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On Statistical Tsunami Risk of the Philippines

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I Introduction

Philippines are on the Circum-Pacific Earthquake Zone, so that they have suffered from the earthquakes and tsunamis for many times repeatedly. The latest example is the earthquake and tsunami at the south of Mindanao Island in August 1976. The suffers caused by the earthquakes and tsunamis have been compiled and analyzed to develop an effective countermeasure against the destructions. The reference for the countermeasure is the compiled data as a chronological records. Adding to that, the earthquakes and tsunamis have been understood as one of the significant geophysical phenomena and studied by a dynamical analysis. And the fruitful results of the research seems yet not fully utilized in the prediction and countermeasure against the risk of the earthquakes and tsunamis. In this article, the tsunamis in Philippines are analyzed statistically to obtain basic data for the prediction and countermeasure against the next occurrence. At first, the compiled data of the tsunamis in Philippines are rearranged to tabulate chronological tsunami tables for the localities and to reduce the local return period of the tsunami occurrences. And, the tsunami occurrences are assumed as a Poisson process which is a special case of stochastic processes through the analysis to obtain the local probabilities of the wave height exceeding the given height during the given time interval for any locality. Referring to the statistical result of the tsunami risk, countermeasures and recommendations may be offered effectively to the protection of the coast in Philippines.

II Compiled data of tsunamis in Philippines

The data of the earthquakes in Philippines have been presented by Minõza et al. (1960)[1], Repetti (1946)[2] and Damasco (1969)[3]. As for the tsunamis in Philippines, we have only two catalogs edited by Iida et al. (1967)[4] and Soloviev and Gao (1970)[5]. The catalog 1967 is a chronological table of the tsunamis observed in the world with a remark to the localities. And the catalog 1970 is classifying the tsunamis in each nationality and tabulated in a local chronological table with a digest of the documents. Soloviev and Gao gave a chronological table of the tsunamis for each of the six local districts in Philippines: northeastern Philippines, northwestern Philippines, central Philippines, eastern Philippines,

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Table 1 Chronological catalogs of local tsunamis in Philippines.

