W PHASE ANALYSIS FOR TSUNAMI WARNING

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ABSTRACT

We applied W phase inversion for the large (M>7) Indonesian earthquakes that occurred in the period of 2004-2009 by using global data obtained from IRIS DMC. The W phase inversion was made for the PDE location, optimum centroid location and the GCMT location. These three locations gave similar inversion results; both moment magnitude and focal mechanism were generally in very good agreement with the GCMT solutions. Comparison of moment magnitudes M_w indicates that seismic moments from the GCMT and W phase inversions are larger than that from body waves for three events that caused damaging tsunamis (the 2004 Aceh, 2005 Nias and 2006 Java earthquakes). Therefore it is necessary to perform analysis of long-period seismic waves to accurately evaluate the tsunami potential. Tsunami simulation was performed for the 2006 Java, 2007 Bengkulu (mainshock), 2008 Sulawesi and 2009 Papua (mainshock) events for the three different centroid locations and sea floor deformations based on the W phase inversion results. The simulation shows that these three models yields similar tsunami arrival times and heights on the coasts where the tsunami arrival times are more than 30 minutes. Based on the W phase inversion and tsunami simulation results we suggest that the PDE location yields good enough solution so that it can be used in real time situation for the warning purpose. For coastal regions near the earthquake source with tsunami arrives less than 30 minutes, W phase analysis cannot be used for the first tsunami warning. Because W phase analysis provides long-period information on the earthquake source and can be performed faster than the GCMT inversion, it can be used to update the tsunami warning at BMKG (Agency for Meteorology Climatology and Geophysics).

Keywords: W phase inversion, Indonesia, Large earthquakes, Tsunami warning.

1. INTRODUCTION

Agency for Meteorology Climatology and Geophysics (BMKG) Indonesia has been assigned the tasks to produce the tsunami messages during the first five minutes of earthquakes. The main information of tsunami warning is in estimating the tsunami potential of an earthquake from the seismic parameters such as hypocenter and magnitude. Based on BMKG experiences, however the tsunami warning based only on hypocenter and magnitude sometimes disagrees with observation, producing false alarms or missing alarms. Tsunami potential of an earthquake can be underestimated for very large event (such as the 2004 Aceh) and tsunami earthquake (such as the 2006 Java). The objective of this study is to perform rapid determination of seismic source parameters with sufficient accuracy for the issuance of tsunami warning. For this aim, we perform W phase inversion and tsunami simulation.

2. DATA

We used 1 sample-per-second data from vertical component of broadband records (LHZ channel) for station within 90^o taken from the database at the IRIS Data Management System (http://www.iris.washington.edu/dms/wilber.html). For event analysis, we selected 10 Indonesian events with large magnitude (M>7) occurred in the period 2004-2009. We downloaded data from Global CMT catalog (http://www.globalcmt.org) at the same period to compare with our inversion results (Fig.1).

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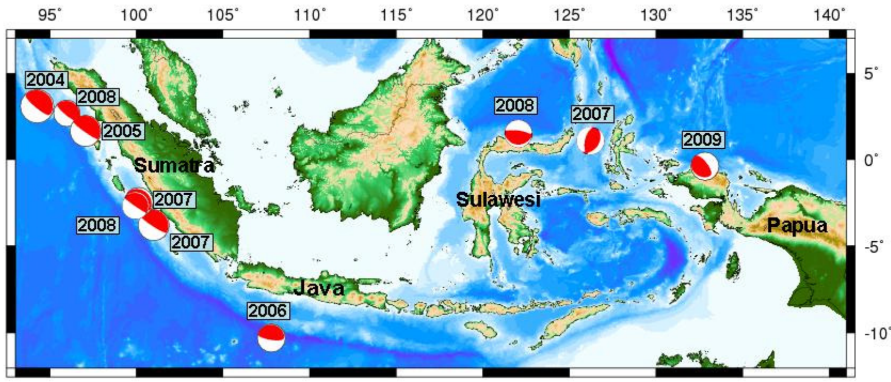

Figure 1. Focal mechanism of events analyzed.

