【Article】

Seismic and Tsunami Hazard Potential in Sulawesi Island, Indonesia

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Abstract

From the middle of 1970's until now, the Sulawesi Island which is surrounded by several small and big tectonic plates had been struck 270 times by earthquake above 5.0 in magnitude. This number of occurrence tends to get higher and higher each year, beginning after the raising activity of Sunda Arc over the past last six years, which recently struck Padang, West Sumatera in September 2009. The goal of this study is to find out the most potential areas for seismic and tsunamis activities in Sulawesi Island, by analyzing the historical data of earthquakes and tsunamis at the areas and also base on the fault system on it. It was found out that the earthquakes with magnitude above 5.0 in the next ten years will occur minimally 49 times; with almost all of them will be sea-epicenter which could generate tsunami in some areas. The most potential areas will be the North Arm of Sulawesi, especially in the coasts of North, South and East.

1. Introduction

As one of several countries that are situated in South East Asia tectonic regime, Indonesia is one of the most seismically active countries in the world. Surrounded by Indo-Australian plate and Philippine Sea plate which subduct beneath the Eurasian plate, with five big islands and several peninsulas, Indonesia had experienced thousands of earthquakes and hundreds of tsunamis over the past four hundred years (Aydan, 2008). Sumatera and Jawa are two of the most vulnerable islands to tsunami impact since they are located directly in front of Indo-Australian Plate. Papua and Sulawesi are the other two big islands that also have been experiencing several tsunamis, even though it was not as often as Sumatera and Jawa. But in the case of tsunami, Sulawesi has several prone areas with subduction zones and faults, which recently become more active seismic areas especially with the epicenters in the sea.

There are several previous researches regarding seismic and tsunami potential in Indonesia, but there is none connected directly to Sulawesi Island. For seismic activity in Sulawesi Island, there are three researches; first is by Guntoro (1999), focusing on the formation of the Makassar Strait, second is the research by Katili (1978), which mainly discusses the past and present geotectonic position of Sulawesi Island and the third is by Villeneuve et al (2002), which discusses the geology of the central belt of Sulawesi Island as constraint of modeling the geodynamic of it.

In previous tsunami researches, they are mainly focusing on the modeling of past tsunami. There is research done by Prasetya et al (2001) regarding the Makassar Strait as one of active tsunamigenic regions, and also research done by

Pelinovsky et al (1997) regarding the 1996 Sulawesi Tsunami.

But amongst all of those researches, the most connected with this research is the research done by Aydan (2008), which is about the seismic and tsunami hazard potential in Indonesia with special emphasis on Sumatera Island due to the active movement of the Sunda Arc. In this research, he has also introduced the empirical formula for tsunami wave height at shore line and tsunami wave run-up specifically for Indonesian waters.

This study is base on the above 5.0 magnitude of earthquake data, compiled from several sources, but mostly from the Global CMT (former Harvard CMT). The data then categorized in regions, with each region is develop based on seismic system of Sulawesi Island. The past tsunamigenic earthquakes which occurred in the most active region then be assessed using numerical simulations to find out the clear estimation of several tsunami parameters, such like arrival time, wave height and wave run-ups. In the end, using all the data and conducting numerical simulations, we can find the positions of potential areas for both seismic and tsunamis activity, along with arrival time estimation and time variation of the tsunami waves, specifically for the Sulawesi Island.

This paper is divided into six parts; i.e. introduction, geographic and geological aspects of Sulawesi Island, earthquake in Sulawesi Island, tsunami history in Sulawesi Island, tsunami simulations, and conclusions.

2. Geographic and Geological Aspects of Sulawesi Island

Geographically, Sulawesi Island that lays on 5.36°N-7.48°S and 117.02°-125.74°E is one of the most secure islands in Indonesian archipelago due to its indirect position of the two oceans, the Pacific and the Indian. Sulawesi is divided into six provinces and has several small archipelagoes, making it one of the big islands in Indonesian archipelago that has very long shoreline. Unfortunately, this also means that the Sulawesi Island is vulnerable to sea hazard events, such as tsunamis that are generated by sea earthquakes of which the epicenter (represented by red pin marker and date of occurrence) distribution is shown in Figure 1, along with the name of each part or so-called the arms of the island.