Locality	No.	Date		Location	Depth	M	Reliability	m
Eastern Luzon	101	1735	2-27	Baler	—	—	PX	1 1/2
	102	1880	7-18	15 N, 121.5E	100km	7 1/2	PX	0
	103	1901	9-10	Lamon Bay	—	7	PX	0
	104	1937	8-20	14.5N, 121.5E	—	7 1/2	LX	1
	105	1949	9-05	17.0N, 121.0E	80	6	E	−4
	106	1949	12-29	17.0N, 121.0E	80	7 1/2	D	1
	107	1968	8-02	19.5N, 122.2E	36	7 1/4	S	—
Western Luzon	201	1627	9-	Bangui	—	8 ?	L	3 1/2
	202	1645	11-30	NW Luzon	—	8 ?	D	—
	203	1872	1-26	16.0N, 119.0E	—	6 ?	L	1 1/2
	204	1915	11-18	18.0N, 119.5E	—	6 1/2	PX	1/2
	205	1924	5-07	16.0N, 119.0E	—	6 1/2	S	1 1/2
	206	1934	2-14	17.4N, 119.3E	—	7 1/2	S	1/2
Near Manila	301	1677	12-07	14.5N, 120.5E	—	—	P	1
	302	1744	-	N Luzon	—	—	PX	1
	303	1770	12-	Manila	—	—	DX	0
	304	1824	10-26	14.3N, 121.3E	—	—	DX	1
	305	1828	11-09	Manila	—	7 1/2	D	1/2
	306	1880	1-18	Manila	—	—	E	—
	307	1852	9-16	14.0N, 120.5E	—	7 1/2	PX	1 1/2
	308	1862	3-04	Manila	—	6	PX	1/2
	309	1863	6-03	14.5N, 121.0E	—	6 1/2	P	1
Central Philippines	401	1653	6 or 7-	NE Mindoro	—	—	D	1
	402	1675	3-	Pola, Mindoro	—	—	P	1
	403	1747	-	SE Luzon	—	—	DX	—
	404	1840	2-22	Sorsogon, Luzon	—	6 1/2	D	1
	405	1865	10-19	13.3N, 123.5E	—	6	PX	0
	406	1869	8-16	12.5N, 123.5E	—	7	PX	0
	407	1887	2-02	Panai	—	—	D	—
	408	1889	5-26	13.5N, 121.0E	—	6 3/4	L	−3
	409	1905	12-08	11.0N, 123.5E	—	6 1/2	DX	0
	410	1922	2-28	10.2N, 124.1E	—	6 1/4	P	0
	411	1922	3-01	9.0N, 123.3E	—	6	PX	1/2
	412	1925	5-05	9.3N, 122.7E	—	6 3/4	PX	1/2
	413	1925	5-25	12.2N, 122.1E	—	6-1/4	PX	1/2
	414	1925	11-13	13.0N, 125.0E	—	7 1/4	PX	1/2
	415	1928	6-15	12.4N, 120.9E	—	7.0	X	1/2
	416	1939	5-07	13.5N, 121.3E	110	6 1/2	DX	1/2
	417	1948	1-25	10.9N, 122.1E	—	8 1/4	L	1
Southern Mindanao	501	1897	9-21	6.0N, 122.0E	—	3.6	D	1
	502	1897	9-21	6.8N, 121.5E	—	8 1/2	S	2 1/2
	503	1902	8-21	7.5N, 123.5E	—	7 1/4	D	—
	504	1917	1-31	5.5N, 125.0E	—		LX	0
	505	1918	8-15	5.5N, 124.5E	—	8 1/4	S	2 1/2
	506	1923	3-03	6.5N, 124.0E	—	7 1/4	LX	1/2
	507	1928	12-19	7.0N, 124.0E	—	7 1/4	L	1
	508	1976	8-16	6.8N, 123.4E		7.8	S	(14 ft)
Eastern Mindanao	601	1910	12-30	9.0N, 125.5E	80	6 1/4	DX	1
	602	1911	7-12	9.0N, 126.0E	50	7 3/4	DX	—
	603	1921	11-12	8.0N, 127.0E	—	7 1/2	LX	1
	604	1923	7-13	9.5N, 127.0E	—	5 1/2	DX	1
	605	1924	4-15	6.5N, 126.5E	—	8 1/4	P	1/2
	606	1924	8-30	8.5N, 126.5E	—	7 1/4	PX	1/2
	607	1929	6-13	8.5N, 127.0E	—	7 1/4	P	1/2
	608	1932	3-19	9.5N, 127.3E	—	7 3/4	S	—
	609	1972	12-04	6.5N, 126.6E	40	7.6	S	−1

In the column of 'reliability' S, L, P, D and E denote sure, likely, probable, doubtful and erroneous respectively. Notation X indicates that the tsunami is registered in Catalog 1970 but Catalog 1967.

southern Philippines and western Philippines.

The author rearranged the table presented by Soloviev and Gao as shown in Table 1 and Fig. 1 in order to have a rational consideration of the localities and to ease the statistical analyses. Another six districts are introduced by the author, i. e., i eastern Luzon, ii western Luzon, iii near Manila, iv central Philippines, v southern Mindanao and vi eastern Mindanao. The formation of the columns in the table (Table 1) is prepared after that presented by Soloviev and Gao. The maximum tsunami heights are estimated referring to the categories of tsunami intensity by Soloviev (1970)[6]. And it seems that many additional and miscellaneous data are included in the catalog 1970 in comparing to the preliminary catalog 1967. Some of the same tsunamis was registered and dated differently in the two catalogs. In Table 1, the latest and recent data are added, i. e., one in 1972 from the record by Osaka Regional Meteorological Observatory and one in 1976 from the report by PAGASA (1976)[7]. In the statistical analyses of the local tsunami risks, reliability of the data is taken into consideration to exclude erroneous and doubtful terms in the local chronological table of the tsunamis.