3. METHOD

3.1. W Phase Inversion

W phase is a distinct long period phase, arriving right after the P phase and carries long period information of the source at a much faster speed than surface waves. It has the group velocity ranging from 4.5 to 9 km/s with period ranging from 100 s to 1000 s (Kanamori, 1993). This study is based on the existing study done by Kanamori and Rivera (2008). We adopted their W phase inversion technique and followed the procedure given by them. We deconvolved the vertical component of global broadband seismograms to the acceleration time series then band-pass filtering them in the time domain followed by twice integration of acceleration time series to get displacement. Fig. 2 shows an example of the vertical displacement after deconvolution and band-pass filter (0.001-0.005Hz) for the 2009 Papua (mainshock) M_w 7.6 at the several stations ranging from distance 13° until 70°. We used a time window of W phase with duration of 15Δ sec (Δ is epicentral distance in degrees) after P arrival.

In W phase inversion, we assume a spatial point source (the centroid location) which is varied in time with a given time history. If the centroid location and the source time history are known, the inversion is linear with respect to the moment tensor element. We use a triangular source function to represent the moment rate function, defined by two parameters half duration t_h (the half width of the triangular moment rate function) and the centroid delay t_d (the temporal position of the centre of the triangle measured from the assumed origin time). We made the W phase inversion with three different locations. First, we fixed centroid location at PDE location then we estimate the best time delay as the optimized t_d by a simple 1-D grid search minimizing the root mean square (RMS) of the waveform misfit. Secondly, we estimate the optimum Centroid location by spatial grid search using the above t_d. Thirdly, we use the Global CMT parameters (GCMT location, GCMT t_d and t_h). We set t_h=t_d for the inversion of PDE location and optimum Centroid location. We used band-pass filter 0.001 to 0.005 Hz for M_w>=7.5 and 0.002 to 0.006 Hz for M_w<7.5. We concatenated them in order of distance then we compute the synthetics for a unit source for each station using the Green's functions by convolving them with a triangular source time function.

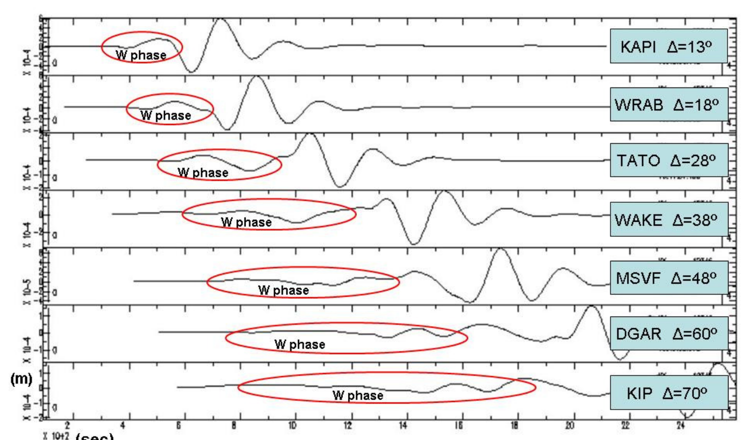

Figure 2. Vertical displacement of the 2009 Papua; as the result of retrieval the W phase.

3.2. Tsunami Simulation

In this study we use TUNAMI-N2 code of tsunami numerical model. It is for investigating near field tsunami based on tsunami numerical simulation with the staggered leap-frog scheme, and was developed by Dr. Fumihiko Imamura et al at Tohoku University. TUNAMI-N2 program uses the bathymetry of the area as input data. In this study we use bathymetry data of GEBCO (General Bathymetric Chart of the Oceans) which are digitized from nautical charts and gridded with an interval of one minute; http://www.gebco.net/data_and_products/gridded_bathymetry_data/. For initial condition of tsunami simulation, we need to provide fault parameters to compute sea floor deformation. The fault parameters need to be computed are: the location of the fault coordinates (latitude, longitude and depth), the fault length (L), the width (W), the strike angle (ϕ), the dip angle (δ), the rake angle (λ), slip amount (u) (Okada, 1985). In this study, we compute fault parameters based on W phase inversion results. We assumed that centroid locations (latitude, longitude, depth) of the W phase inversion are located at the fault centre hence we needed to calculate the coordinates of the left corner of fault as the input in TUNAMI-N2.