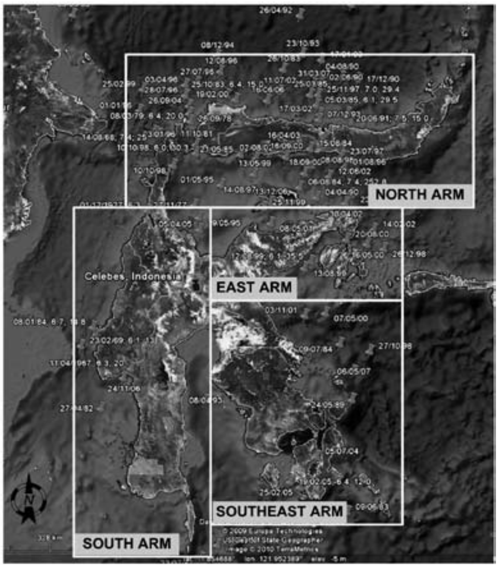

Figure 1: Earthquake epicenter, which are represented by red pin marker with date of occurrence, from 1976 of all the four arms of Sulawesi Island, collected from Global CMT (http://www.globalcmt.org/CMTsearch.html)

Geologically, there are several forming theories of Sulawesi Island. The most profound one is the theory mentioned by Parkinson (1998) that was built based on ophiolite and hydrocarbons findings with consideration of the faults present situation. The formation scheme is based on the idea of movements of the arms; where the North and South arms basically attached at the edge of the Sundaland Craton, while the the East and Southeast were originally laid in the Indian Ocean Plate at the upper part of Papua Island. During Eocene (45 million years ago) until late Miocene (10 million years ago), all the four arms drifted and joined together at the East of Eurasia and formed Sulawesi Island with several faults and subduction zones, such as Palu-Koro and North Sulawesi Trench (Figure 2). This forming process makes Sulawesi an island that has a complicated fault system; with several types of faults connected with each other literally and definitely can produce big quakes (Katili, 1978).

Figure 3 shows all the active faults, trenches, trusts and spreading centers which build the complex seismic systems of the Sulawesi Island. There are four Spreading Centers or SC; three are in Makassar Strait and one is in Gulf of Bone. There are also eleven faults, consisting of six strike-slips (Palu-Koro, Walanae, Matano, Hamilton, Sorong. South Sula-Sorong), three trenches (North Sulawesi, Sangihe, Tolo) as subduction zones and two trusts (Sula and Batui); in which the most active faults are the Palu-Koro fault, North Sulawesi Trench and Sangihe Trench. Besides the big and active ones, the Sulawesi Island also has several small strike-slip faults which a lot of them are situated in the Central Sulawesi Province (Guntoro, 1999, Prasetya et al, 2001, Villeneuve et al, 2002).

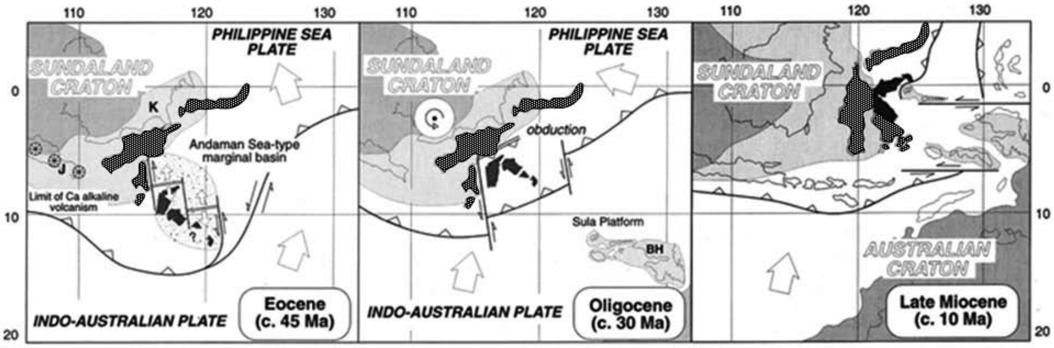

Figure 2: Movements of all four arms of Sulawesi (Parkinson, 1998)

In addition to the complexity of the seismic system, the movements of Pacific Plate to the West and Indian-Australian Plate to the North have made Sulawesi Island highly vulnerable to earthquakes.

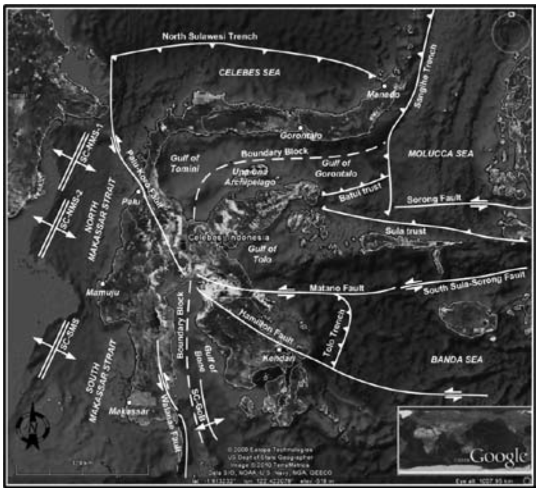

Figure 3: Sulawesi Island seismic system, based on Guntoro (1999), Prasetya et al (2001) and Villeneuve (2002).

