Tsunami Potential Due To Strike-Slip Earthquake Affected by Submarine Landslide

Potensi Tsunami akibat Gempabumi Sesar Geser yang Dipengaruhi oleh Longsoran Bawah Laut

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ABSTRACT: The most of earthquakes in the western part of North of Sumatra, Indonesia have tsunami potential. This paper discuss about tsunami height which was triggered by large energy of earthquake along strike-slip fault and submarine landslide. Beyond of a view historical tsunamis in the western part Sumatra in Aceh, which was occured on April 11, 2012 have given several questions for the majority of earth scientist in relation with the potential for tsunami. The 8.6 M earthquake might have no tsunami potential significantly, with the hypothesis that mechanism of the earthquake source is strike-slip. However BMKG, in accordance with standard operating procedures stated that this earthquake "potential tsunami". But here we will give other parameters that affect a potential tsunami by performing the calculation of the effects of landslides. This paper describes how potential and kinetic energy spread during landslide and analysis of mechanism and underwater structures named as guyot as the cause of the earthquake along strike-slip fault. This paper discuss about scoup study on landslide which give the hypothesis that the type of submarine landslide or landslide of near shore cliff also will have influence to tsunami height or run-up. The key is, how strongly the all of disturbance above will increasing or decreasing of sea water volume. The result for the first case, strike-slip earthquake without the submarine landslide obtain maximum run-up in Meulaboh is 1.5864 m, with E~Mo (seafloor deformation). For the second case is strike-slip earthquake influenced by submarine landslide obtained $E_{Total} \sim 10^{20} \sim$ Mo (seafloor deformation) which obtained tsunami run-up in Meulaboh 1.7726 m. So in this case, the landslide under the sea it also affected to the maximum tsunami height, but not significantly influence. For the last case, strike-slip earthquake influenced by landslide of near shore cliff: E_{Total} is estimated $Ek_{fall} \sim 10^{22} \sim M_w \sim$ 8 SR, equivalent with vertical of seafloor deformation and obtain tsunami run-up in Meulaboh 16.9372 m.

Keywords: tsunami run-up, fault, strike-slip, submarine landslide, uppper the sea landslide, potential energy, kinetic energy

ABSTRAK: *Sebagian besar gempabumi yang terjadi pada area barat Sumatera Indonesia berpotensi tsunami. Tulisan ini memodelkan kemungkinan ketinggian tsunami yang dipicu oleh gempabumi dengan energi besar sepanjang sesar geser yang dipengaruhi oleh longsoran bawah laut. Gempabumi dengan kekuatan 8,6 Mw pada 11 April 2012 yang terjadi di bagian barat Sumatera telah menimbulkan kepanikan akan tetapi tidak menimbulkan bencana tsunami besar karena terjadi di sepanjang sesar geser kerak Samudera Hindia. Berdasarkan pemodelan, gempabumi sepanjang sesar geser dapat memicu tsunami besar bilamana diikuti oleh longsoran bawah laut. Tujuan dari penelitian ini adalah untuk memodelkan propagasi gelombang tsunami dengan proses mekanisme gempabumi strike-slip yang dipengaruhi oleh kondisi batimetri, volume struktur, jumlah dan jenis tanah longsor bawah laut yang dapat memicu ketinggian gelombang tsunami. Perhitungan dan pemodelan ini melibatkan simulasi energi potensial dan energi kinetik yang mempengaruhi ketinggian gelombang tsunami pada garis pantai. Hasil pemodelan pertama, dengan anggapan gempabumi sesar geser yang tidak dipengaruhi oleh proses longsor bawah laut menghasilkan ketinggian tsunami di Meulaboh 1,5864 m, dengan E ~ Mo (deformasi dasar laut). Untuk kasus pemodelan kedua dengan anggapan gempabumi sesar geser disertai oleh longsoran di bawah permukaan laut diperoleh* $E_{total} \sim 10^{20} \sim$ *Mo (deformasi dasar laut) yang menghasilkan ketinggian tsunami di Meulaboh 1,7726 m. Untuk pemodelan ketiga, gempabumi sesar geser yang diikuti oleh longsoran di tebing dekat pantai dengan* E_{total} *diperkirakan* $Ek_{fall} \sim 10^{22} \sim$

Mw ~ 8 SR setara dengan jenis mekanisme deformasi vertikal yang dapat menghasilkan ketinggian gelombang tsunami di Meulaboh sampai dengan 16,9372 m.

Kata Kunci: *run-up tsunami, sesar geser, longsoran bawah laut, longsoran diatas permukaan laut, energi potensial, energi kinetik*

INTRODUCTION

The potential for a tsunami can be predicted after the earthquake occurred beneath the ocean surface/ seafloor. The tsunami generation was not always able or not precisely prediction. This is due, the tsunami triggered not only by magnitude and depth of the earthquake but also possibly influenced by bathymetry and landslide. This research has been conducted previously concerning landslide (Ma et al., 2015), numerical modeling (Setyonegoro, W., et al., 2012, sediment transport (landslide), (Gusman., et al., 2012), and further analyzed earthquake event Aceh, April 11, 2012 (Setyonegoro and Masturyono, 2013), and also analysis of bathymetri structure. The Novelty on this research is understanding how landslide influence to tsunami run-up. Where it explained potential energy and kinetic energy on landslide force. This paper describes how potential and kinetic energy spread during landslide (Figure 1a) and analysis of mechanism and underwater structures named as guyot as the cause of the earthquake along strike-slip fault. A tsunami risk assessment that generated by submarine landslides includes both geotechnical and geological considerations for the probability and the tsunamigenic force of landslide (Oreskes and Naomi, 2003), as well as tsunami evaluations for determination of the consequences in terms of spatial distribution and run-up heights of the waves (Harbitz, C.B, et al., 2006, p:1-2). Underwater avalanches are often triggered a tsunami or large ocean waves in the area of high-speed avalanche can reach very far distance (Budiono K, 2009, p:1). This study is expected to give an idea, how the energy of source mechanism of earthquake is always influenced to changes in the seafloor structure. Theory of tsunami wave propagation is formulated based on the data below sea level conditions. This is due to energy by the tsunami with shorter wavelength that induces larger flow acceleration than the ocean wave with longer wavelength. The ocean wave with longer wavelength distributes sand layer more smoothly along the coastal plain than the tsunami with shorter wavelength (Gusman., et al., 2012, p: 819). Seafloor surface has a different structure for each location (Tanimoto and Thorne. 2000). The differences structure are based on the history of the formation of the Earth's surface topography through the process of tectonic movements of earth plates (Bock and Prawirodirdjo, 2003). Energy release process will cause an earthquake event affected by landslide (Figure 1a, b) which calculate propagation model for tsunami wave generation (Ma et al., 2015,p:40–55).

We would to know the calculating result and relation energy between tsunami amplitude without landslide (normal modeling) after earthquake occured and tsunami amplitude that influenced by landslide. The tsunami wave propagation was indicated by low peak amplitude in the center of disturbance, in this case is epicenter of earthquake in the ocean bottom, and the wave will increase the peak amplitude when it reaches to shoreline. This is due to the fact that the tsunami wave propagation was influenced by the seafloor of bathymetry structure changes (landslide). We measure or assumed the real equation between earthquake and landslide, is following that in accordance to the law of conservation of energy. We could make energy resultant between the seafloor deformation cause by earthquake (Mo) and potential or kinetic energy by landslide which both have influence to disturbance of wave of mass volume of sea water. Further more, both earthquake and landslide have mass movements of material volume in each equation of energy produced. In this research, we defines three types of landslide relates to earthquake. The first type is strike-slip earthquake without submarine landslide, its mean simulation model without any disturbance by another parameter. The second type is strike-slip earthquake influenced by submarine landslide. In this case, we assumed that ETotal is equal with Mo (seafloor deformation) + Mo (Landslide), and it can be used as a new equation to calculate energy total. We can mention that numerical tsunami modeling is affected by Ept (potential energy) by mass volume of sediment transpot caused by landslide. We assumed the $EPT = 1/2\rho g\eta$ as energy resultan that occurred on near time with energy realese during seafloor deformation. We assumed also $\rho = 1$ g/cm^3 for all coral reef as a landslide material (figure 1). The third type is strike-slip earthquake inluenced by landslide of near shore cliff, it follow the equation: $E_{Total} = Ek_{fall} + Ep_{sinks} (m_{cliff})(v_{cliff})^2$, that depend on weight (kg) of mass volume landslide material. We estimated maximum weight of landslide material which triggered by earthquake is ~ about 10^{10} kg where sediment transport affected by landslide refers to (Gusman., et al., 2012). The landslide energy influence is depend on magnitude and distance of earthquake in related with impact tsunami wave to the material both on submarine or near shore cliff (Budiono K, 2009, p:1).

