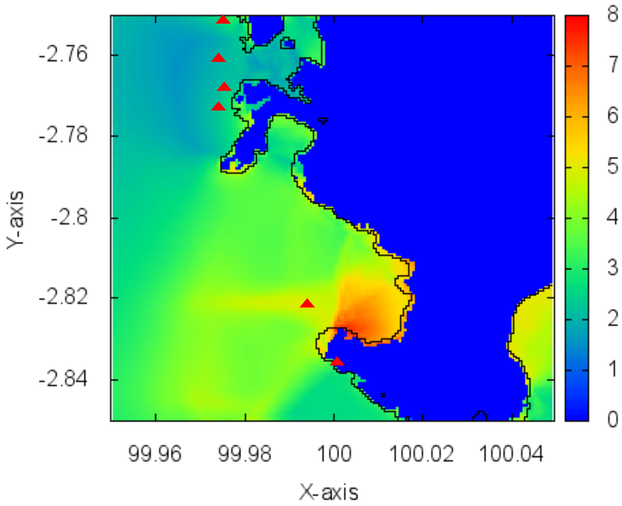

Figure 5. October 25, 2010 Tsunami Heights Model using Tsunami Travel Time (TTT)

The results of the BMKG survey in Malakopak Village, South Pagai, the tsunami height reached 6 meters and sea water entered the land as far as 290 meters and the estimated arrival time of the tsunami was 7 minutes after the earthquake, while in Purourougat Hamlet the tsunami height reached 7 meters and sea water entered the land as far as 420 meters and the estimated arrival time of the tsunami was 5 minutes after the earthquake occurred, which means that the tsunami hit Purourougat in South Pagai at the same time as the warning issued by BMKG, while in Muntei Baru-baru village the tsunami height reached 5 meters and sea water entered the land as far as 400 meters and the estimated arrival time of the tsunami was 10 minutes after the earthquake.

Six years after this tsunami, the other event occurred on the 636 km South Western off Mentawai island at 2 March 2016 19:49:47 Western Indonesia Time with 7,8 magnitude, followed by insignificant tsunami in Cocos island 10 cm at 21.15 Western Indonesia Time and in Padang 5 cm at 21.40 Western Indonesia Time. One year ago, a M7.1 earthquake just occurred off the west coast of Sumatra. The location is very close to a M6.7 that occurred in

March of 2022. The earthquake occurred on the megathrust zone of Mentawai West Sumatra, at 25 April with the 6.9 magnitude, triggering the insignificant tsunami 11cm; shallow depth and thrust origin focal mechanism.

In the Mentawai earthquake in 2010, where the tsunami occurred only 5-10 minutes after the earthquake occurred, and the location of South Pagai Island which is similar to the location of Simeuleu Island, is the island that was first passed by the earthquake and tsunami. At that time, in the Mentawai Islands the early warning system in the form of a siren for evacuation in the event of a tsunami is less useful, because the arrival time of the tsunami wave is coincide with the warning time issued and there is even a possibility that the tsunami will arrive faster than the tsunami warning.

Figure 6. North Pagai Coast Tsunami Affected Area after 14 Years
Source: Ocean-X (2024)

Based on the modeling results carried out on North Pagai Island, the results are as shown in **Figure 5.** The modeling results carried out with TTT parameter input show that the height value at the observation point reaches 4.86 m and the maximum inundation is 920 m. At observation point A, the wave height value reaches 2.473 m and the wave inundation distance reaches 200 m. At point B, the wave height reaches 2.749 m and the wave inundation distance is 168 m. At observation point C, the height reaches 4.282 and the wave inundation distance to the mainland is 920 m. At point D, the wave height is 3.339 m and the inundation distance is 111 m. At observation point E, the height value is 4.86 m and the inundation distance is 372 m. At point F, the wave height value is 3.29 m and the inundation distance is 188 m. Figure 7 shows the location of BMKG survey (Blue Square) and the points of Tsunami modelling in North Pagai island (Red triangle). There is no much difference about Tsunami height in the locations. The Tsunami height ranges between 2 – 5 meters.

Static displacement is a permanent shift in the land surface around the epicenter due to an earthquake. This shift occurs if the earthquake magnitude is relatively large and the distance is relatively close. In the 2010 Mentawai earthquake, with a magnitude of 7.8 and a sensor distance to the hypocenter of 94 km, the sensor experienced a static shift of 15 cm. In larger earthquakes such as Tohoku, static displacement can be several meters.

