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REGIONAL CHARACTERISTICS OF TSUNAMIS ALONG PACIFIC COAST OF HOKKAIDO*

Susumu TAKAHASHI
Associate Professor, Department of Engineering, Hokkaido University, Sapporo
and
Isao YAKUWA
Professor, Department of Engineering, Hokkaido University, Sapporo

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ABSTRACT

On the basis of analyses of wave motions recorded at Hanasaki, Kushiro, Tomakomai, Muroran and Hakodate along the Pacific Coast of Hokkaido in Japan, regional characteristics of tsunamis are investigated.

Tide gauge records in ordinary times and in four typical tsunamis: Tokachi-oki (1952, 1968), Chilean (1960) and Off - Nemuro Peninsula (1973) are analyzed. From the results of power spectral analyses of the records, peaks of spectra in ordinary times are amplified in tsunamis and the predominant period is elongated as the magnitude of the earthquake increases. Dominancy of oscillation modes is different with each gauge station because oscillation systems vary locally.

1. INTRODUCTION

The region off the Pacific Coast of Hokkaido in Japan belongs to one of the most active earthquake zones in the world. As shown in Table 1, large tsunamis were frequently generated by earthquakes off this shore and caused heavy damage on the south coast of Hokkaido.

In order to protect the coasts and harbors, it is necessary to know the local characteristics of wave motion caused by various tsunamis. Various tsunami sources and topographies near harbors cause different tsunami motions.

In this paper, tide gauge records of the Tokachi-oki (1952, 1968), Chilean (1960) and Off-Nemuro Peninsula tsunami (1973) observed at Hanasaki, Kushiro, Tomakomai, Muroran and Hakodate Harbor are used.

In order to investigate the regional characteristics of tsunami motion. tide records of ordinary times before or after the tsunami (and in the early and later parts of tsunamis at Kushiro and Hakodate) are analyzed and the causes of predominant periods examined.

The general aspects of the Tokachi-oki, Chilean and Off-Nemuro Peninsula tsunami have been reported[1-4] by the special committees for investigation and others. Magnitudes and epicenters of earthquakes accompaning the tsunamis are shown in Table 1.

According to Hatori[5, 6] and Kishi[7], source areas of these tsunamis are estimated as ellipses with the long axes about 160km (1952 Tokachi-oki), 240km (1968 Tokachi-oki) and 130km (Off-Nemuro Peninsula) respectively.

In the Chilean earthquake, the tsunami reached the Pacific Coast of Japan early in the morning of the next day and caused heavy damage, especially to Hokkaido and the Sanriku district.

Fig. 1 shows the Pacific Coast of Hokkaido and locations of harbors with tide gauges.

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KEY WORDS: Tsunami, Period of seiche

Table 1 Earthquakes accompanied by tsunamis along the Pacific Coast of Hokkaido (Japan Meteorological Agency).

Date	Time	Epicenter		Location	Depth (km)	Magnitude
		Latitude N	Longitude E			
2 Dec., 1611		38.2	143.8	Sanriku		8.1
1 May., 1780		45.3	151.2	Urup		7.0
25 Apr., 1843		41.8	144.8	Nemuro		8.4
4 Jun., 1893	02 : 27	43.1	147.0	Nemuro		6.6
22 Mar., 1894	19 : 23	42.4	146.3	Nemuro		7.9
15 Jun., 1896	19 : 33	39.6	144.2	Sanriku		7.6
8 Sept., 1918	02 : 20	45.7	151.8	Urup		7.9
8 Nov., 1918	13 : 42	44.1	148.9	Iturup		7.8
3 Mar., 1933	02 : 31	39.1	144.7	Sanriku	0-20	8.3
4 Mar., 1952	10 : 23	42.2	143.9	Tokachi-oki	45	8.1
5 Nov., 1952	02 : 02	55.8	159.5	Kamchatka	0	8.2
9 Mar., 1957	23 : 28	51	W175	Aleutian	0	8-8.5
7 Nov., 1958	07 : 58	44.3	148.5	Iturup	80	8.3
24 May., 1960	(23 May) 04 : 31	S41	W 73.5	Chile		8.5-8.7
12 Aug., 1961	00 : 51	42.85	145.32	Kushiro	40	7.3
13 Oct., 1963	14 : 19	43.8	150.0	Iturup	20	8.1
28 Mar., 1964	12 : 44	61.1	W147.6	Alaska	20	8.4
16 May, 1968	09 : 49	40.7	143.6	Tokachi-oki	0	7.9(7.8)
16 May., 1968	19 : 39	41.4	142.8	Tokachi-oki	40	7.5
12 Aug., 1969	06 : 28	42.7	147.6	Hokkaido	30	7.8
2 Aug., 1971	16 : 25	41.2	143.7	Tokachi-oki	60	7.0
17 Jun., 1973	12 : 55	43.0	146.0	Nemuro	40	7.4
24 Jun., 1973	11 : 43	43.0	146.8	Nemuro	30	7.1

