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W phase inversion and tsunami inundation modeling for tsunami early warning: case study for the 2011 Tohoku event

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6

7 Abstract

8

9 Centroid moment tensor solutions for the 2011 Tohoku earthquake are 10 determined by W phase inversions using 5 min and 10 min data recorded by the Full 11 Range Seismograph Network of Japan (F-net). By a scaling relation of moment magnitude to rupture area and an assumption of rigidity of 4×10^{10} N m⁻², simple 12 13 rectangular earthquake fault models are estimated from the solutions. Tsunami 14 inundation area and heights are simulated in the Sendai Plain, Minamisanriku, and 15 Rikuzentakata using the estimated fault models. Then the simulated tsunami 16 inundation area and heights are compared with the observations. Even the simulated 17 tsunami heights and inundations from the W phase solution that used only 5 min data 18 are considerably similar to the observations. The results are improved when using 10 19 min of W phase data. These show that the W phase solutions are reliable to be used 20 for tsunami inundation modeling. Furthermore, the technique that combines W phase 21 inversion and tsunami inundation modeling can produce results that have sufficient 22 accuracy for tsunami early warning purposes.

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24 Keywords: Tsunami early warning; tsunami inundation modeling; W phase inversion.

27

28 On 11 March 2011, only 3 minutes after the origin time of the 2011 Tohoku 29 earthquake (14:46 JST), the Japan Meteorological Agency (JMA) warned that 30 tsunami larger than 3 m would hit east coast of Tohoku area. The actual tsunami that 31 struck the coastal area was more than 10 m and reached 40 m in some places (Mori et 32 al., 2012). The JMA used strong motion data to get the $M_{ima} = 7.9$ that was then used 33 to generate the first tsunami warning of the 2011 Tohoku earthquake. After an 34 offshore tsunami data was analyzed by the JMA about 25 min latter, the tsunami 35 warning was updated in which the estimated coastal tsunami heights was larger than 36 10 m. After 54 minutes from the earthquake's origin time, a magnitude Mw 8.8 was 37 obtained for the earthquake 38 (http://www.jma.go.jp/jma/en/2011_Earthquake/Information_on_2011_Earthquake.ht 39 ml).

40

41 The JMA issued three types of messages for coastal areas in Japan during the 2011 event, which are tsunami advisory, tsunami warning, and major tsunami 42 43 warning. These advisory and warning messages are visualized as color-coded lines 44 along the Japanese coastlines and broadcast on television (Figure 1). These messages 45 save many lives but apparently were not enough for many other people to 46 immediately evacuate. Large-scale maps of the predicted tsunami inundation area and 47 heights might have been able to better illustrate the dangers that threaten and 48 convinced them to evacuate immediately.

50	To produce the map of predicted tsunami inundation, accurate moment
51	magnitude estimation is required. The W phase, a distinct long-period (200 to 1000
52	sec) phase that arrives before S phase, can be used for rapid and robust determination
53	of great earthquake source parameters with sufficient accuracy (Kanamori and Rivera,
54	2008). The Full Range Seismograph Network of Japan (F-net) provides enough data
55	to determine the 2011 Tohoku earthquake's magnitude. Moment tensor solution for
56	the earthquake can be estimated by using a W phase inversion algorithm developed by
57	previous studies (Kanamori and Rivera, 2008; Duputel et al., 2011).

58

59 In this study, the 2011 earthquake parameters such as the centroid location, 60 magnitude and focal mechanism are estimated using the W phase data. A magnitude 61 to area scaling relationship is then used to estimate simple rectangular fault models 62 for tsunami inundation simulation. The Sendai Plain in Miyagi prefecture, 63 Minamisanriku in Miyagi prefecture, and Rikuzentakata in Iwate prefecture (Figure 2) 64 are selected for tsunami inundation simulation. To evaluate the computed tsunami 65 inundation areas for a tsunami early warning, we compare the simulated tsunami 66 inundation areas and tsunami heights with the observations. Finally, we discuss the 67 possibility of using the W phase inversion and tsunami inundation modeling for 68 tsunami early warning purpose.

- 69
- 70 2. Data
- 71

72 2.1. Seismic wave data for W phase inversion

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We retrieved the LH and LL channels from global networks through the Incorporated Research Institutes for Seismology (IRIS) data center and from F-net through the National Research Institute for Earth Science and Disaster Prevention data center. These data are used to estimate moment tensor of the 2011 Tohoku earthquake by W phase inversion.

