The Effects of Sub-Faults Strike Direction and Landslide Energy on the Propagation of the 2011 Tohoku Earthquake and Tsunami

Wiko Setyonegoro (✉ wiko_setyonegoro@yahoo.co.id)

Badan Meteorologi Klimatologi dan Geofisika

Febty Febriani

Indonesian Institute of Sciences: Lembaga Ilmu Pengetahuan Indonesia

Muzli Muzli

Indonesian Agency for Climatology and Geophysics: Badan Meteorologi Klimatologi dan Geofisika

Pepen Supendi

Agency for Meteorology Climatology and Geophysics: Badan Meteorologi Klimatologi dan Geofisika

Rahmat Setyo Yuliatmoko

Agency for Meteorology Climatology and Geophysics: Badan Meteorologi Klimatologi dan Geofisika

Supriyanto Rohadi

Agency for Meteorology Climatology and Geophysics: Badan Meteorologi Klimatologi dan Geofisika

Nelly Florida Riama

Agency for Meteorology Climatology and Geophysics: Badan Meteorologi Klimatologi dan Geofisika

Dwikorita Karnawati

Agency for Meteorology Climatology and Geophysics: Badan Meteorologi Klimatologi dan Geofisika

Research Letter

Keywords: Earthquake, tsunami, fault, landslide

Posted Date: November 19th, 2020

DOI: <https://doi.org/10.21203/rs.3.rs-108449/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

The effects of sub-faults strike direction and landslide energy on the propagation of the 2011 Tohoku earthquake and tsunami

Wiko Setyonegoro^{1*}, Febty Febriani², Muzli Muzli¹, Pepen Supendi¹, Rahmat Setyo Yuliatmoko¹, Supriyanto Rohadi¹, Nelly Florida Riama¹, Dwikorita Karnawati¹

¹Agency for Meteorology, Climatology, and Geophysics (BMKG), Jakarta, 10720, Indonesia

²Research Center for Physics, Indonesian Institute of Sciences (LIPI), Tangerang Selatan, 15314, Indonesia

*Corresponding author: wiko_setyonegoro@yahoo.co.id

Abstract

We carried out a tsunami simulation of the 2011 (Mw 9.0) Tohoku earthquake. We analyze the tsunami run-up modeling by applying additional variables to seismic moment and moment magnitude equation to find out what extent it affects of sub-faults strike direction and landslide energy to tsunami propagation. To investigate the accuracy of run-up and inundation of the tsunami, we processed and analyzed the mainshock and aftershocks by applying scaling law method and inundation equation. We applied the aftershocks data to determine the wide area of the fault. The fault is divided into several sub-faults to make simulation design and scaling formulation adjustment. Each of sub-faults strike direction on simulation design has a different energy one another, which is determined by the strike direction of each fault position. Furthermore, we calculated the affects of submarine landslides on tsunami propagation. To obtain the variable of resultant energy of earthquake and landslide it performed by using the law of mechanical energy conservation. We applied both L-2008 and ComMIT tools for

processing tsunami simulation modeling. The result presents that the sub-fault strike direction and landslide energy can increase the propagation energy of the tsunami waves.

Keywords : Earthquake, tsunami, fault, landslide.

Introduction

The 2011 (Mw 9.0) Tohoku earthquake occurred in Fukushima Prefecture, Japan, on 12.46 JST (UTC+9) with a depth of 25.8 km followed by tsunami was released on Japan Meteorological Agency (JMA). The epicenter approximately 70 kilometers on the East of the Oshika Peninsula of Tohoku and the hypocenter at an underwater depth of approximately 29 km (United States Geological Survey (USGS)). The tsunami caused more than 10.000 deaths, mainly due to drowning, although trauma from blunt objects also caused many deaths. A recent report from Damage Situation and Police Countermeasures (2019) confirms that 15.899 deaths, 6.157 injured, and 2.529 missing people in twenty prefectural regions, and reports from 2015 indicate that 228,863 people are living in evacuation.

This study is the elaboration of earlier tsunami modeling research, consists of landslide method (Ma et al. 2015; Bullarda et al. 2019), the direction of landslides (Ruffini et al. 2019), slips distribution along fault strike which bases concept the sub-faults of strike direction (Gusman et al. 2012), landslide experimental (Wang et al. 2017), the transpot of Mechanical energy on free-falling wedge during water-entry phase (Wang et al. 2012), and the conservation of mechanical energy and the Galilean principle of relativity (Santos et al. 2010).

We would like to confirm the tsunami run-up modeling by applying additional variables to seismic moment and moment magnitude equation to find out to what extent the affects of sub-faults of strike direction and landslide energy on tsunami propagation. We attempt to provide the answers on the investigation, about to what extent it affects the sub-faults of strike direction

and landslide energy on tsunami propagation. The results indicated the comparison of the graph of each sub-faults of strike direction and the graph of calculations between earthquake energy with landslides and that of without landslides.

Data and Method

We analyzed the mainshock and aftershocks of the 2011 (Mw 9.0) Tohoku earthquake to obtain the fault location. The result became the starting point of coordinate in tsunami propagation. In this analysis, the fault of earthquake is determined as the amount of the tsunami propagation energy of each sub-fault.

