TSUNAMI AND EARTHQUAKE ACTIVITY IN INDONESIA*

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ABSTRACT

Tsunami and earthquake activity in Indonesia during the period from 1901 to 2000 have been analyzed. A total of 108 tsunamis caused by earthquakes and 298 shallow earthquakes with magnitude $M_s \geq 6.5$ occurred in the region. The tsunamigenic earthquakes occurred along subduction zones (Sunda, Banda, Pacific, and Philippine) and in the Sunda back-arc thrusting and Molucca Sea collision zones. Approximately 81% of tsunamis and 80% of shallow earthquakes occurred in Eastern Indonesia – i.e. the region east of 118° E – where tectonics show a more complicated pattern than the region in the west. The ratio between the number of tsunamis and shallow earthquake occurrence in the east part is slightly higher than in the west part. The tsunami and earthquake time occurrences show no systematic pattern although it can be noted that the most silent period was from 1941 to 1960. The earthquake magnitude of tsunamigenic earthquakes varies from 5.0 to 8.6 where about 86% of them have magnitude $M_s > 6.0$. The tsunami magnitude-earthquake magnitude relationship can be written as: $m = 0.29\ M_s - 0.93$ for $M_s < 6.5$, and $m = 1.17\ M_s - 7.46$ for $M_s \geq 6.5$. While the tsunami intensity–earthquake magnitude relationship can be written as $I = 0.23\ M_s - 0.22$. Most of the tsunamigenic earthquakes (about 93%) are shallow earthquakes that have focal depth less than 100 km.

1. INTRODUCTION

The Indonesian region is prone to earthquake and tsunami disasters. The region has been frequently affected by earthquake and tsunami, which killed approximately 22,000 people during the 20th century [*ADRC*, 2000]. Among the destructive earthquakes were the 1976 Jayapura (6,000 killed), 1994 Liwa (210 killed), and the 2000 Bengkulu (90 killed) earthquakes. The 1992 Flores (2,100 killed), 1994 Banyuwangi (240 killed), and the 1996 Biak (160 killed) tsunamis were classified as major destructive tsunamis in recent years.

Although the region is prone to tsunami disaster, tsunami activity is not well understood. This is partly because of very limited available information on historical tsunami activity. Fortunately, in recent years there were two tsunami catalogues [Latief *et al*., 2000; Gusiakov, 2001] developed. Latief *et al*. [2000] developed a tsunami catalog for the Indonesian region, while Gusiakov [2001] developed the catalog for the entire Pacific region.

By utilizing the two catalogues, this paper attempts to analyze tsunami – as well as earthquake – activity in the Indonesian region for a period from 1901 to 2000. The data was mainly taken from the work of Gusiakov, while tsunami data from Latief *et al*. were used in case when the data of Gusiakov were absent. Only tsunamis caused by earthquakes were considered in the analysis.

2. TECTONIC SETTING

The Indonesian region is one of the most tectonically complicated regions. The region is the place of plate convergence of the Eurasian, Indian-Australian, Pacific, and the Philippine Sea plates (Figure 1). The plates move relative to each other in a rather complicated manner. Plate boundaries are located along Java trench, Timor trough, New Guinea trench, Philippines trench, and Yap trench.