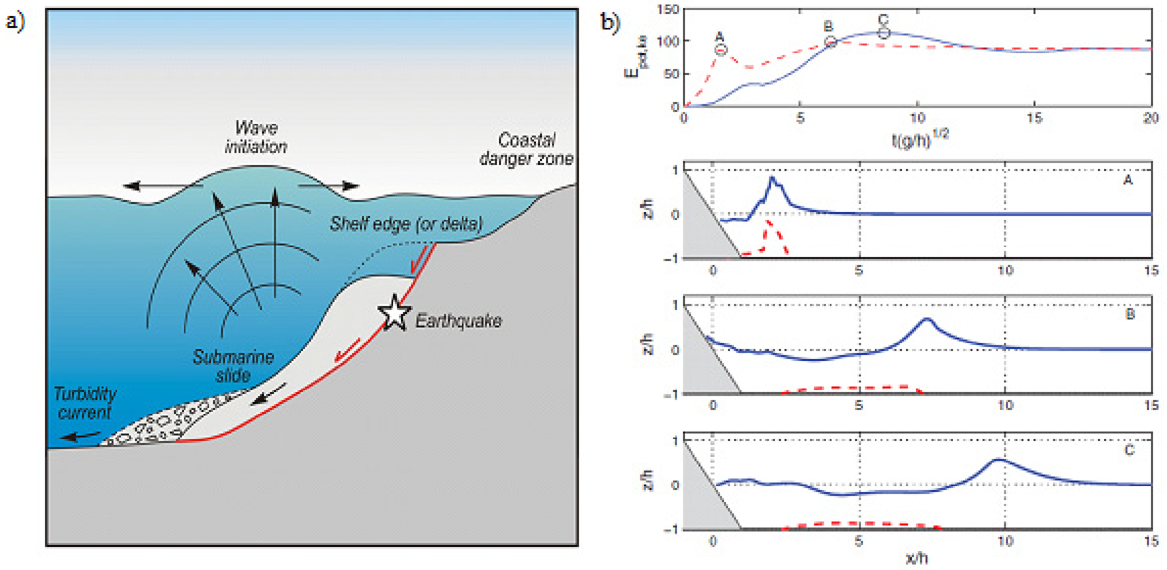


Figure 1. a) Shown illustration of potential or kinetic energy influence to wave of mass volume of sea water, b) Calculated potential energy (solid line) and kinetic energy (dashed line) per unit width for the simulation with $\lambda = 0.5$ after the impact (tg/h =0 at impact) (Ma et al., 2015, p:40–55).

Tectonicaly, the April 11, 2012 earthquake is located along oceanic fracture zone between Ninety East Ridge (NER) in the west and Investigator Fracture Zone (IFZ). The NER and IFZ were moving northeastward relative to Sumatra Island or Eurasia. The CMT data suggest the earthquake mechanism clearly occurs along sinistral horizontally slip of fault (Figure 2).

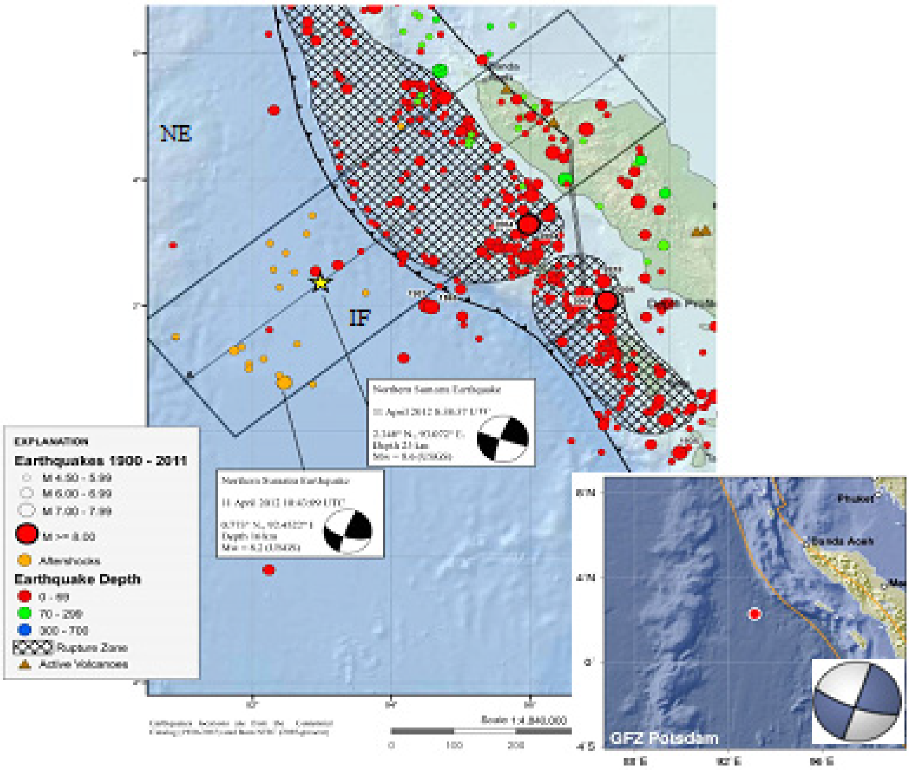
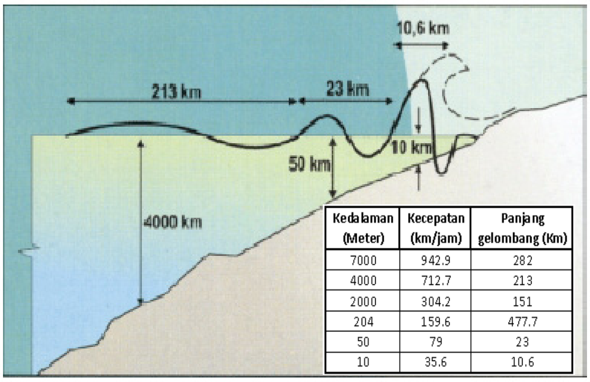


Figure 2. The location of Aceh earthquake event in April 11, 2012. The mainshock is yellow star and the orange circle is aftershock, continuously sloughing of a major earthquake. (USGS Centroid Moment Tensor (CMT) Solution, 2012), and validation event by GFZ, 2016.

This research is talk about case event of earthquake on April 11, 2012, according to earthquake monitoring system through GFZ Event, Further more, the April 11, 2012 earthquake occured in 08:38:34.6 UTC, with Mw8.6 at 16 km depth along strike-slip faulting in the ocean lithosphere of the Indo-Australian plate (GFZ, 2016). The source mechanism could be differentiated, the NP1: strike: 109^{o}, dip: 77^{o}, slip: 180^{o}, and the NP2: strike: 199^{o}, dip: 90^{o}, slip: 13^{o}. The epicenters located respectively 100 km and 200 km to the southwest of the Sunda Subduction Zone, about 92.97^{O} E and 2.25^{O} N (USGS Centroid Moment Tensor (CMT) Solution, 2012; Figure 2). As we know, tsunami was trigger by the disturbance of sea water volume. The disturbance came from a several things such as : as volcano eruption form ocean bottom which give disturbance through pyroclastic from magma chamber. Another disturbance is came form meteorit impact which striking the sea surface. And the main cause of tsunami is triggered by earthquake. And several of earthquake event is include with landslide process. The tsunami is not a single wave but a series of waves, the sea within ½ meters high waves, but as he neared shore 15 m height can be even greater.



Kedalaman (Meter)	Kecepatan (km/jam)	Panjang gelombang (Km)
7000	942.9	282
4000	712.7	213
2000	304.2	151
204	159.6	477.7
50	79	23
10	35.6	10.6

Figure 3. The relation between length, height and velocity of Tsunami (Nakamura, M. 2006).

Tsunami has a very large force for a very large volume of water and the effect speed. The speed is approaching the coast about 48 km / h but its strength be able reach millions of tons (figure 3) (Nakamura, M. 2006). Tsunami height caused by the conversion of wave kinetic energy into potential energy. That is, the energy loss due to reduced speed is transferred in the form of high magnification wave (run up). Speed run up to the mainland can reach 25-100 km / h (figure 3). For earthquakes on the seafloor, the formation mechanism of the tsunami wave was when the earthquake occurred, there was the movement of oceanic crust, which suddenly occurs rapture or drop in the ocean floor (Nakamura, M. 2006).

Tsunami wave propagation parameters are:

1. High-Tsunami is the vertical distance between the the wave peaks with mean sea level from the center of the formation of a tsunami to the shoreline.
2. Run Up Tsunami, is the vertical distance between the the wave peaks with the mean sea level at the time was on the shoreline. Run up a tsunami depends on the magnitude of the earthquake, the seafloor morphology and shape of shore.
3. Inudantion, is the horizontal distance calculated between the shoreline to the furthest reach of the tsunami.