III Statistical model of tsunami occurrences

In this article, the tsunamis caused by the earthquakes are treated.

As a prevailed concept, the tsunamis have been accepted as the accompanied phenomena with the earthquakes. Recent statistical studies have shown that the tsunami occurrence can be analyzed as a Poisson process similar to the earthquake occurrence (Newmark and Rosenblueth, 1971)[8].

When the frequency of the tsunamis exceeding the wave height H is $\Lambda(H)$, then, the mean time interval to appear the tsunamis exceeding the wave height H is

$$T(H)=1/\Lambda(H) \qquad (1)$$

where $T(H)$ is defined as 'return period'. If we can find $T(H)$ or $\Lambda(H)$ by any processing of the data, a probability P can be obtained for the case that the maximum wave height Y exceeds H at once at least during the time interval t. If the tsunamis are analyzed as a Poisson process,

$$P=1-\exp(-t/T(H))=1-\exp(-\Lambda(H)\cdot t) \qquad (2)$$

Wiegel (1970)[9] had shown the linear relations between H and the logarithm of $\Lambda(H)$ for the tsunamis at Hilo in Hawaii, San Francisco and Crescent City in California. That is

$$(H)=\Lambda_0\exp(-\beta(H-H_0))\ ;\ H\geqslant H_0 \qquad (3)$$

where $\Lambda_0=\Lambda(H_0)$, β is a constant, H_0 is the smallest value of the maximum wave height H in the statistical and reliable tsunami data.

Rascón and Villareal (1975)[10] considered that the relation shown by Wiegel as mentioned above can be found on the coast of Mexico facing Pacific Ocean ad analyzed to apply Bayes' theorem in order to refine the statististical analyses. Although this refinement does not include any dynamical or physical consideration. Now, the author introduce a result of the statistical analyses by the use of the above three relations under some suitable assumptions.

IV Return period of tsunami occurrence

The return period of tsunami occurrence for each local blocks (Fig. 1) are analyzed, though the available samples are not necessarily sufficient as a statistical sample ensemble.

4. 1 Eastern Luzon

The tsunami occurrences were 5 times during 243 years from 1935 to 1977. In the table, some ambiguity in reliability was checked to assure the estimated tsunami height, for example, 1m. The result of the analyses is shown in Fig. 2. In this case, the obtained constants are

$$A_0=0.0206,\ \beta=0.747,\ H_0=0.9 \qquad (4)$$

4. 2 Western Luzon and near Manila

The two districts, western Luzon and near Manila, are considered to analyze. In the table, the estimate of the tsunami in 1627 is surely little reliability as the statistical data. If that is reliable, we have to understand so as that the amomarous tsunami which might scarecely occur appeared in the finite time interval of 351 years from 1627 to 1977. If the time interval is taken to be longenough statistically, of cause, the enormous tsunami, such as that in 1627, is scarecely expected to be observed.

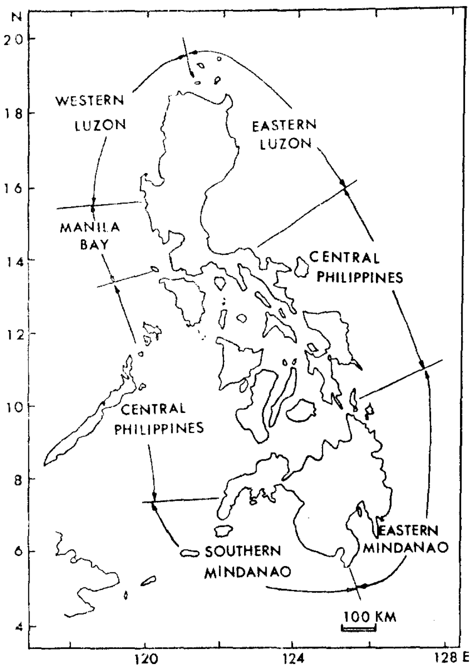

Fig. 1 Zoning of the coastal areas in Philippines.

