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On Statistics of Tsunamis in Indonesia

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Abstract

A statistical analysis of the tsunamis caused by earthquakes in Indonesia was carried out to evaluate the frequency of tsunamis. After a geographical and chronological consideration of tsunami occurrence and the distribution of tsunami sources, recurrence of tsunami was analyzed with an assumption that tsunami occurrence follows a Poisson process. For the analysis of tsunamis with a variable of tsunami intensity, it seemed preferable to introduce a modified Poisson process. This analysis produces a probability for occurrence of a tsunami exceeding a given magnitude in a given period in Indonesia. Some comment is made on the locality of tsunami risk.

I Introduction

The Indonesian islands are located in a zone of significant seismic activity, where many earthquakes and accompanying tsunamis have been observed and recorded. The most recent event was at the south of Sumbawa Island on 19th August 1977. This earthquake and tsunami caused considerable damage on the coast of Indonesia. I therefore analyzed statistically the tsunamis caused by earthquakes in Indonesia to find out how often tsunamis occur. After chronological and geographical consideration of tsunami occurrence and of the distribution of the tsunami sources, I evaluated the recurrence of tsunami making the assumption that tsunami occurrence follows a Poisson process. I further proposed a modified Poisson process for occurrence of tsunami with a variable of tsunami intensity. The analysis predicts the probability of occurrence of one tsunami exceeding a given tsunami magnitude in a given period in Indonesia. Some comment is made on the locality of tsunami occurrence in the context of a chronological tsunami catalog.

II Chronological Catalogs of Tsunamis

Iida *et al.* (1967) prepared a tsunami catalog of the world. Subsequently, Soloviev and Gao (1974) published tsunami catalogs of the western Pacific Ocean with detailed descriptions of tsunamis and resultant damage.

Following the classification of the districts in Indonesia made by Soloviev and Gao, the local frequency of the tsunami occurrence is tabulated as in Table 1. The first column shows the local area with the year of the earliest recorded tsunami in parentheses. The local frequency of tsunami occurrence is in the second column. For each local

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Table 1 Tsunami Intensity and Locality in Indonesia

Area	tsunami intensity (m) / local frequency	-3	$-2\frac{1}{2}$	-2	$-1\frac{1}{2}$	-1	$-\frac{1}{2}$	0	$\frac{1}{2}$	1	$1\frac{1}{2}$	2	$2\frac{1}{2}$	3	$3\frac{1}{2}$	4
A. Talaud Is. and Cangihe Is. (1910–)	1					1										
B. Northern Molucca Sea (1673–)	13							3	3	2	3	0	1	1		
C. Ceram Sea (1860–)	7					2	2	2	1							
D. Celebes Is. (1897–)	6								1	2	1	0	1	1		
E. Eastern Borneo Is. (1921–)	2							1	1							
F. Sumatra Is. and Malacca Str. (1816–)	6							3	1	1	1					
G. Southwestern Sumatra Is. (1770–)	18							3	3	3	3	3	1	2		
H. Java Is. (1722–)	11	1	0	1	1	0	1	3	1	2	0	1				
I. Lesser Sunda Is. (1814–)	10							3	3	0	1	1	0	0	1	1
J. Northern Banda Sea (1629–)	24							7	2	1	7	3	2	1	1	
Total	98	1	0	1	1	3	3	25	16	11	16	8	5	5	2	1
Frequency		98	97	97	96	95	92	89	64	48	37	21	13	8	3	1

area, the frequency of the tsunami occurrence is tabulated for each tsunami intensity. At the bottom of the table, frequency of the occurrence of tsunami of unusual intensity is given. The frequency of occurrence of tsunamis of intensity 0 or above is 89.

In the tsunami catalog published by Soloviev and Gao reports of tsunamis in Indonesia are classified into five categories for reliability: sure(S), likely(L), probable(P), doubtful(D) and erroneous(E). In both Table 1 and the following analysis, tsunamis classified as D and E in the catalog are excluded. The table shows that detailed observations and records of tsunamis are found in Java Island but not in other areas. Thus many tsunamis in Indonesia must have gone unrecorded.