We applied the xyz grid of bathymetry data (Satellite Geodesy 2016) in this study. In data processing, our data format was in vector *.xyz. We used the krigging method to increase the resolution of bathymetry data. By applying surfer tools, we converted the *.xyz data to the *.grd as a raster data. We also did a gridding by changing the spacing up to obtain resolution from 3 km to 20 m. After gridding, we reconverted the *.grd to the *.xyz by using Global Mapper. Then, it is ready to be used in L-2008 tools for tsunami modeling.

The earthquake source parameter data consisting of magnitude, origin time, hypocenter location (latitude, longitude, depth), strike, dip, and slip from Agency for Meteorology, Climatology, and Geophysics (BMKG), United States Geological Survey (USGS), International Seismological Centre (ISC), and Geo Forschungs Zentrum (GFZ) to determine the source location for modeling tsunami. The estimation of the fault area was calculated using aftershocks hypocenter distribution, tsunami run-up, and tsunami inundation in the affected area by applying the method suggested by the previous studies (Wells and Coppersmit 1994; Hanks et al. 1979). The tsunami simulation and run-up model were performed by applying the Nakamura method (Nakamura 2006). The empirical computation to find out the value of inundation was conducted by applying the Hills and Mader method (Hills and Mader 1997).

These results were then processed to conduct an analysis of tsunami potential based on the condition of bathymetry.

The fault parameters are presented in Table 1 and the area of the fault is obtained based on the destruction of the earthquake (Fig. 1). This tectonic process causes the earth's crust in the Japanese region to move actively and dynamically (Seno et al. 1993). The wide area of epicenter of the earthquake along with the size of the fault based on the destruction is around 90.000 km² (Gusman et al. 2012).

Table 1 Earthquake data parameter of fault

No	Parameter	Fault Parameters	Sub-Fault of strike direction	Fault Parameters	Fault Parameters to ComMIT
		L-2008 Tools	Parameters to L-2008 Tools	to ComMIT Tools	Tools Affected by landslide
1	Magnitude	Mw 9.0	Mw 9.0	Mw 9.0	Mw 9.218
2	Latitude	41.17638° N	Applied on fig.1	38.58372° N	Applied on fig.1
3	Longitude	143.80280° E	Applied on fig.1	142.7622° E	Applied on fig.1
4	Length (L)	~2500 km	180 km	300 km	100 km
5	Width (W)	~300 km	105.356 km	100 km	50 m
6	Slip (D)	10 m	62 m	10 m	10 m
7	Strike	193.0°	Applied on fig.1	188.0°	188.0°
8	Dip	76.0°	76.0°	21.0°	21.0°
9	Rake	90.0°	90.0°	90.0°	90.0°
10	Wide of sub-fault (A)	-	18.964,25 km ²	5000 km ²	5000 km ²
11	Wide of fault (A)	75.857 km ²	-	30.000 km ²	30.000 km ²
12	Wide area of Landslide material (A)	-	-	-	3.9747 x 10 ⁴ km ²

13	Weight of Landslide material (A)	-	-	-	151.715 x 10 ¹³ kg
14	Depth	25.8 km ²	25.8 km ²	21.28 km ²	21.28 km ²

Seismic moment indicates the energy which is released when an earthquake occurred (Hanks and Kanamori 1979). It can be calculated by using the moment magnitude formula. The calculation of moment magnitude formulated by Hanks and Kanamori is presented in Wells and Coppersmith equation (Wells and Coppersmith 1994).

We then applied seismic moment to measure the static displacement value (m) which represents the surface deformation due to earthquake. In general, the seismic moment is calculated by using the following Equation (1).

$$M_0 = \mu * A * D \quad (1)$$

M_0 is seismic moment (Nm), μ is modulus rigidity of earth's crust (N/m²), A is fault wide area (km²), and D = Displacement (m).

Fault plane area is all physical parameters in the fault that is applied in tsunami modeling process, such as displacement (m), Dip (⁰), rake (⁰), length (km), width (km), strike (⁰), longitude (⁰), latitude (⁰) and depth (m).

The fault-plane area (A) is a function of fault length (L) and fault width (W) describe in the previous study (Papazachos et al. 2004), as defined by Equations (2) and (3) :

$$\log L = -2.42 + (0.58 * M_w) \quad (2)$$

$$\log W = -1.61 + (0.41 * M_w) \quad (3)$$

L is length of fault and W is width of fault.

The tsunami run-up and inundation are the propagation of tsunami wave triggered by earthquake in the seafloor. It can be estimated by using Equation (4), (5) and (6) as follows:

$$V = \sqrt{g * H} \quad (4)$$

$$\eta * H^{\frac{1}{4}} = Constant \quad (5)$$

$$\eta_1 = \eta_2 * (H_2/H_1)^{1/4} \quad (6)$$

V is tsunami wave velocity (m/s), g is gravitational acceleration (9,8 m/s²), H is earthquake source depth (m), and η is tsunami wave height (m). We applied the formula suggested by Hills & Mader method (Hills and Mader 1997) as presented in Equation (7) to calculate the tsunami inundation distance.

$$X_{max} = (\eta)^{1.33} * n^{-2} * k \quad (7)$$

X_{max} is Maximum inundation (m), H is maximum run-up (m), k is a constant (0.06), n is Manning's n = 0.015 for very smooth terrain, 0.03 for building-covered areas, and 0.07 densely treed landscapes.