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80 2.2. Bathymetry data for tsunami numerical simulation

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82 The bathymetry dataset used for tsunami simulation is based upon the General 83 Bathymetric Chart of the Oceans (GEBCO) 30 arc-sec grid resolution, Japan 84 Hydrographic Association's M7005 bathymetric contour data, Advanced Spaceborne 85 Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation 86 Model (GDEM), and Geospatial Information Authority of Japan (GSI) topographic 87 contour maps. Publicly available ASTER GDEM topographic data with grid 88 resolution of 30 m is not very accurate, coastal terrain and infrastructure such as ports 89 are poorly modeled in the GDEM. Therefore, for topography data below 50 m 90 elevation, we manually digitized topographic contours from the GSI maps and to 91 improve the coastline and used the ASTER GDEM data as the background 92 topographic data.

93

94 2.3. Tsunami inundation data of the 2011 Tohoku tsunami

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The great 2011 earthquake generated a large tsunami that devastated coastal areas along the east coast of Tohoku. Post-tsunami fieldwork along the coast of Japan provided more than 5,200 measurements of inundation, including tsunami height and 99 run-up (Mori et al., 2012). In general, maximum tsunami run-up heights greater than 100 10 m are distributed along 500 km of coast (Mori et al., 2012). Tsunami height 101 exceeds 20 m at heads of V-shaped bays and apexes of peninsulas, and exceptional 102 tsunami run-up heights of over 35 m was measured at a small valley, Aneyoshi, on 103 Omoe peninsula (Shimozono et al., 2012). The inundation limit of the tsunami was 104 also mapped in every major town in the Sanriku coast and Sendai area.

105

106 The Sendai Plain is a vast flat area, which is dominated by rice fields near the 107 coastline. The flat area has topography of lower than 5 m from the coastline until up 108 to 5 km inland which was inundated during the 2011 Tohoku tsunami (Figure 3). The 109 maximum tsunami inundation height was 19.5 m, and the mean tsunami inundation 110 height near the shoreline was about 10 m (Mori et al., 2012). In Minamisanriku, the 111 maximum tsunami run-up was 27 m. The tsunami inundation heights and run-ups 112 were mostly range from 14 to 16 m. The inundation continued as far as 3 km inland 113 (Figure 4), following river valleys into the mountainous terrain (MacInnes et al., 114 2012). In Rikuzentakata, the maximum tsunami run-up height was 21.6 m. The 115 tsunami inundation heights and run-ups were mostly range from 14 to 16 m. Similar 116 to what was observed in Minamisanriku, the inundation in Rikuzentakata continued 117 following river valleys in the mountainous terrain, but in here, the tsunami reached as 118 far as 5 km inland (Figure 5).

- 119
- 120 **3. Method**

121

122 *3.1. W phase inversion*

124 We used the W phase inversion algorithm (Kanamori and Rivera, 2008; 125 Duputel et al., 2011) to estimate moment tensor of the 2011 Tohoku earthquake. The W phase source inversion algorithm was specifically developed to estimate the 126 127 magnitude, centroid location and mechanism of great earthquakes like the 2011 128 Tohoku earthquake (Kanamori and Rivera, 2008; Duputel et al., 2011). Time domain 129 deconvolution is used to retrieve ground displacement and then it is filtered between 1 and 5 mHz using 4th order of the Butterworth filter. The time window is from the P 130 131 wave until 15 times the distance between point source to the station. For more details 132 of the W phase inversion method see Kanamori and Rivera (2008), Duputel et al. 133 (2011), and Duputel et al., (2012).

134

We estimate the moment tensor solutions for the 2011 Tohoku earthquake by the W phase inversion algorithm using 5 min and 10 min data of LH and LL channels belonging to the F-net. We also estimate a final moment tensor solution using data retrieved from global seismic networks through the Incorporated Research Institutes for Seismology (IRIS) data center.

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141 3.2. Scaling relations

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Scaling relations are needed to estimate rupture area from earthquake's moment magnitude. The moment magnitude (Mw) to fault area (A) relation of Wells and Coppersmith (1994) are widely used in seismic hazard analysis. The relationship was derived from a data base including all slip types of continental interplate or intraplate earthquakes, with the exception of subduction zones earthquakes both those at the interface and those within the oceanic slab. There are other recent scaling relationships that focused on continental events (Hanks and Bakun, 2002) and thatfocused on subduction zone events (Blaser et al., 2010).

