

Scenario-based tsunami hazard assessment in the Tolo Thrust, Southeast Sulawesi

Muhammad Amin^{1,5}, Muhammad Taufiq Rafie^{*,2},
Muhammad Alimuiddin Hamzah Assagaf³, Rachmat Jariah Jamal¹,
Muhammad Farid Wajedy², Muhammad Faqih Raihan⁴, Saaduddin³

⁽¹⁾ Master program of Geophysics, Department of Geophysics, Faculty of Mathematics and Natural Sciences, Hasanuddin University, Makassar 90245, Indonesia.

⁽²⁾ Solid Geophysics Laboratory, Department of Geophysics, Faculty of Mathematics and Natural Sciences, Hasanuddin University, Makassar 90245, Indonesia.

⁽³⁾ Coastal and Ocean Dynamics Laboratory, Department of Geophysics, Faculty of Mathematics and Natural Sciences, Hasanuddin University, Makassar 90245, Indonesia.

⁽⁴⁾ Department of Geophysics, Faculty of Mathematics and Natural Sciences, Hasanuddin University, Makassar 90245, Indonesia.

⁽⁵⁾ The Agency for Meteorology Climatology and Geophysics of the Republic of Indonesia, Makassar, Indonesia.

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Abstract

The Tolo Thrust, located in eastern Indonesia, is a potentially tsunamigenic structure capable of generating destructive tsunamis that threaten coastal communities surrounding Tolo Bay. This study presents a scenario-based tsunami hazard assessment using the Cornell Multi-grid Coupled Tsunami Model (COMCOT) to evaluate the effects of earthquake magnitude and rupture configuration on tsunami generation and propagation. Sixteen earthquake scenarios were considered, including a Mw 8.0 worst-case scenario and fifteen alternative Mw 7.5-7.8 scenarios representing variations in rupture geometry and slip distribution. The Mw 8.0 scenario produced the largest tsunami amplitudes and the broadest distribution of coastal impacts, with maximum wave heights reaching 2.76 m at Menui Island, 2.20 m at North Konawe, 2.12 m at Wawonii Island, and 2.05 m at Kendari City. Tsunami travel-time contours calculated at 5-min propagation period indicate that near-field locations such as Menui and Wawonii Islands may experience tsunami arrival within approximately 1-3 min after earthquake occurrence, whereas more distant coastlines, including South Buru and Sula Islands, may receive the first waves after 30-55 min. Although the Mw 7.5-7.8 scenarios generally generated lower tsunami amplitudes, several rupture configurations produced localized wave amplification comparable to larger events, highlighting the importance of rupture directivity, fault geometry, and regional bathymetry in controlling tsunami hazards. The results indicate that tsunami impacts are concentrated along the eastern coast of Southeast Sulawesi and around Menui and Wawonii Islands, while the semi-enclosed geometry of Tolo Bay plays a major role in focusing tsunami energy. These findings provide a scientific basis for tsunami early-warning systems, evacuation planning, and coastal risk mitigation strategies for Southeast Sulawesi and adjacent island communities.

Keywords: Tolo Thrust; Banda Sea; Tsunami modeling; Tsunami hazard; Southeast Sulawesi

1. Introduction

Eastern Indonesia, particularly Sulawesi, is recognized as one of the world's most geodynamically complex regions because multiple major plates and microplates converge, collide, and subduct within a compact space, generating rapid deformation, dense seismicity, and structurally diverse fault systems. This complexity is reflected in the strong spatial variability of the focal mechanisms and earthquake clustering, indicating active stress partitioning across multiple tectonic domains (Cardwell et al., 1980). Consequently, this tectonic setting has created a highly active seismic environment capable of generating destructive earthquakes and tsunamis

Historical records show that tsunami-generating earthquakes have repeatedly occurred along the northern and eastern edges of Sulawesi, highlighting the island's vulnerability to severe ground shaking and tsunami hazards by various mechanisms as shown in Fig. 1. Within the Banda Arc convergence environment, deformation in Southeast Sulawesi is organized by a tiered structural system involving the Hamilton Fault Zone (HFZ) and Tolo-Buton Thrust System (Cardwell et al., 1980). Geodetic and seismological observations indicate heterogeneous strain accommodation, where compressional components are preferentially absorbed by the thrust system, whereas shear-related deformation is distributed more broadly into the surrounding region (Beaudouin et al., 2003; Y. Bock et al., 2003). The Tolo Thrust, together with the HFZ, is interpreted as a major structure accommodating and partitioning convergent deformation in southeastern Sulawesi (Cardwell et al., 1980; Ilham et al., 2019; Al Rubaiyn et al., 2022).

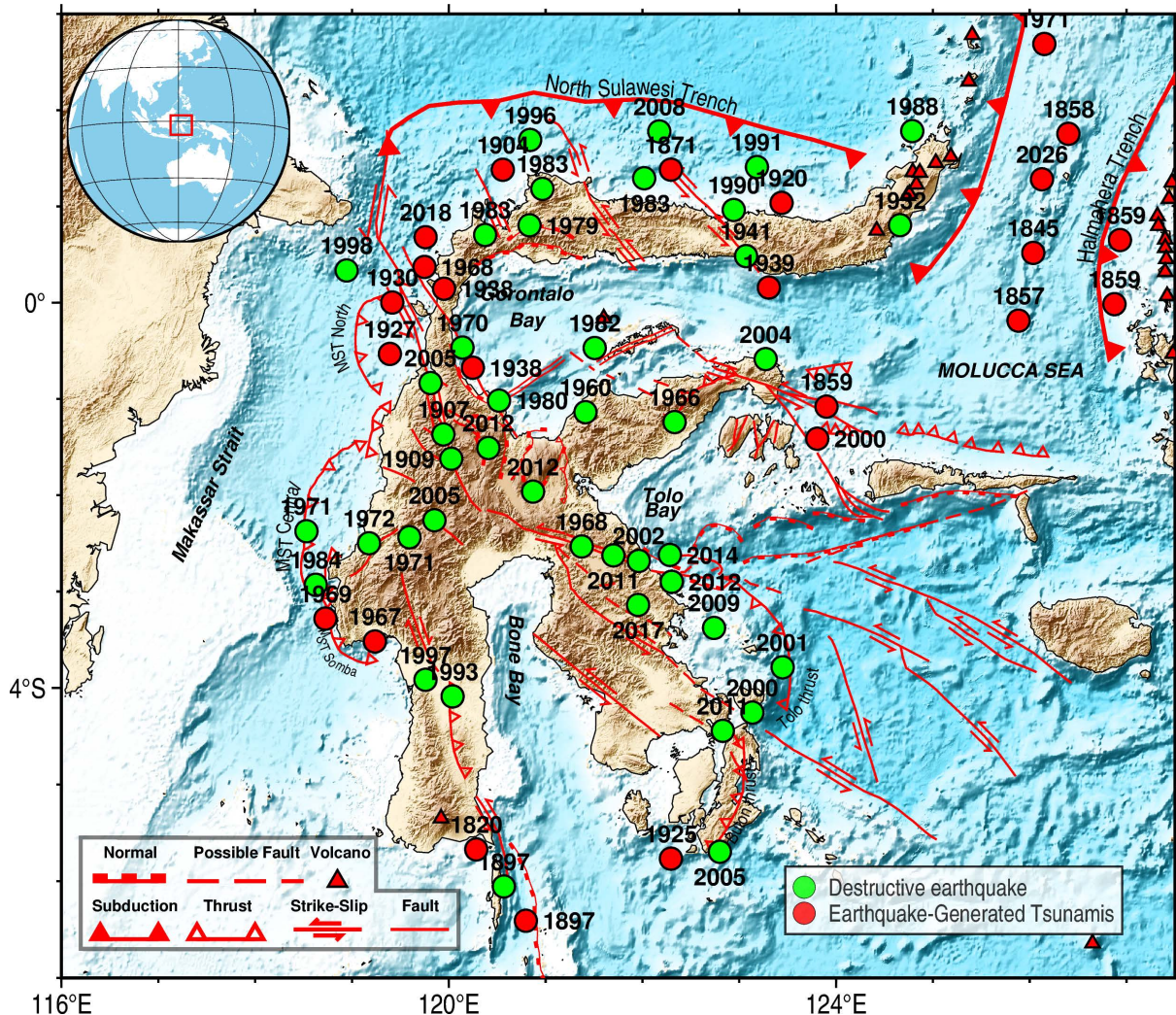


Figure 1. Map of destructive earthquakes and earthquake-generated tsunamis in Sulawesi and adjacent regions during the last century. Green circles denote destructive earthquakes that caused significant damage and/or casualties, whereas red circles denote earthquakes that generated tsunamis. (sources: BMKG; Soloviev and Go, 1974; Soloviev et al., 1992; Wichmann, 1918; Sleberg, 1932; Heck, 1934; Berninghausen, 1969; Priadi, 1993; and USGS).

Geological and morphostructural evidence identifies the Tolo Thrust as a first-order tectonic boundary associated with the opening of the Banda Basin and deformation transfer across the Banda-Sulawesi system (Santoso and Soehaimi, 2010; Baeda, 2011). Earthquake catalogues reveal persistent seismicity ranging from M3 to M7, while spatial variations in b-values (≈ 0.355 -1.337) suggest heterogeneous stress accumulation and crustal strength across the region (Chasanah et al., 2013; Ilham et al., 2019; Al Rubaiyn et al., 2022).

Because shallow thrust faulting can generate significant vertical seafloor displacement, the Tolo Thrust represents a plausible tsunamigenic source. Historical events and numerical studies in eastern Indonesia demonstrate that similar thrust systems have produced destructive tsunamis with substantial coastal impacts (Koshimura et al., 2009; Wang and Power, 2011; Nguyen et al., 2014). Recent disasters further underline the need for local-source characterization. Historical tsunamis such as the 1852 Banda and 1992 Flores events highlight the persistent regional threat posed by tectonically generated tsunamis (Imamura et al., 1995).

Despite advances in tsunami hazard assessment, dedicated evaluations of the Tolo-HFZ upper-plate thrust system remain limited, particularly regarding rupture segmentation, fault geometry, and tsunami potential (Blaser et al., 2012; Risi and Goda, 2016; Widiyantoro et al., 2020). A growing body of work recognizes that these structures can generate consequential local tsunamis, particularly when they are close to populated coasts or within morphologically complex basins that can amplify wave heights (Felix et al., 2022).

This study evaluates the tsunamigenic potential of the Tolo Thrust through integrated tectonic interpretation and scenario-based tsunami modeling. The resulting seafloor deformation and tsunami propagation are simulated using validated numerical models to estimate tsunami wave heights, arrival times, and spatial impact patterns, thereby providing a scientific basis for coastal risk reduction.

2. Data and Methodology

2.1 Source Definition

The earthquake source model was constructed using a deterministic scenario-based approach to represent the tsunamigenic potential of the Tolo Thrust. The maximum credible earthquake (worst-case scenario) was first estimated from the total mapped length of the Tolo Thrust obtained from the IndonesiaFaults.geojson dataset, which is approximately 176.2 km. Following the empirical magnitude-rupture length relationship of Thingbaijam et al. (2017),

$$\log(L) = -2.693 + 0.614 \times M \quad (1)$$

where L is the rupture length (km) and M is the moment magnitude, the total fault length corresponds to an earthquake magnitude of approximately Mw 8.0. This event was therefore adopted as the upper-bound deterministic scenario representing rupture of the entire modeled Tolo Thrust segment.