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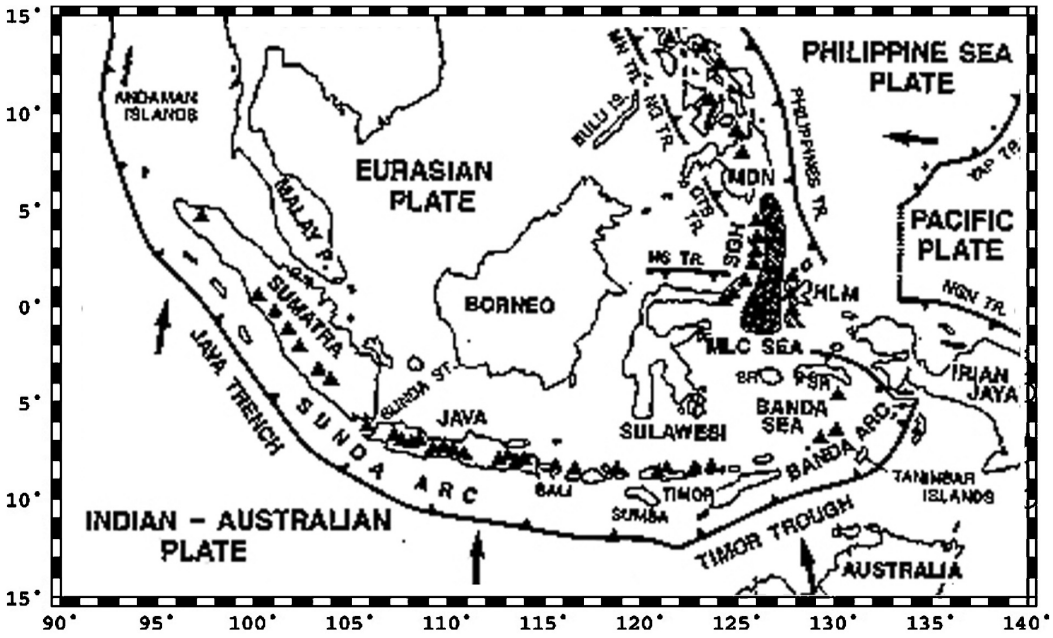

Figure 1. Tectonic Map of the Indonesia region. (Puspito and Shamazaki, 1995)

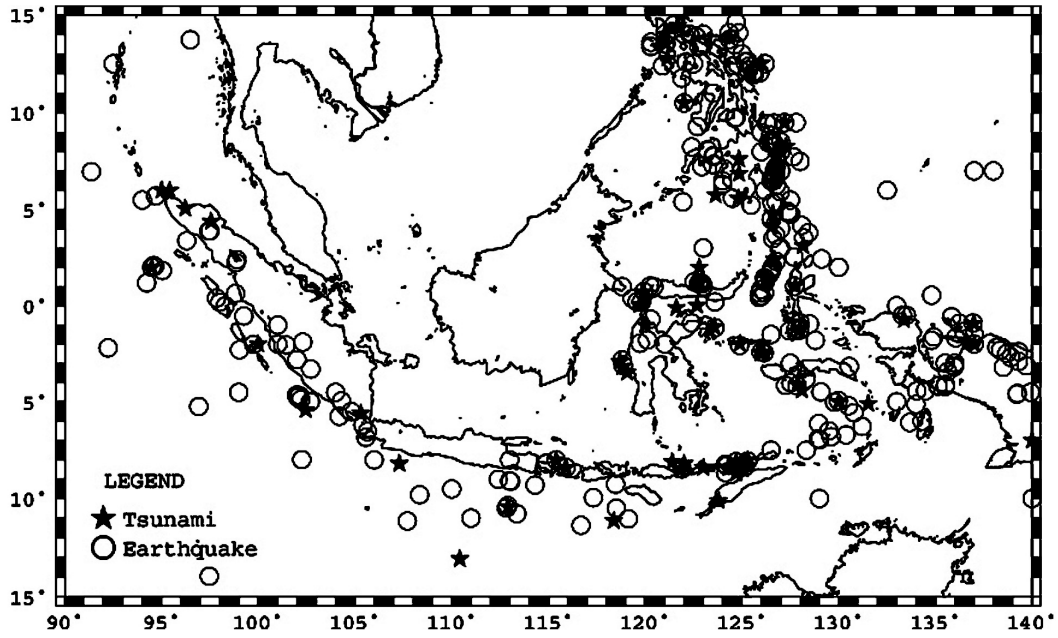

Figure 2. Tsunami and shallow earthquake

The region includes several arcs such as Sunda, Banda, Sangihe, and Halmahera arcs that have their own special seismological features [Puspito and Shimazaki, 1995]. Sunda arc is a product of Indian Ocean and Eurasian plate convergence. The arc extends westward from Sumba passing through Java, Sumatra and Andaman islands. Banda arc extends eastward from Sumba passing through Tanimbar and Aru Islands and thence curves sharply counterclockwise to a westward through Seram and Buru. In the northeastern part of the region, Sangihe and Halmahera arcs move in opposite directions, i.e. Sangihe moves to the east while Halmahera moves to the west. The movement has made Molucca Sea region known as the place of an active arc-arc collision zone. This type of collision zone is unique in the world.