By applying the physical dimension equation of the earthquake and landslide energy, we obtained each value between earthquake and landslide energy to generate a tsunami propagation. We added landslide value to the resultant energy value of the deformation produced by the earthquake process of its potential or kinetic energy generated by the landslide movement from the sea floor. The deformation causes the earthquake which to trigger landslides in the submarine and/or landslide in a coastline cliff. Furthermore, can disrupt the seawater mass volume. If it happens, the earthquake and landslide can cause the two resultant energy to generate a propagation tsunami.

To calculate tsunami affected by landslides, we estimated the physical dimension of E_{Total} that is the same as the addition of M_0 from the seabed deformation and landslides, in which M_0 is seismic moment. This formula was applied to calculate the total energy of the earthquake and landslide. The numerical modeling of tsunami is affected by the potential energy (Ept) of the sediment transport caused by landslides. We assumed that Ept is $\frac{1}{2\rho g\eta}$ as the additional energy that occurs simultaneously with the deformation energy of the earthquake battery, in which

$\rho = \frac{1 \text{ g}}{\text{cm}^3}$ for all coral reef material landslides. We then defined it as the new potential energy (E_{pt}) (Ma et al. 2015) as presented in Equation (8):

$$E_{pot} = 12\rho g \int (\eta - ha)^2 dx \quad (8)$$

The changes in mean seal level can be approached using Equation (9) and (10):

$$E_{ps} = \rho g (\eta + h - ha)ha \quad (9)$$

$$E_{pw} = \int E_{pt} \quad (10)$$

where E_{pw} is potential energy, ρ is density, g is gravity and $(\eta - ha)$ is the height of bathymetry structure (Ma et al. 2015). The generation impulse waves by landslide is defined by using Equation (11):

$$E_{pw} = E_{pt} - E_{ps} = \frac{1}{2}\rho g(\eta - ha)^2 - E_{ps} \quad (11)$$

Potential energy will be maximum if E_{ps} = 0. We applied the law of conservation mechanical energy as presented in Equation (12):

$$E_{pw} = M_0 (\text{Submarine landslide}) = \frac{1}{2}\rho g(\eta - ha)^2 \quad (12)$$

Accordingly, we calculated the earthquake affected by the landslide in coastal cliff. In this hypothesis we assumed that the disturbance of the sea water column at the top may occur due to the landslides from coastal cliffs or shallow seas. This landslides are regarded as a sediment transport in the upper seawater column or the movement of material that has slipped due to the collapse of a cliff on the coast with a very large volume of soil material due to earthquakes. Also, we assumed that an earthquake is affected by a landslide from the coastal cliff, so the resultant energy accumulation from the earthquake and landslide will occur in the propagation of the tsunami waves. The second assumption is the distance (h) from the cliff slide when the working kinetic energy is replaced by t .

Therefore, we applied the formula for the law of free-fall motion $v = g * t$ or $v^2 = (gt)^2$.

There are two types of energy at work when the material slips in the landslide process, i.e. the kinetic energy that is formed when the landslide cliff material reaches sea level so that it takes effect ($E_{k_{fall}}$) and the potential energy that is formed when the landslide material begins to sink ($E_{p_{sinks}}$) so that the law of conservation of mechanical energy applies. Other studies include two simple examples of slope margins (Santos et al. 2010), block, and free fall. Landslide of material with mass m slides on an inclined surface of the beach slope. The landslide material will make a repulsive force from the volume of sea water as presented in Equation (13) and (14) :

$$Ek_{(Coastal\ Cliff\ Landslide)} = M_0_{(Coastal\ Cliff\ Landslide)} = Ek_{fall} + Ep_{sinks} \quad (13)$$

$$M_0_{(Coastal\ Cliff\ Landslide)} = \frac{1}{2}(m_{cliff})(v_{cliff})^2 + \frac{1}{2} * \rho_{water-sea} * g(\eta - ha)^2 \quad (14)$$

Annotation:

$E_{k_{fall}}$ = Energy Kinetic when the cliff material fall.

$E_{p_{sinks}}$ = Energy Potential when the cliff material sinks.

m_{cliff} = Real Mass of Cliff.

v_{cliff} = The velocity of material cliff in free-fall motion.

Total Energy of Seafloor Deformation Affected by Landslides

When the law of conservation mechanical energy is applied, the resultant energy from equations (12) and (14) becomes equations (15) and (16):

$$E_{total} = M_0_{(seafloor\ deformation)} + E_m_{(mechanical\ energy\ landslide)} \quad (15)$$

$$E_{total} = M_0_{(seafloor\ deformation)} + M_0_{(submarine\ landslide)} + M_0_{(costal\ cliff\ landslide)} \quad (16)$$

Results and Discussion

The tsunami modeling scenario is a tsunami model by using the mainshock magnitude classification (Nakamura 2006). The calculation by applying the scaling law equation and aftershocks distribution was applied to obtain the area of the fault plane. The results indicate that the wide areas of fault plane are 75857,436 km² and 90000 km².