(SC-NSM: Spreading Center at North Makassar Strait, SC-SMS: Spreading Center at South Makassar Strait, SC-GoB: Spreading Center at Gulf of Bone)

3. Earthquakes in Sulawesi

The Indo-Australian, Pacific, Caroline and Eurasian Plates, which are surrounding the Indonesian Archipelago as shown in Figure 4, are connected and attached to all of the faults in Sulawesi Island as mentioned earlier; making Sulawesi Island a quite vulnerable area for rapidly earthquakes occurrences, even though they would scarcely produce a very strong one.

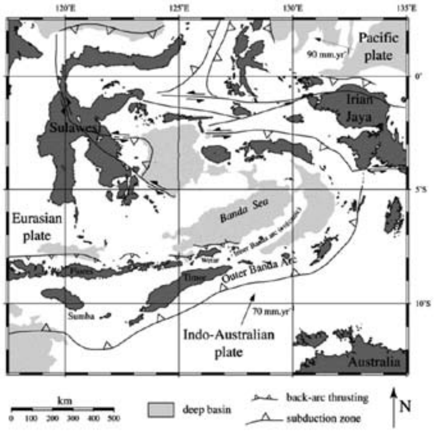

Figure 4: The position of Sulawesi Island due to the movements of the Eurasian Plate, Indo-Australian Plate and Pacific Plate (Hamson, 2004).

There are records from The Global CMT (can be access through www.globalcmt.org) of 270 earthquakes that occurred by these eleven faults during July 1976 to October 2009, with magnitude more than 5.0.

Figure 5 shows that during all three decadal periods from 1976 to 2009, it almost has a linear trend of increasing in total of occurrences; where from the 1st period (1976-1987) the total number increased 100% in the 2nd period (1988-1998), and increased again to almost 64% in the 3rd period (1999-2009). But in terms of the epicenter location, which divided into land and sea, the trends are not totally linear. The data show that the percentages of sea epicenter increase almost 28% between the 1st and the 2nd period, but decrease about 9.45% between the 2nd and the 3rd periods.

By seeing these data, there are two possible trends of reoccurrences. If we assume the linear trend, the number of seismic activity can be expected to increase almost 26.1% in the next period, which is from 2010 until 2020.

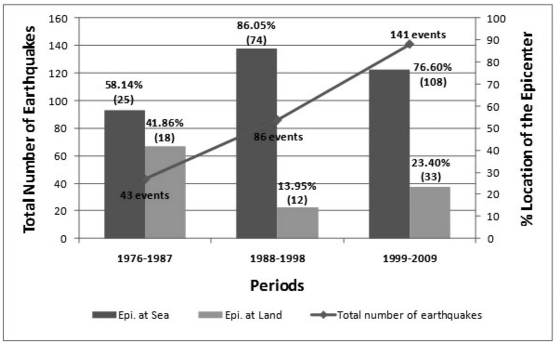

Figure 5: Trend of earthquakes (M>5.0) occurrences during 1976-2009

From the Global CMT data, the author classified seismic prone areas in Sulawesi Island into three big areas as shown in Figure 6, with earthquake epicenters represented by red pin markers along with their time of occurrences. They are:

1. *Region A;* situated from the North Sulawesi trench in the north and the East Arm in the south. It shows that the northern sea of North Arm, which also called Celebes Sea, is the most active area. This area has a subduction zone, where small plates are being pushed above the Eurasian Plate by Indo-Australian Plates and the Pacific along with small plates such as the Caroline plate and the Philippine; making the North Sulawesi Trench. Below the North Arm, there is the Gulf of Gorontalo, which contains the Una-una volcanic archipelago. These two areas, produced almost half of the total earthquakes occurred during the three periods. All of these earthquakes are produced by Palu-Koro Fault, North Sulawesi Trench, Batui Trust and Sangihe Trench (see Figure 3).
2. *Region B;* situated from the East Arm in the north to the Southeast Arm. Earthquakes on this area were influenced by several faults, i.e. Matano Fault, Sorong Fault, Sula Trust, South Sula-Sorong Fault, Hamilton Fault and Tolo Trench (see Figure 3). This region produced the second largest amount of earthquakes during the three decadal periods.
3. *Region C;* situated from the edge of the east side of Southeast Arm up to Palu City and covered all West Sulawesi and South Sulawesi Province. Earthquakes at this area were influenced by Walanae Fault, Hamilton Fault and Palu-Koro Fault (see Figure 3). Even though this region produced small amounts of earthquakes comparing to the two previous regions, unfortunately three tsunami events were recorded in the past.

