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ENHANCING INDONESIA'S TSUNAMI EARLY WARNING SYSTEM USING W PHASE INVERSION

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ABSTRACT

Earthquake source mechanism parameters are crucial inputs for tsunami early warning systems. However, obtaining accurate parameters promptly remains a challenge, particularly in the Indonesian archipelago, with sparse seismic station network. W phase inversion technique is a promising approach for obtaining accurate source mechanisms. Herein, its applicability in the Indonesian region, was evaluated to optimize the station coverage distance for producing accurate source mechanism parameters in the shortest possible time. To this end, W phase inversion was applied to 23 earthquakes with $M_w \geq 6.5$ that occurred between January 2020 and January 2024. The station coverage distance was varied ($\Delta \leq 5°$, $\Delta \leq 12°$, until $\Delta \leq 20°$) to analyze the accuracy of the resulting focal parameters. The accuracy of the W phase inversion output was assessed by comparing the moment magnitude and angular differences to the source mechanism parameters from the global centroid moment tensor (GCMT) as a reference. Results indicated that W phase inversion could yield fairly accurate parameters even with station coverage of ≤ 5°, achieving results in less than 7 min. This was demonstrated by an average moment magnitude difference of ~0.07 and nearly 50% of the outputs having an angular difference of ≤ 20°. A broader station coverage yielded better focal solutions; however, the process is time consuming because of the propagation delay of seismic waves to distant stations. The accuracy of the W phase solution considerably depended on the number of channels analyzed. Thus, accurate results were obtained as long as a sufficient number of recording channels was available. This analysis revealed that W phase inversion could yield results consistent with the reference data (moment magnitude difference of < 0.2 and angular difference < 30°) with a minimum of 20 recording channels.

Keywords: Source mechanism, W phase, Inversion Method.

1. INTRODUCTION

Indonesia is quite susceptible to geological hazards, such as earthquakes and tsunamis due to its location in the junction of the main tectonic plates, namely the Pacific, Philippine Sea, Indo-Australian, and Eurasian plates. The 2004 M_w 9.3 earthquake, which triggered a devastating tsunami along the Indian Ocean, has undoubtedly attracted the world's attention and opened our eyes to the importance of information and early warning and mitigation for earthquake and tsunami disasters. Therefore, as a response to the vulnerability of this tsunami-prone country, after the 2004 tsunami earthquake, the Indonesian government developed the Indonesian Tsunami Early Warning System (InaTEWS). Tsunami potential analysis in InaTEWS is obtained from simulation results based on the earthquake's parameters, consisting of origin time, epicenter location, depth, and magnitude, produced from seismic analysis. These limited parameters for determining the first disseminated information can cause initial tsunami early warning information inaccuracies. Based on the InaTEWS Standard Operational Procedure (SOP), tsunami early warnings must be disseminated less than 5 min after the earthquake's origin time. This very short time makes it a challenge to produce accurate earthquake parameters and focal mechanisms as a basis for estimating tsunami potential. As shown in previous studies, the W phase

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inversion can produce an earthquake's focal mechanism quickly, improving the accuracy of the tsunami estimation in a short time (Kanamori & Rivera, 2008). Therefore, this study examines the effectiveness of the W phase inversion technique for Indonesian earthquakes, aiming to enhance the accuracy and timeliness of tsunami early warnings.

2. METHODOLOGY

2.1. W phase

The W phase is a type of seismic wave with a relatively long period, typically 100 to 1000 seconds. It is recorded at a seismic station between the P- and S-waves (Kanamori, 1993; Kanamori & Rivera, 2008). In normal mode theory, the W phase can be understood as the outcome of the combination of the fundamental mode, the first overtone, the second overtone, and the third overtone of the spheroidal mode at long wave periods. The W phase exhibits a group velocity spanning 4.5 to 9 km per sec.

2.2. Inversion of W phase

Following the method outlined by Kanamori & Rivera (2008), the W phase inversion technique was employed. This method assumes a spatial point source for the W phase inversion, referred to as the centroid location. The point source is characterized by temporal variations consistent with a specified time history. The inversion procedure becomes linear concerning the moment tensor element when the centroid position and the source time history are provided.

