BULLETIN OF THE EARTHQUAKE
RESEARCH INSTITUTE
Vol. 46 (1968), pp. 345-359

15. *Study on Distant Tsunamis along the Coast of Japan. Part 2, Tsunamis of South American Origin.*

By Tokutaro HATORI,

Earthquake Research Institute.

(Read Oct. 24, 1967.—Received Jan. 31, 1968.)

Abstract

Making use of data of tsunamis which occurred in the region of South America, frequencies of tsunami generation and of tsunami which propagated to Japan are investigated. Refraction diagrams and the distributions of tsunami height for seven tsunamis which propagated across the Pacific Ocean are shown. Especially, these phenomena along the coast of Japan are shown in detail with the aid of mareograms. The spectral analysis of records obtained in Japan is made for five tsunamis.

The generating area of the Chilean tsunami of 1960 is estimated by means of an inverse refraction diagram. This source includes the area of aftershock activity extending about 800 km in an elongated shape.

Introduction

Six tsunamis, originating in regions from the Kurile Islands to Alaska since 1952, and the Chilean tsunami of 1960 were studied by the author[1] with respect to the distributions of tsunami energy and refraction diagram along the coast of Japan. Yumura[2] gave a list of tsunamis which were generated far from Japan and observed along the coast of Japan. This list includes several historical tsunamis generated off Peru and Chile. Since 1900, some small tsunamis[3),4)] generated off the coast of South America have been observed by tide gauges at several places in Japan.

In this paper, the behavior of tsunamis generated in regions from

1) T. HATORI, "Study on Distant Tsunamis along the Coast of Japan, Part 1, Distribution of Tsunami Energy and Travel Time," *Bull. Earthq. Res. Inst.*, **43** (1965), 499.

2) T. YUMURA, "List of Tsunamis Which Accompanied Distant Earthquakes," *Technical Rep. JMA*, **8** (1961), 247, (in Japanese).

3) K. HONDA, T. TERADA, Y. YOSHIDA and D. ISITANI, "Secondary Undulations of Oceanic Tides," *J. Coll. Sci. Imp. Univ. Tokyo*, **24** (1908).

4) A. IMAMURA and M. MORIYA, "Mareographic Observations of Tsunamis in Japan during the period from 1894 to 1924," *J. Astr. Geophys. Japan*, **17** (1939), 119.

Colombia to Chile is discussed. Among earthquakes with a magnitude greater than 7 occurring near the Pacific coast of South America during the period from 1900 to 1966, the frequency of tsunami occurrence is investigated. Further, making use of the long-wave records taken at Miyagi-Enoshima since 1958, the frequency of tsunami arrivals to Japan from South America is checked.

For tsunamis of 1868, 1877, 1960 and four other small tsunamis, refraction diagrams and the distribution of tsunami height in the whole region of the Pacific Ocean are shown by using data given in (5), (6) and (7). Refraction diagrams in the adjacent Sea of Japan are drawn in detail on the basis of arrival times of wave fronts estimated from tide records, and also the spectral analyses of tsunami records are made. The generating area of the 1960 Chilean tsunami is estimated by means of an inverse refraction diagram together with date of the field investigation near the origin.[8),9),10)]

Frequency of tsunami generation

According to the "Preliminary Catalog of Tsunami Occurring in the Pacific Ocean,[7)]" about 52 tsunamis have been documented in the sea adjacent to South America, from South Colombia to South Chile (O, P and Q regions), the oldest one occurring in 1562 and the latest one in 1966. Fifteen tsunamis reached the coast of Japan, among which were five tsunamis with heights more than 2 meters which caused damage to the Sanriku coast. The epicenters of earthquakes accompanied by these tsunamis are plotted in Fig. 1, where the radius of the circle indicates tsunami height in Japan and the numerals outside the circles indicate the year of occurrence.

5) J. MILNE, "The Peruvian Earthquake of May 9th, 1877," *Trans. Seism. Soc. Japan*, **2** (1880), 50.

6) S. C. BERKMAN and J. M. SYMONS, "The Tsunami of May 22, 1960 as Recorded at Tide Stations, *USCGS, Washington*, (1964).

7) K. IIDA, D. C. COX and G. PARARAS-CARAYANNIS, "Preliminary Catalog of Tsunamis Occurring in the Pacific Ocean," *Hawaii Inst. Geoph., Hawaii Univ., Data Report No.* **5**, HIG-67-10, Aug. 1967.

8) K. HORIKAWA, "Outline of the Tsunami of 1960 in Chile and Other Places," *Kaigan*, **28** (1961), 1, (in Japanese).

9) T. HIRONO, "The Chilean Earthquake of 1960," *J. Geography*, **70** (1961), 122, (in Japanese).

10) R. TAKAHASI and T. HATORI, "A Summary Report on the Chilean Tsunami," *Rep. Chilean Tsunami, Field Invest. Comm. Chilean Tsunami* (1961), 23.