4. RESULTS AND DISCUSSION

4.1. W Phase Inversion

W phase inversion results can provide the source mechanism and seismic moment of the earthquake. In this study, we analyzed 10 events for the W phase inversion and compared with the result from Global CMT solutions. Here, we show the results of W phase inversion for the three events (Fig. 3): the 2005 Nias, 2006 Java and 2007 Molucca earthquakes. The overall focal mechanism and moment magnitude M_w were very similar for the three kinds of locations: PDE location, optimized centroid location and GCMT location. These three locations gave similar inversion results; both moment magnitude and focal mechanism were generally in very good agreement with the GCMT solutions. Fig. 4 compares the concatenated observed (black traces) and synthetics (red traces) W phases for the 2005 Nias earthquake. The match between the observed and synthetic of W phases is very good; error misfit RMS is 0.241.

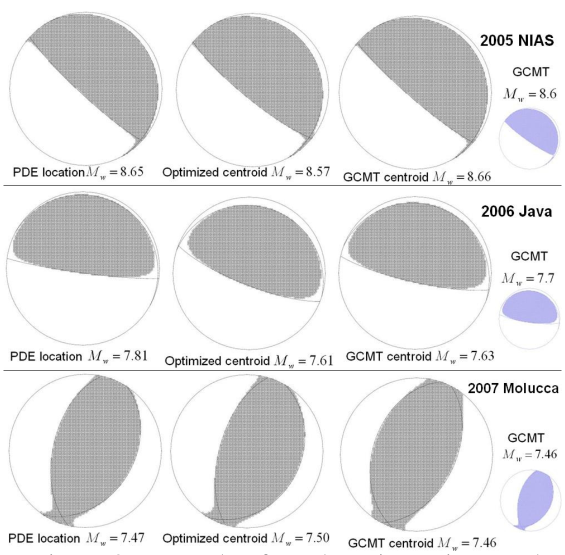

Figure 3. Example of W phase inversion results (focal mechanism and M_w).

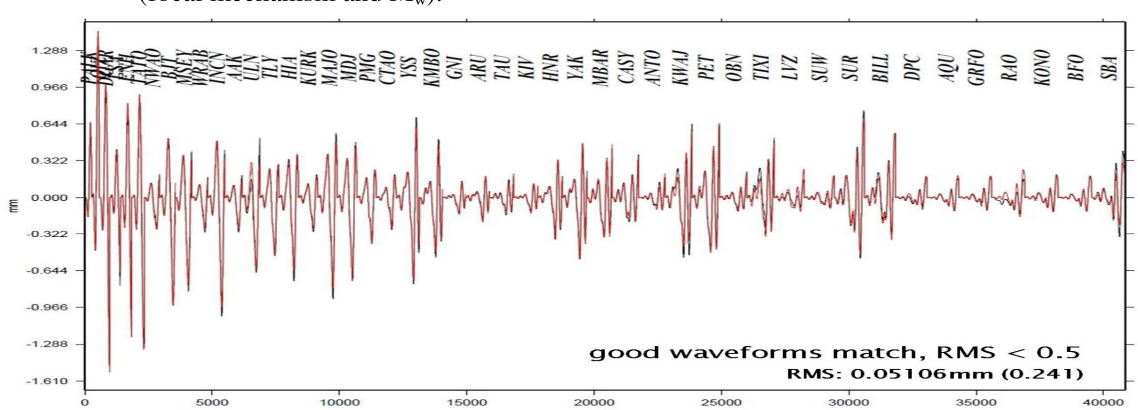

Figure 4. Example of concatenated W phase: observed (black traces) and synthetic (red traces). Synthetic traces are almost overlapped on the observed traces.

Fig. 5 shows comparison of M_w estimated from our W phase inversion with GCMT solutions. They are very similar with difference 0.1 or smaller, except for the 2004 Aceh earthquake. This indicates that inversion of W phase yields results which are very similar to the GCMT solutions although only earlier parts of seismograms (before surface wave arrival) are used while GCMT uses both body and surface waves. The difference for the 2004 Aceh event between our result and the GCMT solution might be due to either difference of power of very long-period component (> 200 sec) or inappropriate CMT location of the GCMT inversion.