First, we find the response of the step function for a unit moment tensor element to determine *u(t)*, called Green's function by superposition of normal modes. Next, we combine Green's function and the source time function, which is called the moment rate function. We then band-pass filtered the output with a frequency range similar to the observed seismograms. The synthetic displacements for a unit source are obtained from this technique. We assumed the value of half duration (h_d) is equal to centroid time shift (t_s) using the initial condition from the preliminary determination of earthquake hypocenter from BMKG. The half duration was derived from the scaling law (Duputel et al., 2012):

$$h_d = 1.2 \times 10^{-8} \times {M_o}^{1/3}$$

where h_d in sec and M_0 is the seismic moment (dyne-cm). Inversion can be done with the hypocenter location as an initial centroid position. In addition to centroid location, time shift is an important parameter that affects the accuracy of waveform inversion. Thus, two step of grid-search process was done to find an optimum centroid time shift and centroid location, minimizing the root-mean-square (RMS) of waveform misfit, for the final centroid moment tensor solution.

Finally, we plotted the results to examine the accuracy by comparing them with the Global CMT, using magnitude difference (ΔM_w) and angular difference (ϕ) as similarity indicators. Following Zhao et al. (2017), the angular difference between the W phase and GCMT source mechanisms was calculated using the normalized moment tensors. The difference, $\Delta_R = \frac{1}{2\sqrt{2}}(D\colon D)^{1/2}$, with D representing the tensor difference, defines the angular difference $\phi = 2 \cdot \arcsin\ (\Delta_R)$, which measures the rotation needed to align the two tensors and reflects the geometric angular distance between focal spheres, as outlined by Kagan (1991).

3. DATA

We investigated 23 earthquake parameters in Indonesia between January 2020 and January 2024 with magnitudes M ≥ 6.5, as shown in Figure 1. Those earthquake parameters were obtained from BMKG. We utilized 3-component broadband data records from approximately 495 deployed seismometers in Indonesia. Additionally, we incorporated seismic data from international networks to encompass earthquake sources on a global scale.

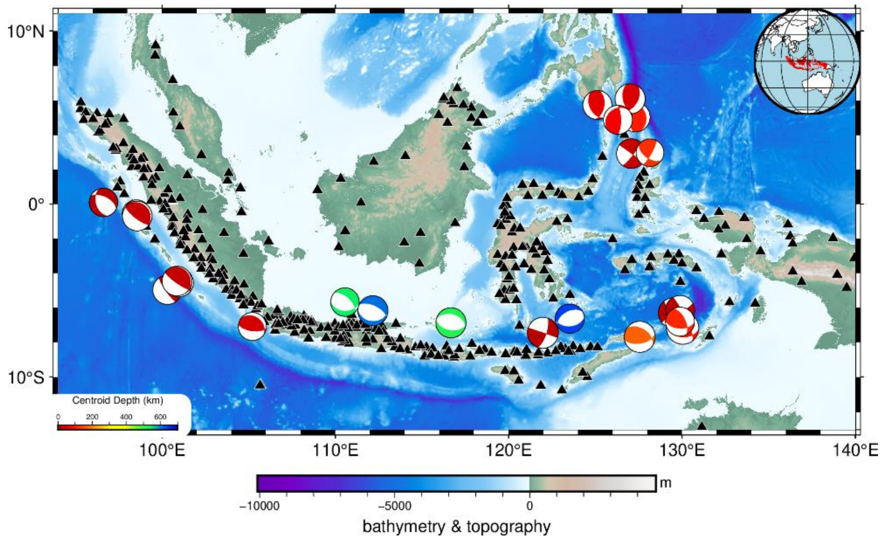

Figure 1. Distribution of $M_w \geq 6.5$ earthquake epicenters from January 2020 to January 2024. The magnitude of the centroid depth is shown by color gradations in the beachball source mechanism circle. The black triangle represents seismic stations integrated into the InaTEWS.

Table 1. Corner frequency bands used for bandpass filtering (modified from Zhao et al., 2017)

Moment magnitude, M_w	Frequency band, mHz
$8.0 > M_w \geq 7.5$	1.7 – 6.7
$7.5 > M_w \geq 7.0$	3.0 – 12.0
$7.0 > M_w \geq 6.5$	4.0 – 10.0

The seismic waveform was first corrected from the instrument response. Since the frequency range of the W phase extends from 0.001 to 0.01 Hz, the band pass filter within this range then needs to be performed to extract the targeted waveform. However, we varied the filter frequency range depending on the earthquake magnitude because the earthquake's strength greatly influences the resulting seismic waves' frequency content, as suggested by Zhao et al. (2017). Table 1 describes the frequency range for each magnitude range. After the filtering, the waveform was converted to a displacement record through the integration process. We also followed Zhao et al. (2017) in setting the window length of the analyzed waveform in each station, which depends on the epicenter-station distance. The waveform was cut between P wave arrival time t_p and $t_p + 180\ s$ for the station distance of $\Delta \leq 12°$, while the rest station distance used a time range from time t_p to $t_p + 15\ \Delta$ s (Δ in degrees).