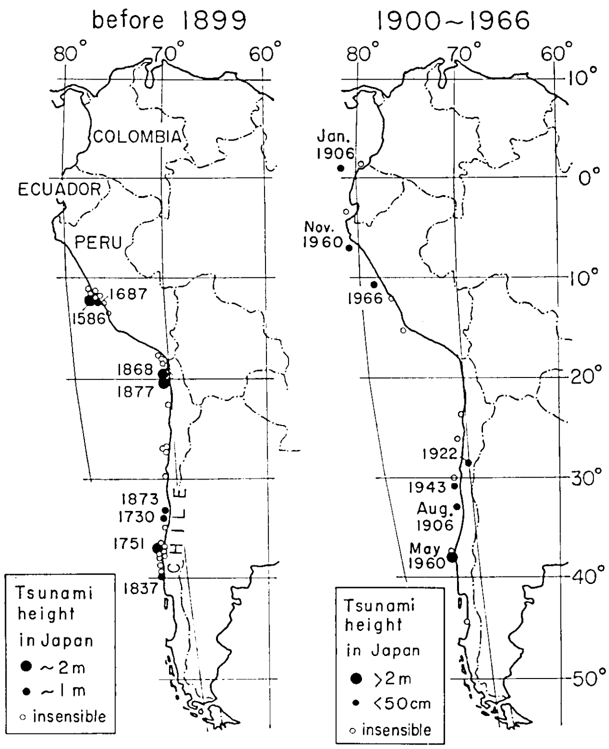

Fig. 1. Geographic distribution of epicenters of earthquakes accompanied by tsunamis.

Table 1. Number of earthquakes (A), tsunamigenic earthquakes (B) which occurred near the Pacific coast of South America and of tsunami (C) which was observed in Japan during the period from 1900 to 1966.

Earthquake magnitude M	A	B	C
<6.9	—	1	1
7.0~7.2	49	3	0
7.3~7.5	22	3	1
7.6~7.8	9	3	0
7.9~8.1	4	2	1
8.2~8.4	2	2	2
8.5~8.6	2	2	2

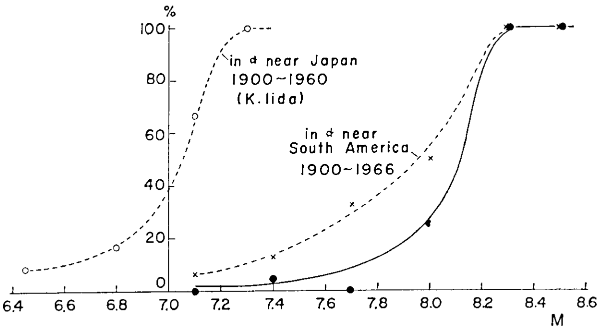

Fig. 2. Percentage of earthquakes accompanied by tsunamis (dotted line) and of tsunamis propagated to Japan (solid line).

Making use of data listed in Rika-Nenpyo (Tokyo Astronomic Obs., 1967) and the Yellow Card (1964~1966) of the U. S. Coast and Geodetic Survey, the number of earthquakes with magnitude greater than 7 occurring near the Pacific coast of South America has been counted during the period from 1900 to 1966. Some of these earthquakes are known to be accompanied by tsunamis but not all of the tsunamis reached Japan. Table 1 shows the number of earthquakes, tsunami generation, and tsunamis which reached Japan. The percentage of tsunami occurrence classified by the earthquake magnitude is shown with a dotted line in Fig. 2. The occurrence in the magnitude range of $7.9>M>8.1$ is 50 percent. In contrast, shallow submarine earthquakes having magnitude greater than 7.3 occurring in the sea adjacent to Japan are always accompanied by tsunami.[11] This difference may possibly be caused by the following reasons. For the counting of earthquakes in South America, land earthquakes near the coast and deep-focus earthquakes are also included. Moreover, small tsunamis might have been overlooked owing to a sparse population along the coast of South America.

The percentage of tsunamis propagated to Japan during the same period is shown with a solid line in Fig. 2. For earthquakes having magnitude greater than $6\frac{1}{2}$ during the period from 1958 to 1966, the possible tsunami arrivals after about 20 hours following the earthquake occurrence were examined by the long-wave records at Miyagi-Enoshima. Although six tsunamis were generated during this period near the earthquake origin, only three tsunamis (May 1960, Nov. 1960 and Oct. 1966)

11) K. IIDA, "Magnitude of Tsunamigenic Earthquake, Aftershock Area, and Area of Tsunami Origin," *Geophysical Papers dedicated to Prof. Kenzo Sassa*, (Kyoto, 1963), pp. 115-124.

were observed at Miyagi-Enoshima. Other tsunamis could not be identified because of the background noise due to continental shelf oscillations. The percentage of tsunamis propagated from the origin to Japan is 25 percent in the range of earthquake magnitude 7.9>M>8.1. However, tsunamis generated by shallow submarine earthquakes having magnitudes greater than 8.3 are always propagated from the origin to Japan. Small tsunamis of Nov. 20, 1960 and of Oct. 17, 1966 generated off Peru were