Using a slightly different classification of districts in Indonesia from that prepared by Soloviev and Gao, I rearranged the data into the chronological catalog of tsunamis in Indonesia shown in Table 2, in which the tsunamis are numbered in chronological order. The areas in the third column correspond to the areas in Table 1. The sixth column indicates the depth of focus of the earthquake causing the tsunami. The notation M and m are Richter's earthquake magnitude and tsunami intensity respectively. Data on tsunamis occurring between 1968, when Soloviev and Gao's catalog was completed, and 1977 were obtained from the Seismological Section of Japan Meteorological Agency

Table 2 Chronological Catalog of Tsunamis in Indonesia

No.	Date	Area	Location	Depth	M	Reliability	m
1	1629- 8-01	J	6.0S, 130.0E	-km	7	L	3
2	1648- 2-29	J	Ambon	-	-	E	-
3	1657-12-	J	Buru Is., Ambon	-	-	P	1
4	1673- 5-20	B	Ternate Is.	-	-	E	-
5	1673- 7-12	J	Ambon	-	-	E	-
6	1673- 8-12	B	Ternate Is.	-	-	L	1
7	1674- 2-17	J	3 3/4S, 127 3/4E	40	6 3/4	S	1 1/2
8	1674- 5-06	J	3 3/4S, 127 3/4E	-	6	L	0
9	1708-11-28	J	Ambon	-	-	L	2
10	1710- 3-06	J	Bandanaira	-	-	L	1 1/2
11	1711- 9-05	J	4.0S, 129.0E	-	7	S	1 1/2
12	1722-10-	H	Jakarta(Batavia)	-	-	D	0
13	1754- 8-18	J	3 1/2S, 128 1/2E	-	6 1/2	L	0
14	1754- 9-07	J	3 1/2S, 128 1/2E	-	-	P	0
15	1757- 8-24	H	Jakarta	-	7 1/2	P	-1/2
16	1763- 9-12	J	6.0S, 130E	-	-	L	2 1/2
17	1770- -	G	5.0S, 102.0E	-	7	L	1/2
18	1775- 4-19	J	Ambon	-	-	L	0
19	1797- 2-10	G	0.0, 99.0E	-	8	S	3
20	1802- 8-	J	Ambon	-	-	P	1 1/2
21	1814- -	I	Timor Is., Kupang	-	-	P	0
22	1815-11-22	I	8.0S, 115.0E	150	7	L	1 1/2
23	1816- 4-29	F	5.0S, 96 1/2E	-	-	P	0
24	1818- 3-18	G	4.0S, 101 1/2E	-	7	L	1 1/2
25	1818-11-08	H	7.0S, 117.0E	600	8 1/2	P	2
26	1820-12-29	I	7.0S, 119.0E	80	7 1/2	S	3 1/2
27	1823- 9-09	H	6 1/2S, 108 1/2E	150	6 3/4	P	-1 1/2
28	1833-11-24	G	2 1/2S, 100 1/2E	75	8 1/4	S	2 1/2
29	1836- 3-05	I	Bima	-	-	P	1/2
30	1836-11-28	I	Bima	-	7 1/2	P	1/2
31	1837- 9-	F	5 1/2S, 96.0E	100	7 1/4	P	1/2
32	1840- 1-04	H	8.0S, 110 1/2E	150	7	P	0