This paper discuss about scoup study on landslide which give the hypothesis that the type of submarine landslide also will have influence to tsunami height or run-up. The key is, how strongly the all of disturbance above will increasing or decreasing of sea water volume.

The submarine or near shoreline landslide occurrence is still unpredictable without any warning system equipment. This case how difficulties in the real-time related to make decision that the big event of strike-slip of earthquake on the seafloor will trigger tsunami or not. Information about possibility tsunami generated or not and earthquake source and type of source is very important for decision makers in Meteorological Climatological and Geophysical Agency (BMKG) whose run national mandate in tsunami early warning (Ina TEWS, BMKG, 2016). BMKG have main role is to monitor earthquake event and possible tsunamis generation and submit the information to public. In the BMKG SOP mentioned that when an earthquake occur under the seafloor with magnitude > Mw6,5 with a depth < 65km , it will automatically be issued a warning the possibility of a tsunami. Lesson learnt to April 11, 2012 Aceh earthquakes with magnitude Mw8,6-8,2 and depth 16-25Km (Report-Gempa-BMKG, 2016; CMT Solution, 2012; GFZ, 2016), in fact no big tsunami generated because the quake source happen around the oceanic shear fault zone.

This experience lead to re-thinking about our SOP concerning earthquake and tsunami generation. In the next future, We need to add information earthquake source type, tectonic setting of source (eq. oceanic shear fault zone or subduction zones) or vertical dislocation information to facilitate decision-making in issuing early warnings. It is very important to be added in the SOP early warning is parameter of possibility of submarine landslide or coastal cliff avalanche followed an earthquake).

The purpose of Study

This paper describes how potential and kinetic energy spread during landslide (Figure 1a) and analysis of mechanism and underwater structures named as guyot as the cause of the earthquake along strike-slip fault (page 2). This paper discuss about scoup study on landslide which give the hypothesis that the type of submarine landslide or landslide of near shore cliff also will have influence to tsunami height or run-up. The key is, how strongly the all of disturbance above will increasing or decreasing of sea water volume (page 5).

METHODOLOGY

In this paper we runned numerical simulation that used the vertical deformation mechanism data by nodal plane 1 (NP1) and nodal plane 2 (NP2) (USGS Centroid Moment Tensor (CMT) Solution, 2012) (figure 4), where the vertical deformation result of earthquake will shows as fault direction plot (Figure 5). Then we analysed and processed the earthquake parameter data to plot, and run the tsunami run-up modeling on bathymetry map cross-section along the Andaman & Nicobar ridge to the Sunda Trench of the western part of Sumatra (Figure 5). This plot results provide information about subsurface conditions and run-up of tsunami from earthquake source to the coastline in the study area (Setyonegoro, W. 2011). Earthquake source mechanism parameters for modeling tsunami of Aceh 11 April 2012 earthquake in related with landslide explained in figure 4.

Furthermore, we will perform calculations on the type of landslides effect that will influence resultant energy in the tsunami.

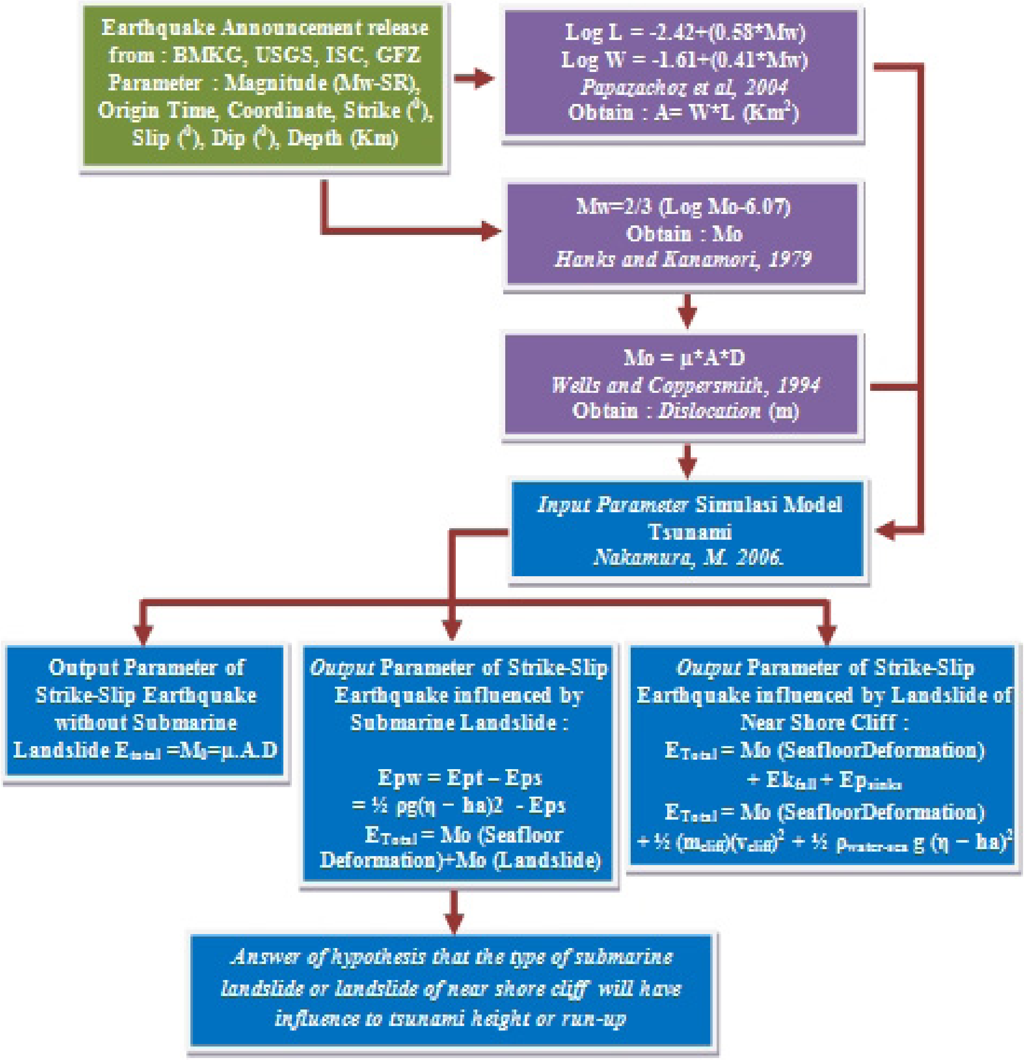


Figure 4. Flowchart of tsunami simulation processing (Setyonegoro, W., Khoiridah, S., Ibad, M, I. 2015, p:27-28, Setyonegoro, W. 2011).

Strike-Slip Earthquake without Submarine Landslide

This methode was applicable for strike-slip earthquake without any tsunami potential. We assumed there are no change of sea water volume in the ocean bottom. We used seismic moment equation (Hank dan Kanamori, 1979) to calculate the amount of energy released by an earthquake and displacement that occurred along strike-slip fault and fault slip on seafloor surface.

$M_0=\mu.A.D$ ....(1)
$M_w = 2/3 \text{ Log } M_0 - 6{,}07$ ....(2)

Where: M_0 = Earthquake seismic moment (Nm)
μ = Rigidity (stiffness object, the harder the object is the energy required to move it greater, meaning greater seismic moment) (NM2)
A = Wide Field Fault (m^2)
D = Dislocation (m)
M_w = Moment magnitude

In tsunami modeling required some physical formulation of earthquake source data, including that obtained from equation above (Wells, D.L., & Coppersmith, K.J, 1994) (Figure 4). The dislocation (D) and width area (A) of strike-slip rupture mechanism could produced big energy in Mw, without accompanied by addition or reduction of seawater volume. The slip of movement was only horizontal shear, therefore no potential tsunami will occured. In tsunami simulation modelling as a result of the strike slip earthquake without being followed by submarine landslide, we were exluded input parameter of sea water volume disturbance. In this case we done calculation pure tsunami models numerical simulations. The next step in the simulation processing are described as in the flow chart (Figure 3). To determine the parameters in 11 April 2012 Aceh earthquake, we refer to previous publications (Setyonegoro and Masturyono, 2013). The next tsunami modelling, submarine landslide effect parameters were added in the simulation processing. To obtain parameters as required in figure 4, performed by processing steps as in figure 3, with the earthquake parameters using equations Hank and Kanamori, 1979, and Wells, DL, & Coppersmith, KJ, 1994. The parameters are known from the earthquake Catalog (USGS Centroid moment Tensor (CMT) Solution, 2012) and the GFZ, 2016. We also have other equation to compare with the equation to calculate the slip parameter (m) and the parameters which has been published in Setyonegoro, W., Khoiridah, S. , Ibad, M, I. 2015, p: 27-28. The of the equation comparison formulated by Madrinovella 2011 and Papazachos, et al, 2004. In our tsunami numerical simulation modeling using bathymetric maps of NOAA, 2016 and Topex, 2016 and ETOPO with 1 minute resolution (Figure 4).