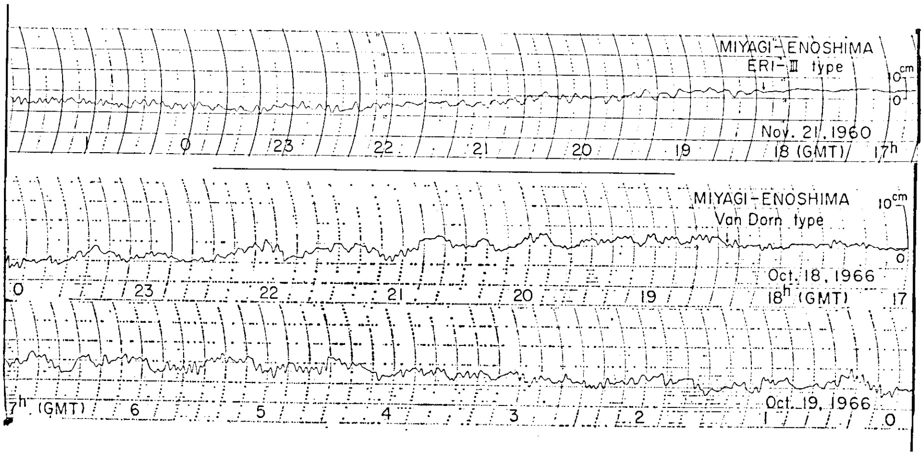

Fig. 3. Records of Peruvian tsunamis of Nov. 20, 1960 and Oct. 17, 1966 observed at Miyagi-Enoshima.

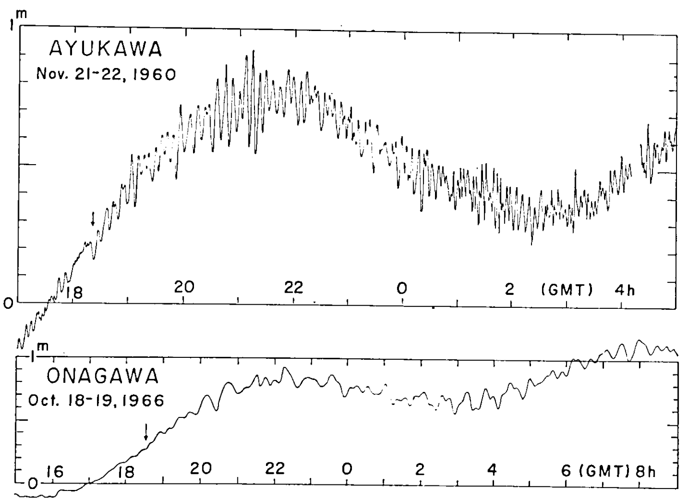

Fig. 4. Records of Peruvian tsunami of Nov. 20, 1960 at Aukawa (above) and of Peruvian tsunami of Oct. 17, 1966 at Onagawa (below).

observed along the coast of Japan. The records at Miyagi-Enoshima, Ayukawa and Onagawa (the Magnetic Observatory, Tohoku Univ.) are shown in Figs. 3 and 4. The height and travel time of these two tsunamis observed at tide stations along the coast of Japan are shown in Fig. 11. As shown in these examples, tsunamis occasionally reached Japan, even when the earthquake magnitude was 7 or less.

Effect of tsunamis in the Pacific Ocean

The magnitude of tsunamis of 1868 and 1877 generated near Arica were as large as that of the 1960 Chilean tsunami. The tsunami of 1877 hit Kujukuri-hama, Chiba Prefecture, and caused much damage and loss of life.[12] As shown in Fig. 5, tsunami heights of 1877 and 1960 were about 10 meters in a region of 500 kilometers along the coast near

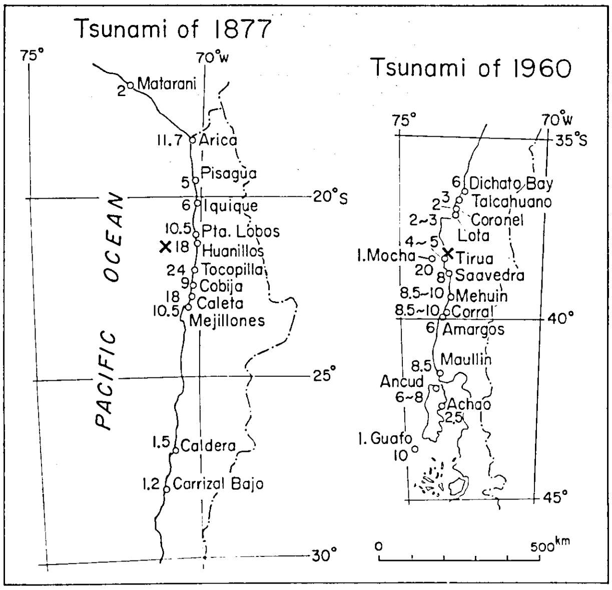

Fig. 5. Distribution of tsunami height, in meters, for tsunamis of 1877 and 1960.

the origin. The heights of other historical tsunamis which hit Japan and Hawaii were of the order of 10 meters near the origin. For the period from 1900 to 1966, wave-height of tsunami along the coasts of

12) H. MIYOSHI, "Tsunami," *J. Oceanogr. Soc. Japan, 20th Anniversary Vol.*, (1962), 265, (in Japanese).