151

The major slip area of the 2011 Tohoku earthquake is approximately 150 km 152 153 wide by 300 km long, which is relatively compact compared with the aftershock 154 region (Ammon et al., 2011; Pollitz et al., 2011; Gusman et al., 2012). For this 155 particular event, the major slip area estimated by the previous studies is similar to 156 rupture area estimated by the relationship of Hanks and Bakun (2002). Therefore, in 157 this study, the magnitude to area scaling relationship ($Mw = 4/3 \log A + 3.03$) for rupture area larger than 1000 km^2 of Hanks and Bakun (2002) is used. The fault 158 159 length (L) and fault width (W) are calculated from the estimated rupture area by a 160 simple relationship of fault length (L) = $2 \times$ fault width (W). Then a slip amount can 161 be estimated from the ruptured area and scalar moment by assuming the rigidity of along the plate interface, in this study we assume that the rigidity is 4×10^{10} N m⁻². 162

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164 3.3. Tsunami Inundation Model

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166 To simulate tsunami inundation, the non-linear shallow water equations in a 167 Cartesian coordinate system are solved by the finite different scheme (Goto et al., 168 1997). Tsunami inundation is numerically computed using moving boundary 169 condition. Discharge across the boundary between two cells is calculated if the 170 ground height in the dry cell is lower than the water level in the submerged cell; 171 otherwise, discharge is considered to be zero (Imamura, 1996). In this study, tsunami 172 inundation in the Sendai Plain, Minamisanriku, and Rikuzentakata are simulated. To 173 simulate tsunami inundation in the Sendai Plain, a grid system with grid size of 50 m

is used. While for Minamisanriku and Rikuzentakata, the grid system that is used has
a grid size of 15 m. For all sites, the Manning's roughness coefficient is assumed to
be 0.025.

177

178 3.4. Comparisons of tsunami simulations and observations

179

180 We used the measured tsunami data for comparison with simulated tsunami to 181 evaluate the performance of each source model in reproducing the actual tsunami 182 height and inundation. For each post-tsunami observation at a simulated site, the height above sea level of the simulated tsunami (H_{sim}) is compared with the actual 183 184 measurement (H) at the same position, or the closest numerically inundated point 185 when the observed point did not numerically inundated. The ratios between simulated 186 and observed tsunami heights (H_{sim}/H) at each site are plotted in a histogram with interval of 10%. The kurtosis (β) of the ratio distribution shows how well the 187 188 simulation produced the overall observed pattern of inundation. The more peaked and 189 narrow the histogram, or larger the kurtosis value, the better the simulation was able 190 to reproduce the pattern of observation.

191

192 **4. Results and discussion**

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We estimated three centroid moment tensor solutions, two of which are using 5 min data and 10 min of W phase data recorded at Japan stations, and a final W phase centroid moment tensor (WCMT) solution (Figure 2) using data recorded in global networks. The final moment tensor solution providing Mw estimation of 9.0, strike = 200° , dip = 13° , rake = 89° (Table 1), and centroid location is up-dip the 199 epicenter (Figure 2), which are consistent with the moment tensor solutions provided 200 by Duputel et al. (2011) and the USGS W phase solution. The W phase solution using 201 5 min data after the p wave arrives at the Japanese stations providing Mw estimation 202 of 9.0, which is consistent with the final W phase moment tensor solution. However, 203 the centroid location and focal mechanism are poorly resolved. While the solution 204 using 10 min of W phase data providing Mw estimation of 9.1 that is slightly larger 205 than Mw 9.0 from the final moment tensor solution. The earthquake parameters of 206 strike, dip, and rake angles obtained using 10 min of W phase data are similar to those 207 of the final moment tensor solution. The centroid locations of the solutions estimated 208 using the Japanese F-net data are poorly resolved because of the limited azimuthal 209 coverage. For simplicity, we will refer the centroid moment tensor solutions estimated 210 using 5 min, 10 min, and the global data as Solution 1, Solution 2, and Solution 3, 211 respectively.

212

Rupture areas calculated for given moment magnitudes of Mw 9.0 and Mw 9.1 by Mw = 4/3 log A + 3.03 (Hanks and Bakun, 2002) are approximately 30,000 and 36,000 km², respectively. By applying a relationship of fault length (L) = 2 × fault width (W), we obtained fault dimension of L = 123 km and W = 246 km for Mw 9.0, and L=134 km and W = 268 km for Mw 9.1. By assuming the rigidity of 4×10^{10} N m⁻², the slip amount calculated from the scalar moments of the Solutions 1, 2 and 3 are 31 m, 37 m, and 32 m, respectively (Table 1).