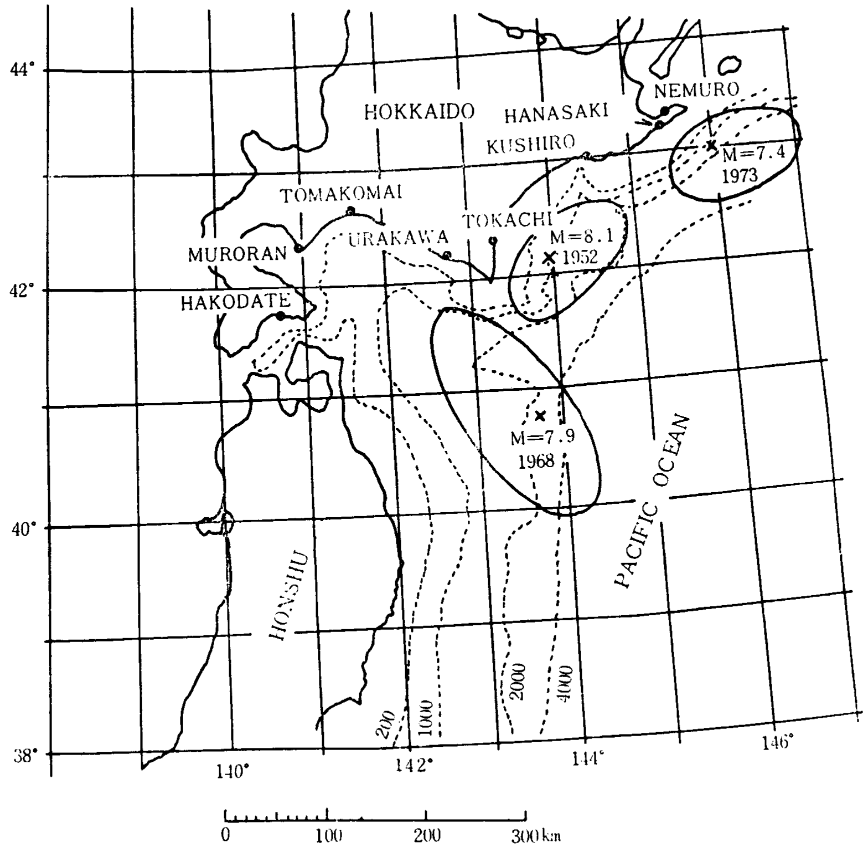


Fig. 1 Locations of harbors with tide gauges and estimated tsunami source areas of Tokachi-oki (1952, 1968) and Off-Nemuro Peninsula tsunami (1973).

Estimated tsunami source areas of Tokachi-oki (1952, 1968) and Off-Nemuro Peninsula tsunami are also shown.

A continental shelf of 20-30km width lies off the shore along the Pacific Coast of Hokkaido and contour lines run almost parallel to the coast line. On this continental slope there are distributed many tsunami sources. Seiche and edge waves generated on this shelf exert remarkable influences on tsunami motions in the harbors.

2. MAXIMUM TSUNAMI HEIGHT

Fig. 2 shows the relationship between magnitudes of earthquakes and the maximum tsunami heights observed at Hanasaki, Kushiro, Tokachi, Urakawa, Tomakomai, Muroran and Hakodate. From the figure, it can be seen that the maximum tsunami heights were generally lower than the values from the empirical formula given by Wilson[8].

$$\log_{10} H = 0.75M - 5.07 \qquad (1)$$

where H is the tsunami height in m and M is the magnitude of the earthquake. According to Saeki, Miyaki and Ozaki[9], tsunami heights are lower than values estimated from Wilson's formula when the shore line is flat, as along the Pacific Coast of Hokkaido.