The maximum observed run-up of the Tohoku earthquake is 37.8 m, higher than that of the unmodified scaling law calculation that result is 17.52 m. Furthermore, the modified scaling law equation presents that the maximum run-up of 26 m (Table 2). It indicates that the calculation using the modified scaling law equation has a better result since it is closer to the actual observation of the run-up.

Table 2 The run-up values of mainshock in Honshu island and its surrounding on March 11, 2011 with Mw 9.0 magnitude earthquake

Area observation of Run-up						Fault area	Fault area	Run-up	Run-up from Fault	Run-Up	Run-Up	
						based on	based on	Based on	area based on	Based on	Based on	
						Scaling Laws	Gusman et	Scaling Laws	adjusting Scaling	Petukhin,	Løvholt	
						Wells and	al. 2012,	Tsunami simulation	Laws	et al. 2012,	et al.	
						Coppersmith,	(km ²)	use L-2008 tools and	fault area on	(m)	2012,	
						1994 (km ²)	Wells and	Tsunami				
						Coppersmith 1994			Simulation			
						equations (m)			Gusman et al, 2012,			
									(m)			
Hachinohe	40.32	141.31						5.4	20.76	8.0	8.4	
Kuji	39.11	142.46						10.28	18.919	10	9.8	
Kamaishi	39.26	141.88						10.7	20.214	9.5	19	
Ofunato	39.47	141.74						20.58	27.98	28	29	
Onagawa	38.26	141.27	193	76	24	75857,436	90000	13.8	18.019	14	18	
Miyako	39.38	141.57						17.52	26	30	37.8	
Sendai	38.16	141.52						10.7	14.33	12	14.4	
Soma	39.32	142.19						8.2	12.49	12	8.23	
Asahi	39.72	142.17						2.4	6	4.5	7.6	
Kitaibaraki	36.47	140.45						8.21	8.2	8.5	8.2	

PLTN	37.25	141.01	10.7	10.96	13	14
Fukushima						

Fig. 2 shows the sub-fault simulation design of L-2008 tools to make the scenario of tsunami modeling. We divided the main fault into several sub-faults to improve the accuracy of the run-up height. We made a sub-faults classification as the representative of the real fault dimension. We then calculated the strike direction and seismic moment precisely from the fault dimension, then the tsunami propagation M_0 in the affected area will be in a good correlation to the plate boundary line.

The fault dimension can be calculated based on the identification of the type of an earthquake event, e.g. foreshock, mainshock, and aftershocks since the release of energy (M_w) is different for each type of an earthquake event. The fault area-based earthquake parameters processing provides information that moment seismic force is affected by the location of observation (A), which is not in a straight-line position with the strike direction of sub-fault 4 of L-2008 tools. It then resulted in improper simulation. Therefore the scenario was carried out by dividing the faults based on the segments. Plot cross-section A-B it's correct when A-B is straight line. Assume : 1 degree ~ 111 km from A to B is 660.0771 km, interval is 6.60 km (Fig. 2.a).

The modeling scenario-based sub-faults is determined by finding the combination between the slip and the fault length from the epicenter to the coordinates of the affected location by considering the strike direction, e.g. the modeling scenario for Sendai City (B) applied the second sub-fault. Other parameters, such as depth, dip and other parameters were estimated by using equation from the previous studies (Hanks and Kanamori 1979; Wells and Coppersmith 1994). Each sub-fault has different strike angle that corresponds to the main fault. The area of the sub-faults is based on the epicenter distribution of the foreshocks, mainshock, and

aftershocks. We then divided the seismic moment (M_0) into several sub-moments based on the sub-fault segments.

Fig. 2. b is represent of Equation (16), result of ComMIT tools which it indicate landslide energy were affected to Tohoku tsunami propagation on the March 11, 2011. We may compare that tsunami with landslide it generate a higher tsunamis than those without the affect of landslide.

The assumption of the fault area parameter tsunami modeling is a rectangular shape although, in fact, the fault area is polyline or spiral following plate boundary topography. The sub-fault's numbers and dimensions affect strike accuracy. The smaller sub-fault dimensions will give more accurate strike direction in the result (table 3).

Table 3 Results of the run-up on sub-faults of strike direction simulation design with Mw 9.0 earthquake

Tsunami affected area	Lat.	Long.	Sub-fault 1				Sub-fault 2				Sub-fault 3				Sub-fault 4				Run-up based on F. Løvholt et al. 2012,			
			Run-up (m)	Slip	Strike	Dip	Run-up (m)	Slip	Strike	Dip	Run-up (m)	Slip	Strike	Dip	Run-up (m)	Slip	Strike	Dip	Run-up (m)	Slip	Strike	Dip
Hachinohe	40.32	141.31	8.30				5.02				9.30				7.17				8.40			
Kuji	39.11	142.46	6.70				18.10				-				11.30				9.8.00			
Kamaishi	39.16	141.53	12.28				7.02				9.30				-				19.00			
Ofunato	39.47	141.74	12.05				23.56				19.72				14.67				29.00			
Onagawa	38.26	141.27	7.02				14.00				14.70				-				18.00			
Miyako	39.38	141.57	-				-				18.19				-				37.80			
Sendai	38.16	141.52	10.70	55	203	76	13.40	47	193	76	12.68	70	189	76	14.61	62	212	76	14.4	30	193	76
Soma	39.32	142.19	12.81				14.80				-				7.17				8.90			
Asahi	39.72	142.17	12.50				11.30				-				5.60				7.60			
Kitaibaraki	36.47	140.45	-				-				15.19				9.90				8.20			
Fukushima Power Plant	37.25	141.01	6.20				11.40				19.47				14.71				14.00			