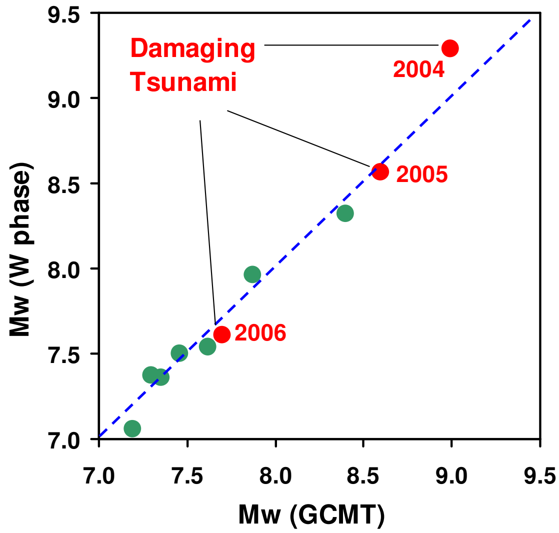

Figure 5. Comparison of Mw (W phase) and Mw (GCMT).

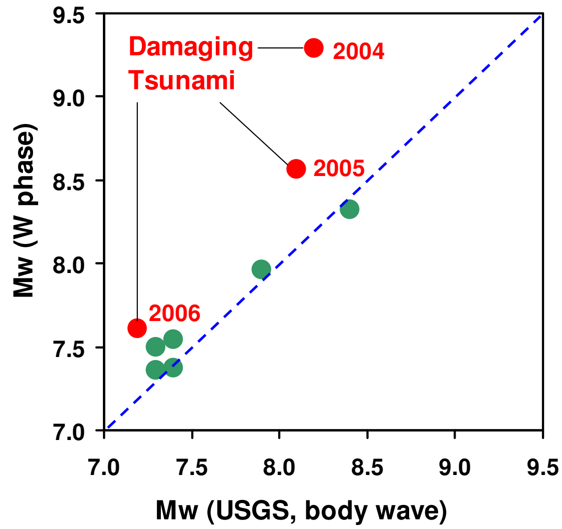

Figure 6. Comparison of Mw (W phase) and Mw (USGS, body wave).

Fig. 6 shows the comparison of M_w (W phase) versus M_w (USGS). M_w (USGS) is determined by using body wave (period about 25 sec) and M_w (GCMT) is determined by using body and surface waves (period 50-150 sec), while M_w (W phase) is determined by using W phase which is very long period wave (period 200-1000 sec). From Fig. 6 we can see that most of the events scatter around the line $y = x$, except for the 2004 Aceh, 2005 Nias and 2006 Java earthquakes; their M_w (W phase) are larger than M_w (USGS). Because these three events generated damaging tsunamis, estimation of M_w based on long-period waves is essential to estimate the tsunami potential. The GCMT analysis takes longer time as it includes both body and surface waves. The W phase inversion, on the other hand, does not include surface wave and can be performed with earlier (< 20 min) parts of seismograms recorded globally. It is therefore useful to examine the tsunami potential.

4.2. Tsunami Simulation

We performed numerical simulation of four tsunami events (the 2006 Java earthquake, the 2007 Bengkulu mainshock, the 2008 Sulawesi earthquake and the 2009 Papua mainshock) using W phase inversion results as the initial conditions of fault parameters and sea floor deformation. Here we show one example of tsunami simulation results for the 2007 Bengkulu mainshock. Based on W phase inversion results we obtained source parameters (focal mechanism and fault parameters are shown in Fig. 7). Then we used those parameters to perform tsunami simulation for three models of fault locations; PDE location, GCMT location and optimum centroid location.