In the Chilean tsunami, values of maximum tsunami height were nearly the same at

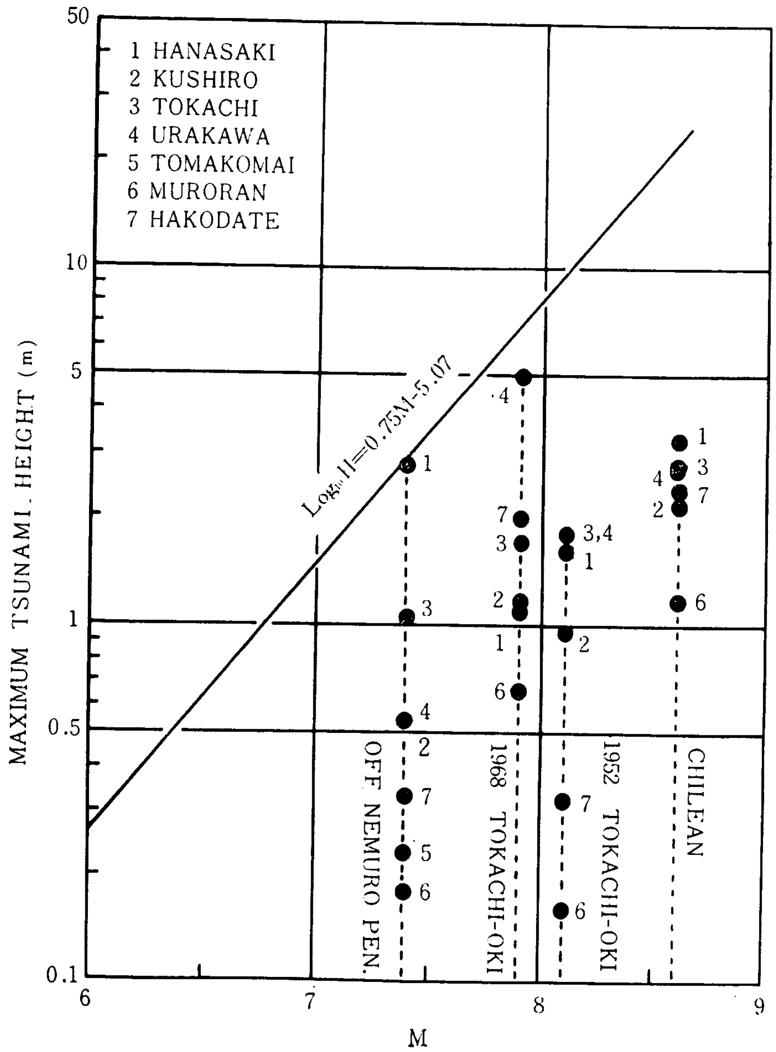


Fig. 2 Relations between maximum tsunami height and magnitude of the earthquake.

seven harbors because the tsunami source was very distant. On the other hand. when sources lay near Hokkaido, tsunami heights took various values depending on the location of harbors. Namely, in the 1973 tsunami, the origin was off the Nemuro Peninsula and an especially high tsunami height (of 3.0 m) was observed at Hanasaki, compared with Kushiro Tokachi and Urakawa where tsunami heights were in the range of 0.5-1.0m. However, when the origin was located off the Erimo Cape in the 1968 tsunami, the maximum height was 5.0m (at Urakawa) and it was lower than 2.0m at Hanasaki, Kushiro, Tokachi and Hakodate. Because the harbor of Muroran was located behind the Etomo Cape for all these tsunamis, maximum tsunami heights were lower there compared with those of other harbors.

3. PREDOMINANT PERIODS OF TSUNAMI

In this section, local characteristics of tsunami motion are investigated on the basis of power spectral analyses of tide records observed at Hanasaki, Kushiro, Tomakomai, Muroran and Hakodate. Predominant periods of wave motion in each harbor are also estimated by considering the topography of harbor and are compared with observed values.