Table 2 continued

No.	Date	Area	Location	Depth	M	Reliability	m
33	1840- 2-14	B	Ternate Is.	-km	-	P	1/2
34	1841-11-26	J	Bandanaira	-	-	L	1 1/2
35	1841-12-16	J	4.0S, 127 1/2E	-	6	L	1 1/2
36	1843- 1-05	G	1 1/2N, 98.0E	70	7 1/4	S	2
37	1843- 2-07	H	7.2S, 114.0E	-	6	D	0
38	1845- 2-08	B	Kema	-	7	L	0
39	1846- 1-25	B	2.0N, 126 1/2E	-	7 1/4	S	1/2
40	1852- 1-09	H	6 1/2S, 105 1/2E	150	6 1/2	L	1/2
41	1852-11-11	G	1 1/2N, 98.0E	-	6 3/4	D	0
42	1852-11-19	J	Ambon	-	-	D	0
43	1852-11-26	J	5 1/4S, 129 3/4E	100	8 1/4	S	2 1/2
44	1852-12-24	J	5.0S, 130 1/2E	-	7	D	2
45	1854- 1-04	J	3.5S, 128.6E	-	6	P	0
46	1854- 9-27	B	Ternate Is.	-	-	L	1/2
47	1856- 7-25	I	8 1/2S, 116.0E	-	-	P	0
48	1857- 5-13	I	8.0S, 115 1/2E	50	7	S	2
49	1857-11-17	B	Kema, Ternate Is.	-	-	L	1 1/2
50	1857-11-18	B	Kema	-	-	P	0
51	1858-12-13	B	1.0N, 126.0E	-	7 1/4	P	1 1/2
52	1859- 6-28	B	1.0N, 126 1/2E	-	7	S	3
53	1859- 7-20	J	Lontor Is.	-	-	L	0
54	1859- 7-29	B	0.0, 125 1/2E	-	7 1/4	S	1 1/2
55	1859- 9-25	J	5 1/2S, 130 1/2E	-	6 3/4	P	1/2
56	1859-10-20	H	9.0S, 111.0E	-	-	P	1
57	1859-12-17	B	Belang	-	-	P	0
58	1860- 8-	B	Minahasa District	-	-	D	0
59	1860-10-06	C	1 1/4S, 128 1/2E	-	-	L	0
60	1861- 2-16	G	1.0N, 97 1/2E	70	8 1/2	S	3
61	1861- 3-09	G	0.0, 98.0E	20	7	S	2
62	1861- 4-26	G	1.0N, 97 1/2E	70	7	S	1 1/2
63	1861- 6-17	G	1.0N, 97 1/2E	-	6 3/4	L	1/2
64	1861- 9-25	G	1 1/2S, 100.0E	-	6 1/2	L	1 1/2
65	1862- 4-08	H	Lenor	-	-	E	-
66	1863- 3-16	H	Jarigin	-	-	D	0

Table 2 continued

No.	Date	Area	Location	Depth	M	Reliability	m
67	1871- 8-25	B	Gorontalo	-km	-	D	0
68	1876- 5-28	C	3.0S, 127 1/4E	50	6 3/4	L	-1
69	1882-10-10	J	Bandanaira	-	7 1/2	L	1/2
70	1885- 4-30	C	2 1/2S, 127 1/2E	-	7 1/4	L	1/2
71	1885- 7-29	G	0.0, 99 1/2E	-	6 3/4	P	0
72	1885-12-14	F	Banda Area	-	-	D	-
73	1886- 1-31	F	Banda Area	-	-	D	-
74	1887- 5-19	F	Cigli	-	-	D	-
75	1888- 3-21	F	Broeh Is.	-	-	D	-
76	1889- 9-06	B	1.0N, 126 1/4E	70	8	S	2 1/2
77	1889-11-23	H	7.0S, 113 1/2E	-	6	P	1
78	1891- 5-19	F	Cigli	-	-	D	-
79	1891-10-05	I	9.0S, 124.0E	80	7	L	1/2
80	1892- 5-17	F	2 1/2N, 99 1/2E	120	7 1/2	L	1
81	1892-11-18	C	3.0S, 127 3/4E	70	7	L	-1
82	1896-10-10	G	3 1/2S, 102 1/2E	130	6 3/4	P	0
83	1897- 3-15	D	6.8S, 120.8E	15	5 1/2	P	1
84	1899- 9-30	J	3 1/2S, 128 1/2E	-	7.8	S	3
85	1900- 1-10	B	Galela	-	-	D	0
86	1903- 3-30	C	3.0S, 127 1/2E	-	6 1/2	P	0
87	1904- 9-07	H	Chilachap	-	-	D	0
88	1907- 1-04	G	1 1/2N, 97.0E	50	7 1/2	S	2
89	1907- 3-30	D	3.0N, 122.0E	500	7 1/4	D	2?
90	1908- 2-06	G	2.0S, 100.0E	130	7 1/2	L	1
91	1908- 3-23	I	10.0S, 129.0E	-	6.6	E	-
92	1909- 6-04	G	2.0S, 101.0E	40	7 1/2	P	1
93	1910-12-18	A	Talaud Is.	-	6	P	-1
94	1913- 3-14	A	4 1/2N, 126 1/2E	-	8	E	-
95	1915- 5-23	C	Kaimana	-	-	D	0
96	1915- 7-26	G	Lais	-	-	D	0
97	1917- 1-21	I	Bali Is.	-	6 1/2	L	0
98	1920- 1-$\frac{29}{30}$	D	Gorontalo, Dongala	-	-	D	1
99	1921- 5-14	E	0.0, 118.1E	20	6 1/4	P	1/2
100	1921- 9-11	H	11.0S, 111.0E	-	7 1/2	S	-2