The modeling using the fourth sub-faults of L-2008 tools is presented in Fig. 3. It shows the run-up comparison among the tsunami modelings for the fourth subsection, the modeling by modifying the scaling law empirical equation, and the modeling by using the algorithm from the previous studies in the affected area around the fourth sub-fault. The results of the run-up simulation of the fourth sub-fault in the affected area are listed.

On the other hand, based on the sub-fault of the earthquake source of L-2008 tools, this study obtained the result as shown in Fig. 4 and Fig. 5. Run-up observation points with a blue square dash line showing run-up estimation at that point are closer to the valid run-up distribution pattern than the estimation of run-up outside the square. It may happen due to the observation in area A (Fig. 4) and points in the square facing in the same direction as the strike position of sub-fault 1, then M_0 of the sub-fault 1 can represent area A (Fig. 4), and sub-fault 2 can represent the result of run-up modeling in area B as well as the area closest to B (Fig. 5).

We divided the study area into several observation areas based on the strike direction of the sub-faults. Group A is the observation area that becomes the result of the run-up model that is suitable for sub-fault 1, i.e. Hachinohe and Kuji (Fig. 4), but Hachinohe has similar values and correlation with the distribution pattern. Group B is the result of the run-up model that is suitable for sub-fault 2, i.e. Miyako, Kamaishi, Ofunato and Onagawa (Fig. 5). The run-up model that has similar values and correlation with distribution pattern are Ofunato and Onagawa. Group C is the result of run-up model that is suitable for sub-fault 3, i.e. Sendai and Soma (Fig. 6). Both areas have similar values and correlation with the distribution pattern.

The results of the run-up modeling substitute to Equation (7) and obtain inundation in the affected area (Fig. 7). Inundation calculations were carried out for the types of field areas, building areas, and forest areas. The results of the calculations were then verified using the results of the modeling and direct measurements carried out by (Løvholt et al. 2012; Lesley 2011). The results of the inundation calculations and their verification are listed in Table 4.

There was a conformity between the results of the inundation calculation and the model references. The lowest inundation is 722.52 meters that occurred in Asahi, Chiba Prefecture, a residential area surrounded by cliffs and trees. The highest inundation is 5600.36 meters that occurred in Ofunato, Iwate Prefecture.

The result of the comparison in inundation calculations among field area, building area, forest area, and field observation is presented in Fig. 7. It shows the effects of landslide energy on tsunami propagation.

The inundation model is more suitable for inundation calculation in the field area ($n = 0.015$) than that of the field observations. The inundation that occurred in the is relatively high, while the building area has a lower inundation distribution in Onagawa, Miyako, Sendai, and Soma (Table 4).

Table 4 The inundation model based on equation (8) to calculate the tsunami inundation distance with n is constant from the type of building area, smooth/spacious and forest (in meters).

Tsunami affected area	Maximum Run-up on the Coastline (Hs) (m)	Estimated Inundation for Tsunami scenarios in the building area (m) of L-2008 tools	Estimated Inundation for Tsunami scenarios in smooth / field area (m) of L-2008 tools	Estimated Inundation for Tsunami scenario in forest area (m) of L-2008 tools	Estimated Inundation for Tsunami scenario of ComMIT tools	Estimated Inundation for Tsunami scenario Mw 9.218, (Affected by landslide) of ComMIT tools (m)	Inundation Based on F. Løvholt et al. 2012, pp.: 1024 and Lesley E. P. Miyamoto et al 2012 (m)
Hachinohe	20.76	3765.486677	15061.94671	6.916200019	~1500	~3300	-
Kuji	18.919	3327.999992	13311.99997	6.112653047	~1700	~3400	-
Kamaishi	20.214	3634.345812	14537.38325	6.675329043	~600	~1200	-
Ofunato	27.98	5600.363229	22401.45292	10.28638144	~3000	~6500	-
Onagawa	18.019	3119.109004	12476.43602	5.728975721	~5600	~12500	~15000
Miyako	26	5079.527241	20318.10896	9.329743912	~900	~1800	~15000
Sendai	14.33	2299.93824	9199.752961	4.22437636	~5800	~11000	~10000
Soma	12.49	1915.740956	7662.963824	3.518707878	~5600	~11200	~11700
Asahi	6	722.5200511	2890.080204	1.327077645	~2500	~5000	-
Kitaibaraki	8.2	1094.664829	4378.659316	2.010608869	~2000	~4200	-
Fukushima	10.96	1610.114563	6440.45825	2.957353278	~1500	~3300	-