Strike-Slip Earthquake influenced by Submarine Landslide

For this models, we used potential energy (Epot) to calculate following equation below (Ma et al., 2015,p:40–55):

$Epot = 12\rho g\ (\eta - ha)^2dx$ ....(3)

The first part is due to the static increase of water level with the presence of underwater landslide, which can be estimated as:

$Eps = \rho g(\eta + h - ha)ha$ ....(4)
$Epw = Ept$..(5)

Where, Epw is potential energy, ρ is density, g is gravity and (η – ha) is the height of bathymetry structure (G. Ma et al., 2015, p:40–55). The second part is due to the generation impulse waves by landslide motion, which can be calculated by:

$Epw = Ept - Eps = ½\ \rho g(\eta - ha)2\ \text{ - } Eps$......................(6)

For maximum potential energy where Eps = 0. Applies the law of conservation mechanical energy (Abdullah, M, 2007, page 115-117).

$Epw =$ Mo (Landslide).. 7)

For maximum potential energy where Eps = 0. Through the equation (1), (6) and (7) :

E_{Total} = Mo (Seafloor Deformation) +Mo (Landslide) (8)

Strike-Slip Earthquake influenced by Landslide of Near Shore Cliff

In this tsunami modeling, we put parameter of sea water column disturbance of upper ocean due to avalanche of coastal cliff wall or at the edge of a shallow sea. This avalanche understood as sediment transport in the upper ocean water column or as material movements form were derailed by the collapse of the cliff on the beach side with a very large scale volume caused by the earthquake. First step, we have assumed that both earthquakes and landslides on upper ocean water column occur at the same time, so it certainly will be an accumulation of energy produced from sea water column disturbance represented as increased volume of sea water. The second assumption is that we do not calculate the distance (h) from a cliff landslide when the kinetic energy works, so that h is replaced by t.

Therefore, we apply formula the law of free fall motion v = gt or v2 = (gt) 2. There are two types of energy that works during material slip in landslides processes. The first is the kinetic energy that is formed when the landslide cliff material reach to sea surface, so it applies (Ekfall). The second is the potential energy that is formed when the landslide material begins to sink (Epsinks), here applies the law of mechanical energy conservation (Abdullah, M, 2007). Other studies (Santos, Soares and Tort 2010) give two simple examples of slopes margin, block and free fall. A block (avalanche of material) with mass m sliding on the inclined surface (slope margin of coastal), with mass M. Avalanches m material will experience a repulsive force of the volume of sea water. So, the equation that applies is:

$$E_{Total} = Mo\ (SeafloorDeformation) + Ek_{fall} + Ep_{sinks}\ \ldots (9)$$

$$E_{Total} = Mo\ (SeafloorDeformation) + \tfrac{1}{2}\,(m_{cliff})(v_{cliff})^2 + \tfrac{1}{2}\,\rho_{water\text{-}sea}\,g\,(\eta - ha)^2\ \ldots (10)$$

Where:

Ek_{fall} = Energy Kinetic when the cliff material fall.

Ep_{sinks} = Energy Potential when the the cliff material is sinks.

m_{cliff} = Real Mass of Cliff.

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

RESULTS AND DISCUSSION

Strike-Slip Earthquake without Submarine Landslide

Tsunami numerical modeling calculations using the equations (1) and (6), with input tsunami modeling parameters: Mw, Strike, Dip, Dislocation (D), latitude, longitude, L, W, Depth. Tsunami modeling was made to the strike slip earthquake source of April 11, 2012 Aceh earthquake. There are two types of nodal to establish the direction of the fault in relation to the maximum tsunami high on observations of each region (Figure 5).

For more input processing on NP1: M:8.6 Data Tipe: Non Linear; Maximum Time: 3600 S; Graph Interval Ste: 50; Hmax (m): 5; Hmin (m): -5; Save Interval: 50 S; bathymetri data: Topex, 2016, ETOPO (1 minute), with range area: 3N -(-3) S and 89E - 95E, with the displacement result shown in figure 5.

The calculation result for input parameters (equation Nakamura, 2006), shown in Table 1, Table 2, Figure 5 and Figure 6, the input parameters for numerical modeling of tsunamis is: X_eq and Y_eq: convert the epicenter coordinates from grids to adjust in the bathymetry calculation, Z_eq as depth (km), strike and dip in unit degrees (°), shear fields 1 and 2 with units of meters (m) or shift in the model fault 3D. AL1, Al2, AW1 and Aw2 is the area of the fault in 2D). Max Time (s) with units in second (s) as a travel time of tsunami which arranged in model. Graph Interval (Step) is the number of interval to data store, we called interval of length data. H max and H Min and coloring were adjusted to approximate run-up. Input data processing for NP2; M: 8.6 Data Tipe: Non Linear; Maximum Time: 3600 S; Graph Interval Step: 50; Hmax (m): 3; Hmin (m): -3; Save Interval: 50 S; bathymetri data for tsunami numerical simulation from Topex, 2016, ETOPO (1 minute), with coverage data range 3N-(-3)S and 89E-95E, with the displacement result shown in figure 6.

Similarly, the NP1 (nodal plane) fault strikes to north-east direction, the results of modeling produces a major force at the time the tsunami wave heading towards Pulau Batu Islands, and produces a maximum

Tabel 1. Input parameter of Tsunami numerical simulation for Nodal Plane 1 of April 11, 2012 earthquake

X_eq (Grid)	Y_eq (Grid)	Z_eq (Km)	Slip (^{0})	Strike (^{0})	Dip (^{0})
109	280	16	180	109	77

Slip 1 (m)	Slip 2 (m)	Al1 (Km)	Al2 (Km)	Aw1 (Km)	Aw2 (Km)
0	8	-60	60	-85	0

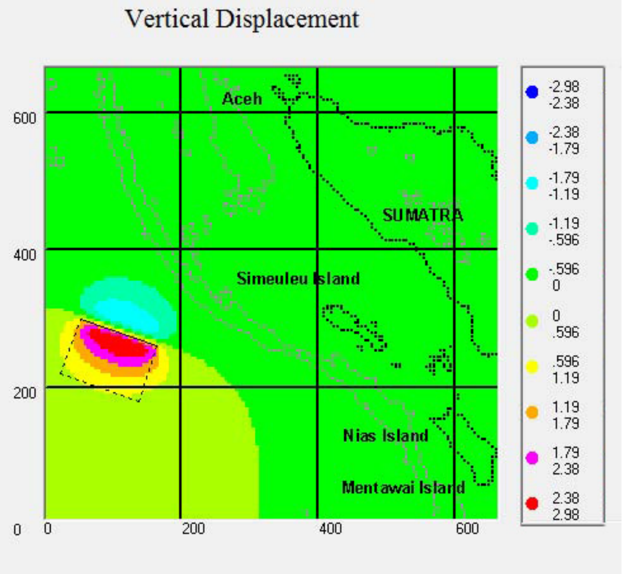


Figure 5. The calculating result of partially input parameter and display of vertical displacement by the model NP1 (Nodal Plane 1). Red color, means the peak of displacement on 1.93m up to 2.42 m, whereas blue color means valley of diplacement on -1.93m up to -2.42m. And green is the center of collision between two fault plane around 0.00m, called earthquake epicenter.

run-up in the Meulaboh, Aceh 1.58 m, and 0.8 m according data observation in BMKG operation room.

Data run-up around the earthquake location can be seen in more detail in Table 1 and Figure 7. Interestingly, the Aceh earthquake on April 11, 2012 had a magnitude greater then Mw8 and shallow but the earthquake mechanism did not triggered seismicity high tsunami waves. did not trigger high tsunami wave.

Earthquake on April 11, 2012 from the focal mechanism is strike-slip that is referred to as shear fault. Shown in figure 3 the maximum tsunami high along the ridge of the Andaman & Nicobar to the Sunda Trench in the western part of Sumatra to NP1 USGS data. in this model explains that, horizontally slip did not generate a tsunami propagation significantly. It is not capable of causing a large wave. The type of fault mechanism of Aceh earthquake it caused a tsunami with not too significant, with mean there is no victim in this kind of hazard. In case of horizontally slip of earthquake with influenced by submarine landslide or from upper sea landslide, also do tsunami simulation modeling shown in figure 3 and figure 4, and the result is show in tabel 1.