220

The simulated tsunami inundation areas from all source models and the observed tsunami inundation data for the Sendai Plain, Minamisanriku, and Rikuzentakata are shown in Figure 3, 4, and 5, respectively. Histogram plot of ratiobetween simulated and observed tsunami height for each case are shown in Figure 6.

225

226 The simulated tsunami inundation area in the Sendai Plain from the simple 227 source model of Solution 1 are underestimated the observation. While results of 228 tsunami simulations from Solutions 2 and 3 resemble the actual tsunami inundation 229 area and heights with mean ratios of 156% and 133%, respectively. Although the 230 mean ratio from Solution 1 is the smallest compare to that from other solutions, the 231 ratio distribution is rather random with local maxima and has the smallest kurtosis. 232 The mean ratios and histogram plots for the Sendai Plain in Figure 6 show that the 233 pattern of the simulated tsunami heights from Solution 3 resembles better the 234 observations.

235

236 For Minamisanriku, tsunami simulation from Solution 1 is slightly 237 underestimated the actual tsunami heights with mean H_{sim}/H ratio of 72% but has 238 inundation area that is similar to the observation. While tsunami simulations from 239 Solutions 2 and 3 give good results with mean H_{sim}/H ratios of 109% and 100%, 240 respectively. High kurtoses of the ratio distributions from all simulations show that the simulated tsunami heights are consistent to the measured tsunami heights. The 241 242 simulated tsunami inundations from all source models match well the observed 243 inundation area.

244

For Rikuzentakata, tsunami simulations from Solutions 1 and 3 give good results of tsunami inundation area with mean H_{sim}/H ratios of 109% and 99%, respectively. High kurtoses of the ratio distributions from these simulations show that

the simulated tsunami heights are consistent to the measured tsunami heights. Although tsunami simulation from Solution 2 produced slightly higher tsunami heights compare the measured ones with mean ratio of 140%, the simulated inundation area is also similar to the actual one. At this site, the difference in sizes of moment magnitude affected the simulated tsunami heights more than the difference in focal mechanisms.

254

255 Tsunami simulation results in the three locations from the three W phase 256 solutions are considerably similar to the observed tsunami heights and inundations. 257 Even though the W phase solution that used 5 min data has centroid location and focal 258 mechanism with low accuracy, the resulting simulated tsunami heights and 259 inundations are considerably similar to the observations. The simulated tsunami 260 inundation area may give estimation of scale or threat of the incoming tsunami, and it could suggest for an immediate evacuation. The simulated tsunami inundation results 261 262 are much improved when using the source model of the 10 min W phase solution. 263 These suggest that the technique that combines the W phase inversion and tsunami 264 inundation modeling can produce results that have sufficient accuracy for tsunami 265 early warning purposes. A system that incorporates W phase inversion, pre-calculated 266 tsunami propagation and tsunami inundation modeling might be able to estimate 267 robustly the tsunami inundation area due to great earthquakes.

268

Because the scaling relationship of Hanks and Bakun (2002) was made to estimate the fault area of continental earthquakes, our selection to this scaling relationship over the one for subduction zone earthquakes by Blaser et al. (2010) in this study is counter intuitive. The estimated fault size for the Mw 9.1 earthquake

273 (Solution 2) by Blaser et al. (2010) relationships is 656 km x 212 km, which is larger 274 than 268 km x 134 km estimated from Hanks and Bakun (2002) relationship. Hence 275 the estimated slip amount on the larger fault size for the Mw 9.1 earthquake is 10 m, 276 which is much smaller than 37 m for the smaller fault size. We also simulate the 277 tsunami inundation in the Sendai Plain, Minamisanriku, and Rikuzentakata using the 278 fault model with smaller slip amount. As expected, the simulated tsunami inundations 279 in those locations are underestimating the observations. Figure 7 compares the 280 maximum tsunami heights from both simple fault models, along the coastline of 281 northeast Honshu on a 60 arc-seconds grid system. The comparison shows that the 282 simulated tsunami heights from the fault model with the larger slip amount are larger 283 between 37° to 40° N but similar else where. However, the simulated tsunami from 284 the larger size fault model arrives noticeably sooner at locations to the north and south 285 of the smaller size fault plane. In a case of real tsunami event, the worse scenario of 286 tsunami inundation area, heights, and arrival time should be send to the coastal 287 community for consideration of an immediate evacuation.