Data screening is crucial to ensure the quality of the inversion process. As done by Duputel et al. (2012), we also used initial noise screening to discard traces with high noise levels. Median screening eliminates traces with significant deviations from the median values. Additionally, misfit screening is performed after each inversion process to ensure the quality of the results by discarding data that do not meet specific thresholds.

4. RESULTS AND DISCUSSION

4.1. W phase inversion result

W phase inversion was performed several times by applying data screening and bandpass filtering adjusted to the initial magnitude obtained from the previous preliminary parameters analysis results that disseminated by BMKG. For data within an epicentral distance of $\Delta \leq 5°$, it takes approximately 3–4 min to initiate the inversion process using a waveform with a 180 s time window. With a sufficient amount of data at this epicentral distance, the entire inversion process can be completed in 1–2 min. Therefore, reliable solutions can be retrieved within 6–7 min after the origin time using data within $\Delta \leq 5°$.

As example, W phase inversion processing for the January 21, 2021, $\mathrm{M_w}$ 7.0 Talaud earthquake was conducted using data within a predetermined epicenter distance radius, namely at $\Delta \leq 5°$, $\Delta \leq 12°$, and $\Delta \leq 20°$, by applying a bandpass filter of 3–12 mHz for each distance. In the initial inversion process, we assumed $t_s = h_d$ of 9.9 s, a moment magnitude of $\mathrm{M_w}$ 7.05 was obtained for the inversion results carried out with data within epicentral distance $\Delta \leq 5°$. For epicentral distance, $\Delta \leq 12°$, by utilizing 51 channels from 24 stations, a moment magnitude of $\mathrm{M_w}$ 7.0 was obtained, which is similar to $\mathrm{M_w}$ by GCMT. At an epicentral distance, $\Delta \leq 5°$, the difference between $\mathrm{M_w}$ and $\mathrm{M_{w-GCMT}}$ is only 0.05, and the estimated thrust mechanism was consistent with the GCMT solution, as evidenced by the beachball shape and also the angular difference (ϕ), both of which were 13.2° and 5.4°. In Figure 2, we compare the source mechanism results obtained in this study with those from the GCMT as a reference. Figure 3 illustrates the grid search process to identify the optimal centroid time shift and location, and also presents concatenated W phase traces and comparison between synthetic and observed waveforms at each station.

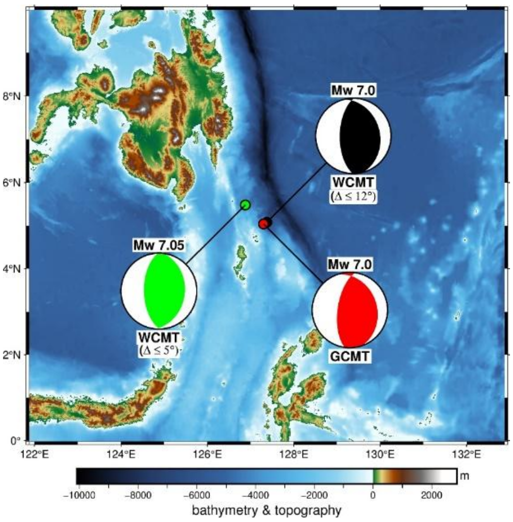

Figure 2. Comparison of source mechanisms results for the January 21, 2021 $\mathrm{M_w}$ 7.0 Talaud Earthquake.