To account for smaller but still potentially tsunamigenic earthquakes, Mw 7.5 was selected as the minimum scenario because earthquakes of this magnitude are generally capable of producing measurable seafloor deformation and tsunami generation along active offshore thrust faults. Two intermediate scenarios, Mw 7.6 and Mw 7.8, were additionally introduced to represent progressive increases in rupture size between the minimum and maximum events. The rupture lengths for these three scenarios were calculated using the inverse form of the Thingbaijam et al. (2017) scaling relationship, resulting in rupture lengths of 82.7 km, 94.1 km, and 124.8 km for Mw 7.5, Mw 7.6, and Mw 7.8, respectively. For these partial-rupture scenarios, the rupture width was assumed to follow a constant aspect ratio of ($W = L/2$) (Nakata et al., 2019), yielding widths of 40.8 km, 47.0 km, and 62.4 km, respectively.

For the worst-case scenario with a magnitude of Mw 8.0, the corresponding fault width is calculated to be 70.99 km. A constant dip angle of 25° is adopted for all scenarios, while the downward reach of the fault is limited to a maximum depth of 30 km. The three-dimensional visualization of this depth and dip has been shown in Fig. 2B.

The average coseismic slip for each earthquake scenario was subsequently estimated from the seismic moment relationship,

$$D = \frac{M_0}{\mu A} \quad (2)$$

where D is the average slip, A is the rupture area, μ is the shear modulus assumed to be 3×10^{10} Pa, and M_0 is the seismic moment derived from the moment magnitude relation of Hanks and Kanamori (1979).

$$M = \frac{2}{3} \log M_0 - 10,7 \quad (3)$$

The resulting average slips are 3.0 m, 2.4 m, 2.1 m, and 2.0 m for the Mw 8.0, Mw 7.8, Mw 7.6, and Mw 7.5 scenarios, respectively.

In total, sixteen deterministic earthquake source scenarios were constructed, comprising one worst-case rupture of the entire Tolo Thrust segment and fifteen partial-rupture scenarios with varying rupture dimensions and source locations. Although a spatially uniform slip distribution was assumed for each earthquake scenario, the rupture geometry was represented using a finite-fault approach to accommodate the arcuate geometry of the Tolo Thrust. The fault plane was discretized into multiple rectangular patches following the mapped fault trace, and the calculated

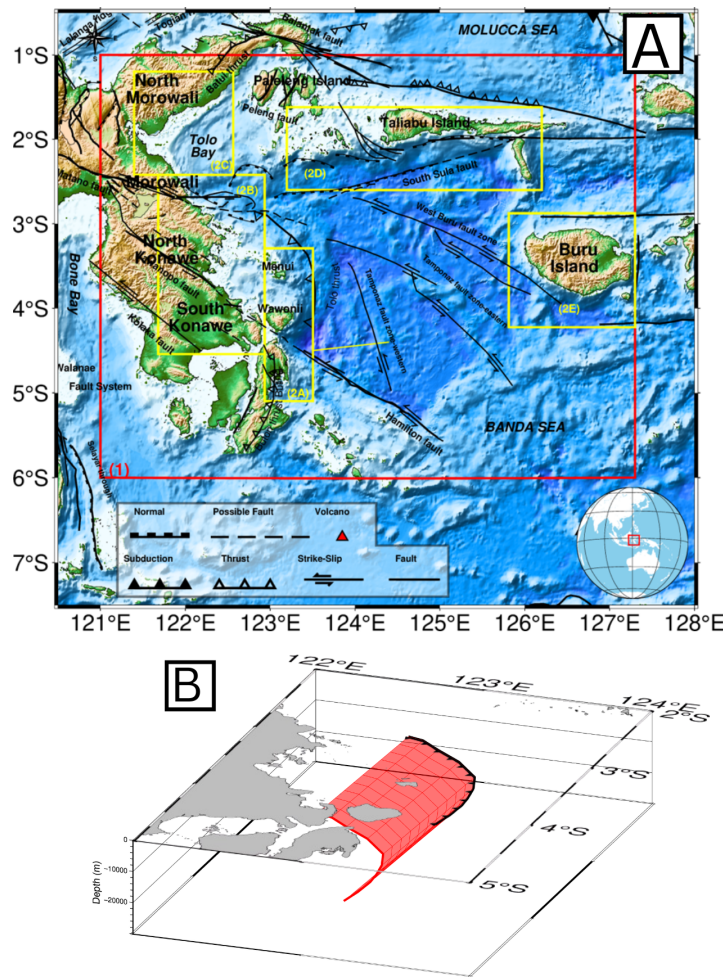


Figure 2. (A) A tectonic framework map of the study area showing the position of the Tolo Thrust and the active fault network in Eastern Indonesia. Tiered grid configuration for tsunami simulation. Red rectangles represent the coarsest domain (Domain 1), yellow rectangles represent the more localized areas (Domain 2, Table 2). (B) Three-dimensional visualization of the Tolo Fault geometry adopted for the coseismic deformation model. The fault surface was constructed by projecting the mapped surface fault trace downward toward the southwest with a constant dip angle of 25° to a maximum depth of 30 km. The black polyline indicates the surface expression of the fault, whereas the semi-transparent red plane represents the modeled rupture surface. The red grid corresponds to the computational mesh used to define the fault geometry in the tsunami source model. The surrounding topography is displayed to illustrate the spatial relationship between the fault plane and the study area.

average slip was uniformly assigned to all activated patches within each scenario. For the Mw 7.5, Mw 7.6, and Mw 7.8 cases, alternative rupture scenarios were generated by systematically shifting the activated patch group along the strike direction of the fault while maintaining identical rupture dimensions, average slip, and seismic moment. This strategy enables evaluation of the influence of rupture location on tsunami generation and coastal wave characteristics while preserving physically consistent earthquake source parameters. The complete source parameters for all scenarios are summarized in Table 1, and representative finite-fault rupture models are presented in Fig. 2A.

Table 1. Estimated fault geometry derived from empirical scaling relationship by Thingbaijam et al. (2017).

Scenario	Mw	Length (L) km	Width (W) km	Slip (m)
Scenario A	8.0	176.2	70.9	3.0
Scenario B-D	7.8	124.8	62.4	2.4
Scenario E-I	7.6	94.1	47.0	2.1
Scenario J-P	7.5	81.7	40.8	2.0

2.2 Tsunami Modeling

Tsunami propagation was simulated using the Cornell Multi-grid Coupled Tsunami Model (COMCOT), a widely used numerical model for tsunami generation and propagation based on the nonlinear shallow-water equations (Liu et al., 1994; Wang and Power, 2011). The initial sea-surface deformation generated from the earthquake source model was directly imposed as the initial condition for each simulation.

Bathymetric data were obtained from the Indonesian National Bathymetry Dataset (BATNAS) provided by the Geospatial Information Agency of Indonesia (BIG), with a maximum spatial resolution of 6 arc-sec (Ina-Geoportal). A nested-grid configuration was employed to efficiently simulate tsunami propagation from the regional scale to the coastal areas while preserving computational efficiency. The outer computational domain covers the region between 1°S-6°S and 121°E-128°E using an 18 arc-sec grid resolution, whereas five nested inner grids were generated with a spatial resolution of 6 arc-sec, corresponding to the highest resolution available from the BATNAS dataset (Table 2 and Fig. 2A).

Table 2. The domains utilized in the nested grid configuration of this study.

Domain	xmin	xmax	ymin	ymax	Grid size		
					Degree	Arc-sec	Meter
1	121.00	127.30	-6.00	-1.00	0.005	18	555.7
2A	122.93	123.50	-5.09	-3.29	0.00167	6	185.2
2B	121.68	122.93	-4.54	-2.42	0.00167	6	185.2
2C	121.40	122.56	-2.42	-1.19	0.00167	6	185.2
2D	123.19	126.20	-2.60	-1.62	0.00167	6	185.2
2E	125.81	127.30	-4.22	-1.87	0.00167	6	185.2

Each tsunami scenario was simulated for a duration of 1 hour, which is sufficient to capture tsunami generation, basin-wide propagation, and the first arrivals along the surrounding coastlines of the Banda Sea and eastern Sulawesi. Tsunami wave characteristics were evaluated using a network of eleven virtual gauge stations located along the 20 m isobath. The stations were distributed around the Banda Sea, including Buru Island, the Sula Islands, Taliabu Island, Menui Island, Wawonii Island, and the eastern coast of Sulawesi (Fig. 3, Table 3). Stations along the eastern Sulawesi

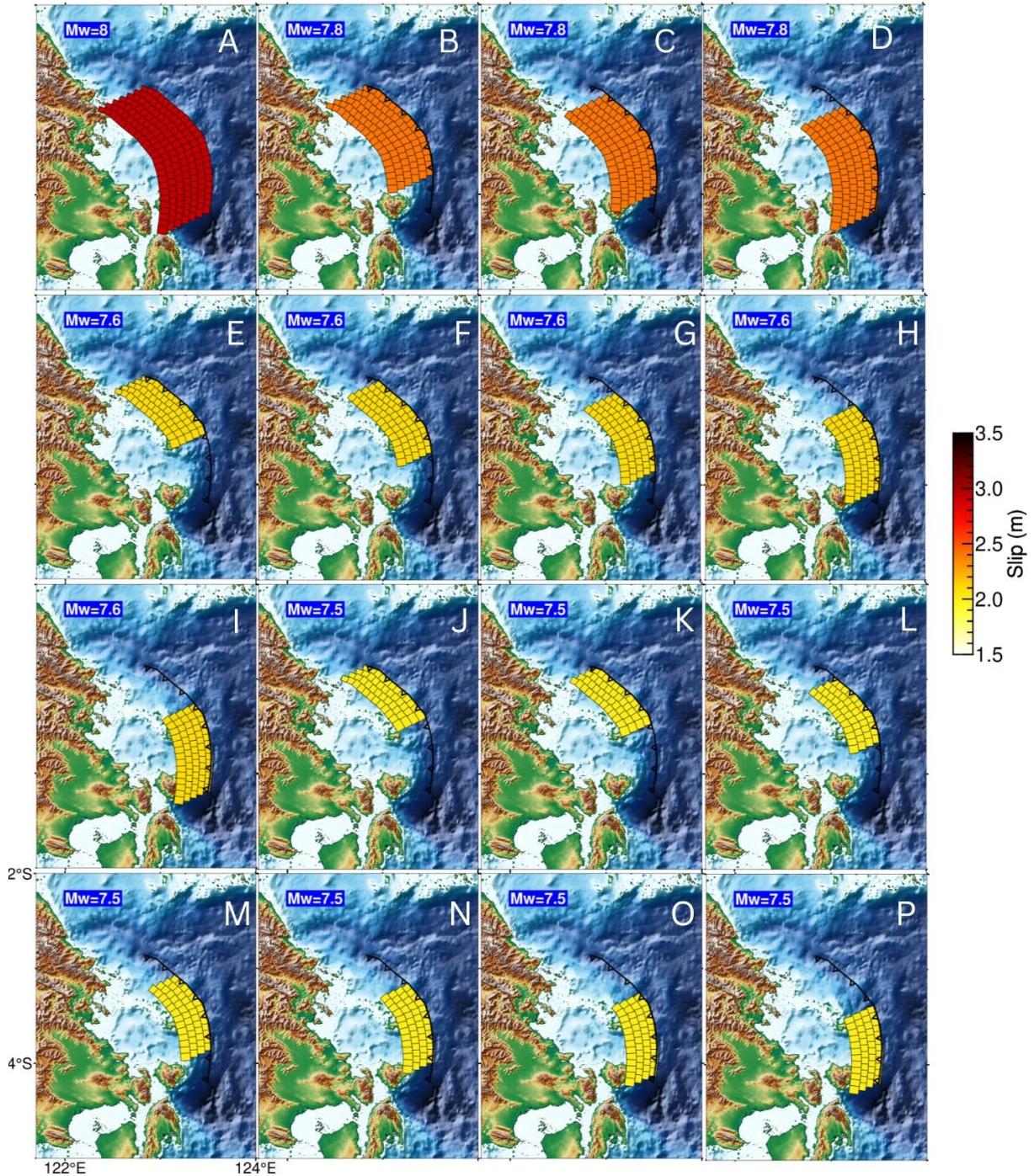


Figure 3. Spatial distribution of sixteen earthquake source scenarios along the Tolo Thrust used for tsunami modeling. Scenario A represents a Mw 8.0 earthquake, scenarios B-D represent Mw 7.8 earthquakes, scenarios E-I represent Mw 7.6 earthquakes, and scenarios J-P represent Mw 7.5 earthquakes. The red line denotes the mapped trace of the Tolo Thrust, while the colored rectangular patches indicate the rupture areas discretized into sub-faults. Variations in rupture location and dimension were implemented to evaluate the sensitivity of tsunami generation and propagation to different earthquake source configurations along the fault system.

coastline were designed to capture spatial variations in tsunami characteristics near the source region, whereas stations surrounding the adjacent islands were intended to evaluate tsunami propagation and transformation across the island chain and the semi-enclosed basin. This observation network provides a consistent basis for comparing tsunami arrival times and maximum wave heights among all earthquake scenarios.