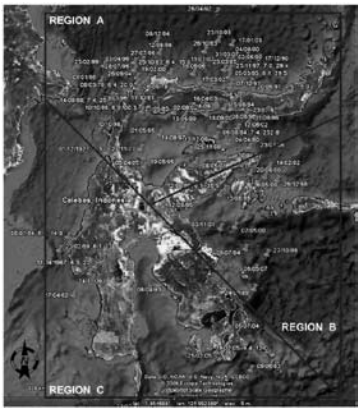

Figure 6: Sulawesi Island seismic prone areas

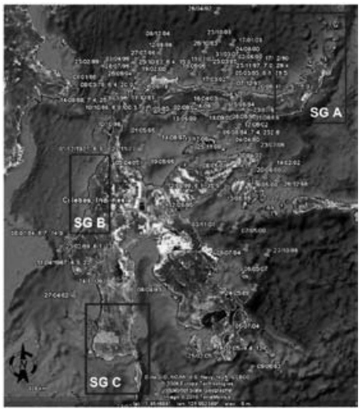

Figure 7: Sulawesi Island seismic gaps

From these seismic prone areas, it also shows several seismic gaps in the entire area. Seismic gap is an area within a known active earthquake region or zone which no significant earthquakes have been recorded. Figure 7 shows three of the possible seismic gap, SG, with earthquakes epicenters represented by red pin markers along with their time of occurrences. They are:

1. **SG A:** at the East Coast of North Arm. This area does not have any record of earthquakes above 5.0 in magnitude, even though it located just at the east side of the Sangihe Trench.
2. **SG B:** at the West Coast of South Arm. This area does not have any record of earthquakes even though it is situated near Palu-Koro Fault which is quite active.
3. **SG C:** at the West, South and East Coast of the southern part of the South Arm. This area also does not have any record of earthquakes even though it is situated just east side of Walanae fault and a Spreading Centre at Gulf of Bone.

   These seismic gaps were projected based on earthquakes data above 5.0 in magnitude.

4. Tsunami History in Sulawesi

According to Latief et al. (2000) and Lander et al. (2003), Sulawesi had been struck by tsunami 24 times in 1692-2000. Unfortunately not all of these data can be proven and connected with historical data of earthquakes that generated them. From those 24 data, there are only 7 data of tsunami impact that can retrieve and truly connect with the earthquake events, as shown in Table 1.

Table 1: Tsunami generated by earthquakes in Sulawesi Island, Indonesia

#	Region Name	Date of Occurrence	Epicenter Location		Focal Depth (km)	Magnitude	Max Run-Up (m)
			Lat.	Lon.			
1	Makassar Strait	01-Dec-27	-0.75	119.70	n.a.	6.3	15 (app)
2	Makassar Strait	11-Apr-67	-3.30	199.40	20.00	6.3	8 (app)
3	Celebes Sea	14-Aug-68	0.70	199.80	25.00	7.4	10
4	Makassar Strait	23-Feb-69	-3.10	118.50	13.00	6.1	10
5	Makassar Strait	08-Jan-84	-2.77	118.72	14.80	6.7	n.a.
6	Celebes Sea	01-Jan-96	0.74	119.93	15.00	7.9	3.4
7	Peleng Island	04-May-00	-1.29	123.59	18.60	7.5	6

These events have several strong connections to each other, since they all have the following characteristics:

- Generated by shallow earthquakes; the focal depths were not more than 25km. Even though the 1927 event did not have any record of focal depth, most of the experts said that it definitely had a shallow one.
- Having moderate to large moment magnitudes from 6.1 until 7.9. The magnitudes level is based on Scawthorn (2003) categorization.
- Having epicenters close to the shore line within 50km offshore.

Nevertheless, these events also contain several unusual facts, which are:

- Three of them, 1967, 1969, and 1984 events, are situated on the center of the Makassar Strait (Region C), which is also the weakest amongst all of the seismic prone areas in Sulawesi Island. All of them were generated by shallow quakes produced by a small fault called Paternoster and SC-SMS, with the depth below 20km.
- Only two of them were in Region A, which is the strongest amongst all the seismic prone areas in Sulawesi Island. They are 1968 and 1996 events. They are also generated by shallow earthquakes (focal depth below 25km) produced by Palu-Koro Fault, North Sulawesi Trench and SC-NMS-1.
- The Peleng Island event in 2000 was the only event that occurred in Region B, which is the second highest seismic prone area. It is generated by shallow earthquakes produced by Batui Trust, Sula Trust and Sorong Fault, with the depth of approximately 18.6km.
- Six of them occurred in the West Coast of Sulawesi Island; four in Makassar Strait and two in Celebes Sea, and only one in East Coast of Sulawesi Island, near Peleng Island.

