SEISMIC AND TSUNAMI HAZARDS POTENTIAL IN SULAWESI ISLAND, INDONESIA

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For this past one of third century, 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 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 of seismic and tsunami in Sulawesi, by analyzing the historical data of earthquakes and tsunami at the areas and also base on the fault system on it. It found out that the earthquakes with magnitude above 5.0 in the next ten years will occurred minimally 49times; with almost all of them will be sea-epicenter which makes strong believe could generate tsunami on some areas. The most potential areas will be the North Arm of Sulawesi, especially in the coasts of North, South and East.

Key Words: *earthquake, tsunami, Sulawesi Island*

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 past four hundred years (Aydan, 2008). Sumatera and Jawa are two of the most vulnerable islands to tsunami impact since there located directly in front of Indo-Australian Plate. Papua and Sulawesi are also had experienced several tsunamis, even though there were 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 small number of researches regarding earthquake and tsunami in Sulawesi Island. For seismic activity research, a lot of them focusing on the formation process of the island and substance material involve in it. For tsunami research, they are mostly focusing on modeling the past tsunamis events and comparing the result with field data. The most connected with this research is the research done by Aydan (2008), regarding the seismic and tsunami hazard potential in Indonesia with special emphasis of Sumatera Island due to the active movement of the Sunda Arc. In this research, he also introduces 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 mostly from the Global CMT (former Harvard CMT); which then categorized in regions, with each region was developed based on seismic system of Sulawesi Island. The past tsunamigenic earthquakes which occurred the most active region then be assess using numerical simulations to find out several tsunami parameters, such like arrival time, wave height and wave run-ups.

2. GEOLOGY OF SULAWESI ISLAND

The 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. The island also had several small archipelagoes, making it had a very long shoreline, which vulnerable for sea hazards, like tsunami.

Based on the theory of Parkinson (1998), the Sulawesi was formed by four small islands from several places and connected at end of Miocene era (10 million years ago). This forming process explained the basic seismic system of the Sulawesi Island (shown on Fig.1), which include four Spreading Centers (SC), six strike-slips faults (Palu-Koro, Walanae, Matano, Hamilton, Sorong, South Sula-Sorong), three trenches (North Sulawesi, Sangihe, Tolo), and two trusts (Sula and Batui); in which the most active faults are the Palu-Koro fault, North Sulawesi Trench and Sangihe Trench (Guntoro, 1999, Prasetya et al, 2001, Villeneuve et al, 2002).

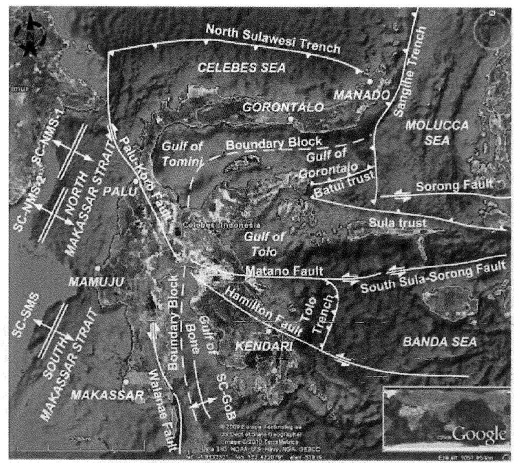

Fig.1. Seismic System of the Sulawesi Island, based on Guntoro (1999), Prasetya et al (2001) and Villeneuve (2002), Google.

3. EARTHQUAKE IN SULAWESI ISLAND

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. Fig.2. shows that during all three decadal periods from 1976 to 2009, it almost has a linier 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 being linier. The data shows that the percentage of sea epicenter increased almost 28% between 1st and 2nd period, but decreased about 9.45% between 2nd and 3rd periods.

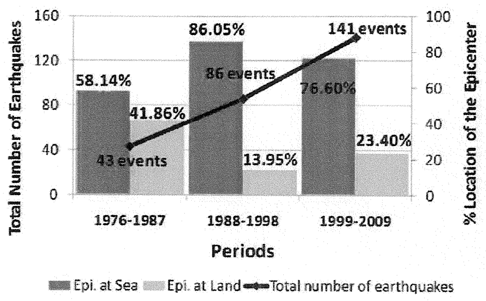

Fig.2. Trend of earthquakes (M>5.0) occurrences during 1976-2009

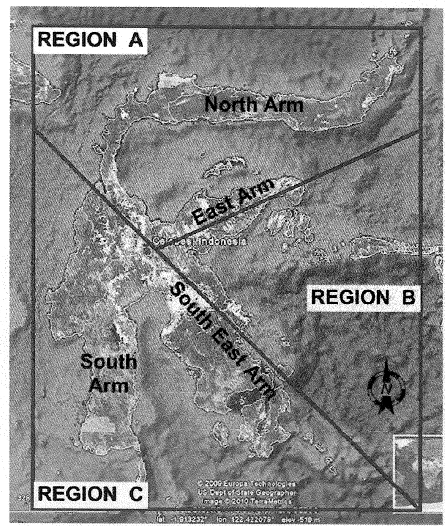

Fig.3. Seismic prone areas in Sulawesi Island

From the Global CMT data, the authors classified seismic prone areas in Sulawesi Island into three big areas as shown in Fig.3. They are:

1. *Region A*; from North Sulawesi trench in the north and the East Arm in the south. This area has a subduction zone, where small plates are being pushed above the Eurasia Plate by Indo-Australia Plates and the Pacific along with small plates such as the Caroline plate and the Philippine; making the North Sulawesi Trench. This area is the most active seismic area in Sulawesi Island since it produced almost half of the total earthquakes occurred during the three periods.
2. *Region B*; from East Arm in the north to the Southeast Arm. This region produced second largest amount of earthquakes during the three decadal periods.
3. *Region C*; from the edge of the east side of Southeast Arm up to Palu City and covered all West Sulawesi and South Sulawesi Province. Even though this region produced small amounts

of earthquakes comparing the two previous regions, but unfortunately recorded three tsunami events.

4. TSUNAMI IN SULAWESI ISLAND

According to Latief et al (2000) and Lander et al (2003), Sulawesi had been struck by tsunami 24 times from 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	Focal Depth (km)	M
1	Makassar Strait	01-Dec-27	n.a.	6.3
2	Makassar Strait	11-Apr-67	20.00	6.3
3	Celebes Sea	14-Aug-68	25.00	7.4
4	Makassar Strait	23-Feb-69	13.00	6.1
5	Makassar Strait	08-Jan-84	14.80	6.7
6	Celebes Sea	01-Jan-96	15.00	7.9
7	Peleng Island	04-May-00	18.60	7.5

These events have several strong connections to each other, which are:

- Generated by shallow earthquakes; the focal depths were not more than 25km.
- 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, those were:

- Three of them, 1967, 1969, and 1984 events, were situated on the center of Makassar Strait, which is also on the lowest seismic prone area (Region C).
- Only two of them were in Region A, which is the highest seismic prone area. They are 1968 and 1996 events. Both of them were also generated by shallow quakes produced by Palu-Koro Fault, North Sulawesi Trench and SC-NMS-1, with the depth below 25km.
- Peleng Island event in 2000 was the only tsunami generated event that occurred in Region B, which is the second highest seismic prone area. It was generated by shallow quakes produced by Batui Trust, Sula Trust and Sorong Fault.
- Six of them were occurred in the West Coast, four in Makassar Strait and two in Celebes Sea, and one in East Coast near Peleng Island.

These facts clearly show the trend of movements of big earthquakes epicenters which are suitable enough for producing tsunami, from the West Coast to the East Coast of Sulawesi. It also showed that even though it situated near strike-slip fault, such as Palu-Koro, the big earthquakes that produced tsunami at Makassar Strait and Celebes Sea, were also influenced by the spreading centers and North Sulawesi Trench. These facts are making the Region A as the area which has to be taken into high consideration for potential big earthquakes and tsunamis in the future.

5. TSUNAMI SIMULATIONS

To estimates approximate affected areas and 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 is Region 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 Fig.4). 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.

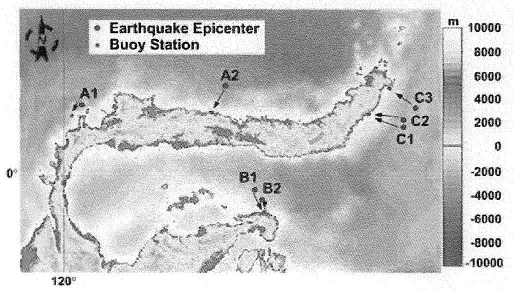

Fig.4. Positions of epicenters and buoys at each event, respectively to the bathymetric condition of the area

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 on graphical user friendly interface. The SiTProS can use ETOPO2 or ETOPO1 as basic ocean topographical grid data; with grid resolution of 3700m for ETOPO2 and 1850m for ETOPO1. The time step, Δt, is calculated based on grid resolution used and the initial tsunami propagation speed.

For model verification, the 7.9 in magnitude 1996 event was chosen in this study, which 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. The fault dimension was 65km in length, 26km in width, with 1.8m dislocation. The epicenter was 10.2km from the closest beach. All the seismic data were based on Gomez et al (2000), USGS and Global CMT.

The artificial buoys to measured arrival time were placed on four places; i.e. Dongko, Balukang, Siwalempu and Tonggolobibi. The simulation results were compared to the field data collected by Pelinovsky (1997). In Table 2, it is showed 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 the eyewitness data (Pelinovsky, 1997) 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

For finding out the estimated arrival time of tsunamis in the most potential seismic events, Region A, seven earthquakes were chosen as the main generator of the tsunamis (Table 3). The earthquakes were originally real events, which fortunately did not cause 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 magnitude more than 6.0. For measuring arrival time and wave profile of every event, one artificial buoy for each event was installed in several places near shore which are considered as populated areas. Results showed that all the events had experienced draw down at the shores as first sign of the incoming wave attack.