Japan and Hawaii was plotted against the magnitude of the earthquake as in Fig. 6. From this figure, it is found that the wave-height is less

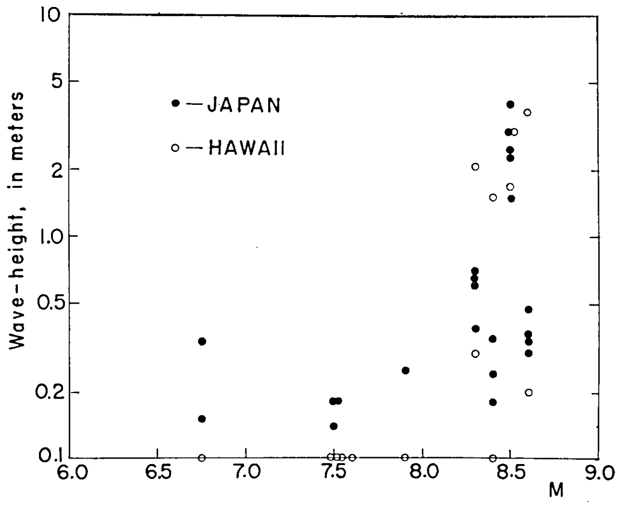

Fig. 6. The relation between wave-heights at several places in Japan and Hawaii and magnitude of the South American earthquakes.

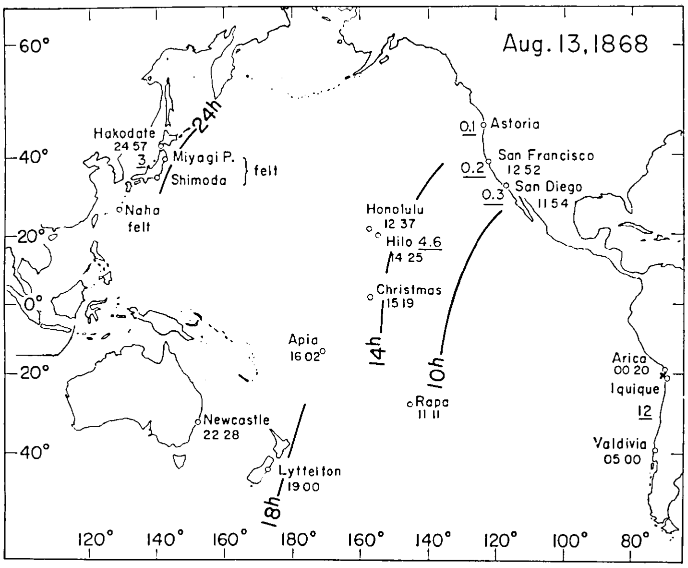

Fig. 7. Refraction diagram for the 1868 tsunami, in which arabic numerals indicate travel time (h, m), and distribution of tsunami height, in meters.

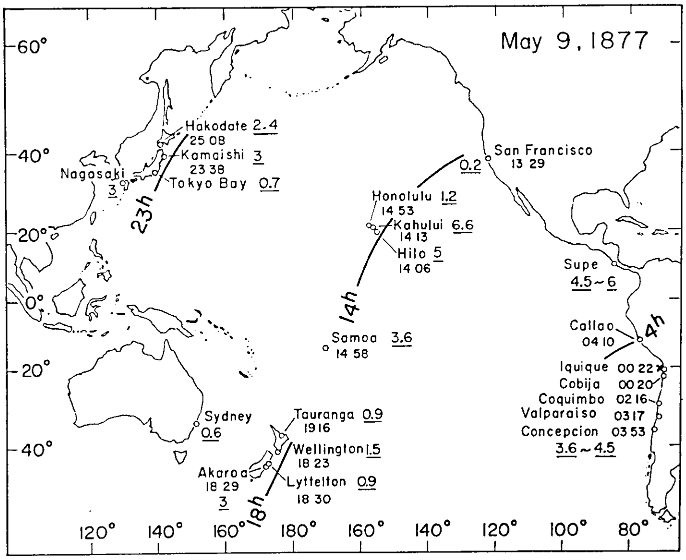

Fig. 8. Refraction diagram for the 1877 tsunami, in which arabic numerals indicate travel time (h, m), and distribution of tsunami height, in meters.