In Fig. 3, the result (A) from the data for 351 years (1627–1977) and the result (B) from the data for 301 years (1677–1977) are shown.

As for the curve (A),

$$A_0=0.0256,\ \beta=0.336,\ H_0=1.3 \qquad (5)$$

As for the curve (B),

$$A_0=0.0266,\ \beta=0.454,\ H_0=1.3 \qquad (6)$$

4. 3 Central Philippines

The tsunamis in the central part of Philippines had been observed 10 times during 325 years (1653–1977). In Table 1, the tsunami intensity in 1889 is anomarously small. We now have to understand that the other tsunamis of the anomarously small intensity should be excluded through the compilation or should be not registered as the tsunamis. This might be likely when the registered earthquake occurrences are considered to be similar to

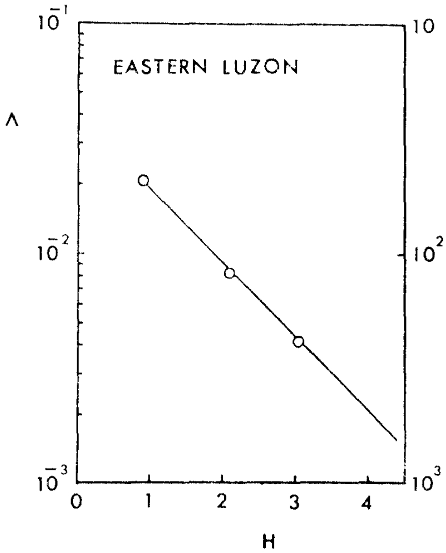

Fig. 2 Return period in eastern Luzon. (A, T and H are in units of per year, year and meter respectively.)

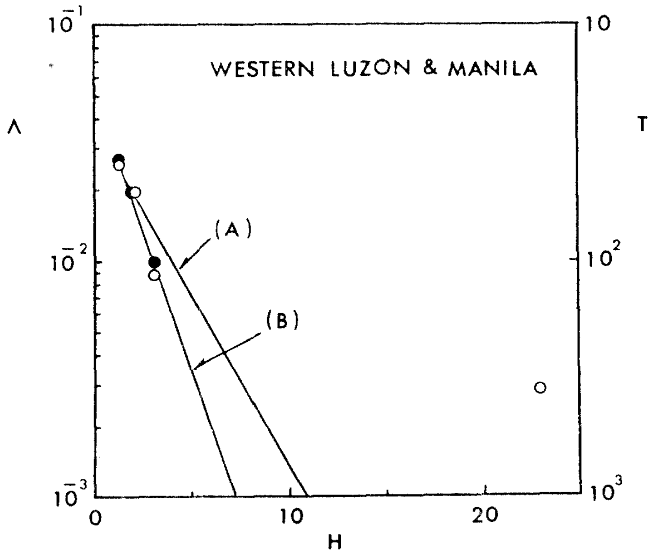

Fig. 3 Return period in western Luzon and near Manila. (A, T and H are in units of per year, year and meter respectively.)

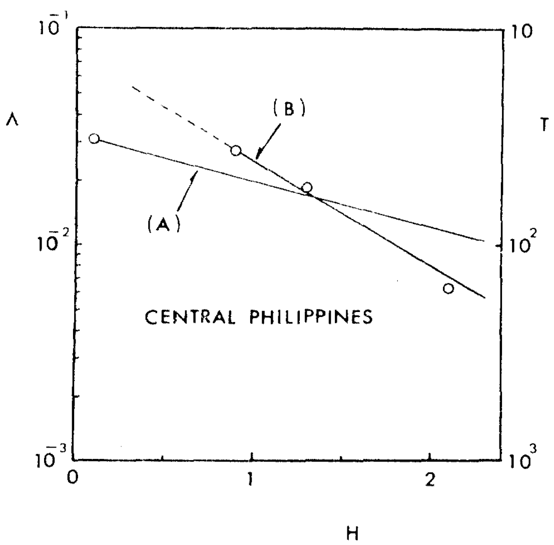

Fig. 4 Return period in central Philippines. (A, $T$and H are in units of per year, year and meter respectively.)