Table 4. TDDmax, T1st W, TWmax and *d* of each event

Event	TDDmax (min)	T1stW (min)	TWmax (min)	*d* (km)
A1	5.18	8.88	8.88	22.4
A2	22.76	28.31	58.28	63.34
B1	25.9	34.78	34.78	44.03
B2	14.8	24.42	24.42	14.13
C1	38.8	44.96	60.5	113.62
C2	34.41	40.52	57.17	98.68
C3	28.86	34.97	34.97	98.87

Table 4 shows the time of the maximum draw down (TDDmax), the time of the first incoming wave (T1stW), the time of the maximum wave (TWmax) in minutes, and *d* distance between the epicenters and the buoy.

The A1, B1, B2 and C3 did experiencing the first incoming waves as the maximum wave height because of their *d* values, which were below 50km respectively and can be categorized as near field tsunami. Nevertheless, C3 is an exception due the position of the buoy which just in front of a steep sea floor, making the traveling wave did not have a time to slow down.

The A2, C1 and C2 show that the smaller value of *d*, the faster arrival of first wave. 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 appeared.

But even though for A2, C1 and C2 events, where 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 changing velocity and forming of the waves in the time range from first wave arrival to the maximum wave height occurrence.

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			M
		Date	hr	min	sec	Lat.	Lon.		Strike	Dip	Slip	
A1	Minahasa Peninsula	16-Jul-96	10	7	42.4	1.27	120.35	21.00	63	14	71	6.5
A2	Minahasa Peninsula	08-Aug-91	2	9	57.6	1.54	122.63	33.20	88	25	86	6.6
B1	Minahasa Peninsula	26-Oct-08	9	8	37.4	-0.18	123.16	74.10	207	44	36	5.6
B2	Minahasa Peninsula	23-Jul-06	8	22	8.6	-0.41	123.30	35.70	168	55	37	5.9
C1	Molucca Passage	09-Dec-93	4	32	28.2	0.53	125.81	18.40	41	15	137	6.9
C2	Molucca Passage	09-Dec-93	11	38	37.9	0.63	125.71	16.60	35	11	122	6.7
C3	Molucca Passage	28-Oct-98	16	25	10.9	1.00	125.98	15.00	57	77	174	6.5

Based on these facts, A1, B1, B2 and C3 will have very fast tsunami propagations, but will not have enough time to create big tsunami on the beach, because of their epicenters were very close to the shore, and also because of 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, A2, C1 and C2 events will have tsunami almost noticeable since they appeared not in the first wave. This happened because of the mild slopes near the shores in wave propagation, which makes the waves slows down and then changes their profiles; as the wave velocity becomes smaller, the wave profile become higher (see Fig.4). Fig.5 clearly shows that even though the A2, which is resulting a small wave maximum profile, and does not have earthquake magnitude as big as C1 and C2, their time difference between the draw down (DD) to an appearance of the maximum wave height are almost twice comparing to C1 and C2; making the incoming of maximum wave of A2 slower than them. This happened because of the bathymetric of the propagation area of A2 has topography of steep slope offshore connecting to sudden mild slope onshore; making the wave unable to develop to higher profile with reduction of its velocity.

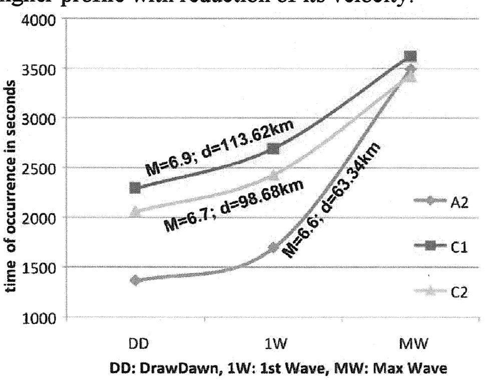

Fig.5. Time of occurrence of draw dawn (DD), 1st and maximum wave of A2, C1 and C2 events

6. CONCLUSIONS

Based on the statistical data, number of earthquakes in Sulawesi in one decade has a trend to increase in the next decade to be almost twice, as a result of continuously movements of Philippine, Caroline and Pacific Plates to the west. For the future big and shallow depth of sea-epicenter earthquake which could most likely produce tsunami, the sea at North, South and East of the North Arm will be the most potential areas, which also based on the trend of epicenters movements from West to East and North Coast of Sulawesi.

Regarding of tsunami on beaches, especially due to the range of wave traveling time and eyes visibility, it showed 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 wide and evenly on North and East coast of the North Arm (see Fig.4); making it a difficult choice for the local government to choose and implement a suitable countermeasures for tsunami 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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