Table 2 continued

No.	Date	Area	Location	Depth	M	Reliability	m
101	1922- 2-22	J	Amahai	-km	-	D	1/2
102	1922- 4-10	G	Padang	-	-	D	0
103	1922- 7-08	F	Lhoknga	-	-	D	0
104	1925- 1-08	D	Butung Is.	-	-	D	0
105	1926- 6-28	G	1 1/2S, 99 1/2E	-	6 3/4	E	0
106	1927-12-01	D	1/2S, 119 1/2E	-	6	D	3?
107	1930- 6-19	G	5.6S, 105.3E	-	6	L	0
108	1930- 7-19	H	9.3S, 114.3E	100	6 1/2	P	-3
109	1930- 9-11	D	Amurang	-	-	D	0
110	1931- 9-25	G	5.0S, 102 3/4E	-	7 1/2	L	1
111	1932- 9-09	J	3.6S, 128.3E	17	6 1/4	P	0
112	1935-12-28	G	0.0, 98.4E	-	7 3/4	D	0
113	1936- 4-01	A	4 1/2N, 126 1/2E	-	7 3/4	D	-
114	1937-11-06	C	Fakfak	-	6	P	-1/2
115	1938- 2-02	J	5 1/4S, 130 1/2E	-	8 1/4	S	1 1/2
116	1938- 2-13	C	Fakfak	-	6	P	-1/2
117	1938- 5-20	D	0.7S, 120.3E	-	7 1/2	S	1 1/2
118	1939-12-22	D	0.0, 123.0E	150	-	L	1/2
119	1948- 6-02	F	5 1/2N, 94.0E	-	6 1/2	P	0
120	1950-10-08	J	4.0S, 128.0E	-	7 1/4	L	2?
121	1957- 9-26	H	8.2S, 107.3E	-	5 1/2	L	0
122	1957-10-26	E	2.0S, 116.0E	-	6	P	0
123	1958- 4-22	G	4 1/2S, 104.0E	200	6 1/2	P	1/2
124	1963-12-16	H	6.4S, 105.4E	64	6 1/2	P	0
125	1964- 4-02	F	5.9N, 95.7E	130	7	L	0
126	1965- 1-24	J	2.4S, 126.1E	6	7 1/2	L	2
127	1967- 4-11	D	3.3S, 119.4E	20	5 1/2	P	1
128	1967- 4-12	F	5.5N, 97.3E	100	7 1/2	L	1 1/2
129	1968- 8-10	B	1.4N, 126.2E	-	7 1/2	S	1
130	1968- 8-14	D	0.2N, 119.8E	25	7 1/4	S	2 1/2
131	1969- 2-23	D	3.1S, 118.9E	13	6.1	S	3*
132	1977- 8-19	I	12.0S, 118.0E	-	7.9	S	4**

* Private communication from Seismological Section, Japan Meteorological Agency

** Reported by Indonesian Meteorological and Geophysical Center and the report of the Indonesian Meteorological and Geophysical Center (IMGC) in 1977. In total, 132 tsunamis are listed, covering the period 1629 to 1977.

The geographical profile of Indonesia is illustrated by Fig.1; it lies within the area enclosed by the lines of 10°N, 15°S, 95°E and 135°E. In Fig.1, the main profile of the coast line is simplified. The plates around Indonesia are also shown in Fig.1 and the limits of the plates are illustrated by thick full and dotted lines following the IMGC report of 1977. A glance at Fig.1 will show that the Indonesian area is very complicated from the seismological point of view.

Geographical classification of the area is shown in Tables 1 and 2. Adopting a different method of area classification, the author proposes to divide the area of Indonesia into subdivisions of five degrees square. This is hoped to remove the effects of preconceptions on the area classification. For each, subdivision, the occurrence frequency of the tsunamis exceeding tsunami intensity 0 and the period from the oldest tsunami