These facts clearly show the trend movements of big earthquake epicenters from the West Coast to the East Coast of Sulawesi Island, which are suitable enough for producing tsunami. It also shows that even though they are situated near strike-slip fault, such as Palu-Koro fault, the big earthquakes that produced tsunami at Makassar Strait and Celebes Sea are also influenced by the spreading centers and North Sulawesi Trench. These facts put the Region A and SG A as areas which have to be taken into fully consideration regarding the potential big earthquakes and tsunamis in the future.

5. Tsunami Simulations

In order to estimates and approximate the affected areas and the time of impact, simulations of selected tsunami event have to be carried out. The events have to be representations of the most active seismic and tsunami prone areas, which are the Region A and SG A. Based on that reason and completeness of seismic parametric data, the chosen events are two at Celebes Sea, two at Gulf of Gorontalo and three at Molucca Sea near the Sangihe Trench (see Figure 9). The simulations were done by SiTProS v.1.2 (Chui-Aree, 2007), with basic ocean topographical grid data from ETOPO2 and seismic parameter data from Global CMT.

The SiTProS model stands for "Siam Tsunami Propagation Simulator" model which is a tsunami propagation model and based on wave equation. This software is designed for fast computing in real-time simulation and visualization in 2D domain based of graphical user friendly interface. The numerical code is based on wave equation in 2D grid computing and calculates from tsunami behavior, shallow water equation by defining wave propagation speed. The basic equation can be written as:

$$\frac{\partial^2 U}{\partial t^2} = a^2 \left[\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2}\right] \tag{1}$$

where ***U*** is wave height, ***x*** is spatial grid in x-direction, ***y*** is spatial grid in y-direction, ***a*** is wave propagation speed, ***d*** is water depth.

For the shallow water equation,

$$a = \sqrt{g \times d} \tag{2}$$

Central differences scheme for finite different method (FDM) is use for approximating all the second derivatives of Eq. (1).

The wave propagation term ***a*** is calculated from the shallow wave property from Eq. (2). Since it uses the FDM method to approximate the wave height ***U***, the modification of the wave propagation term in the following form:

$$a_{i,j}^2 = \sqrt{\frac{d_{i,j}}{d_{max}}} \tag{3}$$

where ***ai,j*** is tsunami propagation speed at position ***i,j***, ***di,j*** is the water depth at position ***i,j***, and d_{max} is the maximum water depth in the domain. The time step ***Δt*** is calculated from Eq. (4). Its value is depended on the initial tsunami propagation speed V_0 (m/s).

$$\Delta t = \frac{3700}{60}\left(\frac{V_0}{3.6}\right) \tag{4}$$

The SiTProS can use ETOPO2 or ETOPO1 as basic ocean topographical grid data; with grid resolution of 3700m for ETOPO2 and 1850m for ETOPO1. For these simulations, ETOPO2 was used as basic ocean topographical data. The time step, *Δt*, is calculated based on grid resolution used and the initial tsunami propagation speed. For model verification, the 1996 event was chosen in this study.

5.1. The simulation of 1996 event

The main shock with magnitude of 7.9 was occurred on January 1st 1996, 16:05 at local time on 0.74°N, 119.93°E in the west coast of Toli-Toli district, Central Sulawesi Province. The fault dimension is 65km in length, 26km in width, with 1.8m dislocation. The epicenter is 10.2km from the closest beach (see Figure 8). All the seismic data were based on Gomez et al (2000), USGS and Global CMT.

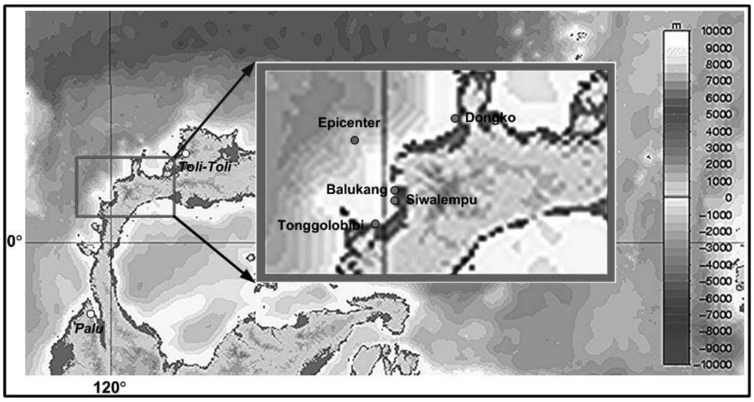

Figure 8: The epicenter of 1996 Sulawesi tsunami event with four observed areas

The artificial buoys to measure the arrival time are placed on water front of four beaches; i.e. Dongko, Balukang, Siwalempu and Tonggolobibi (see Figure 8). The simulation results then compared to the field data collected by Pelinovsky (1997). In Table 2, it shows that SiTProS results on all four places are almost the same as the field data, making this simulation reliable enough for calculating tsunami time arrival for other events.