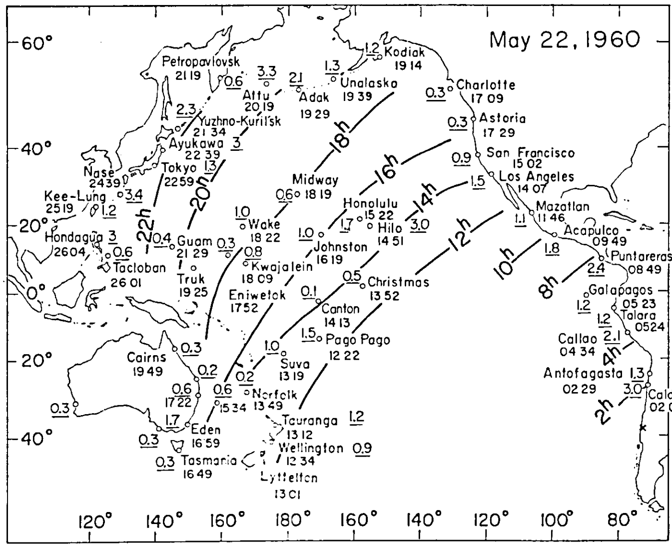

Fig. 9. Refraction diagram for the 1960 tsunami, in which arabic numerals indicate travel time (h, m), and distribution of tsunami height, in meters.

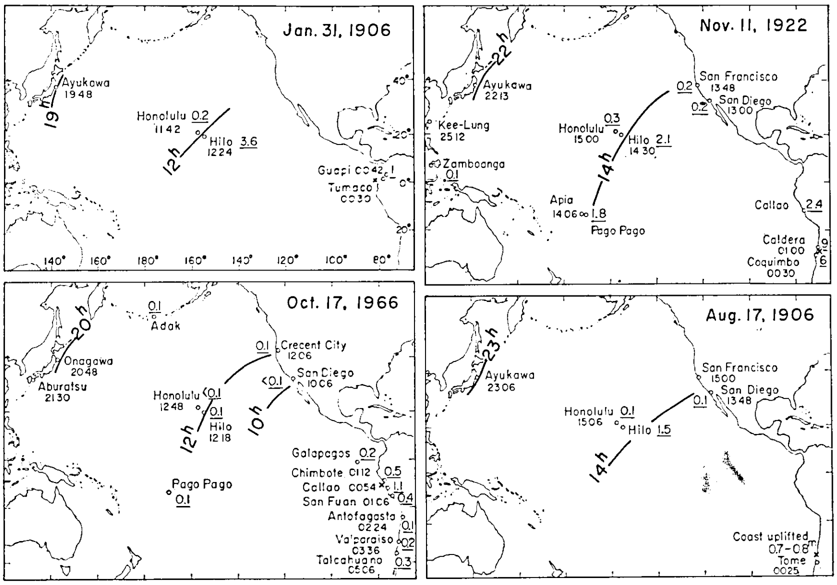

Fig. 10. Refraction diagrams, in which arabic numerals indicate travel time (h, m), and distribution of tsunami height, in meters.

than 50 centimeters when tsunamis are generated by submarine earthquakes having magnitude less than 8.0.

For three large tsunamis and four relatively small tsunamis which were propagated across the Pacific Ocean, the progress of the wave front is shown with the travel time (h, m) in Figs. 7 to 10. These figures also show the distribution of the observed tsunami heights in meters. For seven tsunamis which were observed along the Japanese coast, the progress of the wave front and the distribution of the maximum wave-height (double amplitude, in cm) are shown in Fig. 11 on the basis of the tide records.

Fig. 11 is arranged in order of the location of the earthquake origin from Ecuador to Chile. The travel times at the Sanriku coast are 19, 20 and 23 hours respectively. Fig. 12 shows the relation between the distances from the origin to Honolulu, Ayukawa and Lyttelton (New Zealand) and travel time of the initial wave front. From the figure, the mean wave velocity between the origin and Honolulu or Ayukawa is estimated to be 715 km/hr, which corresponds to a long-wave velocity for the mean depth of 4000 meters. This depth is more than about 20 percent shallower than the actual mean depth. This can be understood by the fact that the wave ray of tsunami does not