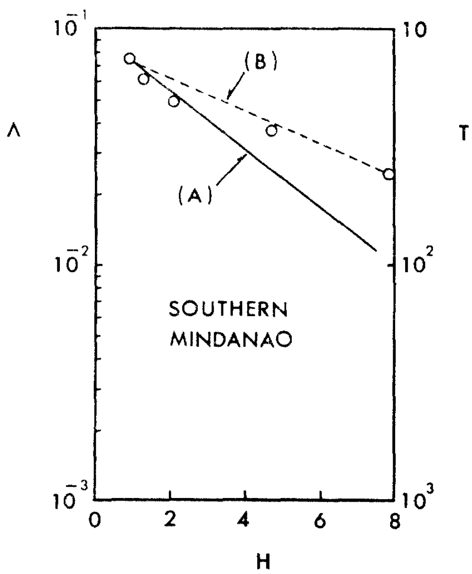

Fig. 5 Return period in southern Mindanao. (A, T and H are in units of per year, year and meter respectively.)

the tsunami occurrences are. With these considerations, the result (A) including and the Result (B) excluding the data in 1889 are shown in Fig. 4.

As for the curve (A),

$$A_0 = 0.0308,\ \beta = 0.454,\ H_0 = 0.1 \qquad (7)$$

As for the curve (B),

$$A_0 = 0.0277,\ \beta = 1.132,\ H_0 = 0.9 \qquad (8)$$

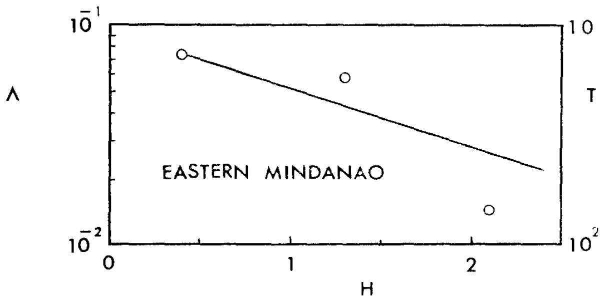

Fig. 6 Return period in eastern Mindanao. (A, T and H are in units of per year, year and meter respectively.)

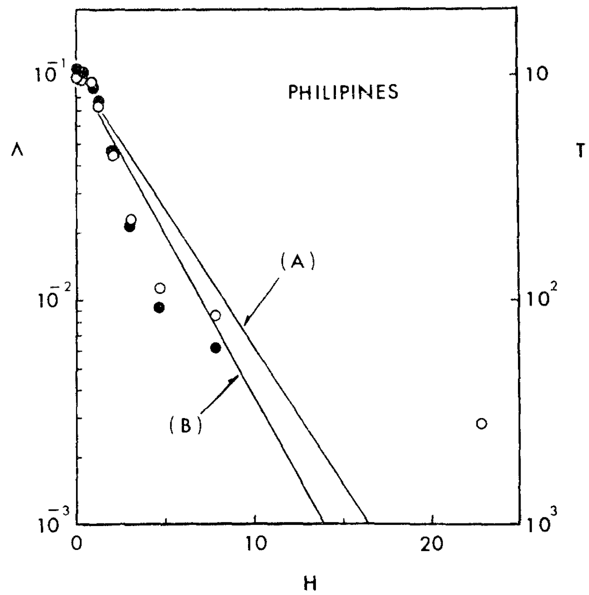

Fig. 7 Return period in Philippines. (A, T and H are in units of per year, year and meter respectively.)

If the curve (B) in Fig. 4 is assumed to be actual, it might be possible to count out the whole tsunami occurrences of the small intensity.

4. 4 Southern Mindanao

Six times observed the tsunamis during 81 years (1897–1977). The intensity of the three tsunamis in the above six are equal to 2 or exceeding 2.