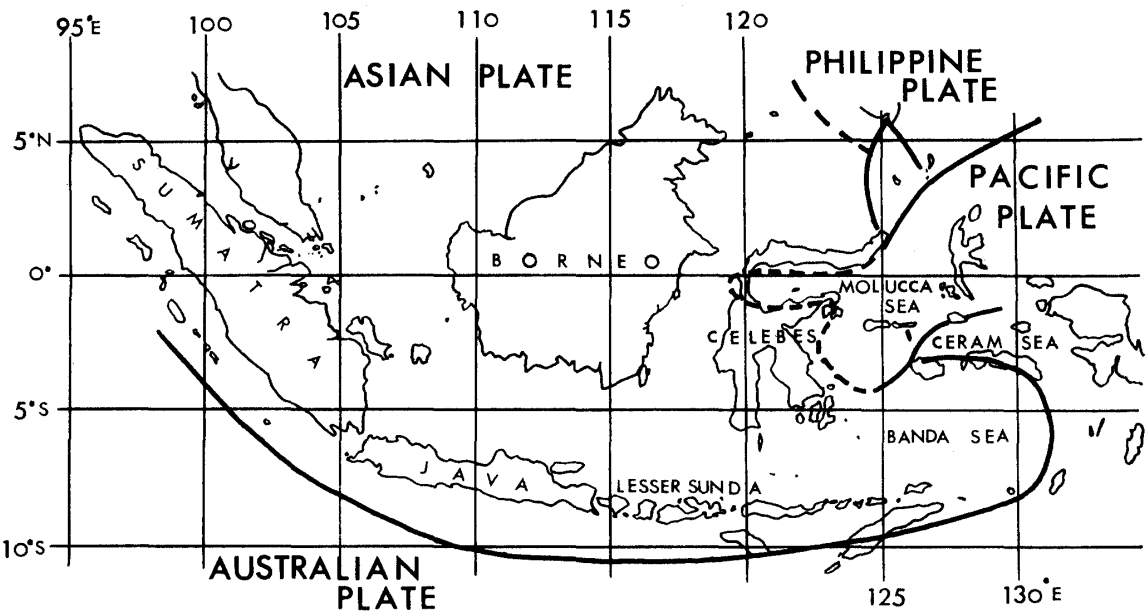

Fig. 1 Coast Line of Indonesia

Table 3 Distribution of Tsunami Sources

Longitude(°E) / Latitude(°)	90-95	95-100	100-105	105-110	110-115	115-120	120-125	125-130	130-135
10°N- 5°N	1/162	3/162							
5°N- 0°		5/162				3/57	1/119	13/305	
0° - 5°S		5/162	8/162			2/57	2/81	21/330	0/118
5°S-10°S			1/208	4/256	3/256	8/164	2/164	3/126	2/119
10°S-15°S					0/256	(1/164)	1/164		

Note: Pairs of integer A and B are shown by A/B, where A is occurrence frequency of tsunami in the area of five degrees square and B is the number of years from the first reliable report of a tsunami to 1977 (in the same area).

record to 1977 are denoted by A and B respectively. Tabulation for A/B is in Table 3. The result in Table 3 shows that the majority of tsunami sources is concentrated in the area adjacent to the lines limiting the plates shown in Fig.1.

III Statistical Analysis

When reliable reported tsunamis exceeding tsunami intensity 0 in Indonesia are reckoned we find 89 cases in the period of 1629 to 1977 in Indonesia. Making the assumption that this "sample population" of tsunami occurrence, it is possible to attempt to estimate the probability of tsunami occurrence.

Occurrence probability $\Lambda(m)$ of the tsunami exceeding a given tsunami intensity m is related to return period $T(m)$ as follows.

$$\Lambda(m) = 1/T(m)$$

When tsunami occurrence in Indonesia is assumed to be a Poisson process, the occurrence probability of a tsunami exceeding tsunami intensity m in a given period t is written as

$$P = 1-\exp\left(-\Lambda(m)\cdot t\right)$$

and

$$\Lambda(m) = \Lambda_0 \exp\left(-\beta(m-m_0)\right) \qquad \text{for } m \geqslant m_0$$

where $\Lambda_0 = \Lambda(m_0)$.

Statistical analysis for tsunami risk have been developed and presented by Wiegel (1970), Rascon and Villareal(1975) and Nakamura(1978).

When it is taken that $m_0=0$, the values of Λ and β for each tsunami intensity m ($m \geqq m_0$) can be determined using the data in Table 1. Each of the value Λ is related to tsunami intensity as plotted by circles in Fig.2. As an average over the range of tsunami intensity $0 \leqq m \leqq 4$, the results are

$$\Lambda_0 = 0.255 \qquad \text{and} \qquad \beta = 0.781$$

The straight line in Fig.2 is the relation between Λ and m obtained by using the above values of Λ_0 and β.