3. DATA COMPILATION

Gusiakov [2001] has developed a tsunami catalog for the entire Pacific region from 47 BC to 2000 AD. The catalog contains – among others – date, location of the source, earthquake magnitude, tsunami magnitude and intensity, run-up, the cause of tsunami, validity, fatalities, and the affected region. The validities were classified into 5 categories, i.e. 4 for definite tsunami, 3 for probable tsunami (probability about 75%), 2 for questionable tsunami (probability 50%), 1 for very doubtful tsunami (probability 25%), and 0 for unknown tsunami.

Based on the catalog we found 181 tsunamis caused by earthquake occurred in the Indonesian region for all of the validities. Among them a total of 103 tsunamis occurred during the period from 1901 to 2000. In this study we selected 90 tsunamis caused by earthquakes whose validities vary from categories 2 to 4 (probability ≥ 50%).

Latief *et al.* [2000] have compiled data for the Indonesian region from 1600 to 1999. They found that 105 tsunamis have occurred in the region. Among them 95 events were caused by earthquake, 9 events were caused by volcanic eruption, while one tsunami was caused by a landslide. Based on those data there were 46 tsunamis caused by earthquakes in this region during a period from 1901 to 1999. Among them 18 events were not listed in Gusiakov [2001]. Table 1 below listed the 18 tsunamis.

In this study we combine those 18 events from Latief *et al*. [2000] and the 90 previous selected events from Gusiakov [2001]. We have a total of 108 tsunamis generated by earthquake during the period from 1901 to 2000. Meanwhile all the earthquake data used in this study were compiled from the work of Gusiakov [2001]. We selected 298 shallow earthquakes that have focal depth < 100 km and magnitude (M_S) ≥ 6.5.

4. TSUNAMI AND EARTHQUAKE ACTIVITY

The selected tsunamis and shallow earthquakes were plotted in Figure 2. We can say that the tsunamis occurred along seismic active zones. Most of the tsunamis occurred in Sunda subduction, Sunda back-arc thrusting, Banda subduction, Molucca Sea collision, Pacific subduction, and the Philippine subduction zones.

The longitude distribution (Figures 2 and 3) shows that the region east of 118^o E (namely Eastern Indonesia) has higher activities than the region in the west (namely Western Indonesia). About 81% (87 events) of the tsunamis and 80% (237 events) of shallow earthquakes occurred in Eastern Indonesia. This is in good agreement with the tectonic pattern that shows that the east part has a more complicated pattern than the west part (Figure 1). The tsunami occurrence efficiency (ratio between the number of tsunami and the number of

shallow earthquakes) in the east part is slightly higher than in the west part, i.e. 37% compare with 34%.

Table 1

List of selected tsunami data from Latief *et al.* [2000]

Date(Y-M-D)	Lat.	Lon.	D	Ms	m	H_{max}	F	Affected Region
1908-03-24	-8.7	124.7	33	6.6	1.0	25	–	Timor Island
1913-03-14	4.8	126.6	25	7.9	–	–	–	North Sulawesi
1938-05-19	-1.0	120.0	60	7.6	1.5	3	–	Central Sulawesi
1961-03-16	-8.2	122.0	75	6.3	–	–	6	Flores
1975-01-15	-5.0	130.0	33	6.9	–	–	–	Bandanaira
1975-03-05	-2.4	126.1	33	6.5	1.0	2	–	Sanana, Sula Island
1975-07-30	-10.1	123.8	16	6.1	–	–	–	Timor Island
1977-08-27	-8.0	125.3	25	6.8	–	–	2	Flores
1979-12-17	-8.4	115.9	33	6.6	–	–	27	Sumbawa, Lombok
1982-03-12	-4.4	128.1	–	5.8	–	–	–	Molucca
1982-08-19	-0.1	121.6	44	5.2	–	–	–	North Sulawesi
1982-12-25	-8.4	123.0	33	5.9	1.0	–	13	Larantuka
1984-01-08	-2.9	118.7	95	5.9	–	–	–	South Sulawesi
1987-11-26	-8.4	124.3	33	6.5	1.0	–	83	Flores, Pantar Is.
1989-07-14	-8.1	125.1	52	6.2	0.0	–	7	Alor Island
1989-07-31	-8.1	121.4	13	6.3	0.0	–	3	Flores
1991-07-04	-8.1	124.7	29	6.2	–	–	13	Alor Island
1992-06-20	2.0	122.8	–	6.2	0.0	–	–	North Sulawesi

Note:

1) Date(Y-M-D) is year, month, and day;
2) Lat. is latitude of earthquake epicentre;
3) Lon. is longitude of earthquake epicentre;
4) D is earthquake focal depth;
5) Ms is earthquake magnitude of surface wave;
6) m is tsunami magnitude;
7) H_{max} is maximum vertical run-up;
8) F is number of fatalities.