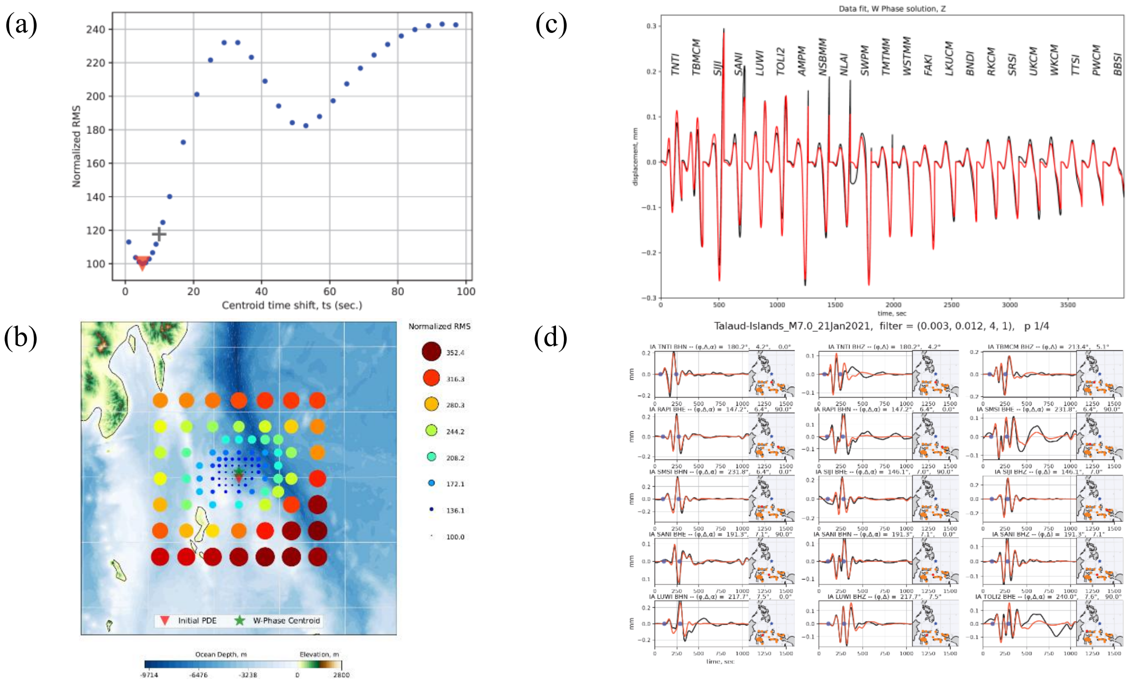

Figure 3. W phase inversion result for the January 21, 2021 $\mathrm{M_w}$ 7.0 Talaud Earthquake using data within $\Delta \leq 12°$. (a) Centroid time shift grid search. (b) Centroid location grid search. The red triangle initial PDE denotes the preliminary epicenter from BMKG, while the green star indicates the optimized

location by the W phase. (c) Concatenated W phase observed (black) and synthetic (red). (d) Comparison between the synthetic (red lines) and the observed waveforms (black lines).

4.2. Comparative analysis

The comparison between W phase inversion results and GCMT solutions reveals a strong correlation in estimating moment magnitude (M_W) and source mechanisms, with most data points aligning closely along the 1:1 line as shown in Figure 4.

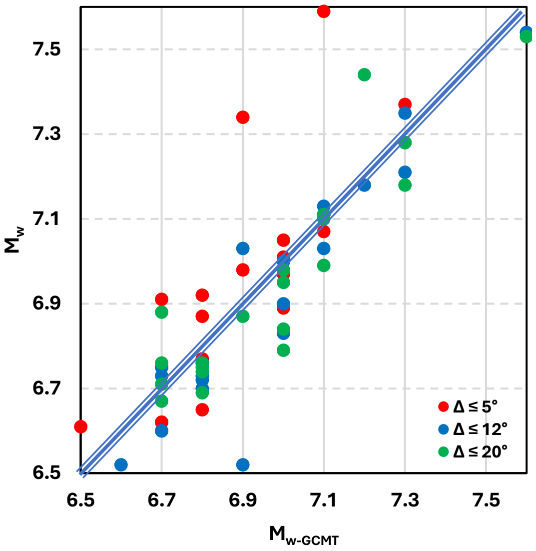

Figure 4. Comparison of seismic magnitudes between W phase inversion results and GCMT based on epicentral distance.

Figure 5 presents ΔM_W stay within ±0.1 when using 10–50 channels, highlighting the high precision of the method. However, some outliers, such as the August 21, 2020, Banda Sea earthquake, which deviated from the average ΔM_W by more than 0.5. Preliminary studies indicated that the expansion of the epicentral distance to 20° resulted in poor data filtration and unsatisfactory inversion, causing insufficient data contribution.

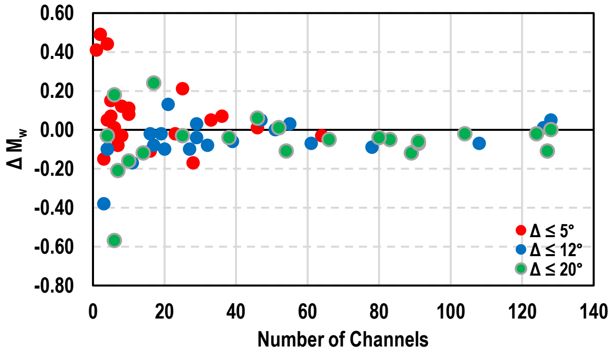

Figure 5. Comparison of ΔM_W between GCMT and W phase inversion according to the number of used data within Δ ≤ 5°, Δ ≤ 12°, and Δ ≤ 20°.