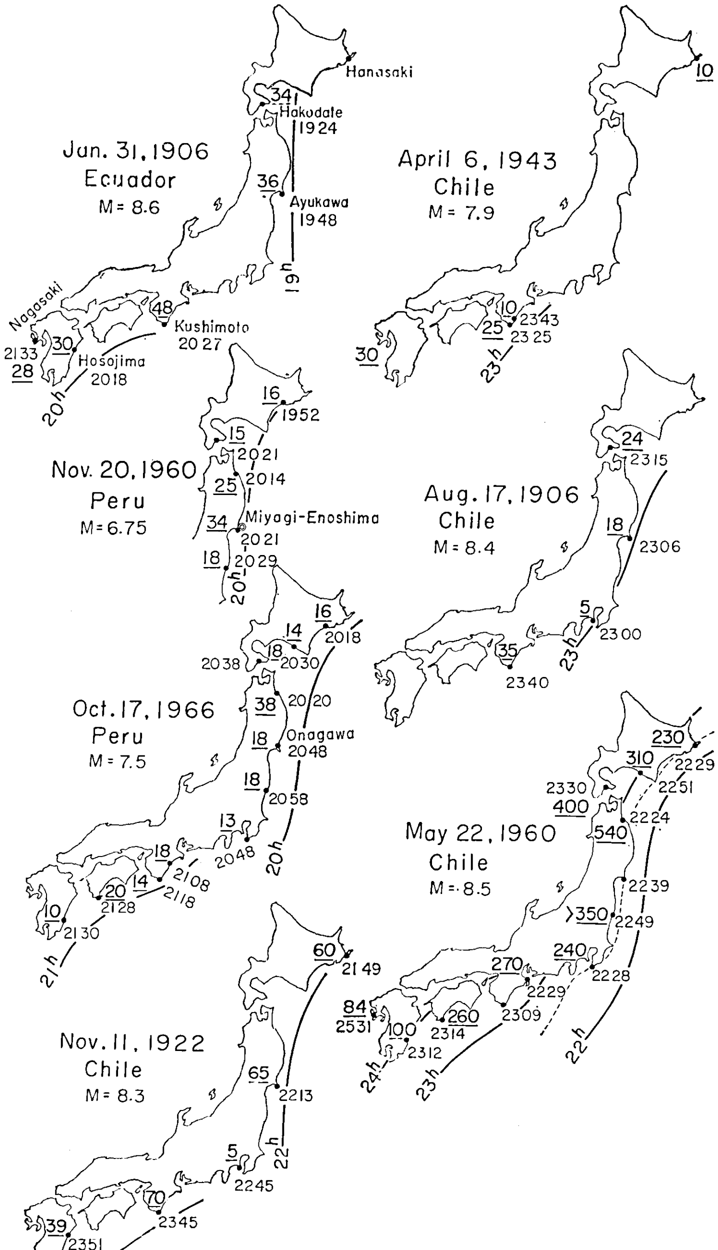

Fig. 11. Refraction diagrams for the South American tsunamis, in which arabic numerals indicate travel time (h, m), and distribution of the maximum wave-height (double amplitude, in cm).

always follow the great circle route from the origin because of the uneven topography of the sea bottom, and also the travel time on the continental shelf cannot be neglected. It may be noticed that the tsunamis of 1868 and 1877 reached New Zealand 6 hours later than the tsunami of 1960 because of the particular topography of sea bottom along the path of the tsunamis.

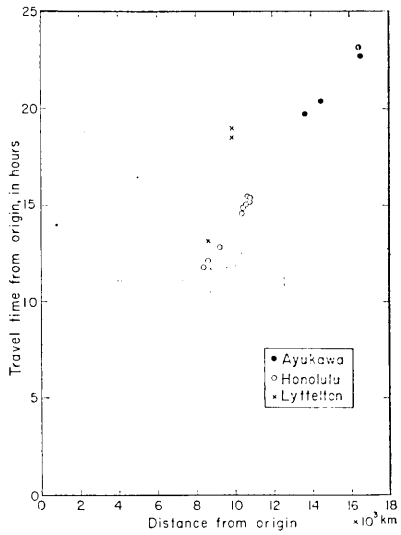

Fig. 12. The relation between the distance from the origin and travel time of the wave front.

Spectral analysis

According to the field investigation near the origin, the predominant periods of tsunamis were reported as follows: 15$\sim$26 min for the tsunami of 1877, 30$\sim$60 min for the tsunami of 1960. Along the coast of Japan for the tsunami of 1877, tsunami period was 20, 15 and 5 min at Hakodate, Kamaishi and Nagasaki respectively. For the tsunami of 1960, the peaks with period of 60$\sim$80 min in Northern Japan and 40$\sim$50 min in Southwestern Japan were found by spectral analysis.[13] From these field investigation, the predominant period for the tsunami of 1877 seems to be shorter than that of the tsunami of 1960.

In the cases of tsunamis of Jan. and Aug. 1906, 1922, 1960 and 1966, spectral analysis of tide records at Hanasaki, Hakodate, Ayukawa, Kushimoto, Hosojima and Nagasaki are made by Tukey's method. Analyzed time interval of the record is 6 hours including the initial wave. In Figs. 13 to 15, the power spectra of these records are shown, where hatched columns indicate the bands of seiche period of the bay. It is remarkable that the features of different tsunami spectra for the same station are similar and that the frequency bands of peaks agree pretty well with each other. The shape of the peak defined by $Q^2 = f/\Delta f$ is given in Table 2, where f is the frequency of the peak (c. p. hr) and Δf the width of the frequency band bounded by the half amplitude of

13) R. TAKAHASI and I. AIDA, "Studies on the Spectrum of Tsunami," *Bull. Earthq. Res. Inst.*, **39** (1961), 523, (in Japanese).

the peak. From the calculated result, the values of Q^2 at the peaks of spectra are almost constant at the fixed stations for different tsunamis.