Figure 4 shows the number of tsunami and earthquake occurrences in every 5 year interval. Almost no systematic pattern can be derived from the figure. However, it is shown that the most silent period was from 1941 to 1960 when only 7 tsunamis and 21 shallow earthquakes occurred in the region.

Figure 5 shows earthquake magnitude (M_s) distribution of tsunamis. Four tsunamis were caused by earthquakes of unknown magnitude. The earthquakes magnitude varies from 5.0 to 8.6, where about 86% (89 events) of them have magnitude greater than 6.0. This suggests that moderate to large earthquakes mainly generated the tsunamis in the region. Earthquake depth distribution (Figure 6) shows that most of the tsunamis (about 93%) have earthquake focal depth less than 100 km.

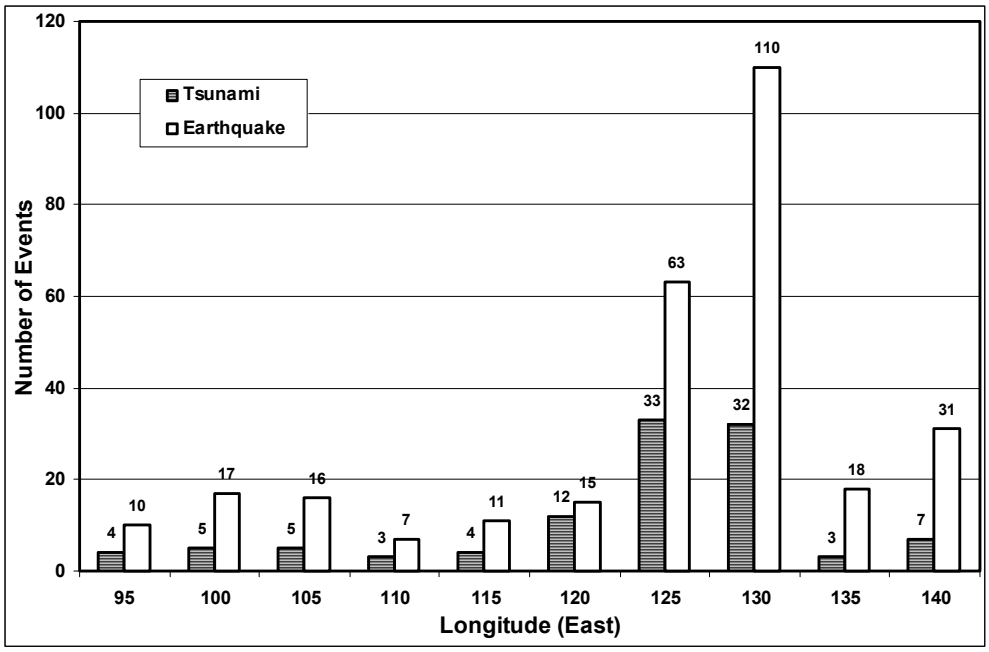

Figure 3. Longitude distribution of tsunamis and shallow earthquakes.