Results of Earthquake Affected by Landslides

We applied ComMIT tools to simulate the earthquakes with or without the effect of landslides. We did the same calculation of tsunami numerical modeling by using the Equation of Wells and Coppersmith. The aftershocks data-based area of fault was measured using the seismic fault field information. The simulation model was performed using six seismic fault planes based on the NOAA database (National Oceanic and Atmospheric Administration 2019) database with the area of the fault area reached 30000 km² in total. We determined the Mw = 9.0 Magnitude by using ComMIT to make this simulation, in which the vertical displacement (D) = 10 m (Fig. 8).

$$M_w = \frac{2}{3} \log M_0 - 6.07 = \frac{2}{3} \log \mu * A * D - 6.07$$

$$9.0 = \frac{2}{3} \log (3 * 10^{10} \text{ m}^2 * A * 10^4 \text{ km}^2 * 9.8) - 6.07$$

The result is $A = 39747 \text{ km}^2$

Epw is potential energy of landslide, ρ is density, g is gravity and $(\eta - h_a)$ is the height of bathymetry structure (Ma et al. 2015). We obtained it from cross section bathymetrical data on fault area, the height of the landslide source from the submarine structure $(\eta - h_a) = 5000 \text{ m}$. We then obtained the maximum fault area of $A = 39747 \text{ km}^2$.

The kinetic landslide of m is mass of slid cliff and the slide movement of free fall of $v_{\text{slope}} = g \cdot t$. The height of fall process $(\eta - h_a) = 4000 \text{ m}$ is obtained if the cliff of falling kinetic energy is applied, in which h is replaced by t . Based on the free fall motion $v = g * t$ or $v^2 = (g * t)^2$, we assumed that the fall movement of $t \sim 3600 \text{ s}$.

We assumed that the weight of fall material is $\sim 151.715 * 10^{13} \text{ kg}$, we assumed that the total depth $(\eta - h_a) = 4000 \text{ m}$ with $A = 39747 \text{ km}^2$. We then obtained through Equation (16):

$$E_{\text{total}} = M_0 (\text{seafloor deformation}) + M_0 (\text{submarine landslide}) + M_0 (\text{costal cliff landslide})$$

$$E_{\text{total}} = \mu * A * D + \left(\frac{1}{2} \rho * g * (\eta - h_a)^2 - 0 \right) + E_{k_{\text{fall}}} + E_{k_{\rho_{\text{sinks}}}}$$

$$E_{\text{total}} = \mu * A * D + \left(\frac{1}{2} \rho g (\eta - h_a)^2 - 0 \right) + \frac{1}{2} (m_{\text{cliff}}) (v_{\text{cliff}})^2 + \frac{1}{2} \rho_{\text{water-sea}} * g (\eta - h_a)^2$$

$$E_{\text{total}} = (1.19382 * 10^{22}) + (2.487 * 10^{11}) + (9.83118 * 10^{22}) + (8.0 * 10^{10}) \text{Nm}$$

$$E_{\text{total}} = M_{0 \text{ total}} = 11.02494 * 10^{22} \text{Nm}$$

Based on above, then substitutions to Wells and Coppersmith formula to obtained the result below:

$$M_w = \frac{2}{3} \log M_{0 \text{ (total)}} - 6.07$$

$$M_w = \frac{2}{3} \log(11.02494 * 10^{22} \text{Nm}) - 6.07$$

$$M_w = 9.2182 \text{ Magnitude}$$

Total energy of seafloor deformation affected by landslides is M_w 9.2182 Magnitude.

Conclusion

This study conducted tsunami modeling simulation process of Tohoku Japan by using calculation of the propagation source originating from fault sources due to earthquakes and landslides through several equations and simulations. The results confirm that both of sub-fault strike directions and landslide energy affect tsunami propagation. It was validated by the results of other studies that the affected area which is directly opposite to the strike directions of the sub-faults will be affected by higher tsunami propagation run-up than the surrounding area. Meanwhile, the effects of the landslide can result in stronger tsunami propagation, thus the inundation range that occurs as a result of the tsunami waves measured from the coastline to the center of the land will be longer. In conclusion, the hypothesis of this study stating that the sub-fault strike direction and landslide can affect the

propagation energy of tsunami waves is correct and we have validated it through comparisons using related research and some equations.

Acknowledgements

We greatly appreciate and deliver their gratitude to BMKG that provided valuable contributions throughout the research process from the beginning to the end of the research.

Author Contributions

Research idea: WS. Conceived and designed of paper: WS. Data Collection: WS. Performed the the experiments: WS. Analyzed data: WS. Revised the manuscript: WS, FF, M, PS, RSY. Contributed reagents/materials/analysis tools: WS, SR, NFR, DK. Paper writing: WS.

Funding

This study was supported and funded by Agency for Meteorology, Climatology, and Geophysics (BMKG)

Availability of data and materials

Bathymetry data extracted from http://topex.ucsd.edu/cgi-bin/get_data.cgi. Historical earthquake data taken from USGS (<http://earthquake.usgs.gov/earthquakes/search/>).

Competing interests

The authors declare that they have no competing interests.