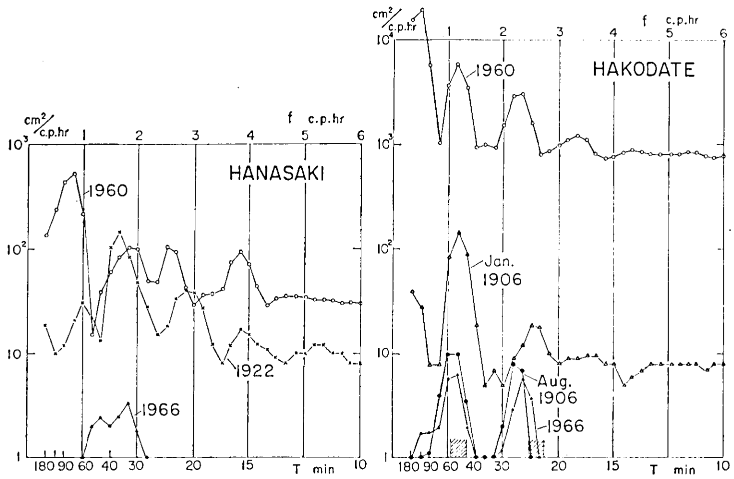

Fig. 13. Power spectra at Hanasaki and Hakodate for the South American tsunamis.

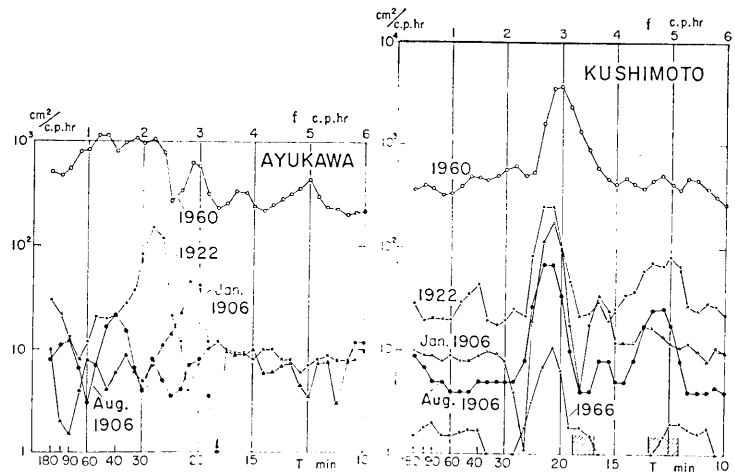

Fig. 14. Power spectra at Ayukawa and Kushimoto for the South American tsunamis.

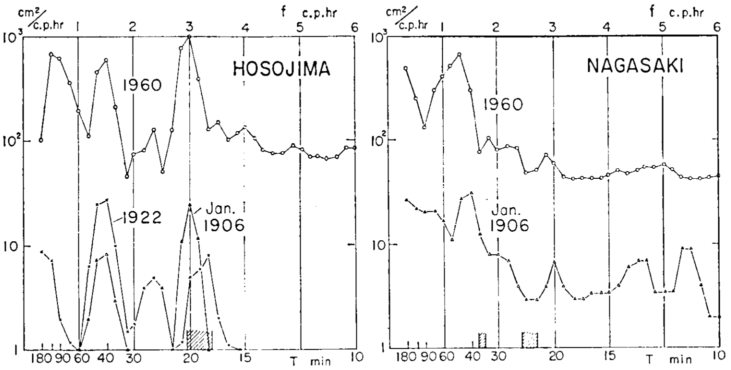

Fig. 15. Power spectra at Hosojima and Nagasaki for the South American tsunamis.

Table 2. Frequency of the peak of spectrum (f: c. p. hr) and the shape of peak, $Q^2=f/\Delta f$, at stations of Japan.

Tsunami	Hanasaki		Hakodate		Ayukawa		Kushimoto		Hosojima		Nagasaki	
	f	Q^2	f	Q^2	f	Q^2	f	Q^2	f	Q^2	f	Q^2
Jan. 31, 1906			1.17	3.3	2.93	9.0	2.85	8.2	1.45	4.5	1.45	3.5
			2.54	4.2			3.76	8.8	3.0	8.9		
Aug. 17, 1906			1.08	3.2	1.52	2.7	2.78	7.0				
			2.25	7.8	2.93	7.3	4.78	7.7				
Nov. 11, 1922	1.02	2.0			2.18	5.3	2.78	7.3	1.45	4.3		
	1.70	1.9					4.83	5.8	2.33	4.7		
	2.9	4.5							3.20	7.6		
	4.05	4.1										
May 22, 1960	0.75	1.8	1.18	3.6	2.93	6.8	2.99	5.9	0.68	1.7	1.18	1.9
	1.82	2.5	2.28	4.3					1.47	4.5		
	2.60	6.2							2.22	4.4		
	3.85	6.6							2.98	9.9		
Oct. 17, 1966			1.10	3.4			2.85	7.9				
			2.37	6.4								

Generating area of the 1960 Chilean tsunami

For the 1960 Chilean tsunami, travel times from the origin to Coquimbo, Valparaiso and Talcahuano are taken as 84, 64 and 54 min respectively by using the tide records. The initial motions of the tsunami were *up* everywhere. Inverse refraction diagrams are drawn in Fig. 16 from three tide stations and from four places where the initial arrival was observed by eyewitnesses. Wave fronts were drawn at 5 minute intervals, but in Fig. 16 only the final wave front corresponding to the travel time is shown.