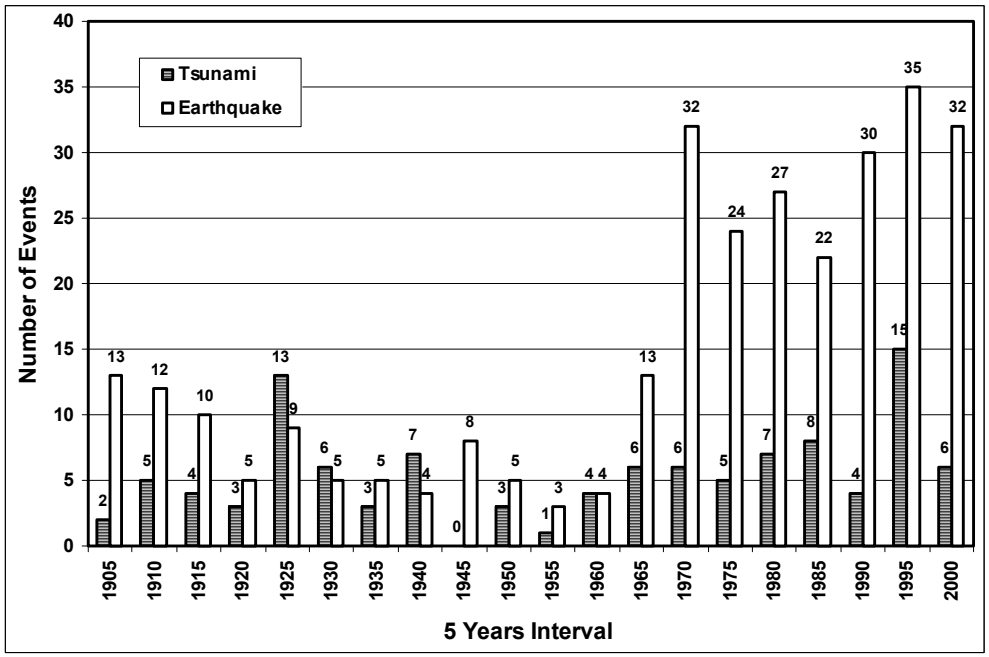

Figure 4. Time occurrences of tsunami and shallow earthquake.

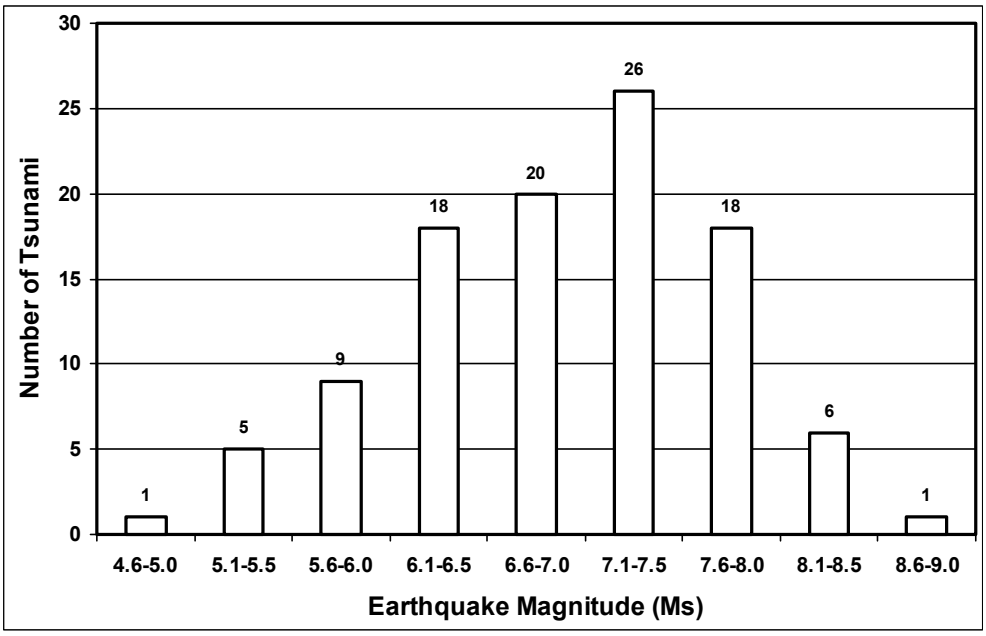

Figure 5. Earthquake magnitude (Ms) distribution.