Table 3. location and depth Tide-gauge Stations.

Name	Location		
	Lat	Long	Depth (m)
TS_Buru Selatan	126.27	−3.69	20
TS_Sula	125.91	−1.97	20
TS_Taliabu Selatan	124.81	−1.91	20
TS_North Morowali	121.80	−1.79	20
TS_Morowali	121.83	−2.28	20
TS_Morowali Power Plant	122.31	−2.96	20
TS_North Konawe	122.35	−3.73	20
TS_Kendari City	122.62	−3.97	20
TS_North Buton	123.15	−4.51	20
TS_Menui Island	123.18	−3.61	20
TS_Wawonii Island	123.22	−4.02	20

3. Results

3.1 Crustal Deformation

Static crustal deformation calculated using the Okada elastic dislocation model reveals a consistent dipolar uplift-subsidence pattern, characteristic of thrust-fault earthquakes (Okada, 1985). All faulting scenarios produce an elongated zone of uplift offshore along the eastern edge of Southeast Sulawesi, accompanied by a broader area of subsidence extending southwestward into the Tolo Basin, as shown in Fig. 4. This deformation pattern reflects the typical elastic response of a compressional tectonic setting and indicates effective vertical displacement of the seafloor.

The Mw 8.0 scenario produces the largest deformation signature, with maximum uplift exceeding 1 m and covering the largest offshore area. As the earthquake magnitude decreases from Mw 7.8 to Mw 7.5, both the amplitude and spatial extent of deformation progressively decrease, although the overall geometry of the uplift-subsidence remains similar. Even in the Mw 7.5 scenario, an uplift lobe remains clearly developed offshore Southeast Sulawesi, indicating that all modeled events can produce substantial disturbances in the overlying water column.

Variations in fault location result in a significant shift in the position of the uplift lobe. The northern fault scenario concentrates uplift toward the Morowali-North Konawe sector, while the southward-shifting fault shifts the center of deformation closer to Wawonii Island and the Kendari region. These differences along the fault line

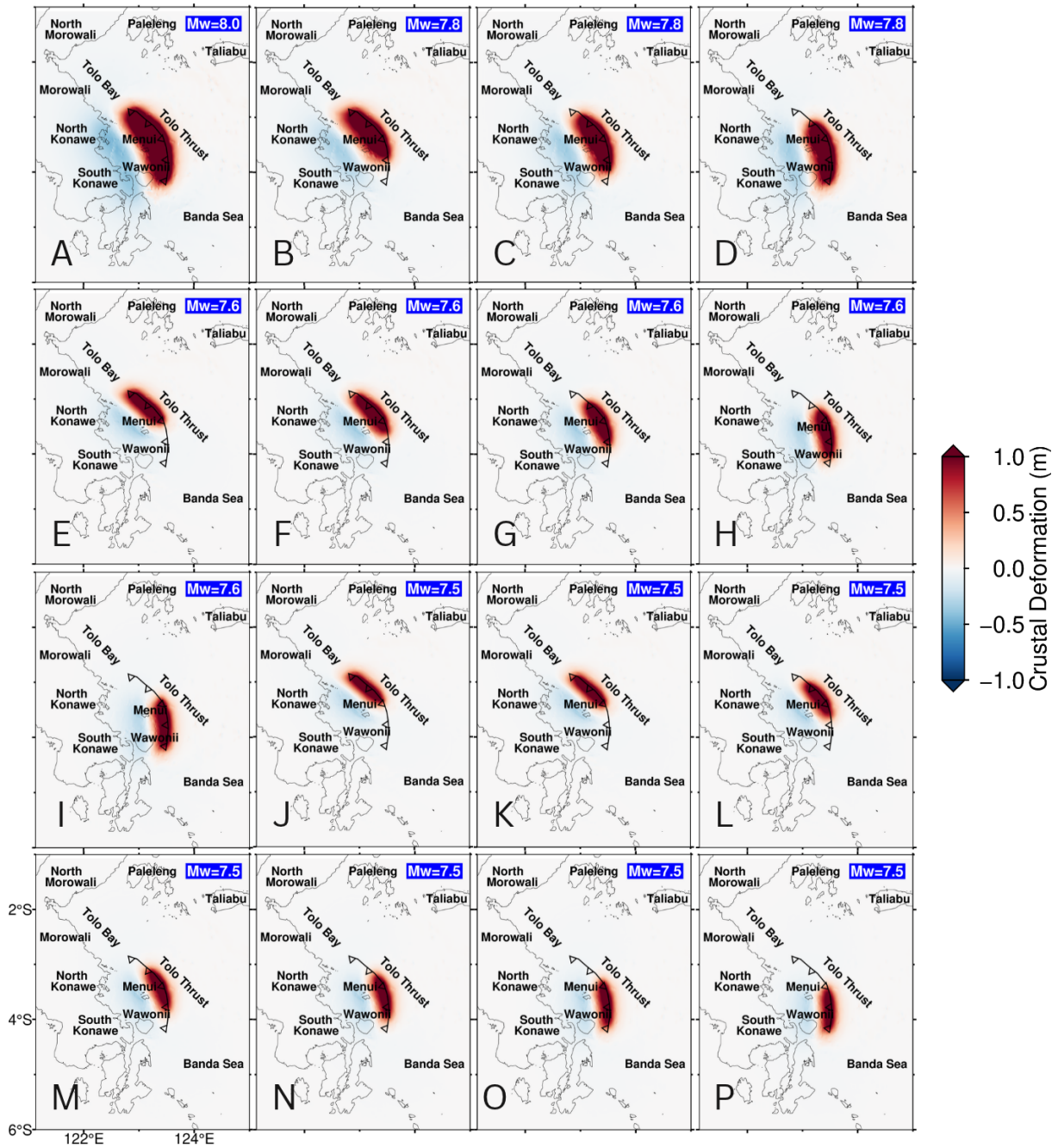


Figure 4. Spatial distribution of coseismic crustal deformation associated with sixteen hypothetical earthquake scenarios along the Tolo Thrust. Scenario A corresponds to Mw 8.0, scenarios B-D to Mw 7.8, scenarios E-I to Mw 7.6, and scenarios J-P to Mw 7.5. Red and blue colors denote positive (uplift) and negative (subsidence) vertical crustal displacements, respectively. The deformation fields were calculated from the fault rupture models and subsequently used as initial conditions for tsunami generation simulations. The Mw 8.0 scenario produces the largest deformation extent and amplitude, while lower-magnitude scenarios generate more localized crustal deformation patterns.

alter the orientation of the deformation gradient and indicate a corresponding change in the preferred direction of tsunami energy propagation.

Following the general assumption that initial sea-level displacement replicates vertical coseismic seafloor deformation (Satake, 2002; Wang and Power, 2011), the modeled deformation fields demonstrate efficient tsunami generation in all scenarios. The steep gradient between uplift and subsidence indicates a strong tsunami potential near the earthquake site, while the location of maximum uplift indicates that the tsunami impact will primarily affect

the east coast of Southeast Sulawesi. Larger magnitude earthquakes, particularly the Mw 8.0 and Mw 7.8 scenarios, produce broader deformation footprints and therefore represent the highest tsunami hazard, while the Mw 7.5 and Mw 7.6 scenarios produce more localized but still potentially damaging impacts.

Overall, the results indicate that relatively small changes in fault position along the Tolo Thrust can modify the spatial distribution of earthquake-induced uplift and, consequently, influence tsunami direction and coastal hazard patterns. Nevertheless, the persistence of dipolar deformation structures across all scenarios highlights the strong tsunami-generating capacity of the Tolo Thrust system.

3.2 Tsunami Propagation and Maximum Wave Amplitudes

The multi-scenario tsunami modelling results reveal pronounced spatial variability in the distribution of maximum tsunami wave heights among the sixteen rupture scenarios considered in this study (Fig. 5). The Mw 8.0 Scenario_A produces the most extensive area of elevated tsunami amplitudes, with significant wave amplification concentrated along the eastern coast of Southeast Sulawesi, particularly from North Konawe to Kendari, as well as around Menui and Wawonii Islands. This pattern reflects the orientation of coseismic uplift and the preferential westward radiation of tsunami energy into the semi-enclosed Tolo Bay basin.

In comparison, the Mw 7.8 scenarios (B-D) exhibit a similar spatial distribution of tsunami energy but with reduced amplitudes and a smaller extent of coastal amplification. At the locations where comparable maximum amplitudes were identified, the maximum wave heights decreased by approximately 0.62-0.70 m (25-31%) relative to the Mw 8.0 Scenario_A. The Mw 7.6 scenarios (E-I) further confined the high-amplitude wave field to areas adjacent to the source region, with maximum amplitudes at the comparable sites reduced by approximately 1.12-1.19 m (41-58%) relative to Mw 8.0. The Mw 7.5 scenarios (J-P) generated the most localized tsunami response, with reductions of approximately 0.50-1.34 m (24-65%) at the comparable sites. Nevertheless, several Mw 7.5-7.8 rupture configurations produce localized wave amplifications comparable to those obtained for larger-magnitude events, particularly along the southeastern Sulawesi coastline and around Menui Island. Such behavior suggests that tsunami generation efficiency is not solely controlled by earthquake magnitude, but is also highly sensitive to rupture position, fault geometry, and the directionality of tsunami energy radiation.

Despite these differences in maximum wave heights, the overall tsunami propagation path remained remarkably consistent across all scenarios. Tsunami travel-time contours, representing the arrival time of the first tsunami wave, defined here as the time when the simulated surface-water elevation first reaches or exceeds a threshold of 0.1 m, were plotted at 5-minute intervals. Rather than radiating uniformly from the source region, tsunami energy tended to travel west and northwest toward the east coast of Southeast Sulawesi, particularly North Konawe, South Konawe, and Kendari, while a secondary energy path extended southwest toward Wawonii and Menui Islands. In contrast, wave propagation toward Sula, South Taliabu, Morowali, and North Morowali was relatively weaker and characterized by lower coastal amplification. The similarity in travel-time contour geometry across all scenarios suggests that regional bathymetry and basin morphology exerted dominant influences on tsunami propagation, while variations in fault magnitude and source configuration primarily influenced tsunami amplitude and the extent of coastal amplification. Consequently, although earthquake magnitude influences the severity and spatial extent of tsunami impacts, source direction and local coastal configuration play an equally important role in determining tsunami hazard across the Tolo Bay region.