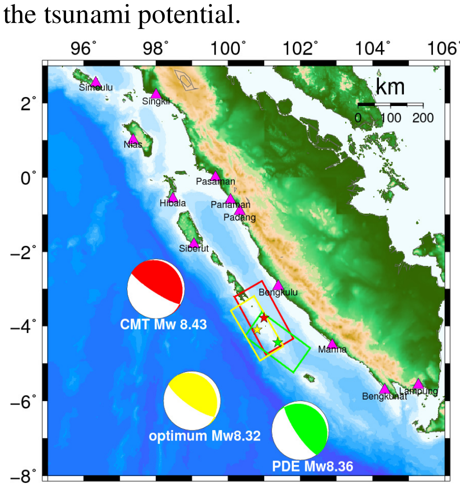

Figure 7. Focal mechanism and fault models for tsunami simulation.

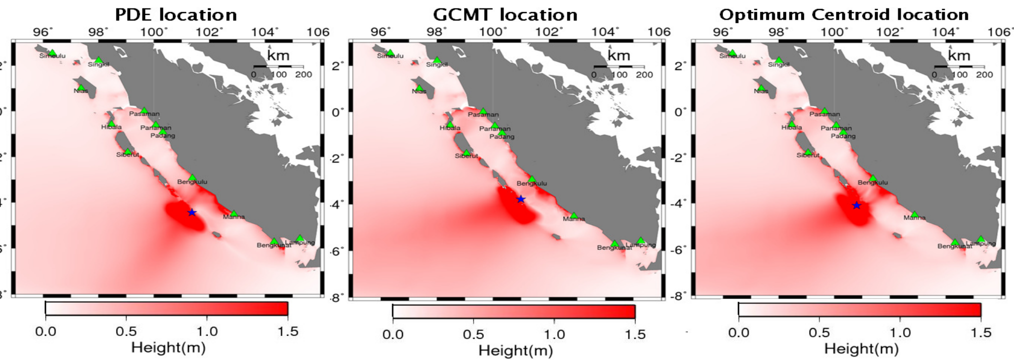

Figure 8. Distribution of maximum tsunami heights for simulation of PDE location, GCMT location and optimum centroid location; asterisk refers to centroid, triangle refers to outpoint at coastal region.

In general, the tsunami simulation results show that the distribution of maximum tsunami wave heights along the southern Sumatra coast has a similar trend for three models of fault locations (PDE Location, GCMT location and optimum centroid location). The maximum tsunami heights are distributed at area in front of tsunami source (Fig. 8). Large wave height is computed at Bengkulu by about 1.4 m (Fig. 9) for models of GCMT and optimum centroid, while in case of PDE, the highest wave are calculated at Bengkunat and Manna. In this case, PDE location is closer to Manna, while the location of GCMT and optimum centroid are closer to Bengkulu. From Fig. 9, we can see that for case of GCMT, the tsunami arrives at Bengkulu about 20 minutes earlier than cases of PDE and optimum centroid. On the other hand, tsunami arrives at Manna, 10 minutes earlier for the PDE case.

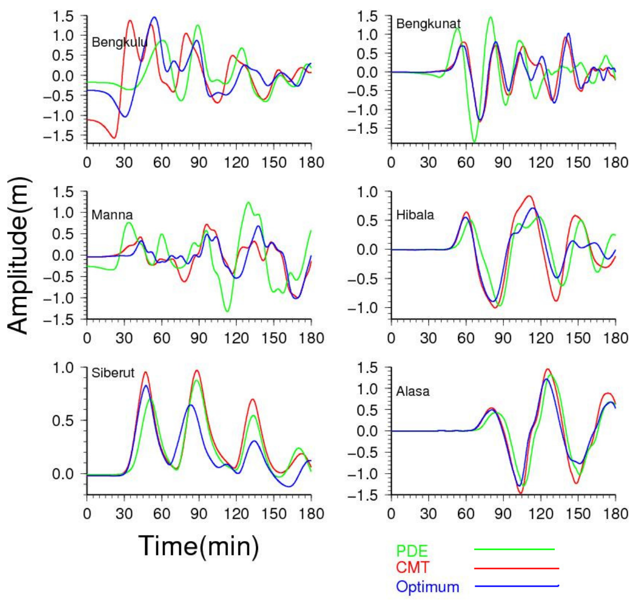

Figure 9. Comparison of tsunami waveform for PDE (green lines), optimum (blue lines) and GCMT (red lines).