In order to find a curve to fit the plotted circles in Fig.2, a modification of Poisson process is considered. By introducing a modified Poisson process, the author proposes to express the occurrence probability of a tsunami exceeding tsunami intensity m in a given period t in form of

$$P = 1-\exp\left(-\Lambda(m)\cdot t\right)$$

and

$$\Lambda(m) = \Lambda_0 \exp\left(-\beta(m-m_0)^n\right)$$

If $m_0=0$, the above relation between Λ and m is

$$\Lambda(m) = \Lambda_0 \exp(-\beta m^n)$$

A systematic analysis was carried out in order to find a curve based on the above formula which would also fit the plots in Fig.2. The set of the values were selected as

$$\Lambda_0 = 0.250, \quad \beta = 0.50 \quad \text{and} \quad n = 1.5$$

In Fig.3, we find that a curve for the above three values fits well whereas the curves for $n=1$ and $n=2$ do not. As a result of this analysis, it is suggested that a modified Poisson process is useful in the analysis of statistical tsunami risk as a function of tsunami intensity.

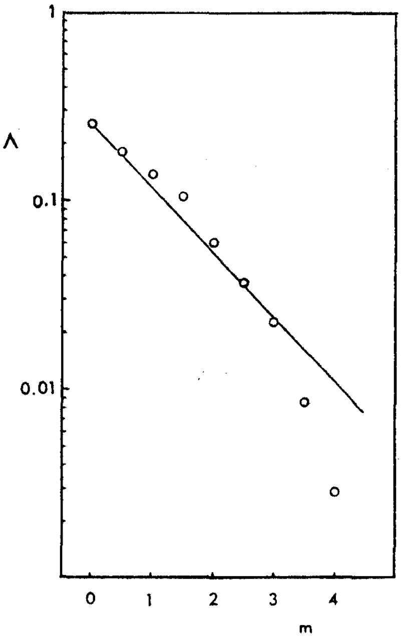

Fig. 2 Relation between Λ and m as a Poisson Process

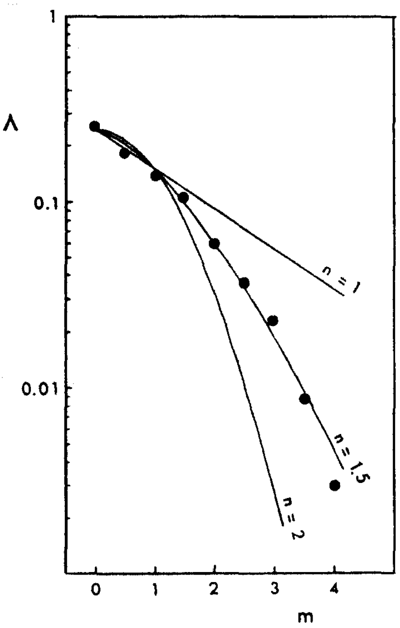

Fig. 3 Curves for a Modified Poisson Process

Using this result, occurrence probability of a tsunami exceeding a given tsunami intensity in a given period t years is calculated as in Fig.4. In Fig.4, the probability P in percent and tsunami intensity m are taken as the abscissa and the ordinate on a normal probability graph with a parameter of period t. This diagram indicates, for example, that the occurrence probability of a tsunami exceeding tsunami intensity 2 in 50 years is about 95 percent. When the probability is related to the period t, a diagram requires a parameter of tsunami intensity on a logarithmic probability graph as in Fig.5.

Rascon and Villareal applied Bayes' theorem in order to obtain a reliable estimate by the analysis of tsunami occurrence as a Poisson process. If the other statistical factors are similar in characteristics to tsunami occurence, it is useful to introduce Bayes' theorem in order to obtain a reliable solution for tsunami risk. I did not, however, consider Bayes' theorem to be appropriate to this analysis.