The stability of W phase inversion results is particularly evident in the analysis of angular differences (ϕ) between the inversion and GCMT solutions. As shown in Figure 6, angular differences tend to decrease with the inclusion of more channels, especially when the epicentral distance is Δ ≤ 5°. When 20–30 channels are used, the angular difference stabilizes between 5° to 15°, suggesting that this range of channels is sufficient for reliable source mechanism estimation. Beyond this threshold, adding more channels contributes little to reducing angular discrepancies, indicating a plateau in the method's accuracy. This stability persists even when the epicentral distance is expanded to Δ ≤ 12° and Δ ≤ 20°, suggesting that the W phase inversion model reaches its peak accuracy once a critical number of channels is included.

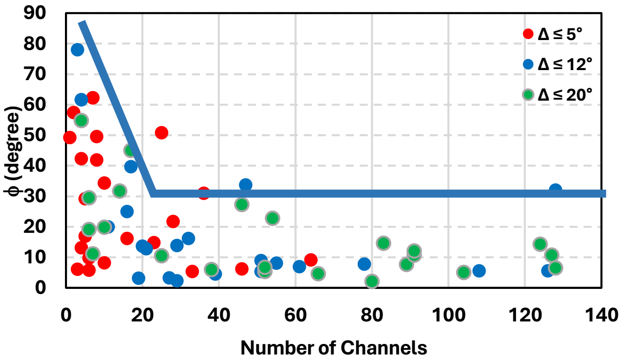

Figure 6. Comparison of angular difference (ϕ) for the source mechanism solution between W phase inversion and GCMT according to the number of used data within Δ ≤ 5°, Δ ≤ 12°, and Δ ≤ 20°.

These results further affirm that, despite fewer channels in certain regions like Talaud and Java, the W phase inversion method consistently produces minimal variations in both magnitude and angular displacement compared to GCMT solutions. This consistency indicates that the existing seismic station infrastructure is generally sufficient for implementing the W phase inversion technique in specific areas. Expanding the number of data channels helps stabilize both the magnitude differences and angular discrepancies, bringing them closer to GCMT values, underscoring the need for improved data quality and sensor distribution for optimal results.

5. CONCLUSIONS

This study aimed to evaluate the effectiveness of the W phase inversion technique for analyzing earthquakes in Indonesia, focusing on its applicability for tsunami early warnings. The method was applied to 23 earthquakes ($M_w \geq 6.5$) between January 2020 and January 2024, with results compared to the GCMT catalog. The results demonstrate that the W phase inversion is a reliable and efficient tool for rapidly estimating moment magnitude M_w and source mechanisms, particularly when data from a sufficient number of stations within an epicentral distance of $\Delta \leq 5°$ are used. This allows for accurate results to be obtained within 6–7 min after an earthquake, which is crucial for timely tsunami warnings.

The study also highlighted that increasing the data set to include stations at higher epicentral distances (up to $\Delta \leq 12°$ and $\Delta \leq 20°$) can enhance the accuracy of the inversion results, reducing variability in ΔM_w and ϕ compared to GCMT solutions. However, it was noted that beyond a certain number of data channels (20–30 channels), additional data did not significantly improve the accuracy, emphasizing the importance of appropriate data selection.

The results underscore the importance of integrating the W phase inversion method into Indonesia's tsunami early warning system (InaTEWS). By utilizing this method, BMKG can enhance the speed and accuracy of its tsunami alerts, especially for issuing updated tsunami early warnings (Bulletin 2) within 10 min after the origin time. The study also identifies the need to improve seismic networks and data quality in specific regions, such as the Banda Sea and Flores Sea, to ensure the continued reliability of the W phase inversion technique.

The integration of W phase inversion into Indonesia's Tsunami Early Warning System (InaTEWS) will significantly improve disaster response capabilities. Additionally, to optimize the use of the W-phase method within the InaTEWS operational system, which is currently not fully utilized, it is necessary to apply appropriate frequency band usage and maximize data filtering. Upgrading equipment with advanced technology for real-time data transmission and high-quality seismic recording is crucial for accurate analysis.

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