Table 2: Comparison of eyewitness data and SiTProS results on the 1996 event

Area	First Wave Arrival (min)	
	Eyewitness	SiTProS
Dongko	10	9.57
Balukang	5	6.06
Siwalempu	5	4.80
Tonggolobibi	5 - 7	6.70

5.2. The simulation of artificial events

For finding out the estimated arrival time of tsunamis in the Region A and SG A, seven earthquakes were chosen as the main generator for the tsunamis (Table 3). The earthquakes are originally real events, which fortunately not causing tsunami. The main criteria for choosing the events is based on the data of past tsunami-generated earthquakes in Sulawesi region which had shallow focal depth and have magnitude above 6.0.

Table 3: The seven chosen event for artificial tsunami simulation (compiled from Global CMT)

#	Region Name	Time of Occurrence				Epicenter Location		Focal Depth (km)	Fault Plane Parameters			Magnitude
		Date	hr	min	sec	Lat.	Lon.		Strike	Dip	Slip	
A1	Minahasa Peninsula	16/09/96	10	7	42.4	1.27	120.35	21.00	63	14	71	6.5
A2	Minahasa Peninsula	08/08/91	2	9	57.6	1.54	122.63	33.20	88	25	86	6.6
B1	Minahasa Peninsula	26/10/08	9	8	37.4	-0.18	123.16	74.10	207	44	36	5.6
B2	Minahasa Peninsula	23/07/06	8	22	8.6	-0.41	123.30	35.70	168	55	37	5.9
C1	Molucca Passage	09/12/93	4	32	28.2	0.53	125.81	18.40	41	15	137	6.9
C2	Molucca Passage	09/12/93	11	38	37.9	0.63	125.71	16.60	35	11	122	6.7
C3	Molucca Passage	28/10/98	16	25	10.9	1.00	125.98	15.00	57	77	174	6.5

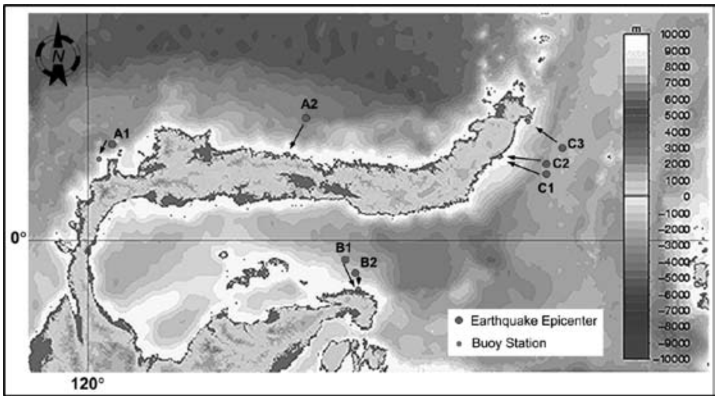

Figure 9: Positions of epicenter and buoys at each event, respectively to the bathymetric condition of the area

The location of the A events is in the North part of North Arm or Celebes Sea, the B events in South part of the North Arm or Gulf of Gorontalo and the C events in East part of the North Arm or Molucca Sea which is also known as Molucca Passage. For the magnitude, events in the A and C are above 6.0 while events in the B are actually did not have big quakes with shallow focal depth. For measuring the arrival time and the wave profile of every event, one artificial buoy for each event is installed in several places near shore which are considered as populated areas. Simulations for each event are based on their own fault plane parameters and magnitudes (see Table 3). For the initial conditions, the entire events are assumed to have 1.8m of dislocation, which was the same value of dislocation of the 1996 event.

Results showed that all of the events are experiencing drawdown at the shores as a first sign of the incoming wave attack (see Figure 10).

For the A1, the maximum drawdown of the sea level occurs around 5.18min after the main shock; while the A2 around 22.76min after the main shock. At the B1, the maximum drawdown occurs around 25.9min after the main shock, while the B2 around 14.8min. Meanwhile for the C1, the maximum drawdown occurs around 38.3min, while the C2 around 34.41min and the C3 around 28.86min after main shock.

Regarding the maximum wave height measured at the buoy, not all of the events experiencing it at the first wave.

In the case of A1, first wave is the maximum one, with time arrival around 8.88min after the main shock; while for the A2, first wave arrives around 28.31min after main shock with maximum wave occurs as the second wave which arrive around 58.28min after the main shock.