The period of seiche in a rectangular closed basin of uniform depth h is given by

$$T=\frac{2}{\sqrt{gh\left(\frac{m^2}{L^2}+\frac{n^2}{b^2}\right)}} \tag{2}$$

where L and b are the length and width of the basin respectively and m, n mean number of nodes. For secondary undulation in a rectangular bay of length L and depth h, oscillation period is found

$$T=\alpha\frac{4L}{(2n-1)\sqrt{gh}} \tag{3}$$

where

$$\alpha=\sqrt{1+\frac{2b}{\pi L}\left(0.9228-\ln\frac{\pi b}{4L}\right)}$$

is a correction factor. On the other hand, the period of seiche on the continental shelf is given by

$$T=\frac{4L}{\sqrt{gh}} \tag{4}$$

where L and h are the width and mean depth of the shelf.

In this paper, one dimentional oscillations in wave direction x are estimated by the equations

$$T=\frac{2}{n}\int_0^L\frac{dx}{\sqrt{gh(x)}} \tag{5}$$

$$T=\frac{4\alpha}{2n-1}\int_0^L\frac{dx}{\sqrt{gh(x)}} \tag{6}$$

$$T=4\int_0^L\frac{dx}{\sqrt{gh(x)}} \tag{7}$$

instead of Eqs. (2), (3) and (4). In these equations depth h is considered as a function of x and integration is carried out by the Gregory-Newton formula.

Power spectral analyses were carried out by the FFT method for records in time intervals given in Table 2 with sampling at three minute intervals. Predominant periods of

Table 2 Time intervals of records used for spectral analyses by FFT method.

Tsunani \ Harbor	Hanasaki	Kushiro	Tomakomai	Muroran	Hakodate
Tokachi-oki (4 Mar., 1952)		10:00, 4 Mar. -08:56, 5 Mar.		12:09, 4 Mar. -15:18, 6 Mar.	
Chilean (24 May, 1960)		18:39, 24 May -20:36, 26 May	13:16, 24 May -07:24, 25 May	10:03, 24 May -09:03, 26 May	11:00, 24 May -12:57, 26 May
Tokachi-oki (16 May, 1968)	10:30, 17 May -13:39, 18 May	10:27, 16 May -09:12, 18 May	10:39, 16 May -12:15, 17 May	10:30, 16 May -13:93, 18 May	10:51, 16 May -09:00, 17 May
Off-Nemuro Peninsula (17 Jun., 1973)		13:33, 17 Jun. -13:30, 19 Jun.	14:30, 17 Jun. -12:57, 18 Jun.	14:00, 17 Jun. -20:21, 18 Jun.	14:51, 17 Jun. -16:00, 18 Jun.

Table 3 Predominant periods of tsunamis (min).

Tsunami \ Harbor	Hanasaki	Kushiro	Tomakomai	Muroran	Hakodate
Tokachi-oki (4 Mar., 1952)		31, 42, 46, 57, 62, 69, 153		57, 59, 250, 300	
Chilean (24 May, 1960)		37, 46, 51, 55, 59, 72	27, 39, 54, 78, 90, 136	39, 56, 65, 148, 187, 234	27, 29, 34, 55
Tokachi-oki (16 May, 1968)	16, 18, 32, 48, 82, 108	26, 31, 43, 47, 51, 55 60	32, 35, 38, 45, 73, 90	48, 56, 59, 250	29, 46, 55, 66, 132
Off-Nemuro Peninsula (17 Jun., 1973)		26, 27, 30, 34, 44, 46	24, 25, 48, 54, 64, 225	55, 228	26, 31, 34, 48, 58, 96, 131

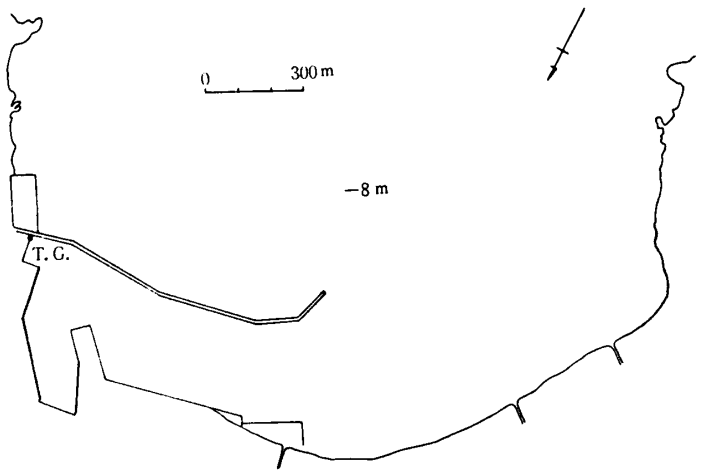
four tsunamis are shown in Table 3. Values underlined twice in the Table are the periods of the largest peaks and underlined ones are the next peaks. As seen in Table 3, predominant periods take various values for different harbors in the same tsunami, but nearly identical values for the same harbor in all tsunamis.