3.3 Coastal Tsunami Wave Heights and Arrival Times

3.3.1 Worst-case scenario

The Mw 8.0 Scenario A rupture generated a tsunami that propagated throughout Tolo Bay and the surrounding seas, with wave heights strongly influenced by rupture directivity, basin morphology, and coastal configuration (Fig. 5A). The highest offshore amplitudes were concentrated along the eastern coast of Southeast Sulawesi, particularly from North Konawe to Kendari and Morowali, reflecting the orientation of coseismic uplift and the focusing effect of the semi-enclosed Tolo Bay geometry (Tomita et al., 2007; Dutykh et al., 2011). These propagation patterns are consistent with the simulated waveforms at eleven observation sites, which exhibit considerable variability in arrival

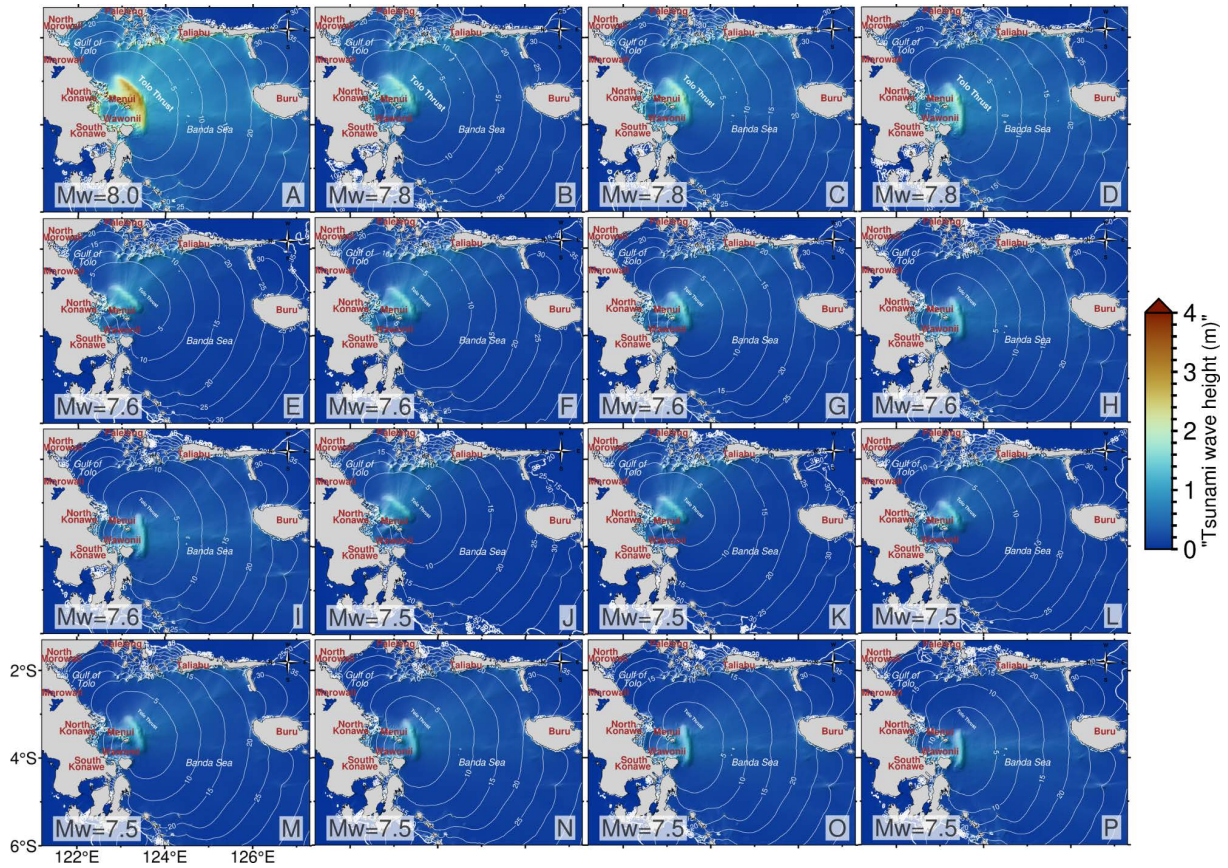


Figure 5. Spatial distribution of maximum tsunami wave heights generated by sixteen earthquake scenarios along the Tolo Thrust. Panel A represents the Mw 8.0 worst-case scenario, panels B-D correspond to Mw 7.8 scenarios, panels E-I to Mw 7.6 scenarios, and panels J-P to Mw 7.5 scenarios. The results demonstrate substantial variations in tsunami energy distribution associated with differences in rupture magnitude, location, and geometry. In all scenarios, enhanced tsunami amplitudes are concentrated along the eastern coast of Southeast Sulawesi and around Menui and Wawonii Islands, although the extent and intensity of amplification vary among rupture configurations.

times and maximum amplitudes (Fig. 6). The earliest arrivals occurred at Menui Island and Wawonii Island within approximately 1-2 min after the earthquake, where the largest positive wave heights of 2.76 m and 2.12 m were also recorded, indicating their proximity to the tsunami source region.

Intermediate arrival times were observed at Morowali Power Plant, North Buton, Kendari City, and Morowali, where tsunami waves arrived within approximately 10-21 min. At Kendari City, the tsunami reached a maximum amplitude of 2.05 m at approximately 33-34 min, whereas Morowali Power Plant and Morowali experienced considerably smaller peak elevations of 0.86 m and 0.66 m, respectively. The relatively reduced amplitudes at these locations suggest partial shielding effects associated with local coastal geometry and bathymetric irregularities.

Along the eastern coast of Southeast Sulawesi, North Konawe exhibited one of the most severe tsunami responses. Although the initial arrival occurred at approximately 27-28 min, the maximum elevation of 2.20 m was reached considerably later, at about 46-47 min, indicating progressive amplification due to wave reflection, shoaling, and possible resonance within embayed coastal environments. A similar delayed amplification pattern was observed in South Taliabu, where the first arrival occurred after about 28-29 min, while the maximum crest of 1.49 m developed near 35 min.

The latest tsunami arrivals were identified at North Morowali, Sula, and South Buru, with first arrivals occurring after approximately 32-50 min. Sula experienced a maximum wave height of 1.64 m at around 53 min, whereas North Morowali and South Buru recorded peak elevations of 1.11 m and 1.39 m, respectively. The delayed arrivals at these sites reflect the longer propagation paths and the influence of regional bathymetry on tsunami travel times.

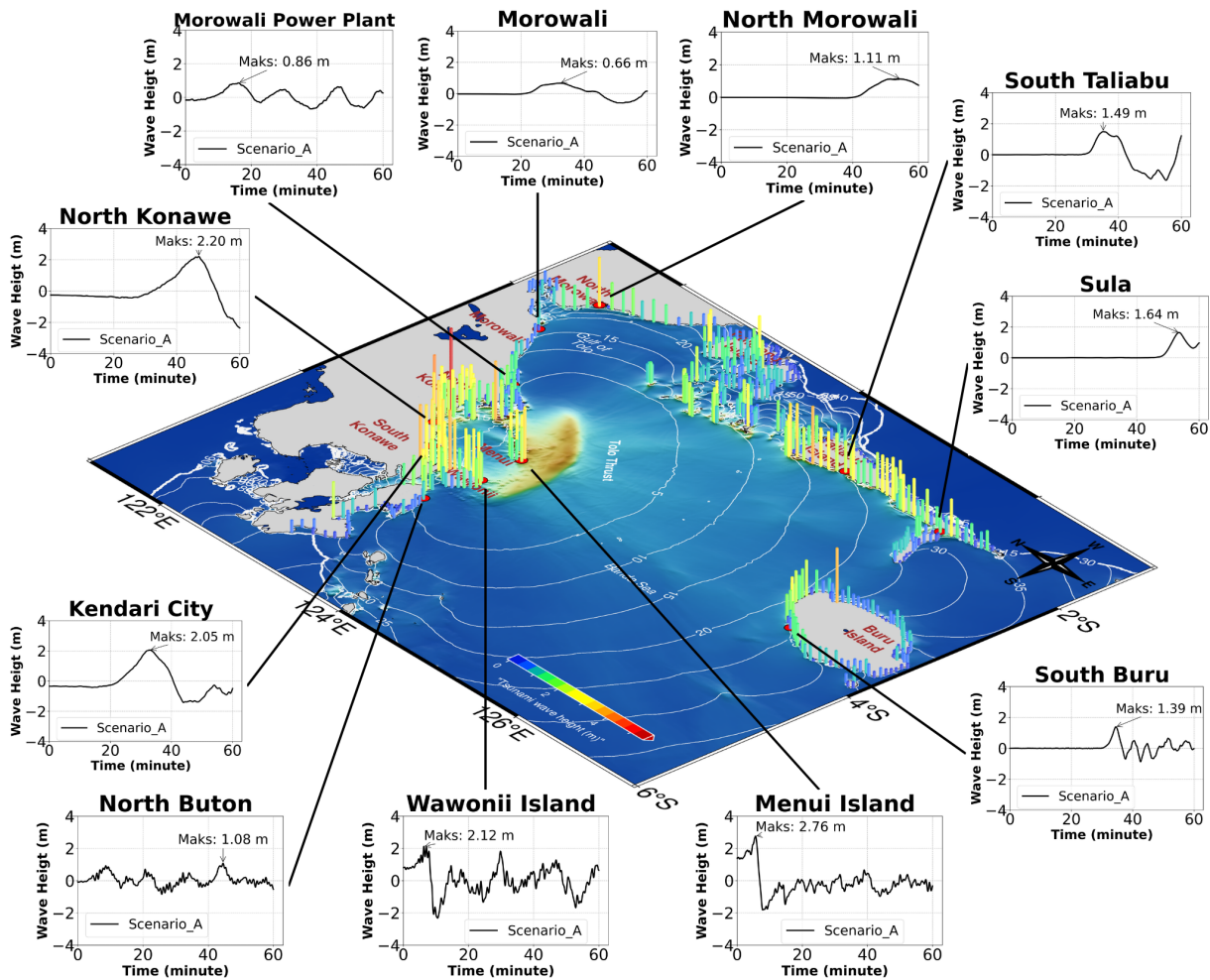


Figure 6. Three-dimensional visualization of the maximum tsunami wave heights generated by the Mw 8.0 Scenario_A rupture along the Tolo Thrust, superimposed on regional bathymetry. Insets show modeled tsunami waveforms at eleven observation sites surrounding Tolo Bay and adjacent regions. Vertical bars represent the maximum positive tsunami amplitudes, while arrows and annotations indicate the peak wave height recorded at each site. The results highlight significant spatial variability in tsunami amplification, with the largest waves occurring at Menui Island (2.76 m), North Konawe (2.20 m), Wawonii Island (2.12 m), and Kendari City (2.05 m).

Overall, the Mw 8.0 Case A scenario indicates that tsunami hazards are concentrated around Menui and Wawonii Islands and along the eastern coast of Southeast Sulawesi, where wave heights exceed 2.5 m and arrival times are less than 15 min. In contrast, more distant coastlines such as Sula and South Buru experience longer warning times and generally lower wave heights. Nevertheless, the results show that damaging tsunami impacts may still occur throughout the wider Tolo Bay region, highlighting the need for effective evacuation planning and site-specific tsunami early-warning strategies. The first arriving wave was not always the largest; at North Buton, for example, the maximum wave amplitude was associated with a subsequent wave rather than the initial arrival in both the Mw 8.0 and Mw 7.5 scenarios. This behavior emphasizes the importance of maintaining evacuation measures until official clearance is issued.