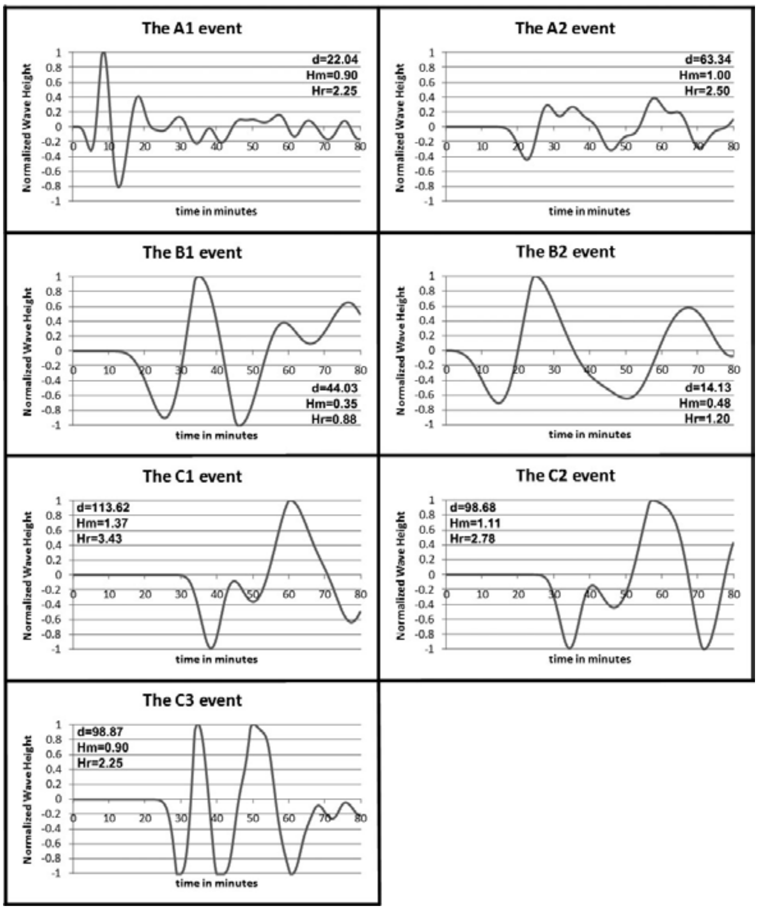

Figure 10: Simulation results of the A1, A2, B1, B2, C1, C2 and C3 events in time series with normalized wave height in vertical axis; d indicates distance between epicenter and buoy in kilometers (see Figure 9), Hm (in meters) indicates maximum wave height at shoreline and Hr (in meters) indicates maximum wave run-up (calculated based on Aydan's empirical formula for Indonesian waters).

In the case of B1, first wave which is the maximum one arrives at the shore around 34.78min after the main shock. For the B2, same situation as B1 also occurs, which is the maximum wave height was the first one coming that hit the shore around 24.42min after the main shock.

In the case of C1, first wave arrives around 44.96min after the main shock, but the maximum one is the second incoming wave which is arriving around 60.5min after the main shock. Same situation also occurred in the C2, which the first wave arrives around 40.52min after the main shock, but the maximum incoming wave is in the second one that arrives around 57.17min after the main shock. As for the C3, different situation with the C1 and C2 occurs; which the first wave is the maximum one, arrives around 34.97min after the main shock.

Figure 10 shows the wave profiles of each event that shows several phenomena as follows. First the A1, B1, B2 and C3 are experiencing the first incoming waves as the maximum wave height; these happen because of their *d* values are below 50km respectively, which is also close enough to the shore and can be categorized as near field tsunami. Nevertheless, the C3 is an exception due the position of the buoy which is just in front of a steep sea floor, making the traveling wave does not have a time to slow down.

Secondly, the A2, C1 and C2 show that the smaller value of d, the faster arrival of the first wave will be. However, concerning the appearance of the wave with maximum height, the bigger value of *d*, the shorter time range from the first drawdown to maximum wave height appears.

Thirdly, even though for the A2, C1 and C2 events, which the value of *d* suggested as the main factor for determining the schematics of time impact at each event, the bathymetrical pattern also contributes quite big, especially on the changing velocity phenomena and the forming process of the waves in the time range from first wave arrival to the maximum wave height occurrence.

Based on these facts, the A1, B1, B2 and C3 are having very fast tsunami propagations, but do not have enough time to create big tsunamis on the beach. The reasons are: 1) most of their epicenters are located very close to the shore, especially the A1, B1 and B2. 2) The bathymetry near the shore at all four events are very steep, making the waves cannot change their profile as quick and big as it should happen in mild-slope floor.