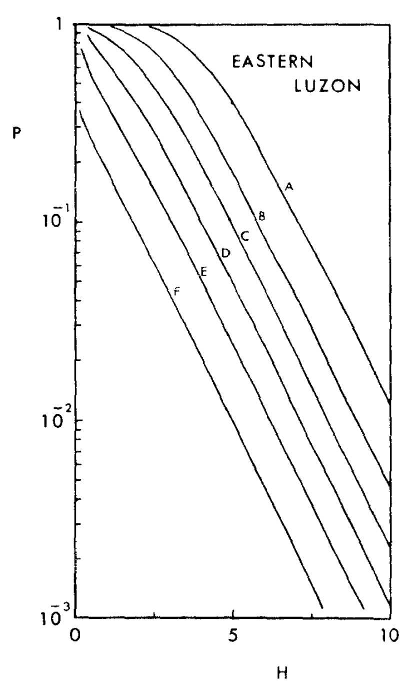

Fig. 8 Statistical tsunami risk in eastern Luzon. Curves A, B, C, D, E and F are for T=500, 200, 100, 50, 25 and 10 years respectively. (P and H are exceeding occurrence probability and wave height in meter.)

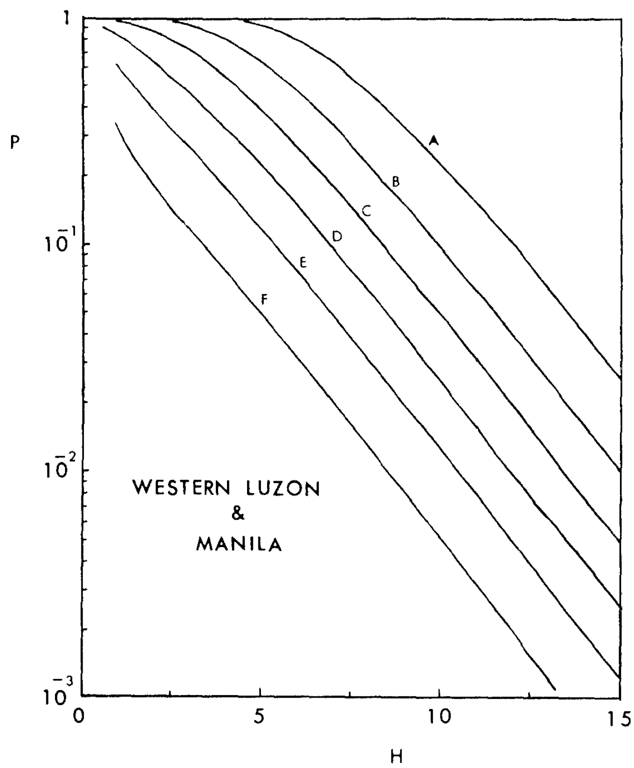

Fig. 9 Statistical tsunami risk in western Luzon and near Manila. Curves A, B, C, D, E and F are for T=500, 200, 100, 50, 25 and 10 years respectively. (P and H are exceeding occurrence probability and wave height in meter.)

The constants in (3) are obtained as follows (A):

$$A_0=9.974,\ \beta=0.283,\ H_0=0.9 \tag{9}$$

The trend of this is shown by the curve (A) in Fig. 5.

Now, we have to remind that the recent records of the tsunamis are more reliable than the old documents of the ancient tsunamis. This might support that the effective appreciation might be in an envelope as shown for example by the curve (B) in Fig. 5, i. e.,

$$A_0=0.074,\ \beta=0.157,\ H_0=0.9 \tag{10}$$

4. 5 Eastern Mindanao

In this district, five tsunamis were observed during 68 years (1910–1977). The result of the analysis is shown in Fig. 6. And the constants are

$$A_0=0.0735,\ \beta=0.598,\ H_0=0.4 \tag{11}$$

4. 6 Philippines

The analyses are carried out the cases including and excluding the data in 1627, i. e., as for the case including 1627, the curve (A) is obtained as shown in Fig. 7 and the constants are

$$A_0=0.0997,\ \beta=0.280,\ H_0=0.1 \tag{12}$$

and as for the case excluding 1627, the curve (B) is obtained and the constants are

$$A_0=0.1046,\ \beta=0.336,\ H_0=0.1 \tag{13}$$

V Risk of local tsunami

When the probability of the tsunami occurrence is assumed to be an indicator of the risk caused by the tsunamis, we may predict the risk by the use of the probability.