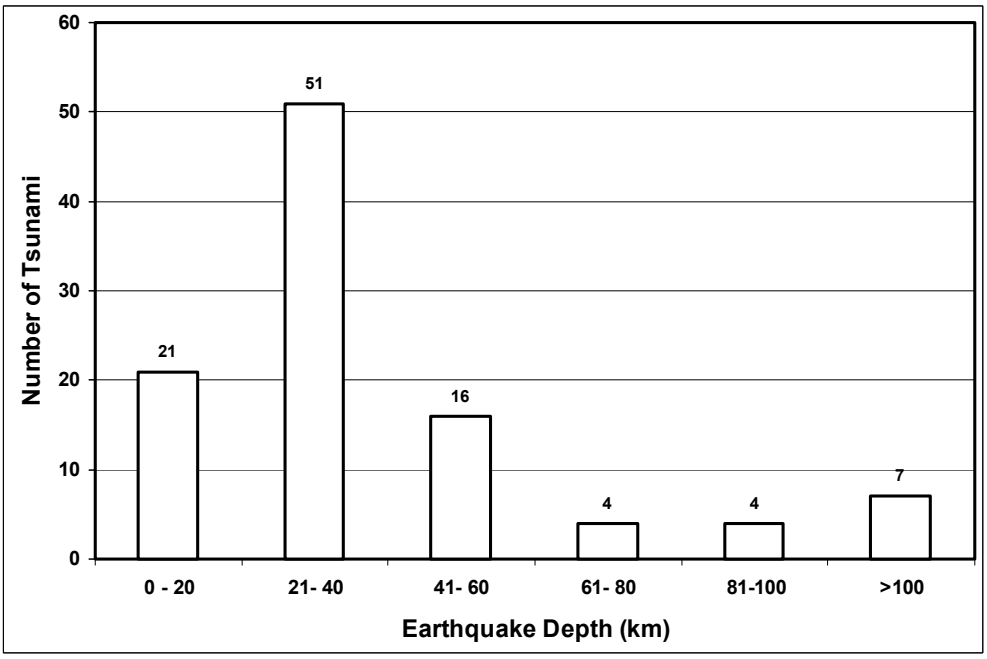

Figure 6. Earthquake depth distribution.

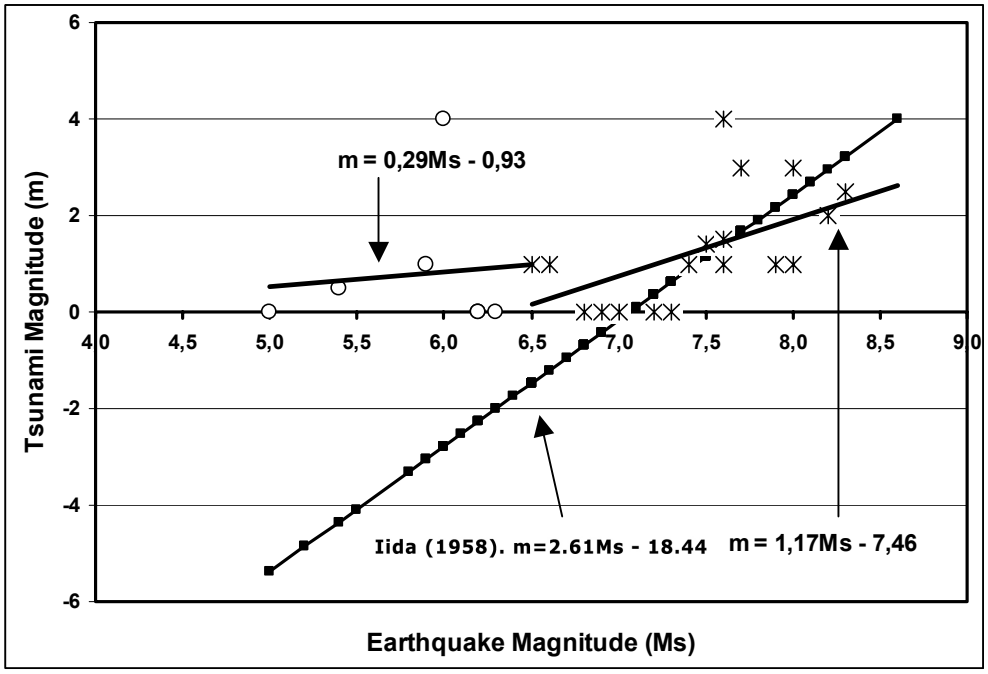

Figure 7. Tsunami magnitude – earthquake magnitude relationship.