References

- Bullarda GK, Mulligana RP, Carreirab A, Takea WA (2019) Experimental analysis of tsunamis generated by the impact of landslides with high mobility. *Coastal Engineering*, vol. 152-103538. <https://doi.org/10.1016/j.coastaleng.2019.103538>
- Damage Situation and Police Countermeasures (2019) National Police Agency of Japan. Retrieved 13 March 2019. https://www.npa.go.jp/news/other/earthquake2011/pdf/higaijokyo_e.pdf. Accessed on March 8th, 2019.
- Geo Forschungs Zentrum (2016) Earthquake catalog data. <http://geofon.gfz-potsdam.de/eqinfo/form.php>. Accessed on August 23th, 2016.
- Gusman AR, Tanioka Y, Sakai S, Tsushima H (2012). Source model of the great 2011 Tohoku earthquake estimated from tsunami waveforms and crustal deformation data. *Earth and Planetary Science Letters*, p: 234–242. <https://doi.org/10.1016/j.epsl.2012.06.006>
- Hanks, Thomas C, Kanamori H (1979) "Moment magnitude scale". *Journal of Geophysical Research*, 84 (B5), p: 2348–2350. <https://doi.org/10.1029/JB084iB05p02348>
- Hills JG & Mader CL (1997) Tsunami produced by the impacts of the small asteroids. *Annals of the New York Accademy of Sciences*, 822, 381-394. <https://doi.org/10.1111/j.1749-6632.1997.tb48352>
- International Seismological Centre (2016) Earthquake catalog data England. <http://www.isc.ac.uk/iscbulletin/search/bulletin/>. Accessed on August 23th, 2016.
- Japan Meteorological Agency (2016) Information on the 2011 Great East Japan Earthquake. http://www.jma.go.jp/jma/en/2011_Earthquake/2011_Earthquake.html. Accessed on August 20th, 2016.

- Lesley EPE (2011) The Tohoku Tsunami of March 11, 2011: A Preliminary Report on Effects to The California Coast and Planning Implications. California Coastal Commission. State of California. *Natural Resources Agency*. Page: 4.
- Løvholt F, Kaiser G, Glimsdal S, Scheele L, Harbitz CB, Pedersen G (2012) Modeling propagation and inundation of the 11 March 2011 Tohoku tsunami. *Natural Hazards Earth System. Sci.*
<https://doi.org/10.5194/nhess-12-1017-2012>.
https://www.coastal.ca.gov/energy/tsunami/CCC_Tohoku_Tsunami_Report.pdf. Accessed on October 8th, 2020
- Ma G, James TK, Hsu TJ, Shi F (2015) A two-layer granular landslide model for tsunami wave generation: Theory and computation. *Ocean Modelling* 93.
<https://doi.org/10.1016/j.ocemod.2015.07.012>.
- Meteorological Climatological and Geophysical Agency (2016) Historical data on earthquake events.
<http://172.19.3.54/query.php>. Accessed on August 23th, 2016.
- Nakamura M (2006) Source fault model of the 1771 Yaeyama Tsunami Southern Ryukyu island Japan Inferred from Numerical Simulation. *Pure Appl. Geophys.*, 163, 41-54.
<https://doi.org/10.1007/s00024-005-0007-9>
- National Oceanic and Atmospheric Administration (2019) Tohoku Earthquake March 11, 2011.
<https://www.ngdc.noaa.gov/hazard/11mar2011.html>. Accessed on August 29, 2016.
- Papazachos BC, Scordilis EM, Panagiotopoulos DG, Papazachos CB, and Karakaisis GF (2004) Global Relations between Seismic Fault Parameters and Moment Magnitude of Earthquakes. *Bull. Geol. Soc. Greece*, Vol. XXXVI. *Proceedings of the 10 International Congress*, Thessaloniki, April 2004Th. <https://doi.org/10.12681/bgsg.16538>
- Petukhin A, Yoshida K, Miyakoshi K, Irikura K (2012) Tsunami simulation for the 2011 Great Tohoku earthquake (M_w 9.0), Japan, using seismic inversion source model and fully nonlinear

- tsunami model. Proceedings of 15th World Conference on Earthquake Engineering (15WCEE). Lisbon, Portugal 24-28 September 2012, Vol. 1 of 38, p: 20733.
https://www.iitk.ac.in/nicee/wcee/article/WCEE2012_3644.pdf. Accessed on October 8th, 2020.
- Ruffini G, Heller V, Briganti R (2019) Numerical modelling of landslide-tsunami propagation in a wide range of idealised water body geometries. Coastal Engineering, vol. 153-103518.
<https://doi.org/10.3850/38WC092019-0720>
- Santos FC, Soares V, Tort AC (2010) A note on the conservation of mechanical energy and the Galilean principle of relativity. Eur. J. Phys. European Journal of Physics Eur. J. Phys. Vol. 3126. 827-834. <https://iopscience.iop.org/article/10.1088/0143-0807/31/4/012>. Accessed on October 8th, 2020
- Satellite Geodesy (2016) Extract Xyz Grid-Topography Or Gravity (Bathymetri Data).
http://topex.ucsd.edu/cgi-bin/get_data.cgi. Accessed on August 11th, 2016.
- Seno T, Seth S, Gripp AE (1993). A model for the motion of the Philippine Sea Plate consistent with NUVEL-1 and geologic data. J Geophysics Res. 101. 11305-11315.
<https://pdfs.semanticscholar.org/37c1/3877e62e988868293c19239fe8389a213c7d.pdf>. Accessed on October 8th, 2020.
- United States Geological Survey (2016) Historical data on earthquake events.
<http://earthquake.usgs.gov/earthquakes/search/>. Accessed on August 23th, 2016.
- Wang W, Huang Y, Wang Y (2012) Analysis of Mechanical Energy Transport on Free-Falling Wedge during Water-Entry Phase. Journal of Applied Mathematics, Vol. 2012, Article ID-738082. <https://doi.org/10.1155/2012/738082>
- Wang Y, Liu J, Li D, Yan S (2017) Optimization model for maximum tsunami amplitude generated by riverfront landslides based on laboratory investigations. Ocean Engineering, vol:142, p:433–440. <https://doi.org/10.1016/j.oceaneng.2017.07.030>.