The constants (4) to (13) for (2) characterize each local district respectively. Using these constants, the probability of the tsunami occurrences is reduced to show curves as in Figs. 8 to 13 for each local district respectively. And the remarks are that the curves in Fig. 10 are reduced by using the curve (B) in Fig. 4 and the curves in Fig. 11 are obtained by the curve (B) in Fig. 5.

As for the whole area of Philippines, the curves are reduced as shown in Fig. 13, which predicts that a tsunami exceeding 10m of the maximum wave height once in 100 years at anywhere in Philippines is expected to occur in probability about 0. 3. And that, the probability is 0. 4 to be expected a tsunami once in 25 years exceeding 5m of the maximum wave height.

With a comparison of the local tsunami occurrence probabilities for the six districts for a given time interval, the most probabl district of threatening to suffer from a tsunami is the southern Mindanao. And the districts of the eastern Mindanao, the western Luzon and near Manila are followed.

To help an understanding to the local tsunami risk, how high is the maximum wave height expected once in 10 years in probability 1/10, is read out of Figs. 8 to 13 to tabulate

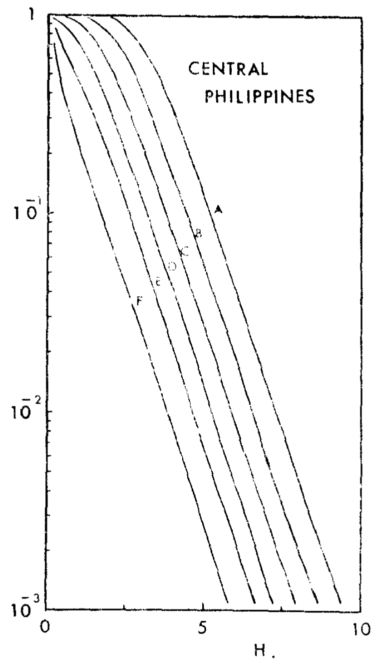

Fig. 10 Statistical tsunami risk in central Philippines. Curves A, B, C, D, E and F are for $T=$ 500, 200, 100, 50, 25 and 10 years respectively. (P and H are exceeding occurrence probability and wave height in meter.)

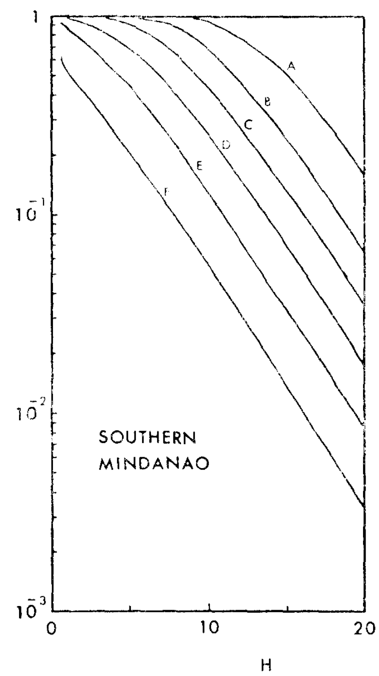

Fig. 11 Statistical tsunami risk in southern Mindanao. Curves A, B, C, D, E and F are for $T=$ 500, 200, 100, 50, 25 and 10 years respectively. (P and H are exceeding occurrence probability and wave height in meter.)