The modeling result is shown on figure 7 and figure 8 for maximum tsunami heights by the NP2

Tabel 2. Input parameter of Tsunami numerical simulation for Nodal Plane 2 of Aceh earthquake on April 11, 2012

X_eq (Grid)	Y_eq (Grid)	Z_eq (Km)	Slip (^{0})	Strike (^{0})	Dip (^{0})
109	280	16	13	199	90

Slip 1 (m)	Slip 2 (m)	Al1 (Km)	Al2 (Km)	Aw1 (Km)	Aw2 (Km)
0	8	-60	60	-85	0

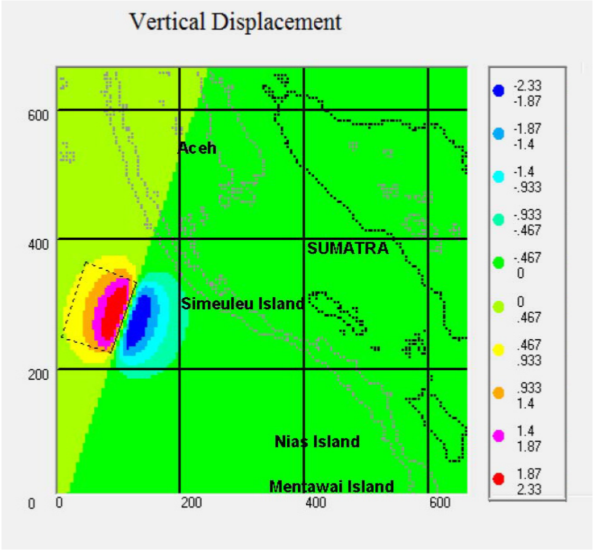


Figure 6. The calculating result of partially input parameter and display of vertical displacement by the model NP2 (Nodal Plane 2). Red color, means the peak of displacement on 1.97m up to 2.46 m, whereas blue color means valley of diplacement on -1.97m up to -2.46m. And green is the center of collision between two fault plane around 0.00m, called earthquake

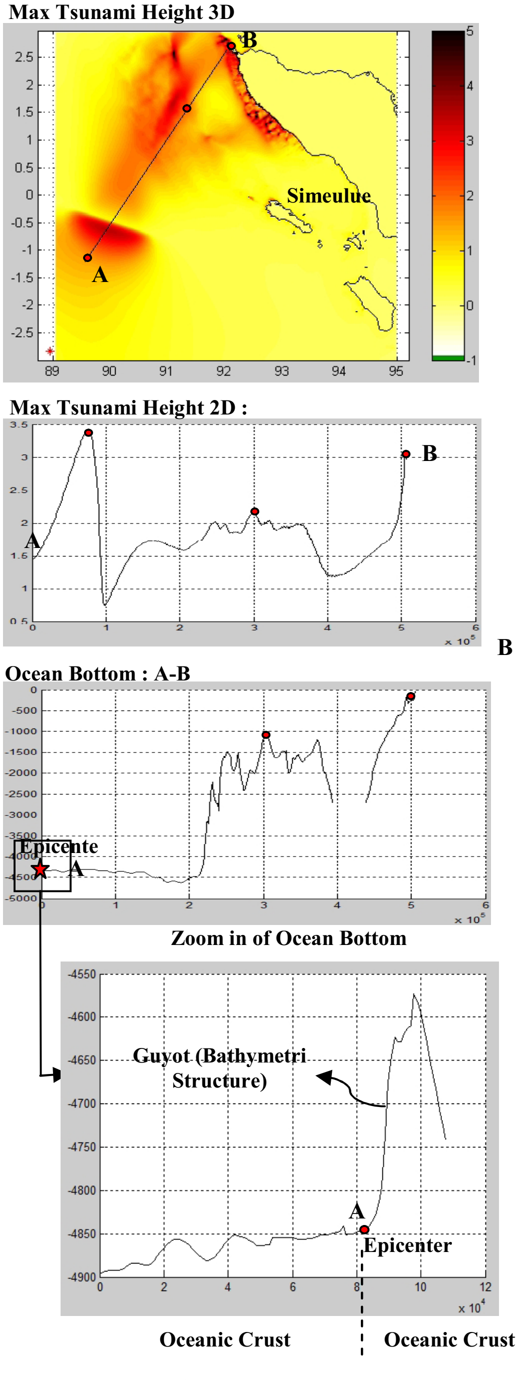


Figure 7. Plot of Cross-section of Aceh earthquake on April 11, 2012 (A-B) for NP1 (Strike: 1090). Plot of AB is corrected when AB is a straight line, assuming 1 degree = 111 km. From A to B is 3145 km with an interval of 3.1985 km. This is modeling for case: Strike-Slip Earthquake without submarine landslide.

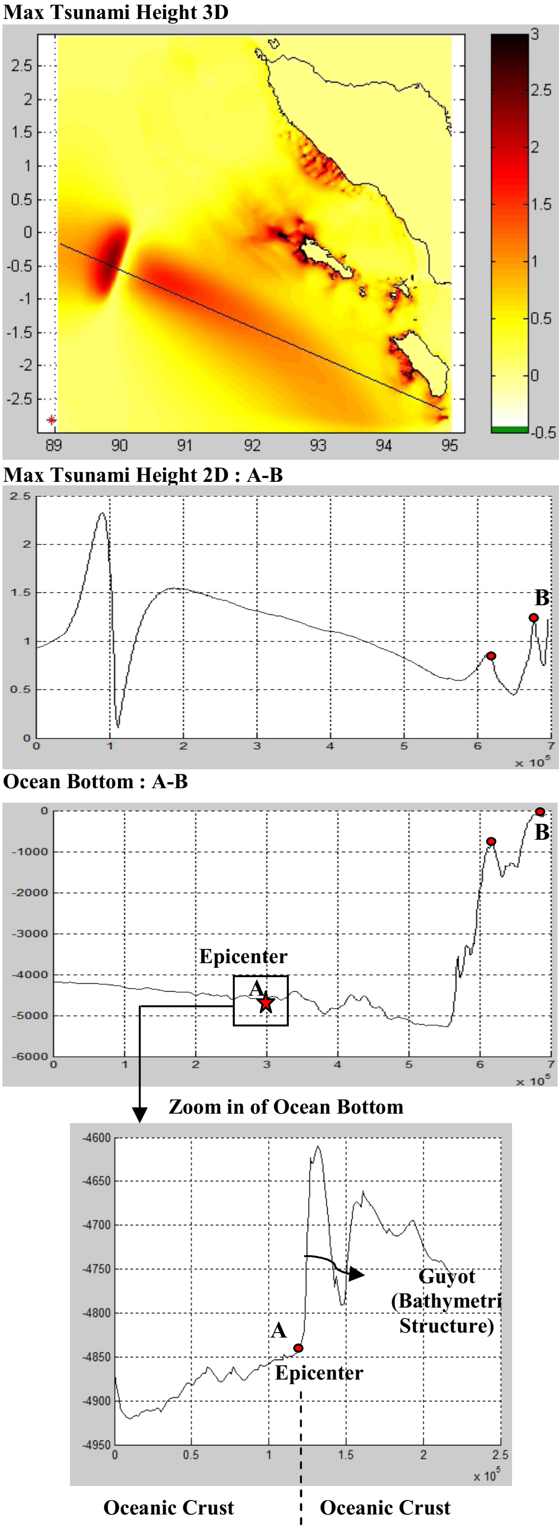


Figure 8. Plot of cross-section of Aceh earthquake on April 11, 2012 for NP2 (Strike: 199°). From A to B is 7128 km with an interval of 2.6768 Km, assume A-B is stright line. This is modeling for case: strike-slip mechanism of earthquake without submarine landslide.

model. Seen that the tsunami run-up have a tsunami height in the sea surface, in line with epicenter on the seafloor, as high as approximately 2.3 m, and then decreased when reaching the Sabang area of approximately 1.6 m. For the case of the earthquake source with strike-slip mechanism is generate low high of tsunami run-up.

Seen in figure 7 and figure 8 is the tsunami numerical simulation with no affected by landslide. Both of that figure show the location of earthquake source (epicenter) in the seafloor. Clearly, the epicenter is located in “Guyot”, A guyot is a seamount with a flat top created by wave action when the seamount extended above sea level. As the seamount is carried by plate motion, it gradually sinks deeper below sea level. The depth was contoured from echo sounder data collected along the ship track (thin straight lines) supplemented with side-scan sonar data, depths are in units of 100 m (Stewart, R, H. 2008, p:28). This kind of earthquake is possible to occured cause by tectonic movement, but the frequency in seismicity rate is low opportunity. Furthermore, guyot means a seamount with a flat top also known as a tablemount, is an isolated underwater volcanic mountain (seamount), with a flat top over 200 m (660 ft) below the surface of the sea. The diameters of these flat summits can exceed 10 km (6.2 mi) (Figure 8).