3.3.2 Multi scenario Assessment

The tsunami modelling results for the Mw 7.5, Mw 7.6, and Mw 7.8 earthquake scenarios reveal considerable spatial variability in wave amplitudes and waveform characteristics among the eleven observation sites (Figs. 7-9). Although tsunami arrival times remain generally similar among scenarios, indicating that wave travel times are primarily

controlled by source-to-site distance and regional bathymetry, wave amplitudes exhibit a strong dependence on earthquake magnitude and rupture geometry.

The Mw 7.5 scenarios (Scenario_J-P) produced the greatest variability in tsunami waveforms and generated the highest amplitudes at several locations. Maximum tsunami heights reached 1.64 m at Menui Island, 1.62 m at Wawonii Island, 0.86 m at North Konawe, and 0.72 m at Kendari City. The oscillatory nature of the waveforms became more pronounced at Menui Island, Wawonii Island, and Morowali Power Plant, suggesting the influence of local bathymetric resonance and wave reflection processes. Conversely, Sula, South Taliabu, and North Morowali consistently exhibited delayed arrivals and relatively small amplitudes, generally remaining below 1 m even in the largest-magnitude scenarios.

For the Mw 7.6 scenarios (Scenario_E-I), tsunami heights generally increased, although Menui Island remained the most affected location with a maximum amplitude of 1.64 m, while North Konawe and Kendari City recorded peak elevations of 1.06 m and 0.86 m, respectively. Tsunami impacts at Morowali and Morowali Power Plant remained relatively limited, with maximum amplitudes generally not exceeding 0.55 m. Under the Mw 7.8

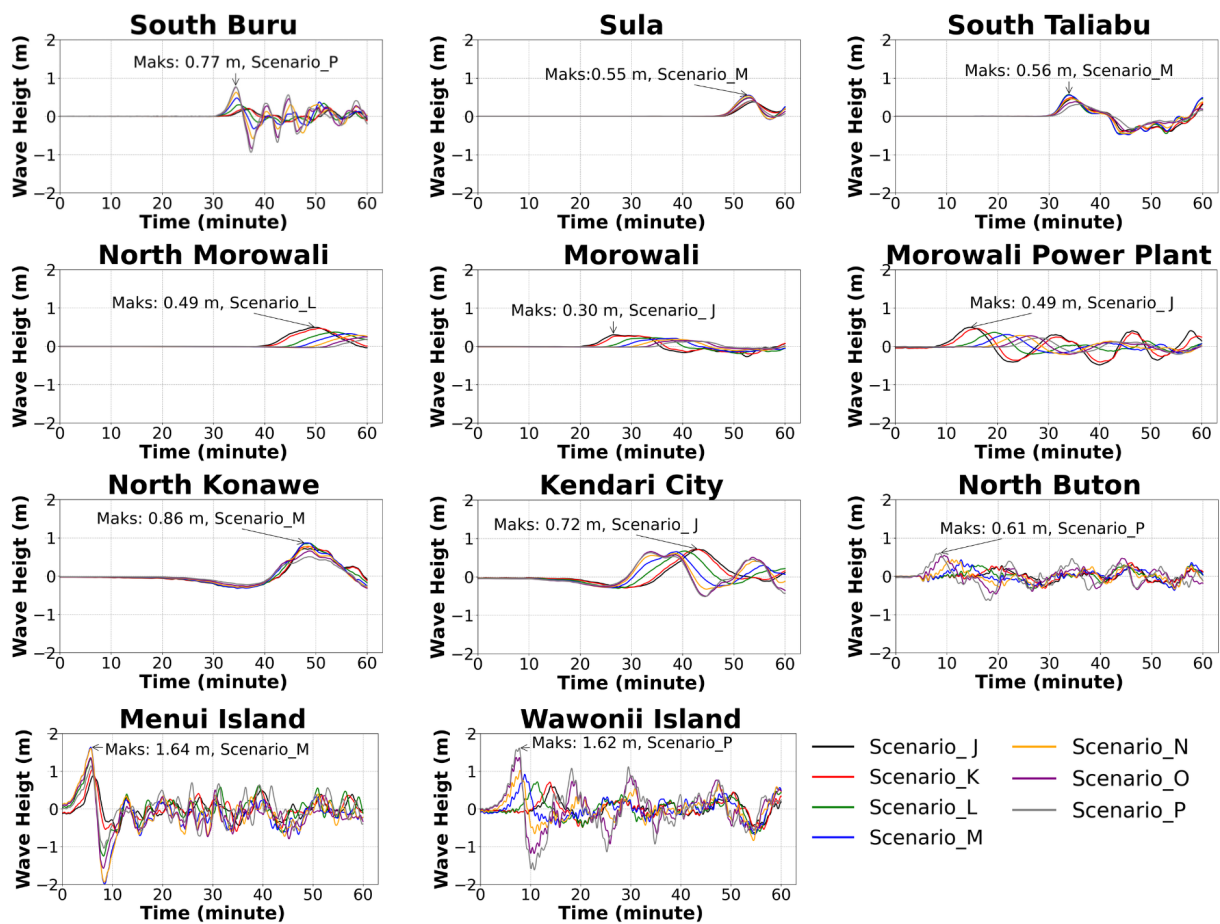


Figure 7. Modeled tsunami waveforms at eleven observation sites generated by the Mw 7.5 earthquake scenarios (Scenarios B-D) along the Tolo Thrust. The comparison illustrates the influence of alternative rupture configurations on tsunami propagation and coastal wave amplification. Arrows and annotations indicate the maximum positive wave height and the corresponding scenario producing the largest amplitude at each location.

scenarios (Scenario_B-D), the numerical modelling predicts the largest tsunami amplitudes at Menui Island, reaching 2.06 m in Scenario_D, followed by North Konawe (1.52 m) and Kendari City (1.43 m). Wawonii Island and North Buton experienced comparatively smaller amplitudes, with maximum wave heights below 0.75 m and 0.40 m, respectively.

Overall, the multi-scenario tsunami modelling approach indicates that Menui Island is the most vulnerable site within the study area, followed by North Konawe, Kendari City, and Wawonii Island. Interestingly, the highest tsunami amplitude at Menui Island was produced by the Mw 7.8 Scenario_D (2.06 m), exceeding those generated by several Mw 7.6 and Mw 7.5 scenarios. This finding suggests that tsunami generation efficiency is not solely controlled by earthquake magnitude but is also highly sensitive to rupture location, slip distribution, and the directionality of tsunami energy radiation. These results highlight the importance of incorporating multiple source configurations in tsunami hazard modelling to better characterize uncertainties associated with future earthquakes along the Tolo Thrust. Similar tsunami propagation and coastal response have also been investigated in other semi-enclosed coastal environments, including Manila Bay, where bathymetric conditions and coastal geometry influence tsunami propagation and wave response (Tomita et al., 2007; Dutykh et al., 2011; Felix et al., 2025).

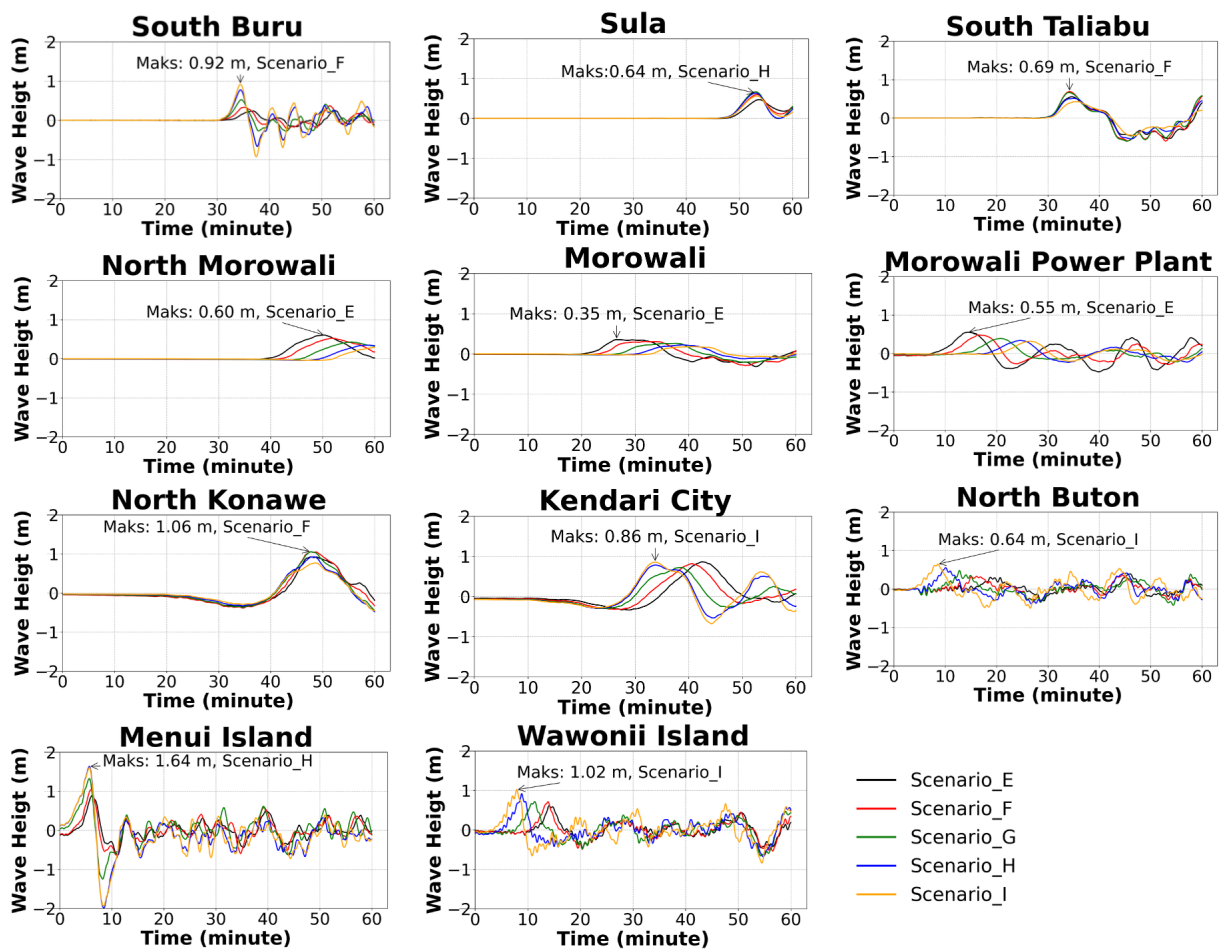


Figure 8. Modeled tsunami waveforms at eleven observation sites generated by the Mw 7.6 earthquake scenarios (Scenarios E-I) along the Tolo Thrust. Variations in waveform shape and amplitude among the scenarios demonstrate the sensitivity of tsunami generation to differences in rupture geometry and slip distribution. Arrows and labels denote the maximum positive wave height and the scenario responsible for the highest tsunami amplitude at each site.