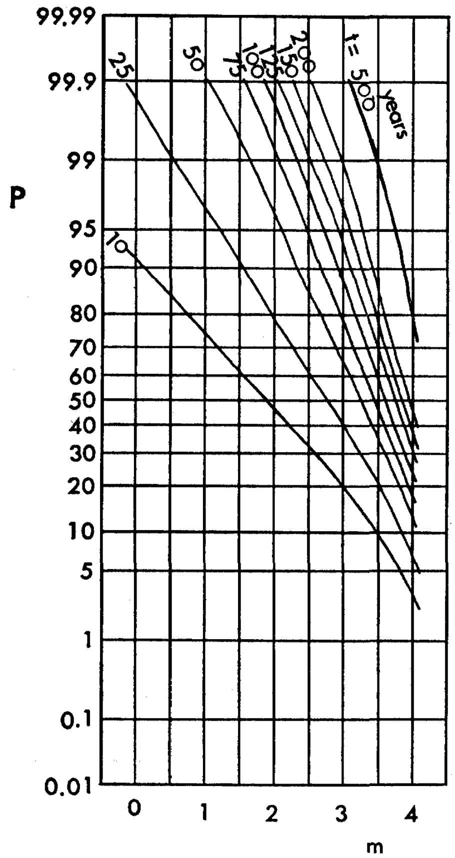

Fig. 4 Probability of Tsunami Risk in Relation to Tsunami Magnitude with Parameter of Period

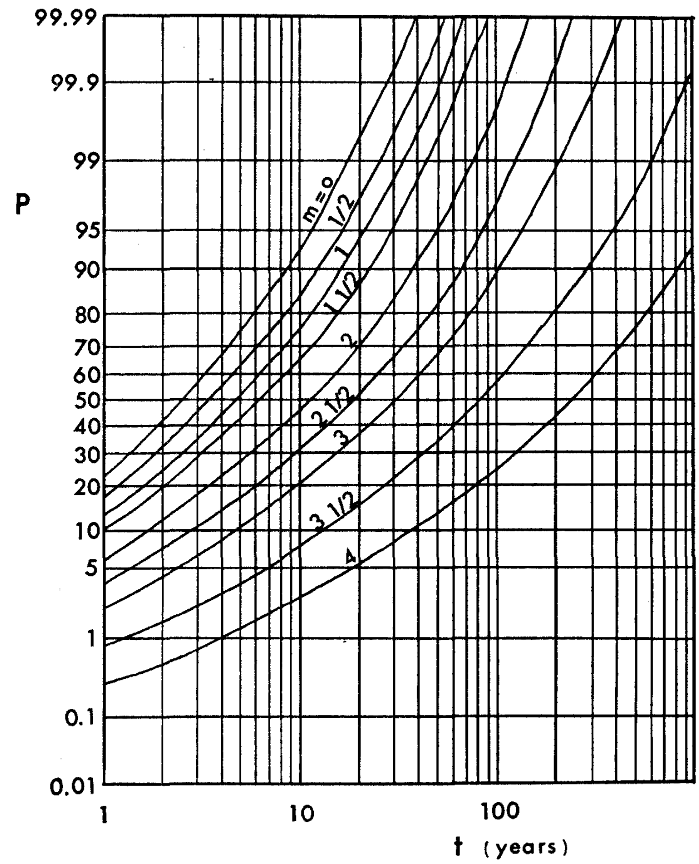

Fig. 5 Propability of Tsunami Risk in Relation to Period with Parameter of Tsunami Magnitude

VI Remarks on Local Tsunami Statistics

When dealing with local tsunami risk, it is necessary to consider the local characteristics of the tsunami occurrence in the subdivision under consideration. And it is usually accepted that the result obtained is uniformly applicable in the area of Indonesia. When, however, the statistical analysis is applied to the data obtained up to July 1977, the possibility of tsunami occurrence on 19th August 1977 in the subdivision encircled by the lines 10°S, 15°S, 115°E and 120°E, is negligible.

And it should be remarked also that the same evaluation of tsunami risk is obtained for the subdivision encircled by 10°S, 15°S, 115°E and 120°E and for the subdivision encircled by 10°S, 15°S, 120°E and 125°E, even when the statistical analysis is carried out by the use of the data including the latest tsunami. Both of the evaluations for the above two subdivisions are the same one as that for the case when analysis is carried out for a subdivision where one tsunami exceeding tsunami intensity 0 has occurred in a period of 164 years.

Lastly, it should be noted that statistical tsunami risk should be considered, as far as possible, in the context of an understanding of the dynamics of the earthquakes and tsunamis in the area or subdivisions under consideration.

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