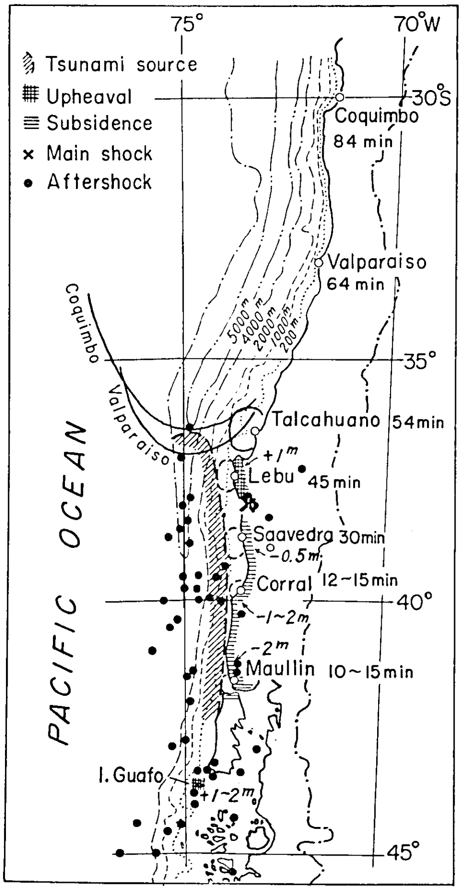

Fig. 16. Generating area of the 1960 Chilean tsunami inferred from an inverse refraction diagram, crustal deformation and the distribution of aftershocks.

As shown in Fig. 16, the estimated area is located along the coast where the crustal deformation was observed and the region corresponds to the area of aftershock activity. Although the southern end of the source cannot be delineated clearly, the linear dimension of tsunami domain seems to be about 800 kilometers, if we take the crustal deformation at Isla Guafo into account. This dimension is the largest ever observed, since the source dimensions of the 1933 Sanriku, 1952 Kamchatka and the 1964 Alaska tsunami are estimated to be 500~600 kilometers.

Conclusion

Tsunamis which were generated off the Pacific coast of South America by shallow submarine earthquakes having magnitude greater than 8.3 were always propagated to the whole region of the Pacific Ocean. The height of past tsunamis which hit Japan and Hawaii were of the order of 10 meters near the origin. However, the distribution of height along the Japanese coast is less than 50 centimeters for tsunamis generated by submarine earthquakes having magnitude less than 8.0.

From refraction diagrams for seven tsunamis, the travel times at the Sanriku coast are 19 to 23 hours for the location of the earthquake origin from Ecuador to Chile. Based on the spectral analysis of the tide records of Japan, the features of different tsunami spectra for the same station are similar and the frequency bands of peaks agree pretty well with each other.

The estimated source area of the 1960 Chilean tsunami includes the area of major aftershock activity extending about 800 kilometers in an elongated shape.

The author thanks Prof. K. Kajiura for his guidance.

15. 日本太平洋沿岸における遠地津波 第2報 南米の津波について

地震研究所 羽鳥 徳太郎

南米太平洋沿岸で発生した歴史津波の資料によると，波源付近の波高が 10 m 程度の津波によつて日本，ハワイは数回相当な被害を受けている．1900 年以後は我が国においても検潮儀によつて 7 個の津波が観測された．このうち 1960 年 11 月 20 日のペル沖で起きた地震 (M=6.75) によつて，微小な津波を観測した例もある． マグニチュードが 8.3 以上の地震に伴なう津波は，例外なく全太平洋沿岸地域で観観されているが，8.0 以下の地震による過去の津波は，日本沿岸で波高 50 cm 以下の微弱なものである．

太平洋を伝播した 7 個の津波 (1868 年，1877 年，1960 年など）の伝播図および波高分布を示し，特に日本沿岸は検潮記録を用いて明細に図示した． これによるとエクワドル，ペル，チリと波源が南下するにつれ，日本への伝播時間はそれぞれ 19，20，22～23 時間と延びてくる．南米の波源からホノルル，鮎川に至る伝播時間から，津波が大圏コースを伝播したものとして太平洋の平均水深を求めると 4000 m となり，実測値より浅い結果となる． これは津波のパスが海底地形によつて大圏コースと一致しないことを意味する．

花咲，函館，鮎川，串本，細島および長崎の検潮記録から数個の津波について，初動を含めた 6 時間分の周期分析を行つた． この結果いずれの津波も同一観測点では，スペクトルのピークの位置およびその形がほぼ一定し，津波によつて顕著な周期の相異は認められない．

1960 年 5 月のチリ津波の波源域を逆伝播図から推定すると，波源は余震域にほぼ一致して海岸線に沿つて横たわり，その長さは約 800 km である．1933 年の三陸，1952 年のカムチャツカ，1964 年のアラスカの各津波の波源の長径は 500～600 km であつたと推定されているが，1960 年のチリ津波は，かつてない最大級の波源域をもつたものと推察される．