Next, the characteristic of tsunami motion at each harbor is investigated by considering the topography of the harbor shown in Fig. 3.

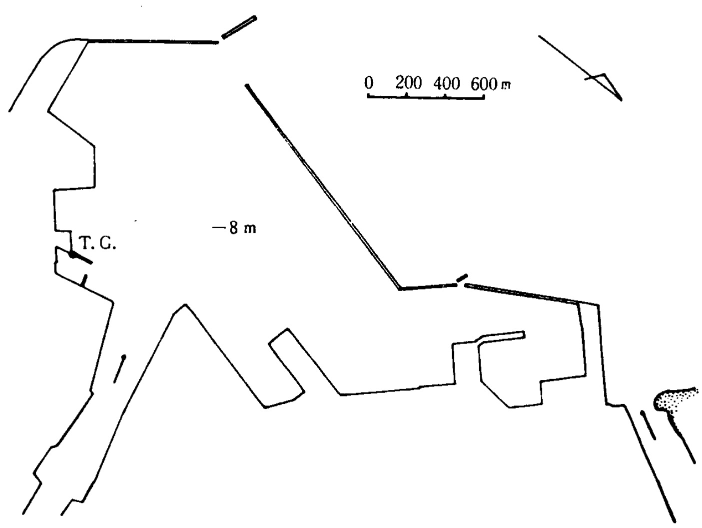
A spectrum of Hanasaki Harbor is shown in Fig. 4. Near Hanasaki, the period of seiche on the continental shelf is estimated as 109 min from Eq. (7) and this value coincides with the observed value of 108 min. Other predominant periods in Table 3 seem to be caused by edge waves, as pointed out by Hatori[10]. However, it is not yet clear what is the probable cause for each predominant period.

Off the shore of Kushiro, a submarine canyon cuts across the continental shelf in the direction from NE to SW and the topography of the sea floor changes on either side of the canyon. In the eastern sea area of Kushiro, the period of seiche on the shelf is estimated as 55 min, while it is estimated as 51 min in the western sea area. These periods are predominant in the Chilean and Tokachi-oki tsunami, but in the Off-Nemuro Peninsula tsunami the predominant periods are generally shorter, compared with the periods in the other tsunamis.

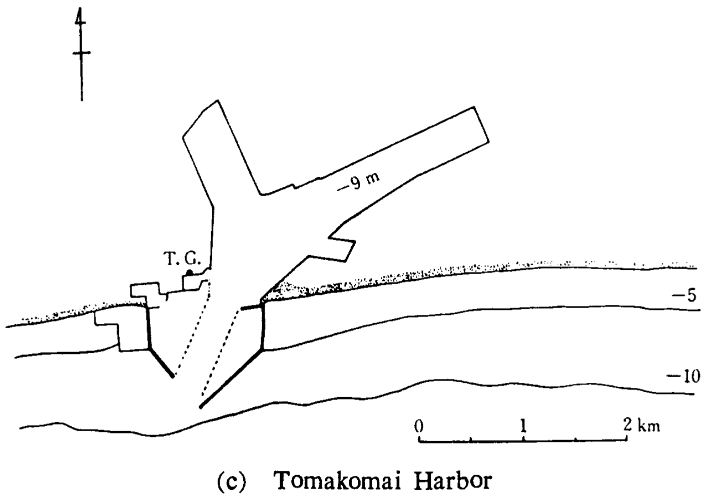
In order to consider the time dependency of tsunami motion at Kushiro Harbor, spectral analyses are made for three cases of a tsunami: namely, for the first half period, the second half period and the whole period. Spectral analyses of tide records before or after tsunamis are also obtained in order to compare spectra of ordinary times with those