Seamounts are isolated or comparatively isolated elevations rising 1000 m or more from the sea floor and with small summit area (Stewart, R, H. 2008, p:28). We assumed the Strike-Slip Earthquake influenced by Submarine Landslide is possible occurred in Guyot, and we assumed E_{Total} is equal of Mo (Seafloor Deformation) + Mo (Landslide), and it can be used as a new equation to calculate the total energy. Which we know, Epw (potential energy) = ½ $\rho g(\eta)^2$ = Mo (Landslide). In this case the potential energy trigger in “Guyot”.

Strike-Slip Earthquake Influenced by Submarine Landslide

We did the same calculation of tsunami numerical modeling using the equation (1) and (2) with addition the equation (7) and (8):

We calculate, when we assume : $A = 4 \times 10^4\ Km^2$, subtitude to equation (2) :

$M_w = 2/3 \operatorname{Log} M_0 - 6{,}07$

$M_w = 2/3 \operatorname{Log} \mu.A.D - 6{,}07$

$M_w = (2/3) \times \operatorname{Log} 3.10^{10} \times 4 \times 10^4\ km^2 \times (10^6\ m^2) \times 9.8) - 6{,}07$

$M_w = (2/3) \times \operatorname{Log} (1.176 \times 10^{22}) - 6{,}07$

$M_w = (2/3) \times (\operatorname{Log} 1.176 + \operatorname{Log} 10^{22}) - 6{,}07$

$M_w = (2/3) \times (0.0704 + 22) - 6{,}07$

$M_w =$ 8.6436 SR (Magnitude for Tsunami Modeling)

Tabel 3. The comparison of Strike-Slip earthquake without landslide or including with landslide (from under the sea or upper the sea) in related with tsunami run-up result to answer the hypothesis that not every landslide will give influences, it's depending on the tipe of landslide.

No	Coordinate Observation	Time Observation	Latitude	Longitude	Run-Up (m) Without Landslide	Run-Up (m) Influenced by Submarine Landslide	Run-Up (m) Influenced by Landslide Upper The Sea (Ek_{fall} estimated)	Tide Gauge of BMKG Data (IOC)
1.	Sabang	13.30 WIB	5.919620	95.30283	0.72628	0.8232	15.2711	0.75
2.	Meulaboh	17.04 WIB	-3.690310	99.98332	1.5864	1.7726	16.9372	0.8
3.	Meulaboh	17.04 WIB	-3.690310	99.98332	1.5864	1.7726	16.9372	0.16
4.	Nias (Lahewa)	16.58 WIB	-3.555555	100.0957	1.01065	1.3394	16.8223	1
5.	Singkil	17.32 WIB	1.450360	97.14696	1.39692	1.7455	17.5866	1.35
6.	Sabang	17.00 WIB	5.919620	95.30283	0.72628	0.8272	17.6530	0.06
7.	Sabang	17.34 WIB	5.919620	95.30283	0.72628	0.8272	17.6530	0.34
8.	Sibolga	17.43 WIB	2.663120	0.65628	0.65628	0.6749	16.4738	0.36

Next step is, we substitute $A = 4 \text{ x } 10^4 \text{ Km}^2$ and $Mo = 1.176 \text{ x } 10^{22}$ Nm to equation (8)

E_{Total} = Mo(Seafloor Deformation)+Mo(Landslide)(8)
$E_{Total} = \mu.A.D + (Epw)$
$E_{Total} = \mu.A.D + (Ept - Eps)$
$E_{Total} = \mu.A.D + (Ept - 0)$
$E_{Total} = \mu.A.D + (1/2\rho g(\eta - ha)^2 \ - 0)$
$E_{Total} = 3.10^{10} \text{ x } 4 \text{ x } 10^4 \text{ Km}^2 \ (10^6 \text{ m}^2) \text{ x } 9.8)$
$\quad + (1/2 \text{ x } 10^3 \text{ Kg/m}^3 \text{ x } 10^1 \text{ m/s}^2 \text{ x } (2.5\text{-}4000)^2)$
$E_{Total} = (1{,}176 \text{ x } 10^{22} \text{ Nm}) + (1/2 \text{ x } 10^4 \text{ x } 16 \text{ x } 10^6)$
$E_{Total} = (1{,}176 \text{ x } 10^{22} \text{ Nm}) + (8 \text{ x } 10^{10})$
$E_{Total} = (1{,}176 \text{ x } 10^{22} \text{ Nm}) + (0{,}000000000008 \text{ x } 10^{22})$
$E_{Total} = 1{,}176000000008 \text{ x } 10^{22}$ Nm, (This is Mo of Seafloor Deformation)

From E_{Total}, we obtain that landslide give influence on half of Mo. So fault displacement it was the main energy which affected to tsunami potential in the sea surface (Figure 8).

Next step is input the $Mo \sim E_{Total} \sim 1{,}176000000008 \text{x} 10^{22}$ Nm to the tsunami modeling parameter through equation (2) :$M_w = 2/3 \text{ Log } M_0 - 6{,}07$, and than make the simulation for tsunami height. Reinput process calculate magnitude for strike-slip earthquake influenced by submarine landslide. Where $A = 4 \text{ x } 10^4 \text{ Km}^2$, subtitude to equation (2) :

$M_w = 2/3 \text{ Log } M_0 - 6{,}07$
$M_w = (2/3) \text{ x Log } (1.176000000008 \text{ x } 10^{22} \text{ Nm}) - 6{,}07$
$M_w = (2/3) \text{ x } (\text{Log } 1.176000000008 + \text{Log } 10^{22}) - 6{,}07$
$M_w = (2/3) \text{ x } (0.07040732 + 22) - 6{,}07$
$M_w = 8.643604881162040$ SR
(Magnitude for tsunami modeling influenced by submarine landslide)

The calculation result suggest submarine landslide caused increase of $Mo \sim E_{Total}$ will increasing the tsunami run-up as shown on Table 3, Table 4, Figure 9 and Figure 11.

Through table 4 and figure 9, we compare difference of earthquake magnitude (Mw-SR) which influenced by landslide. The difference is very dominant depending by $(\eta \;\; ha)2$ (m) parameter.

Strike-Slip Earthquake influenced by Landslide of Near Shore Cliff

If we calculate landslide under the sea through equation (9) and (10) (Abdullah, M, 2007, page 115-117, about free fall by F C Santos, V Soares and A C Tort. 2010, p:829), landslide will experience a repulsive force from sea water volume.

E_{Total} = Mo (Seafloor Deformation) $+Ek_{fall} + Ep_{sinks}$ ......(9)

E_{Total} = Mo (Seafloor Deformation) $+ \frac{1}{2} (m_{cliff})(v_{cliff})^2 + \frac{1}{2} \rho_{water\text{-}sea}\, g\, (\eta - ha)^2$ .....(10)

With m is Mass of slided cliff, and motion of free fall $v_{slope} = g.t$, and example the depth of fall process $(\eta - ha) = 4000$ m, during the cliff is falling when kinetic energi is apply, h is replacement by t. Therefore, the formulation that we apply the law of free fall motion $v = gt$ or $v^2 = (gt)^2$, assumed given t during fall movement: $t \sim 3600$ s. We assumed the weight of fall material is $\sim 16.9753 \text{ x } 10^{10}$ kg, we assumed the total depth: $(\eta - ha) = 4000$ m (located in "Guyot" on the seafloor), and we have input data in case Aceh, April 11, 2012 earthquake, through previous calculation. Where $A = 4 \text{ x } 10^4 \text{ Km}^2$ and $Mo = 1.176 \text{ x } 10^{22}$ Nm, calculated :

Table 4. The comparison of earthquake Magnitude influenced by Submarine landslide

Total Height of landslide Fall (η – ha)2 (m)	Mo(Seafloor Deformation) Nm (Joule)	Epw (Mo-Landslide) Nm (Joule)	E-Total Nm (Joule)	Magnitude Tsunami Modeling (Mw-SR) (10^12)	Magnitude After Inluenced by submarine Landslide (Mw-SR) (10^12)
4000	1.176E+22	79900031250	1.176E+22	8.643604881160080	8.643604881162040
4300	1.176E+22	92342531250	1.176E+22	8.643604881160080	8.643604881162350
4600	1.176E+22	1.05685E+11	1.176E+22	8.643604881160080	8.643604881162680
4900	1.176E+22	1.19928E+11	1.176E+22	8.643604881160080	8.643604881163030
5200	1.176E+22	1.3507E+11	1.176E+22	8.643604881160080	8.643604881163410
5500	1.176E+22	1.51113E+11	1.176E+22	8.643604881160080	8.643604881163800
5800	1.176E+22	1.68055E+11	1.176E+22	8.643604881160080	8.643604881164220