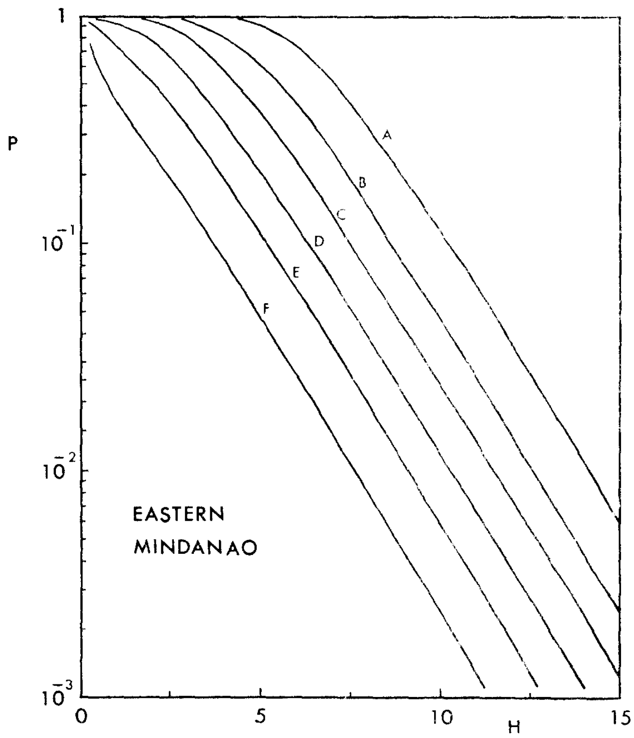

Fig. 12 Statistical tsunami risk in eastern Mindanao. Curves A, B, C, D, E and F are for $T=500$, 200, 100, 50, 25 and 10 years respectively. (P and H are exceeding occurrence probability and wave height in meter.)

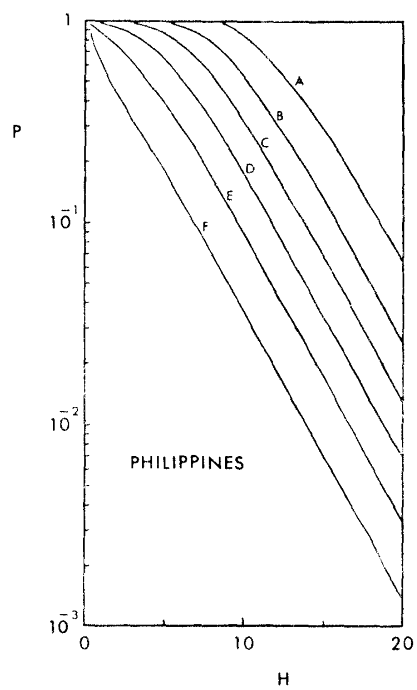

Fig. 13 Statistical tsunami risk in Philippines. Curves A, B, C, D, E and F are for $T=500$, 200, 100, 50, 25 and 10 years respectively. (P and H are exceeding occurrence probability and wave height in meter.)

Table 2 Maximum tsunami height expected to occur once in 10 years in probability 1/10.

Locality	Expected maximum wave height
Eastern Luzon	1.8 m
Western Luzon and near Manila	3.3 m
Central Philippines	1.7 m
Southern Mindanao	7.8 m
Eastern Mindanao	3.6 m
Philippines	6.8 m

Table 3 Probability of the maximum tsunami height exceeding 2m to occur once in 10 years.

Locality	Probability
Eastern Luzon	0.087
Western Luzon and near Manila	0.17
Cetral Philippines	0.077
Southern Mindanao	0.42
Eastern Mindanao	0.24
Philippines	0.43

the prediction as in Table 2. This table shows that the tsunami risk in the southern Mindanao is the most remarkable than that in the other districts and is almost same to the tsunami risk in the whole area of Philippines. That is, in other words, the southern Mindanao will have possibly often experiences of tsunamis in Philippines. This result might be reduced also by Table 3, which shows that the local probabilities of the tsunami occurrence once in 10 years exceeding 2m of the maximum wave height.

Conclusions

A statistical analysis of the local tsunami occurrences is carried out with an assumption that the tsunamis occur as a Poisson process. The obtained results are useful to predict the probability of the wave height exceeding the given height during the given time interval at any locality in Philippines.

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