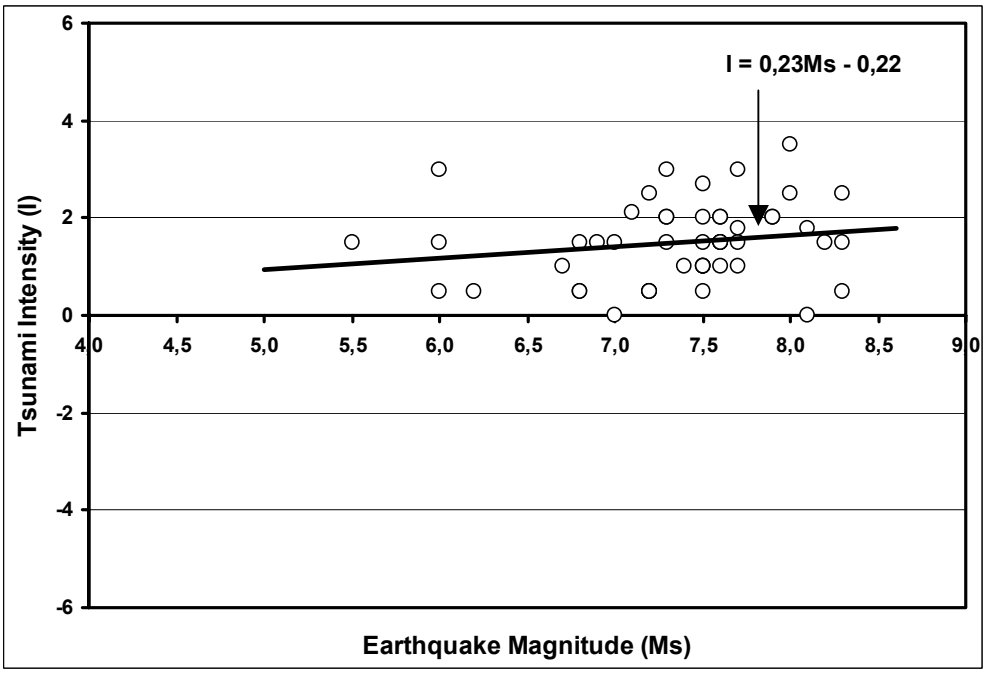

Figure 8. Tsunami intensity – earthquake magnitude relationship.

Iida [1958] proposed an empirical relationship between earthquake magnitude (Ms) and the tsunami magnitude (m). Based on the data of tsunamis occurring near Japan, he proposed an empirical relationship: $m = 2.61\ M_s - 18.44$. Based on the present data (Figure 7) we derived two relationships for the Indonesian tsunami:

$$m = 0.29\ M_s - 0.93 \quad \text{for } M_s < 6.5, \text{ and} \quad m = 1.17\ M_s - 7.46 \quad \text{for } M_s \geq 6.5.$$

The tsunami intensity (I) and earthquake magnitude (M_s) relationship can be seen in Figure 8. Although the data is scattered the tsunami intensity and earthquake magnitude relationship can be derived as $I = 0.23\ M_s - 0.22$.

5. CONCLUSIONS

Based on the compiled data we can conclude the following:

1. A total of 108 tsunamis caused by earthquake and 298 shallow earthquakes (depth < 100 km; $M_s \geq 6.5$) occurred in the Indonesian region during the period from 1901 to 2000. The tsunamigenic earthquakes occurred along Sunda subduction, Sunda back-arc thrusting, Banda subduction, Molucca Sea collision, Pacific subduction, and the Philippine subduction zones.

2. About 81% (87 events) of the tsunamis and about 80% (237 events) of shallow earthquakes occurred east of longitude 118° East where the tectonics show a more complicated pattern than the region in the west. The tsunami occurrence efficiency in the east part is slightly higher than in the west part, i.e. 37% compare with 34%.

3. Time occurrences show no systematic pattern although it can be noted that the most silent period was from 1941 to 1960 when only 7 tsunamis and 21 shallow earthquakes occurred in the region.

4. The earthquake magnitude of tsunamis varies from 5.0 to 8.6, where about 86% (89 events) of them have magnitude greater than 6.0. The tsunami magnitude – earthquake magnitude relationship can be written as: $m = 0.29\ M_s - 0.93$ for $M_s < 6.5$, and $m = 1.17\ M_s - 7.46$ for $M_s \geq 6.5$. While the tsunami intensity – earthquake magnitude relationship can be written as $I = 0.23\ M_s - 0.22$.

5. Most of the tsunamis (about 93%) were generated by shallow earthquake of focal depth less than 100 km.

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