Wells DL and Coppersmith KJ (1994) New empirical relationships among magnitude, rupture length, rupture width, and surface displacements: *Bulletin of the Seismological Society of America*, vol. 84, p. 974–1002. <https://www.resolutionmineeis.us/sites/default/files/references/wells-coppersmith-1994.pdf>. Accessed on October 8th, 2020.

FIGURES

Figure 1. (a) The vertical displacement and sub-faults composition, indicated by number 1, 2, 3, and 4 in the tsunami modeling scenario by applying L-2008 tools, (b) The sub-faults of the earthquake parameter settings indicated by applying ComMIT tools.

Figure 2. (a) Results of the maximum tsunami height generated by the fourth of sub-fault of L-2008 tools with Mw 9.0 (without landslide), (b) Cross-section A to B of maximum tsunami height with run-up of 20.58 m in Ofunato area, (c) Bathymetry structure on cross-section A to B with initial condition of landslide possibility, (d) Results of the maximum tsunami height by using ComMIT tools with Mw

9.218 (affected by landslide), the maximum run-up is ~28 m in Ofunato area, (e) Time series of Maximum tsunami height A to B.

Figure 3. Run-up comparison of the sub-faults modeling curve for the fourth sub-faults in the affected area. Validation curve through Sendai, Soma, Fukushima and Kitaibaraki nuclear power plants looked more validated properly.

Figure 4. Run-up validation curve based on sub-fault 1 of L-2008 tools and is validated with related research (Gusman et al. 2012; Petukhin et al. 2012). It is estimated by a curve pattern from the moving average.

Figure 5. Run-up validation curve based on sub-fault 2 of L-2008 tools and is overlaid with the run-up based on the adjustment of wide fault area of earthquake which it did by a related research (Gusman et al. 2012; Petukhin et al. 2012). It is estimated by a curve pattern from the moving average.

Figure 6. Run-up validation curve based on sub-fault 3 of L-2008 tools and is overlaid with run-up based on the adjustment of the fault area of the earthquake which it did by a related research (Gusman et al. 2012; Petukhin et al. 2012). It is estimated by a curve pattern from the moving average.

Figure 7. The comparison of inundation values of L-2008 tools, based on the type of area and the data from the field observation shows overlay with ComMIT tools with or without landslide effects.

Figure 8. The inundation of tsunami simulation using ComMIT tools (a) Mw 9.0, no landslide occurred in, maximum run-up on inundation area marked by blue circle and it reach ~7.4 m; (b) Mw 9.2182, affected by landslide maximum run-up on inundation area marked by blue circle it reach ~11 m. Also, we may compare the horizontal range of inundation is far-reaching than without landslide and marked by green circle.

Figures

Figure 1

(a) The vertical displacement and sub-faults composition, indicated by number 1, 2, 3, and 4 in the tsunami modeling scenario by applying L-2008 tools, (b) The sub-faults of the earthquake parameter settings indicated by applying ComMIT tools.

Figure 2

(a) Results of the maximum tsunami height generated by the fourth of sub-fault of L-2008 tools with Mw 9.0 (without landslide), (b) Cross-section A to B of maximum tsunami height with run-up of 20.58 m in Ofunato area, (c) Bathymetry structure on cross-section A to B with initial condition of landslide possibility, (d) Results of the maximum tsunami height by using ComMIT tools with Mw 9.218 (affected

by landslide), the maximum run-up is ~28 m in Ofunato area, (e) Time series of Maximum tsunami height A to B.

Figure 3

Run-up comparison of the sub-faults modeling curve for the fourth sub-faults in the affected area. Validation curve through Sendai, Soma, Fukushima and Kitaibaraki nuclear power plants looked more validated properly.

Figure 4

Run-up validation curve based on sub-fault 1 of L-2008 tools and is validated with related research (Gusman et al. 2012; Petukhin et al. 2012). It is estimated by a curve pattern from the moving average.

Figure 5

Run-up validation curve based on sub-fault 2 of L-2008 tools and is overlayed with the run-up based on the adjustment of wide fault area of earthquake which it did by a related research (Gusman et al. 2012; Petukhin et al. 2012). It is estimated by a curve pattern from the moving average.