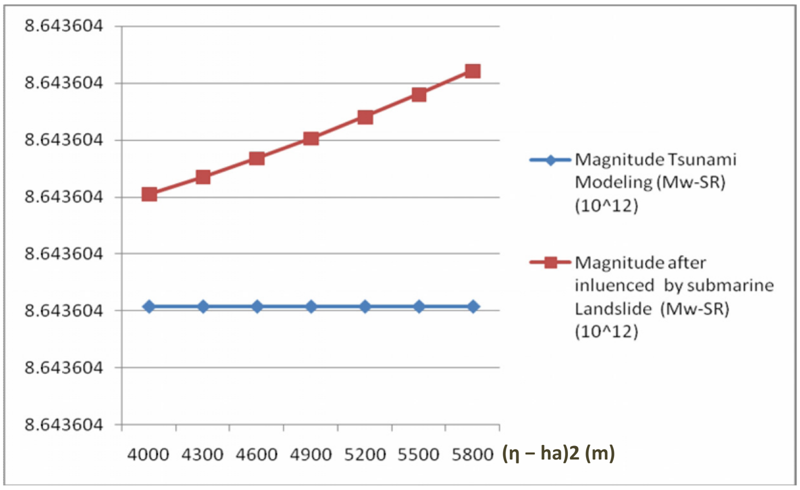


Figure 9. Comparison graphics of earthquake Magnitude influenced by submarine landslide.

Tabel 5. The comparison of earthquake magnitude influenced by landslide of upper the sea

Total Weight of Landslide fall material (Kg)	Mo(Seafloor Deformation) Nm (Joule)	Ekfall +Epsinks (Mo-Landslide) Nm (Joule)	E-Total Nm (Joule)	Magnitude Tsunami Modeling (Mw-SR) (10^12)	Magnitude After Inluenced by Landslide Upper The Sea (Mw-SR) (10^12)
1.69753E+14	1.176E+22	1.1E+23	1.2176E+23	8.643604881160080	9.320336293
1.89753E+14	1.176E+22	1.2296E+23	1.3472E+23	8.643604881160080	9.349621262
2.09753E+14	1.176E+22	1.3592E+23	1.4768E+23	8.643604881160080	9.376214346
2.29753E+14	1.176E+22	1.4888E+23	1.6064E+23	8.643604881160080	9.400569029
2.49753E+14	1.176E+22	1.6184E+23	1.736E+23	8.643604881160080	9.423033054
2.69753E+14	1.176E+22	1.748E+23	1.8656E+23	8.643604881160080	9.443878935
2.89753E+14	1.176E+22	1.8776E+23	1.9952E+23	8.643604881160080	9.463324209

$$E_{Total} = \text{Mo (Seafloor Deformation)} + \tfrac{1}{2}\,(m)(v_{cliff})^2 + \tfrac{1}{2}\,\rho_{water\text{-}sea}\, g\,(\eta - ha)^2$$

$$E_{Total} = \text{Mo (Seafloor Deformation)} + \tfrac{1}{2}\,(m)(g \times t_{fall})^2 + \tfrac{1}{2}\,\rho_{water\text{-}sea}\, g\,(\eta - ha)^2$$

$$E_{Total} = 1.176 \times 10^{22}\ \text{Nm} + \tfrac{1}{2}\,(16.9753 \times 10^{13}\ \text{kg})(10\ \text{m/s}^2 \times 3600\ \text{s})^2 + \tfrac{1}{2}\,1000\ \text{kg/m}^3 \times 10\ \text{m/s}^2\,(4000)^2$$

$$E_{Total} = 1.176 \times 10^{22}\ \text{Nm} + \tfrac{1}{2}\,(16.9753 \times 10^{13}\ \text{kg})(1.296 \times 10^{9}\ \text{s}) + \tfrac{1}{2}\,1000\ \text{kg/m}^3 \times 10\ \text{m/s}^2\,(16 \times 10^{6})$$

$$E_{Total} = 1.176 \times 10^{22}\ \text{Nm} + (11 \times 10^{13} \times 10^{9}) + (8 \times 10^{10})$$

$$E_{Total} = 1.176 \times 10^{22}\ \text{Nm} + (11 \times 10^{13+9}) + (8 \times 10^{10})$$

$$E_{Total} = 1.176 \times 10^{22}\ \text{Nm} + (11 \times 10^{22}) + (8 \times 10^{10})$$

$$E_{Total} = 1.176 \times 10^{22}\ \text{Nm} + (11 \times 10^{22}) + (0.000000000008 \times 10^{22})$$

$$E_{Total} = 12.176000000008 \times 10^{22}\ \text{Nm}$$

$E_{Total} = 12.176000000008 \times 10^{22}$ Nm to the tsunami modeling parameter through equation (2) : $M_w = 2/3 \text{ Log } M_0 - 6{,}07$, and than make the simulation for tsunami height. Reinput process calculate magnitude for strike-slip earthquake influenced by landslide of near shore cliff, Where $A = 4 \times 10^4\ \text{Km}^2$, subtitude to equation (2) :

$$M_w = 2/3 \text{ Log } M_0 - 6{,}07$$

$$M_w = (2/3) \times \text{Log}\,(12.176000000008 \times 10^{22}\ \text{Nm}) - 6{,}07$$

$$M_w = (2/3) \times (1.0855 + 22) - 6{,}07$$

M_w = 9.32 SR (Magnitude for Tsunami modeling influenced by landslide from upper the sea)

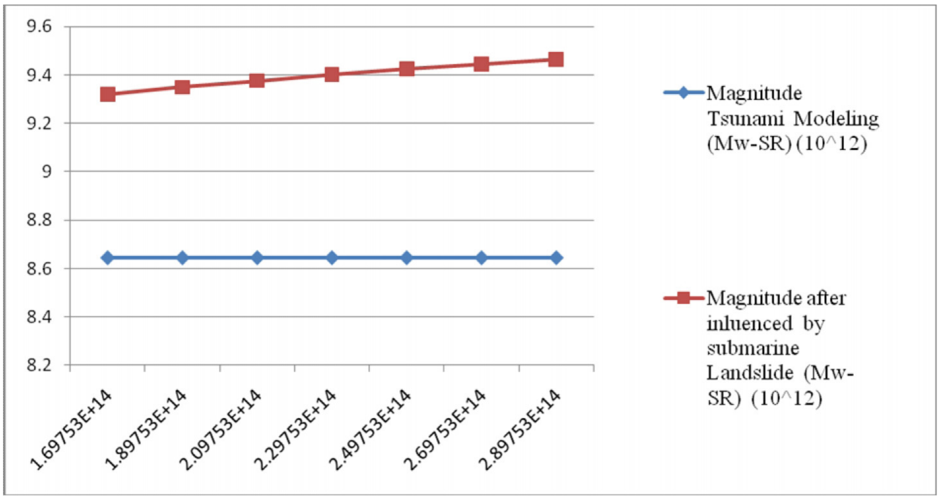


Figure 10. Graphic result The comparison of comparison of earthquake magnitude influenced by landslide from upper the sea

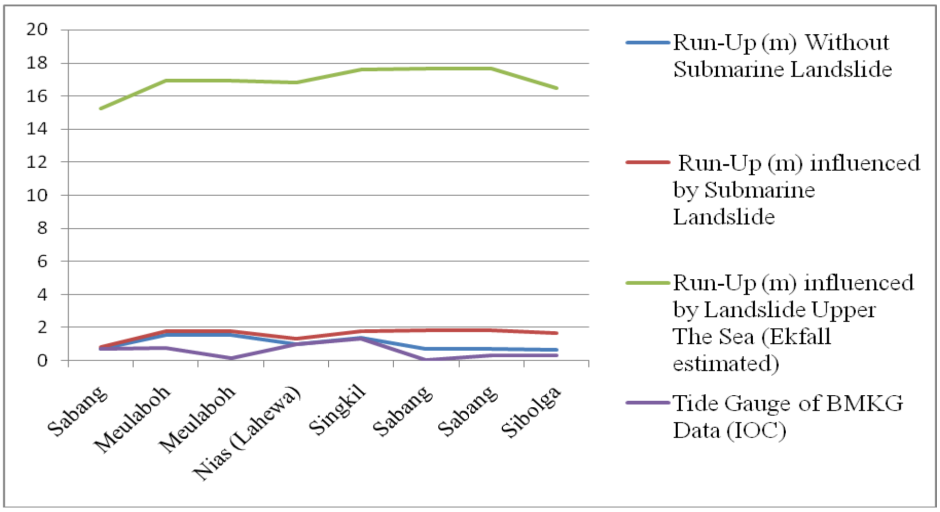


Figure 11. Comparison curve of tsunami run-up between earthquake without lanslide influence, earthquake influenced by landslide and the tide gauge monitoring data of observation area.