Meanwhile, the A2, C1 and C2 events are having almost noticeable tsunamis since their appearances are not in the first incoming wave, but in the second and third. This happened because of the mild slopes near the shores in wave propagation, which makes the waves propagation slows down and then changes their profiles; as the wave velocity becomes smaller, the wave profile become higher. All of these clearly can be seen in Figure 9.

In Figure 9, it is also shows that the events which produce tsunami not at the first wave, i.e. the A2, C1 and C2 events respectively always have mild slope on their propagation areas; on the contrary, the A1, B1, B2 and C3 events have typical high steep slopes. This means that the beaches of mild slope or long shallow water front will experience a bigger tsunami which is much more recognizable comparing with tsunami on the steep slopes.

Since SiTProS is not focusing on wave height and run up, for the maximum wave height at shoreline, *Hm*, and the maximum wave runup, *Hr*, Aydan's empirical formulas which is specifically for Indonesian waters were used (Aydan, 2008). They are:

$$B.Hm = A.Mw \exp(b.Mw) \tag{5}$$

$$Hr = 2.5Hm \tag{6}$$

where the values of *A*, *b* and *B* are 0.0004, 0.9 and 2.5.

Focusing on the A2, C1, and C2 events, it can be shown that a small difference of bathymetric pattern can make quite big differences, regarding the impact time and wave profiles. Figure 11 clearly shows that even though the A2 event, which is resulting the small wave maximum profile, and does not have earthquake magnitude as big as C1 and

C2, its time difference between the drawdown (DD) to an appearance of the maximum wave height are almost two times comparing to the C1 and C2 events; making the incoming of maximum wave of the A2 event, slower than C1 and C2 events. This happened because of the bathymetric pattern of the propagation area of A2 event that has topography of steep slope offshore connecting to sudden mild slope onshore; making the wave unable to develop to their higher profile with reduction of its velocity.

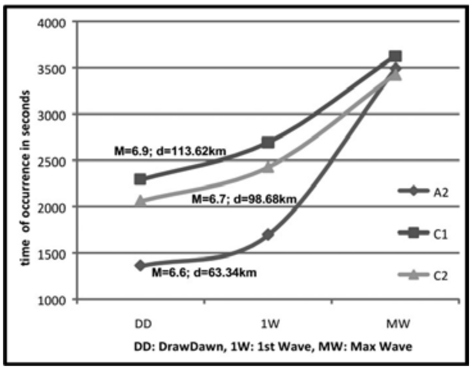

Figure 11: Time of occurrence of DrawDawn (DD), 1st Wave and Maximum Wave of A1, C1 and C2 events

Based on these simulation results, it can be recognized that the North, South and East Coast of the North arm of Sulawesi Island have high potential of experiencing tsunami. Combining the seismic aspects, such as location, intensity and dimension of the faults, with bathymetrical aspects, it is necessary for us to give a certainty of potential seismic and tsunami hazards in the North, South and East waters of the North Arm of Sulawesi Island in the future. The results of this simulation will also determine what scheme or where the tsunami countermeasures will be implemented.

6. Conclusion

In general, the Sulawesi Island will always be a complex system of seismic events, due to its position. It also can be stated that the Sulawesi Island, especially all the northern part and associated with North Sulawesi Trench, Sangihe Trench, Batui Trust, Sorong and Palu-Koro Fault which respectively are very active, stored the biggest potential of producing big earthquakes and tsunamis.

Even though almost all faults corresponding to the Sulawesi Island are strike slips, we still cannot diminish the possibility of big quakes in the land. Based on the statistical data, number of earthquakes in Sulawesi Island in one decade has a trend to increase in the next decade to be almost twice. This is the results of continuously movements of Philippine, Caroline and Pacific Plates to the west.

Due to the future of big and shallow depth of sea-epicenter earthquakes which could most likely produce tsunamis, the sea at North, South and East of the North Arm will be the most potential areas. Based on statistical data and the trend of epicenters movements from West to East and North Coast of Sulawesi, it can be stated that the most potential areas for tsunami generated by sea-epicenter are in that areas.

Regarding of tsunami on beaches, especially due to the range of wave traveling time from the epicenter and naked eyes visibility, it can be shown that the incoming tsunamis from offshore region with steep slope followed by long and mild slope in the near shore will be more noticeable rather than that without long and mild slope topography. Unfortunately, both steep and mild slope types of beaches are spread widely and evenly on North and East coast of the North Arm (see Figure 9); making it a difficult choice for the local government to choose and implement a suitable countermeasures for tsunamis impact on those beaches. For this reason, future researches regarding the suitable countermeasures of tsunami impact at these particularly area have to be carried out.

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