288

The time required for a high-resolution tsunami inundation model to finish is mainly depend on the computer speed, simulation domain and grid size. For this study we used a computer with an Intel® CoreTM 2 Duo processor, running at 3.00 GHz, which supported by 4 GB of memory. To simulate 100 min of tsunami propagation and inundation in Sendai, Minamisanriku, Rikuzentakata, and Taro, the time required are 16.9 min, 34.7 min, 14.6 min, and 43.7 min, respectively.

295

296 Conclusions

298 We estimated three centroid moment tensor solutions where two of which are 299 estimated using 5 min data, 10 min of W phase data recorded at the Japan F-net 300 stations, and another one is a final W phase centroid moment tensor solution for the 301 2011 Tohoku earthquake using the global data. A scaling relation ($Mw = 4/3 \log A +$ 302 3.03) by Hanks and Bakun (2002) is used to calculate the rupture area from the moment magnitude. Then by assuming rigidity of 4×10^{10} N m⁻² along the plate 303 304 interface and a relationship between the length and width of the rupture area (L = $2 \times$ 305 W), we obtained earthquake source parameters for tsunami inundation modeling.

306

307 Tsunami inundation area and heights are simulated in the Sendai Plain, 308 Minamisanriku, and Rikuzentakata using the three estimated fault models for the 309 2011 Tohoku earthquake. Even the simulated tsunami heights and inundations from 310 the W phase solution that used only 5 min data are considerably similar to the 311 observations. The results are improved when using 10 min of W phase data. These 312 show that the W phase solutions are reliable to be used for tsunami inundation 313 modeling. Furthermore, the technique that combines the W phase inversion and 314 tsunami inundation modeling can produce results that have sufficient accuracy for 315 tsunami early warning purposes.

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 Bull. Seism. Soc. Am., 84 (4), 974-1002.
- 365

367 **Table title**

368 Table 1. Earthquake parameters of the W phase solutions for the 2011 Tohoku369 earthquake.

370

371 Figure captions

Figure 1. Tsunami warnings and advisory along the coastline of Japan during the2011 Tohoku earthquake event that was broadcasted on television.

374

Figure 2. The W phase centroid moment tensor (WCMT) solutions and the fault planes for the 2011 Tohoku earthquake. Black star represents the epicenter of the 2011 Tohoku earthquake (JMA), white stars represent the centroid locations for the 5 min, 10 min, and final W phase centroid moment tensor solutions, and rectangles are fault planes for the solutions. Rectangles on the coast represent the tsunami inundation simulation sites.

381

Figure 3. Comparison between observed and simulated tsunami heights and inundation area in the Sendai Plain. (a) Blue bars and red points represent the observed and simulated tsunami height at blue points in Figure 3.b., respectively. The simulated tsunami inundation areas from the (b) final W phase solution, (c) 5 min W phase solution, and (d) 10 min W phase solution, black lines represent the observed limit of tsunami inundation.

388

389 Figure 4. Comparison between observed and simulated tsunami heights and 390 inundation area in Minamisanriku. (a) Blue bars and red points represent the observed 391 and simulated tsunami height at blue points in Figure 4.b., respectively. The simulated

tsunami inundation areas from the (b) final W phase solution, (c) 5 min W phase
solution, and (d) 10 min W phase solution, black lines represent the observed limit of
tsunami inundation.

395

Figure 5. Comparison between observed and simulated tsunami heights and inundation area in Rikuzentakata. (a) Blue bars and red points represent the observed and simulated tsunami height at blue points in Figure 5.b., respectively. The simulated tsunami inundation areas from the (b) final W phase solution, (c) 5 min W phase solution, and (d) 10 min W phase solution, black lines represent the observed limit of tsunami inundation.

402

403 Figure 6. Distribution of ratios between simulated and observed tsunami heights
404 (H_{sim}/H).

405

Figure 7. Maximum tsunami heights along the coast from the fault models for
Solution 2, blue line represents that from the larger fault size with 10 m slip amount
and red line represents that from the smaller fault size with 37 m slip amount.



Okinawa

* and * *

NHK WORLD

tude of the quake is estimated at 7.9.



NEWSLINE

BREAKING NEWS: A powerful quake hit the Paci







Data fit, W Phase solution, Z

















Ratio (H_{sim}/H)