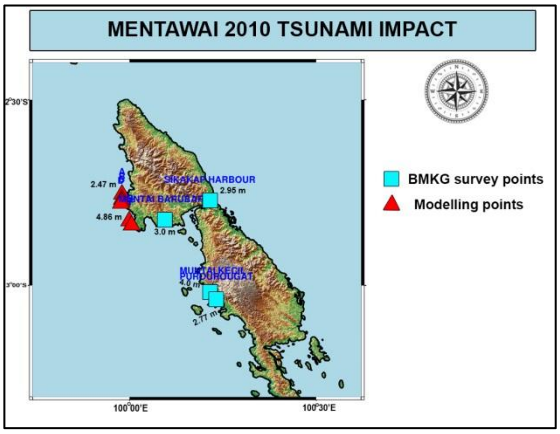

Figure 7. Mentawai 2010 Tsunami Impact Map at North Pagai and South Pagai island

Sabeugunggung experienced an earthquake in 2007, and there was an initiative proposed by its residents, Leisa Saogok, to move or at least build a hut in a higher place from the beach. Because it did not get a response, the initiative failed. In the 2010 tsunami, this hamlet was wiped out by a tsunami marked by a weak earthquake. There was no chance of saving themselves by walking, because this hamlet was surrounded by the sea on its western edge, then by estuaries and rivers around from north to south.

Table 1. List of Daily Aftershocks Series Recapitulation

Dates	Number of Events	Maximum Magnitude
28 October 2010	12	5,1
29 October 2010	16	4.4
30 October 2010	8	5.1
31 October 2010	10	4,3

Residents did not have time to save themselves and Sabeugunggung became the hamlet with the highest number of fatalities due to the 2010 tsunami. The old Sabeugunggung hamlet facing the Indian Ocean was no longer maintained, and its residents moved to temporary housing that had been prepared by the government, namely in the kilometer 4 area, in North Pagai. From kilometer 4 in the area belonging to the Taikako tribe, the victim residents moved again to kilometer 10, still in temporary housing conditions with houses made of plywood and fragile.

It was only in 2013 that residents began to move to the 14 kilometer area, further into the hills and forest, where the foundations and frames of permanent houses began to be built. Now the Sabeugunggung hamlet has been rebuilt with conditions that are very different from their original life. Tonight, the resilient Sabeugunggung residents and other Mentawai residents have passed 5 years since the 2010 Mentawai tsunami.

It is hoped that the people of West Sumatra, especially on the outer islands of West Sumatra, which are included in the Mentawai Islands, namely the islands of Siberut, Sipora, North Pagai, South Pagai, can be more aware, concerned, and not abandon the local wisdom that has been embedded in the West Sumatra region, such as in the 2009 Padang earthquake, where the traditional building of the Rumah Gadang, which is mostly made of wood, remained intact, and was not affected by the earthquake, even though many concrete buildings were destroyed by the earthquakes, and not only rely on the early warning system informed by BMKG.

In addition, it is important to have knowledge about earthquake-safe buildings to reduce the impact caused by earthquakes, namely by making house foundations that must be placed on hard ground, using concrete raw materials, using concrete reinforcement ties, using lightweight roof frames, not using hanging furniture, and ropes for home furnishings on the walls. Considering that the West Sumatra region is an earthquake-prone region, and has 3 active seismic zones, namely the Megathrust Subduction Zone, the Sumatran Fault, and the Mentawai Fault, the surrounding community is urged to be aware of earthquake and tsunami sources originating from the Sumatran Fault and the Mentawai Fault, not only those originating from the Megathrust subduction.

4. CONCLUSION

The 2010 Mentawai earthquake felt in Mentawai was a slow earthquake type with the epicenter located in the southwest of South Pagai Island. Aftershocks were still felt in Sikakap - North Pagai until the fourth day, feeling like being swung. The most victims were found in Muntai Barubaru, the west coast of North Pagai Island because of its position in the bay, precisely at the mouth of the river where more than 300 people died, almost 60% of the victims were disfigured because they were mixed with building debris. The remaining survivors were around 12-15 people.

In tsunami modeling with TUNAMI-N2 using data differences as input parameters for validation on the October 25, 2010 earthquake, and topographic and bathymetry data are also used. From various modeling conducted using Scaling Law and TTT (Tsunami Travel Time), modeling with Scaling Law gives the closest results. The area of the fault plane used is 112 x 36 km with a given slip of 2.81 m. The tsunami waves that reached the coast began in the 12th minute. Modeling with the TTT method with a fault area of 118 x 112 km with a slip used of 6.1 m, the waves reached land in the 10th minute. The maximum wave from the TTT modeling results reached 7.876 m and the minimum wave reached -1.285 m. The RMSE value in the TTT modeling is between 0.1080 and 0.1401 with a correlation value of 0.4683.

There is a small pourorogat village in the South Pagai sub-district near the epicenter which actually had fewer victims. It was also found that there were 2 church administrators who were swept away by the tsunami along with their church. Actually, a tsunami evacuation route had been built to the hill with a 1.25 m wide concrete construction. Most of the survivors' confessions felt they were being swung comfortably for 2 o'clock, like sleeping on a swing.

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