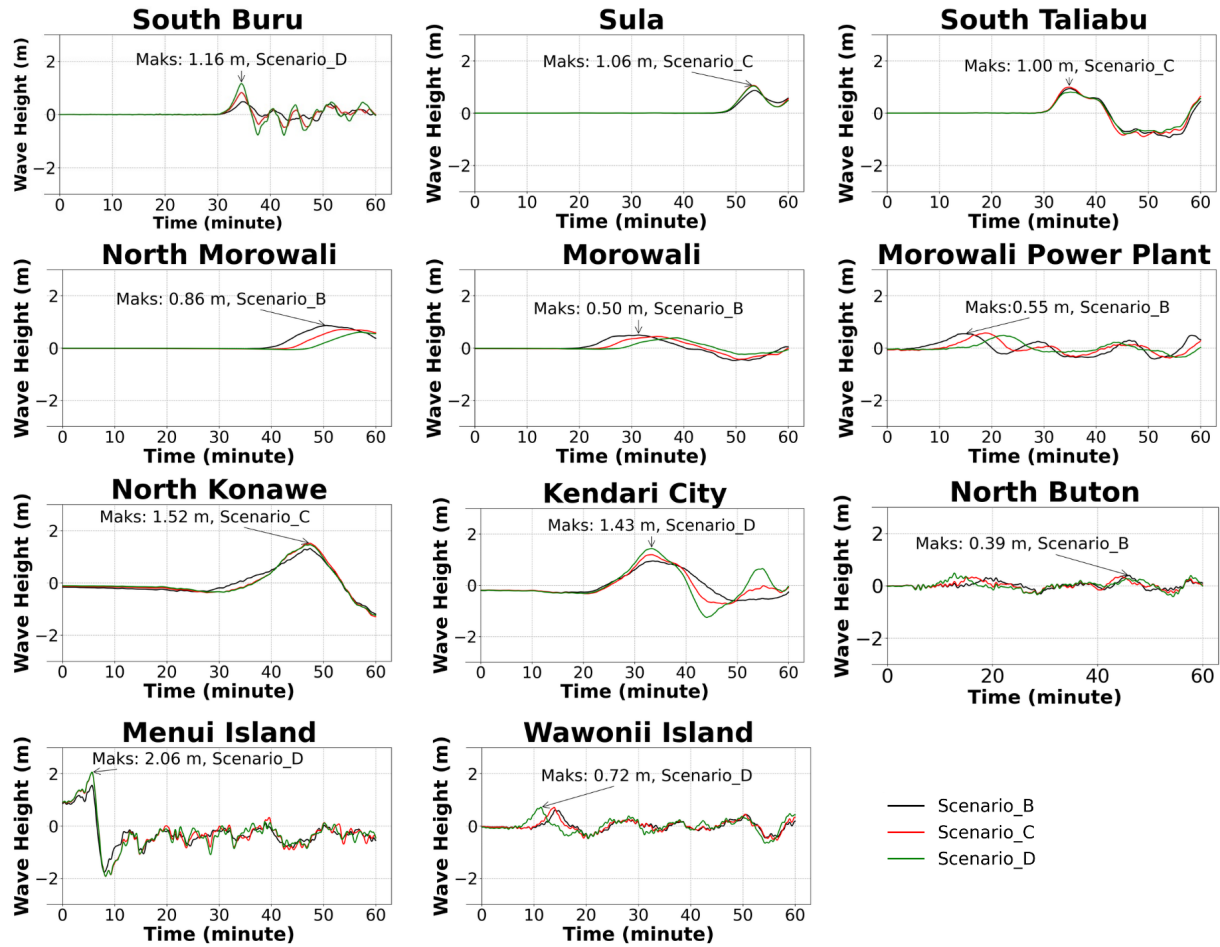


Figure 9. Modeled tsunami waveforms at eleven observation sites resulting from the Mw 7.8 earthquake scenarios (Scenarios J-P) on the Tolo Thrust. The modeled waveforms exhibit increased variability and larger amplitudes compared with the lower-magnitude scenarios, particularly at Menui Island, Wawonii Island, and North Konawe. Arrows and annotations identify the maximum positive wave height and the corresponding scenario producing the peak tsunami amplitude at each observation site.

4. Discussion

4.1 Tsunami hazard implications

The Mw 8.0 scenario produced the largest deformation footprint (Fig. 6), with peak uplift exceeding approximately 1 m and rupture dimensions consistent with empirical scaling relationships for large thrust earthquakes (Thingbaijam et al., 2017). The resulting uplift-subsidence gradient generated an asymmetric initial water surface that preferentially radiated tsunami energy toward the eastern coast of Southeast Sulawesi, particularly North Konawe, Kendari, Wawonii Island, and Menui Island. Maximum modeled tsunami amplitudes reached 2.76 m at Menui Island, 2.20 m at North Konawe, 2.12 m at Wawonii Island, and 2.05 m at Kendari City, indicating significant coastal amplification associated with steep nearshore bathymetry and the semi-enclosed morphology of Tolo Bay.

Travel-time contours computed at 5-min reveal rapid tsunami propagation toward nearby coastlines. The first tsunami arrivals occurred within approximately 1–3 min at Menui and Wawonii Islands, 5–7 min at North Buton, and 12–15 min at Morowali Power Plant. More distant coastlines, including Kendari City and North Konawe, experienced tsunami arrivals after approximately 20–30 min, whereas South Buru and Sula Islands received the first waves after 30–55 min. The modeled waveforms indicate that several locations experienced prolonged oscillations and secondary peaks comparable to or exceeding the first arriving wave, suggesting resonance effects and wave trapping within the semi-enclosed basin.

Multi-scenario modelling demonstrates that variations in rupture position exert a substantial influence on tsunami amplification patterns, even for earthquakes of similar magnitude. Northern-biased ruptures preferentially directed tsunami energy toward Morowali and the northern sector of Tolo Bay, whereas southern-biased ruptures enhanced wave amplitudes around Wawonii Island, South Konawe, and Kendari. Although the Mw 7.5-7.8 scenarios generally produced lower tsunami amplitudes than the Mw 8.0 case, several scenarios generated localized amplifications approaching those associated with larger events, highlighting the importance of rupture directivity, fault segmentation, and coastal geometry in controlling tsunami hazards.

Overall, the results consistently identify the eastern coast of Southeast Sulawesi, together with Menui and Wawonii Islands, as areas of persistently elevated tsunami hazard across the considered rupture scenarios. This interpretation is primarily based on the recurrence of relatively high maximum tsunami amplitudes and the preferential propagation of tsunami energy toward these areas, rather than on the combination of maximum wave height and earliest arrival time alone. The relatively short arrival times at Menui and Wawonii Islands, where the first waves arrived within approximately 1-3 min, provide an additional indication of high response urgency. In contrast, the eastern coast of Southeast Sulawesi generally experienced later arrivals but still exhibited relatively high maximum wave amplitudes. Thus, maximum wave amplitude and tsunami arrival time represent complementary aspects of tsunami hazard, reflecting potential wave impact and available response time, respectively. The combined effects of rupture geometry, island shielding, and bathymetric focusing strongly influence the spatial distribution of tsunami amplitudes, emphasizing the importance of high-resolution numerical modelling for tsunami hazard assessment (Satake, 2002; Synolakis et al., 2007). The present findings provide important input for regional disaster risk reduction efforts, including the preparation of tsunami hazard maps, evacuation route optimization, vertical evacuation planning, and the establishment of community-based tsunami preparedness programs (González et al., 2005; Borrero et al., 2015). The modeled arrival times, which are less than 15 min in several near-field areas, highlight the necessity of rapid self-evacuation procedures and locally based warning systems (Synolakis et al., 2007; Wang and Power, 2011). In addition, these results can support coastal zoning regulations, infrastructure resilience assessments, and the protection of strategic assets such as fisheries facilities, harbors, industrial estates, and power generation facilities within and around Tolo Bay (Grezio et al., 2017; Salmanidou et al., 2020). Future studies integrating inundation modelling, probabilistic scenario ensembles, and socioeconomic exposure data would further enhance tsunami risk management strategies in eastern Indonesia (Grezio et al., 2017; Salmanidou et al., 2020).

4.2 Limitations of the present study

Several limitations should be acknowledged in this study. First, a uniform-slip rupture model was adopted, whereby all activated fault patches were assigned the same average slip value, whereas real earthquakes commonly exhibit heterogeneous slip distributions that may significantly modify seafloor deformation and tsunami generation efficiency. Second, coseismic deformation was assumed to occur instantaneously, neglecting rupture propagation and rise-time effects that may influence tsunami directivity. Third, tsunami simulations were performed under mean sea-level conditions without considering tidal-stage variations. Fourth, the present analysis focused on tsunami propagation and offshore wave characteristics and did not include high-resolution inundation modelling; therefore, coastal flooding extent, run-up heights, and inland penetration distances were not evaluated. Finally, source parameters such as focal depth (30 km), dip angle (25°), rake angle (90°), and shear modulus were treated as fixed values, and uncertainties associated with these parameters were not investigated. Future studies should incorporate heterogeneous slip models, dynamic rupture processes, tidal conditions, and inundation simulations to further improve tsunami hazard assessments for the Tolo Thrust.

Despite the improved representation of coastal bathymetry provided by BATNAS, the present model does not incorporate site-specific hydrographic surveys, harbor-scale bathymetry, or high-resolution topographic datasets required for inundation modeling. Therefore, the simulated tsunami heights represent offshore wave amplitudes at the computational grid scale and should not be interpreted as inundation depths or run-up heights at individual coastal locations.

5. Conclusion

This study presents a scenario-based deterministic tsunami hazard assessment for the Tolo Thrust using COMCOT numerical modelling, considering sixteen rupture scenarios ranging from Mw 7.5 to Mw 8.0. The results indicate that tsunami generation and propagation within Tolo Bay are strongly influenced by earthquake magnitude, rupture geometry, coastal configuration, and regional bathymetry.

The Mw 8.0 worst-case scenario produces the largest tsunami amplitudes and the widest distribution of coastal impacts, with maximum wave heights reaching 2.76 m at Menui Island, 2.20 m at North Konawe, 2.12 m at Wawonii Island, and 2.05 m at Kendari City. Tsunami travel-time contours, computed at 5-min intervals over a 60-min propagation period, suggest arrival times of approximately 1-3 min at Menui and Wawonii Islands and up to 30-55 min at South Buru and Sula Islands. Although the Mw 7.5-7.8 scenarios generally produce lower amplitudes, several scenarios generate localized tsunami amplification comparable to larger events, highlighting the significant influence of rupture directivity and slip distribution.

Overall, the results demonstrate that tsunami hazards are concentrated along the eastern coast of Southeast Sulawesi and around Menui and Wawonii Islands. These findings provide valuable information for tsunami early-warning systems, evacuation planning, and coastal risk mitigation in Southeast Sulawesi and adjacent island communities. Future studies should incorporate heterogeneous slip models, tidal variations, and high-resolution inundation modelling to further refine tsunami hazard assessments.