The result is increasing Mo ~ E_{Total} influenced by near shore cliff is will increasing the tsunami run-up result as shown on Table 3, Table 5, figure 10 and figure 11.

Through Table 5 and Figure 10, we compare the difference of pure earthquake magnitude (Mw-SR) and earthquake magnitude which influenced by landslide. The change is very dominant depending by total weight of landslide fall material (Kg) parameter.

The explanation through figure 11 is the earthquake influenced by landslide of near shore cliff is extreemly has different in energy generated. The sea water volume disturbance of near shore cliff and transfer will more larger than sea water volume disturbance without landslide parameter. Its mean the material movement by submarine lanslide is still fixed the balancing of sea water volume.

CONCLUSION

The result for the first case, strike-slip earthquake occured without submarine landslide, then apply the modeling tsunami without inluenced by landslide parameter. The maximum run-up in Meulaboh is 1.5864 m, with E ~ Mo (Seafloor deformation) = 1,176000000000 x 10^{22} Nm, obtain Mw = 8.643604881160080 SR.

The next case of earthquake was affected by submarine lansdlide was applied the law of conservation of mechanical energy, where E_{Total} = 1,176000000008 x 10^{22} Nm. The tsunami run-up height in Meulaboh is 1.7726 m and in Sabang 0.8272 m. So, its mean, in this case, even there is no energy come-in or come-out to the system, in this case is sea water, but still applies potential energy landslide influenced to maximum tsunami height and run-up, but not too significant.

The submarine landslide in "Guyot" is only moving fixed inside the sea water, before and after landslide process. So, there is no increasing or decreasing sea water volume, therefore no significant disruption. We compare the change of earthquake magnitude (Mw-SR) which influenced by landslide. The changes ~~is~~ was very dominant depending by $(\eta\ ha)^2$ (m) parameter called Total depth of sea water.

The result for the third case, strike-slip earthquake influenced by landslide of near shore cliff. E_{Total} = 12.176000000008 x 10^{22} Nm, M_w = 9.32 SR produce tsunami run-up 16.9372 m height in Meulaboh. This modeling suggest that landslide material of near shore cliff give the high influence to tsunami run-up. The change value of magnitude (Mw) is very dominant depending by total weight of landslide material (Kg) during fall of cliff when kinetic energi is apply, with time of free fall motion $v = gt$ or $v^2 = (gt)^2$.

Through this case, we obtain the hypothesis as a new constanta, with mean, if the mass volume (m) of cliff fall material during the landslide m << 16.9753 x10^{13} kg and or the time during the free fall motion (t) : t << 3600 s then, the landslide will have a low influence to the tsunami run-up.

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I would find proud and excited if this research can be useful for Ina-TEWS (Indonesia Tsunami Early Warning System) BMKG. I expected this article be able to assist dispatchers and officials in the field of earthquake monitoring and tsunami in order to improve the the analysis of the potential tsunami in cases of strike-slip with the influence of landslides below sea level. We would very much look forward to a discussion with BMKG to be able improve the analysis of a potential tsunami.

REFERENCES

Abdullah, M. 2007. Fisika Dasar I – FI-1101. Program Studi Fisika. Penerbit Institut Teknologi Bandung, p: 115-117.

Bock, L. Y. and Prawirodirdjo, J. F. 2003. Crustal motion in Indonesia from Global Positioning System measurements. *Journal of Geophysical Study*, Vol. 108, No. B8.

Budiono, K. 2009. Identifikasi longsoran bawah laut berdasarkan penafsiran seismik pantul di perairan Flores. Jurnal Geologi Indonesia, Vol. 4 No.1 p:9-17.

F C Santos, V Soares and A C Tort. 2010. A note on the conservation of mechanical energy and the Galilean principle of relativity. European Journal Of Physics. IOP Publishing, 31, doi:10.1088/0143-0807/31/4/012. P: 827–834.

G. Ma., et al. 2015. A two-layer granular landslide model for tsunami wave generation: Theory and computation. Ocean Modelling 93. Doi : 10.1016/ j.ocemod.2015.07.012P:40–55.

GFZ. 2016. Earthquake Info. (http://geofon.gfz-potsdam.de/eqinfo/event.php?id=gfz2012hdex), accessed on August 11, 2016.

Gusman, A, R., Tanioka, Y and Takahashi, T. 2012. Numerical experiment and a case study of sediment transport simulation of the 2004

Indian Ocean tsunami in Lhok Nga, Banda Aceh, Indonesia. Earth Planets Space, doi:10.5047/eps.2011.10.009. 64, p:817–827.

Hanks, Thomas C.; Kanamori, Hiroo. 1979. "Moment magnitude scale". *Journal of Geophysical Study 84 (B5): 2348–2350. Retrieved 2007-10-06.*

Harbitz, C.B., Løvholt, F., Pedersen, G. & Masson, D.G. 2006. Mechanisms of tsunami generation by submarine landslides: a short review. *Norwegian Journal of Geology,*Vol. 86, pp. 255-264. Trondheim 2006. ISSN 029-196X.

Ina-TEWS BMKG. 2016. (https://inatews.bmkg.go.id/new/about_inatews.php?urt=12), accesed August 12, 2016.

Madrinovella, Iktri., Sri Widiyantoro, dan Irwan Meilano. (2011). *Relokasi Hiposenter Gempa Padang 30 September 2009 Menggunakan Metode Double Difference.* JTM Vol. XVII No. 1/2011.

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.

NOAA. (2016). Etopo-1 Grid Extract. (*http://maps.ngdc.noaa.gov/viewers/wcs-client/*), accessed on August 11, 2016.

Oreskes and Naomi. 2003. Plate Tectonics: An Insider's History of the Modern Theory of the Earth. Westview. ISBN 0813341329.

Papazachos, B.C., Scordilis, E.M., Panagiotopoulos, D.G., Papazachos, C.B., and Karakaisis, G.F., 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 2004$^{\mathrm{Th}}$.

Repo-Gempa-BMKG. (2016). Information Earthquake that occurred in the Territory of Indonesia and Regional of Ina-BMKG. (2016).(*http://repogempa.bmkg.go.id/query.php), accessed on August 11*, 2016.

Setyonegoro, W. 2011. Tsunami Numerical Simulation Applied to Tsunami Early Warning System, *Journal of Meteorology* and Geophysics *(BMKG)*, Vol.12.No.1, Hal : 21 -32, Mei 2011.

Setyonegoro, W., dkk. 2012. Analisis Sumber Gempabumi dengan Potensi Tsunami pada Segmen Mentawai, *Jurnal Meteorologi dan Geofisika (BMKG).* Vol.13, No.2, page : 139-138, 2012. ISSN 1411 – 3082.

Setyonegoro, W and Masturyono. 2013. Pengaruh Profil Kedalaman Lautan Pada Penjalaran Tsunami (Studi Kasus : Gempabumi Aceh 11 April 2012). Hal 105 – 110, edisi ke-8 Prosiding Seminar Scientific Jurnal Club Tahun 2013. ISBN: 978-979-1241-56-4.

Setyonegoro, W., Khoiridah, S., Ibad, M, I. 2015. *"Validasi Pemodelan Tsunami Berdasarkan Software L-2008 Menggunakan Data Sumber Gempabumi USGS, IRIS, CMT dan GFZ untuk Studi Kasus Tsunami Nias 28 Maret 2005*". *Jurnal Meteorlogi dan Geofisika (BMKG),* Vol.16 No.1, Page: 25-36. ISSN 1411-3082.

Stewart, R, H. 2008. Introduction To Physical Oceanography. Department of Oceanography. Texas A & M University Copyright 2008.

Tanimoto Toshiro, Lay Thorne. 2000. "Mantle dynamics and seismic tomography". Proceedings of the National Academy of Science 97: 12409.

Topex. 2016. Extract Xyz Grid-Topography Or Gravity (Bathymetri Data). (*http://topex.ucsd.edu/cgi-bin/get_data.cgi*), accessed on August 11, 2016.

USGS Centroid Moment Tensor (CMT) Solution. 2012. Aceh Earthquake 2012 April 11 08:38:37 UTC. 2012. *(http://earthquake.USGS.gov/earthquakes/eqinthenews/2012/usc000905e/),* accessed on 30 April 2012.

Wells, D.L., & Coppersmith, K.J. 1994. New Empirical Relationships among Magnitude, Rupture Length, Rupture Width, Rupture Area, and Surface Displacement. *Bulletin of the Seismological Society of America, 84(4).* 974-1002.