We have shown that W phase source inversion yields consistent results with the GCMT solutions for each centroid location: PDE location, optimized centroid location and GCMT location. However GCMT is not suitable for warning purpose since it takes more time to determine it in real time situation. The W phase inversion with PDE parameters can save time, because the hypocentral location and origin time can be determined from P wave arrivals just after the occurrence of earthquake. Based on tsunami simulation results we found that each model (PDE, optimum centroid and GCMT) gives the similar tsunami heights and tsunami arrival times for the coastal area farther from the source where the tsunami arrives at more than 30 minutes. Using the PDE location in W phase inversion, within 20-30 minutes we can determine the seismic source with sufficient accuracy. Following that time we can perform tsunami simulation to predict the tsunami arrival times and tsunami heights at the coastal regions. But for the region nearby the source where tsunami arrives in less than 30 minutes, the available time for warning is too late. The disadvantage of using W phase inversion is the long time waiting for the data collection (because we need long period wave data which is can reach within 15-20 minutes), but by using this method we can get the sufficient accuracy of seismic source and the inversion is easy to be applied.

5. CONCLUSIONS

The W phase inversion results show that both moment magnitude and focal mechanism estimated from W phase are generally in very good agreement with the Global CMT solutions. Comparison of moment magnitudes from body waves, GCMT and W phase show that M_w from GCMT and W phase inversion are larger than M_w from body waves for the 2004 Aceh, 2005 Nias and 2006 Java earthquakes. These events caused damaging tsunamis. This indicates that it is necessary to perform analysis of long-period seismic waves to accurately evaluate the tsunami potential. In general, tsunami simulation results show that the distribution of maximum tsunami wave heights along the coastal points has the similar trend for the PDE location, GCMT location and optimum centroid location. The computed tsunami arrival times and heights are very similar for the three models except for the nearby points (the area which very close to the source with the tsunami arrival time in less than 30 minutes). Based on the W phase inversion and tsunami simulation results, we can conclude that the W phase inversion using PDE location yields good enough solution so that we can use it in real time situation for the warning purpose.

RECOMMENDATION

The goal of this W phase analysis is to perform a rapid determination of seismic source parameters with sufficient accuracy which can be used in performing tsunami simulation to get prediction of tsunami heights and tsunami arrival times at the coastal region. Fig. 10 shows the flow chart of time line for process warning information. The left side shows the current situation at BMKG while the right side shows W phase time frame which is recommended to be applied in BMKG. BMKG has been assigned the tasks to produce the tsunami messages during the first 5 minutes of earthquake occurrence. This tsunami message is the information about tsunami potential based on earthquake location and magnitude which should be determined within 3 minutes after earthquake. In the next 30 minutes, BMKG target is to give the updating. Tsunami potential of earthquake can be underestimated for very large event (such as the 2004 Aceh) and tsunami earthquake (such as the 2006 Java). Therefore we need to update the magnitude which can be determined from long period wave (W phase analysis) with more sufficient accuracy than only from short period wave. Although for this aim we need to wait at least 20 minutes in data collection only, but after that we can do W phase inversion to get source parameters (focal mechanism and moment magnitude) which can be used in tsunami simulation to predict tsunami arrival times and tsunami heights at the coastal region. Then within 30 minutes we can contribute in updating warning information for the region where the tsunami arrival time is more than 30 minutes.

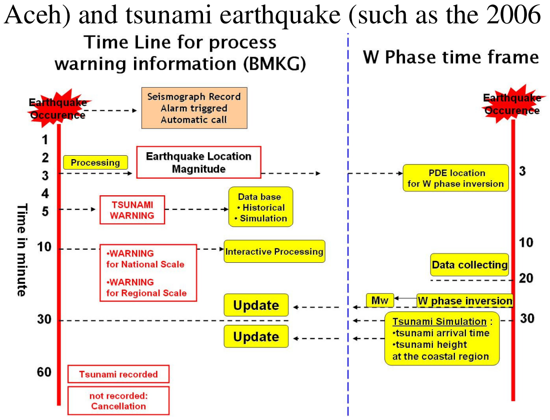

Figure 10. The time line for process warning information at BMKG.

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