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References

- AMCG (2015). Fluidity Manual v4.1.12, Department of Earth Science and Engineering, Imperial College London, doi:10.6084/m9.figshare.1387713.
- Baeda, A. Y. (2011). Seismic and tsunami hazard potential in Sulawesi Island, Indonesia, *Journal of International Development and Cooperation*, 17, 1, 17-30, https://www.researchgate.net/publication/291993145_Seismic_and_tsunami_hazards_potential_in_Sulawesi_Island_Indonesia/link/56dd820b08aedf2bf0c856d9/download?_tp=eyJjb250ZXh0Ijp7InBhZ2UiOiJwdWJsaWNhdGlvbGlzInByZXZpb3VzUGFnZSI6bnVsbH19.
- Beaudouin, T., O. Bellier and M. Sébrier (2003). Present-day stress and deformation field within the Sulawesi Island area (Indonesia): Geodynamic implications, *Bull. Société Géologique France*, 174, 3, 305-317, doi:10.2113/174.3.305.
- Bilek, S. L., E. R. Engdahl, H. R. De Shon and M. El Hariri (2011). The October 25, 2010, Sumatra tsunami earthquake: Slip in a slow patch, *Geophys. Res. Lett.*, 38, 14, doi:10.1029/2011GL047864.
- Bock, Y., L. Prawirodirdjo, J. F. Genrich, C. W. Stevens et al. (2003). Crustal motion in Indonesia from Global Positioning System measurements, *J. Geophys. Res. Solid Earth*, doi:10.1029/2001JB000324.
- Borrero, J. C., K. Sieh, M. Chlieh and C. E. Synolakis (2006). Tsunami inundation modeling for western Sumatra, in *Proceedings of the National Academy of Sciences*, doi:10.1073/pnas.0604069103.

- Blaser, L., F. Krüger, M. Ohrnberger and F. Scherbaum (2010). Scaling relations of earthquake source parameter estimates with a special focus on subduction environments, *Bull. Seismol. Soc. Am.*, 100, 6, 2914-2926, doi:10.1785/0120100111.
- Blundell, D. and A. Richardson (1996). Continental collision in Banda Arc, *Geol. Soc. London Special Pub.*, 106, 1, 47-60, doi:10.1144/gsl.sp.1996.106.01.05.
- Brizuela, B., A. Armigliato and S. Tinti (2014). Assessment of tsunami hazard for the American Pacific Coast from Southern Mexico to Northern Peru, *Nat. Haz. Earth Sys. Sci.*, doi:10.5194/nhess-14-1889-2014.
- Cardwell, R. and B. Isacks (1978). Geometry of the subducted lithosphere beneath the Banda Sea in eastern Indonesia from seismicity and fault plane solutions, *J. Geophys. Res.: Atmosphere* 83, B6, 2825-2838, doi:10.1029/jb083ib06p02825.
- Cardwell, R. K., B. L. Isacks and D. E. Karig (1980). The Spatial Distribution of Earthquakes, Focal Mechanism Solutions, and Subducted Lithosphere in the Philippine and Northeastern Indonesian Islands, *The Tectonic Geological Evolution of Southeast Asian Seas and Islands*, 23, 1-35, doi:10.1029/gm023p0001.
- Carvajal, M., C. Araya-Cornejo, I. Sepúlveda, D. Melnick and J. Haase (2019). Nearly instantaneous tsunamis following the Mw 7.5 2018 Palu Earthquake, *Geophys. Res. Lett.*, 46, 10, 5117-5126, doi:10.1029/2019gl082578.
- Chasanah, U., Madlazim and T. Prastowo (2013). Analisis Tingkat Seismisitas dan Periode Ulang Gempa Bumi di Wilayah Sumatera Barat Pada Periode 1961-2010, *Jurnal Fisika*, 2, 1-6.
- Choiruddin, A., Aisah, F. Trisnisa and N. Iriawan (2021). Quantifying the effect of geological factors on the distribution of earthquake occurrences by inhomogeneous Cox processes, *Cornell University*, doi:10.48550/arXiv.2104.06180.
- Cilia, M., W. Mooney and C. Nugroho (2021). Field insights and analysis of the 2018 Mw 7.5 Palu, Indonesia, earthquake, tsunami, and landslides, *Pure Appl. Geophys.*, 178, 12, 4891-4920, doi:10.1007/s00024-021-02852-6.
- Dresback, K. M., R. L. Kolar and J. C. Dietrich (2005). On the form of the momentum equation for shallow water models based on the generalized wave continuity equation, *Adv Water Resour.*, 28, 4, 345-358, doi:10.1016/j.advwatres.2004.11.011.
- Dutykh, D., R. Poncet and F. Dias (2011). Volna code for the numerical modeling of tsunami waves: generation, propagation, and inundation, *European J. Mechanics – B/Fluids*, 30, 6, 598-615, doi:10.1016/j.euromechflu.2011.05.005.
- Felix, R., J. Hubbard, K. Bradley, K. Lythgoe, L. Li and A. D. Switzer (2022). Tsunami hazard in Lombok and Bali, Indonesia, due to the Flores back-arc thrust, *Nat. Haz. Earth Sys. Sci.*, 22, 5, 1665-1682, doi:10.5194/nhess-22-1665-2022.
- Felix, R., E. H. Z. Tan, M. Watanabe et al. (2025). Funwave-based open-access mapping applications (FUNMAP) applied to Tsunami modelling from the Manila Trench to Manila Bay, Philippines, *Geosci. Lett.* 12, 49, doi:10.1186/s40562-025-00422-5.
- Fernandes, M. A. G. (2009). Systematic comparison on the inundation response of AnuGA and COMCOT Tsunami modeling codes applied to the Boca do Rio and Alvor Bay area, *Universidade do Algarve*.
- Fuady, M., M. R. Farrel, M. A. Kevin, R. Munadi and A. Triaputri (2025). The Concept of a Resilient City in Indonesia as a Strategy to Increase Urban Resilience, *Iop Conference Series Earth and Environmental Science*, doi:10.1088/1755-1315/1479/1/012026.
- Fukahata, Y. and Y. Mori (2024) 3-D Numerical Simulation of Island Arc Deformation based on the Dislocation Model for Plate Subduction and its Insight into Topographic Evolution of Island Arcs, *EGU General Assembly 2024*, Vienna, Austria, 14-19 Apr 2024, EGU24-14479, doi:10.5194/egusphere-egu24-14479.
- Geist, E. L. and T. Parsons (2006). Probabilistic analysis of tsunami hazards, *Natural Hazards*, 37, 237-314, doi:10.1007/s11069-005-4646-z.
- Goda, K. and K. Abilova (2016). Tsunami hazard warning and risk prediction based on inaccurate earthquake source parameters, *Nat. Haz. Earth Sys. Sci.*, 16, 2, 577-593, doi:10.5194/nhess-16-577-2016.
- Grezio, A., A. Babeyko, M. A. Baptista, J. Behrens et al. (2017). Probabilistic tsunami hazard analysis: multiple sources and global applications, *Rev. Geophys.*, 55, 4, 1158-1198, doi:10.1002/2017rg000579.
- González-Riancho, Pino et al. (2013) Tsunami evacuation modelling as a tool for risk reduction: application to the coastal area of El Salvador, *Nat. Haz. Earth Sys. Sci.* 13.12, 3249-3270, doi:10.1098/rsta.2006.1809.
- Hamimu, L., S. Asfar, L. Ngkoimani and A. Rubaiyn (2022). Quantitative analysis of the relative tectonic activities of geothermal areas of Lainea, South Konawe District, Southeast Sulawesi Province, Indonesia, *Int. J. Adv. Sci. Engin. Info. Technol.*, 12, 5, 1981-1988, doi:10.18517/ijaseit.12.5.13908.
- Hamzah, L., N. Puspito and F. Imamura (2000). Tsunami Catalog and Zone Indonesia, *J. Nat. Disaster Sci.*, 22, 1, 25-43, https://www.jstage.jst.go.jp/article/jnds/22/1/22_1_25/_pdf.

- Harig, S., N. Zamora, A. Gubler and N. Rakowsky (2022). Systematic Comparison of Tsunami Simulations on the Chilean Coast Based on Different Numerical Approaches, *GeoHazards*, 3, 2, 345-370, doi:10.3390/geohazards3020018.
- Hill, J., G. S. Collins, A. Avdis, S. C. Kramer and M. D. Piggott (2014). How does multiscale modeling and inclusion of realistic palaeobathymetry affect numerical simulation of the Storegga Slide tsunami? *Ocean Modelling*, 83, 11-25, doi:10.1016/j.ocemod.2014.08.007.
- Horspool, N., I. Pranantyo, J. Griffin, H. Latief et al. (2014). Probabilistic tsunami hazard assessment for Indonesia, *Nat. Haz. Earth Sys. Sci.*, 14, 11, 3105-3122, doi:10.5194/nhess-14-3105-2014.
- Howell, A. and K. Clark (2022). Late Holocene coseismic uplift of the Kaikōura coast, New Zealand, *Geosphere*, 18, 3, 1104-1137, doi:10.1130/ges02479.1.
- Hsu, P., H. Chiang and C. Wang (2011). Optimal selection of international exhibition agency by using the delphi method and ahp, *J. Information and Optimization Sciences*, 32, 6, 1353-1369, doi:10.1080/02522667.2011.10700124.
- Imamura, F., E. Gica, T. Takahashi and N. Shuto (1995). Numerical simulation of the 1992 Flores tsunami: interpretation of tsunami phenomena in northeastern Flores Island and damage at Babi Island, *Pure Appl. Geophys.*, 144, 3-4, 555-568, doi:10.1007/bf00874383.
- Jaffe, B. E. and G. Gelfenbaum (2007). A simple model for calculating tsunami flow speed from tsunami deposits, *Sedimentary Geol.*, doi:10.1016/j.sedgeo.2007.01.013.
- Karima, S., H. Latief and I. E. Mulia (2026). Probabilistic tsunami hazard assessment in the Lesser Sunda Islands, Indonesia, *Stochast., Eviron. Res., Risk Asses*, 40, 83, doi:10.1007/s00477-026-03208-z.
- Kanamori, H. and D. L. Anderson (1975). The Theoretical basis of some empirical relations in Seismology, *Bull. Seismol. Soc. Am.*, 65, 5, 1073-1095, doi:10.1785/BSSA0650051073.
- Khoirunnisa, H., S. Karima, G. Gumbira and R. Rachman (2021). A numerical study of submarine-landslide-generated tsunami and its propagation in Majene, West Sulawesi, *Iop Conference Series Earth and Environmental Science*, 925, 1) 012035, doi:10.1088/1755-1315/925/1/012035.
- Koshimura, S., T. Oie, H. Yanagisawa and F. Imamura (2009). Developing fragility functions for tsunami damage estimation using numerical model and post-tsunami data from Banda Aceh, Indonesia, *Coastal Engineering Journal*, 51, 3, 243-273, doi:10.1142/S0578563409002004.
- Kreemer, C., W. Holt, S. Goes and R. Govers (2000). Active deformation in eastern Indonesia and the Philippines from GPS and seismicity data, *J. Geophys. Res.: Atmospheres*, 105, B1, 663-680, doi:10.1029/1999jb900356.
- Kriswati, E., S. Primulyana and S. Dirasutisna (2016). Volcanic Hazard Map of Awu Volcano, North Sulawesi Province, Center For Volcanology and Geological Hazard Mitigation, <https://magma.esdm.go.id/v1/gunung-api/peta-kawasan-rawan-bencana>.
- LeVeque, R. J. (2002). *Finite Volume Methods for Hyperbolic Problems*, Cambridge University Press, doi:10.1017/CBO9780511791253.
- Liu, P. L. F., Y. S. Cho, S. B. Yoon and S. N. Seo (1995). Numerical Simulations of the 1960 Chilean Tsunami Propagation and Inundation at Hilo, Hawaii, in *Tsunami: Progress in Prediction, Disaster Prscenarioion and Warning*, 99-115, Springer, Dordrecht, doi:10.1007/978-94-015-8565-1_7.
- Liu, P. L. F., Y. S. Cho, M. J. Briggs, U. Kanoglu and C. E. Synolakis (1995). Runup of solitary waves on a circular island, *J. Fluid Mech.*, 302, 259-285, doi:10.1017/S0022112095004095.
- Liu, L. F. P., S. Y. Cho, B. S. Yoon and N. S. Seo (1994). Numerical simulaitons of the 1960 Chilean tsunami propagation and inundation at Hilo, Hawaii. *Recent Development in Tsunami Research*, 99-115. Kluwer Academic Publishers.
- Liu, X. and S. Guillas (2017). Dimension reduction for Gaussian process emulation: An application to the influence of bathymetry on tsunami heights. *SIAM/ASA Journal on Uncertainty Quantification*, 5, 1, 787-812, doi:10.1137/16m1090648.
- Løvholt, F., G. Pedersen and G. Gisler (2008). Oceanic propagation of a potential tsunami from the La Palma Island, *Sci. Tsunami Hazards*, doi:10.1029/2007JC004603.
- Marfai, M. A., E. Trihatmoko, K. Ervita and I. S. Purnama (2019). Granulometric extraction value to determine waves, currents, and tides characteristics of Tangsi beach (Pink beach), East Lombok Regency, Indonesia. *IOP Conference Series: Earth and Environmental Science*, 256, 012030, doi:10.1088/1755-1315/256/1/012030.
- Ma, Q. X. and N. Kusznir (1994). Effects of rigidity layering, gravity, and stress relaxation on 3-d subsurface fault displacement fields, *Geophys. J. Int.*, 118, 1, 201-220, doi:10.1111/j.1365-246x.1994.tb04684.x.
- McCaffrey, R. (1988). Active tectonics of the eastern Sunda and Banda Arcs, *J. Geophys. Res: Atmospheres*, 93, B1, 15163-15182, doi:10.1029/jb093ib12p15163.

- Morrice, M. G., P. A. Ježek, J. B. Gill, D. J. Whitford and M. Monoarfa (1983). An introduction to the Sangihe Arc: Volcanism accompanying Arc-arc Collision in the Molucca Sea, Indonesia, *J. Volcan. Geoth. Res.*, 19, 135-165, doi:10.1016/0377-0273(83)90129-4.
- Nakata, K., Y. Hayashi, H. Tsushima et al. (2019). Performance of uniform and heterogeneous slip distributions for the modeling of the November 2016 off Fukushima earthquake and tsunami, Japan, *Earth Planets Space* 71, 30, doi:10.1186/s40623-019-1010-1.
- Nguyen, P. H., Q. C. Bui, P. H. Vu and T. T. Pham (2014). Scenario-based tsunami hazard assessment for the coast of Vietnam from the Manila Trench source, *Phys. Earth Planet. Int.*, 236, 95-108, doi:10.1016/j.pepi.2014.07.003.
- Ningrum, R., R. Amelia, H. Hasmawati, M. Aswan and S. Sapudin (2021). Earthquake disaster risk assessment analysis in the Jailolo coastal region, *Techno Jurnal Penelitian*, 10, 2, 152-163, doi:10.33387/tjp.v10i2.3523.
- Okada, Y. (1985). Surface deformation due to shear and tensile faults in a half-space, *Bull. Seismol. Soc. Am.*, 75, 4, 1135-1154, doi:10.1785/BSSA0750041135.
- Pranantyo, I., M. Heidarzadeh and P. Cummins (2021). Complex tsunami hazards in eastern Indonesia from seismic and non-seismic sources: deterministic modeling based on historical and modern data, *Geosci. Lett.*, 8, 1, doi:10.1186/s40562-021-00190-y.
- Pranantyo, I. R., A. Cipta, H. A. Shiddiqi, T. Baba and K. Imail (2022). Source Reconstruction of the 1969 Western Sulawesi, Indonesia, *Earthquake and Tsunami, Pure Appl. Geophys.*, 180, 1765-1783, doi:10.1007/s00024-022-03064-2.
- Prawiradisastra, S. (2003). Analisa Informasi Bencana Sebagai Dasar Pengembangan Wilayah di Kabupaten Kepulauan Sangihe Talaud, *Jurnal Alami*, 8, 3, 57-61.
- Pribadi, S., A. Afnimar, N. T. Puspito, G. Ibrahim (2013). Characteristics of Earthquake-Generated Tsunamis in Indonesia Based on Source Parameter Analysis, *J. Mathematical and Fundamental Sciences*, doi:10.5614/j.math.fund.sci.2013.45.2.8.
- Purba, J., L. Restele, L. Hadini, I. Usman, H. Hasria and H. Harisma (2024). Spatial study of seismic hazard using classical probabilistic seismic hazard analysis (pscha) method in Kendari City area, *Indonesian Physical Review*, 7, 3, 300-318, doi:10.29303/ipr.v7i3.325.
- PuSGeN. (2017). Peta Sumber dan Bahaya Gempa Indonesia 2017/Indonesian Earthquake Source and Hazard Map 2017. Pusat Studi Gempa Nasional (National Center for Earthquake Studies), Bandung: Kementerian PUPR.
- PuSGeN. (2024). Peta Sumber dan Bahaya Gempa Indonesia Tahun 2024 (515 hlm.). PUPR Press, Kementerian Pekerjaan Umum dan Perumahan Rakyat.
- Rachmawati, P., L. Wardana and H. Fajrin (2023). Community – based disaster management in trimurti, Bantul Yogyakarta. *Proceedings Internaional Conference Community Service*, 1, 1, 348-355, doi:10.18196/iccs.v1i1.74.
- Ragon, T. and M. Simons (2022). A secondary zone of uplift measured after megathrust earthquakes: caused by early downdip afterslip?, *Geophys., Res. Lett.*, 50, 7, e2022GL101510, doi:10.1029/2022GL101510.
- Reid, J. A. and W. D. Mooney (2022). Tsunami occurrence 1900-2020: a global review with examples from Indonesia, *Pure Appl. Geophys.*, 180, 5, 1549-1571, doi:10.1007/s00024-022-03057-1.
- Risi, R. D. and K. Goda (2016). Probabilistic earthquake-tsunami multi-hazard analysis: application to the Tohoku region, Japan, *Front. Built Environ.*, 2, doi:10.3389/fbuil.2016.00025.
- Rubaiyn, A., J. Safani and K. Anwar (2022) Analisis Tingkat Seismisitas dan Percepatan Tanah Maksimum (PGA) Wilayah Sulawesi Tenggara Berdasarkan Data Gempa Bumi Periode 1973-2022. *Jurnal Rekayasa Geofisika Indonesia*, doi:10.56099/jrgi.v5i02.17.
- Satake, K. (2002). Tsunamis. In *International Handbook of Earthquake and Engineering Seismology EDS*: W. H. K. Lee, H. Kanamori, P. C. Jennings, C. Kisslinger, 437-451, Elsevier.
- Salmanidou, D., M. Heidarzadeh and S. Guillas (2020). Assessing future uncertainties: Earthquake tsunami hazard in the Java Trench, Indonesia, In the EGU General Assembly Conference Abstracts, 10762, doi:10.5194/egusphere-egu2020-10762.
- Silver, E. A., R. McCaffrey and R. B. Smith (1983). Collision, rotation, and initiation of subduction in the evolution of Sulawesi, Indonesia, *J. Geophys. Res.: Solid Earth*, 88, B11, 9407-9418, doi:10.1029/jb088ib11p09407.
- Smith, R. C., J. Hill, G. S. Collins, M. D. Piggott et al. (2016). Comparing approaches for numerical modeling of tsunami generation by deformable submarine slides, *Ocean Modelling*, 100, 125-140, doi:10.1016/j.ocemod.2016.02.007.
- Sugawara, D. (2021). Numerical modeling of tsunami: Advances and future challenges after the 2011 Tohoku earthquake and tsunami *Earth-Sci. Rev.*, 214, 103498, doi:/10.1016/j.earscirev.2020.103498.

- Synolakis, C. E. and E. N. Bernard (2006). Tsunami science before and beyond Boxing Day 2004, *Philos. Trans. Royal Soc. A*, 364, 2231-2265, doi:10.1098/rsta.2006.1824.
- Syukri, U., N. A. Deliarnoor and I. Widianingsih (2025). Comparison of disaster management practices in indonesia: a study of resilience in garut and majene districts, *Discover Sustainability*, 6, 712, doi:10.1007/s43621-025-01526-w.
- Thingbaijam, K. K. S., P. M. Mai and K. Goda (2017). New empirical earthquake source-scaling law, *Bull. Seismol. Soc. Am.*, 107, 5, 2225-2246, doi:10.1785/0120170017.
- Titu-Eki, A. and R. Hall (2020). The Significance of the Banda Sea: Tectonic Deformation Review in Eastern Sulawesi Indonesian Journal Geosci., 7.3, doi:10.17014/ijog.7.3.291-303.
- Tomita, T., K. Honda and T. Kakinuma (2007). Application of three-dimensional tsunami simulator to estimation of tsunami behavior around structures, *Coastal Engin.*, 1677-1688, doi:10.1142/9789812709554_0142.
- Wahyu, R. O., R. Djamaluddin, G. E. Mamuaya, T. Yatimantoro and P. Priyobudi (2018). Pemodelan Inundasi Tsunami di Sepanjang Pesisir Manado Akibat Gempabumi M8, 5 di Zona Subduksi Sulawesi Utara, *Jurnal Meteorologi dan Geofisika*, 19, 1, 13-18, doi:10.31172/jmg.v19i1.448.
- Wang, X. and P. L. F. Liu (2007). Numerical simulations of the 2004 Indian Ocean tsunamis – coastal effects. *Journal of Earthquake and Tsunami*, 1, 03, 273-297, doi:10.1142/S179343110700016X.
- Wang, X. and W. L. Power (2011). COMCOT: a tsunami generation propagation and run-up model, *GNS Science*, <https://www.gns.cri.nz/data-and-resources/comcot-a-tsunami-generation-propagation-and-run-up-model/>.
- Wendt, J., D. D. Oglesby, E. L. Geist (2009). Tsunami and splay fault dynamics, *J. Geophys. Res.: Solid Earth*, doi:10.1029/2009GL038295.
- Widiyanto, W., P. Santoso, S. Hsiao and R. Imananta (2019). Post-scenario field survey of the 28 september 2018 sulawesi earthquake and tsunami, *Nat. Haz. Earth Sys. Sci.*, 19, 12, 2781-2794, doi:10.5194/nhess-19-2781-2019.
- Widiyantoro, S., E. Gunawan, A. Muhari, N. Rawlinson et al. (2020). Implications for megathrust earthquakes and tsunamis from seismic gaps south of Java Indonesia, *Sci. Rep.*, 10, 1, doi:10.1038/s41598-020-72142-z.
- Woods, K., L. M. Wallace, C. A. Williams, I. J. Hamling et al. (2024). Spatiotemporal evolution of slow-slip scenarios at the offshore Hikurangi Subduction Zone in 2019 using GNSS, InSAR, and seafloor geodetic data, *J. Geophys. Res. Solid Earth*, 129, 8, e2024JB029068, doi:10.1029/2024JB029068.
- Yue, H., T. Lay, L. Li, Y. Yamazaki et al. (2015). Validation of linearity assumptions for using tsunami waveforms in joint inversion of kinematic rupture models: Application to the 2010 Mentawai Mw 7.8 tsunami earthquake, *J. Geophys. Res. Solid Earth*, 120, 3, 1728-1747.

***CORRESPONDING AUTHOR: Muhammad Taufiq RAFIE,**

Hasanuddin University, Department of Geophysics, Jl. Perintis Kemerdekaan No. KM.10,
Tamalanrea Indah, Kec. Tamalanrea, Kota Makassar, Sulawesi Selatan, 90245, Indonesia
e-mail: taufiqrafie@unhas.ac.id

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