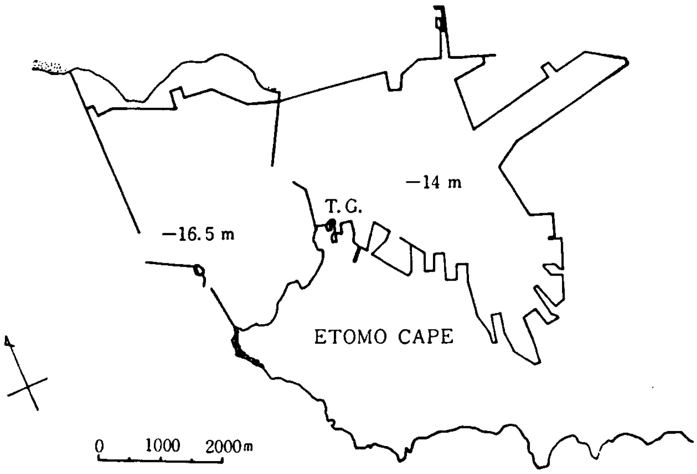
(a) Hanasaki Harbor



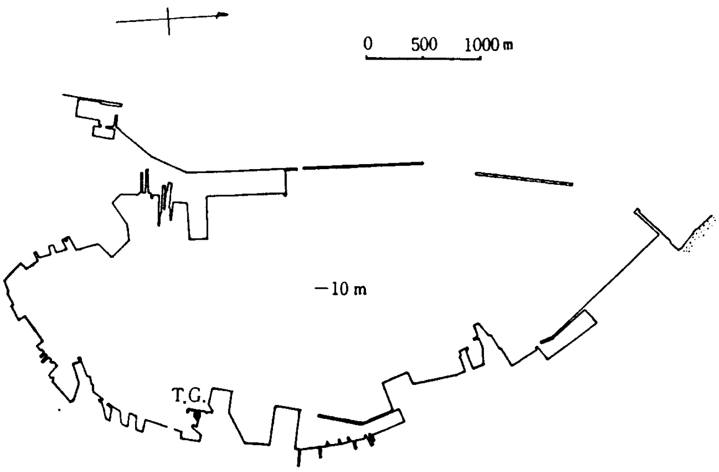
(b) Kushiro Harbor



(c) Tomakomai Harbor



(d) Muroran Harbor



(e) Hakodate Harbor

Fig. 3 Topography of harbors.

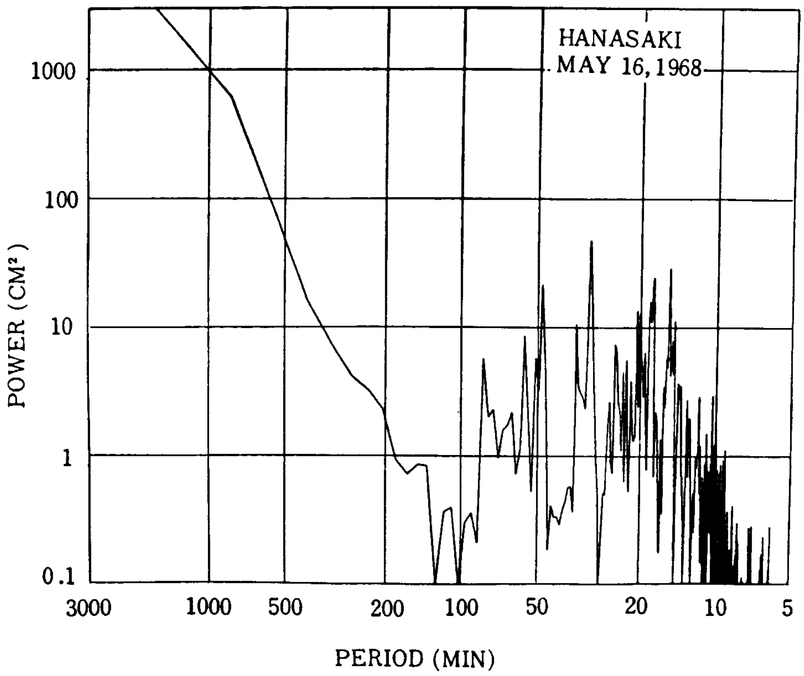
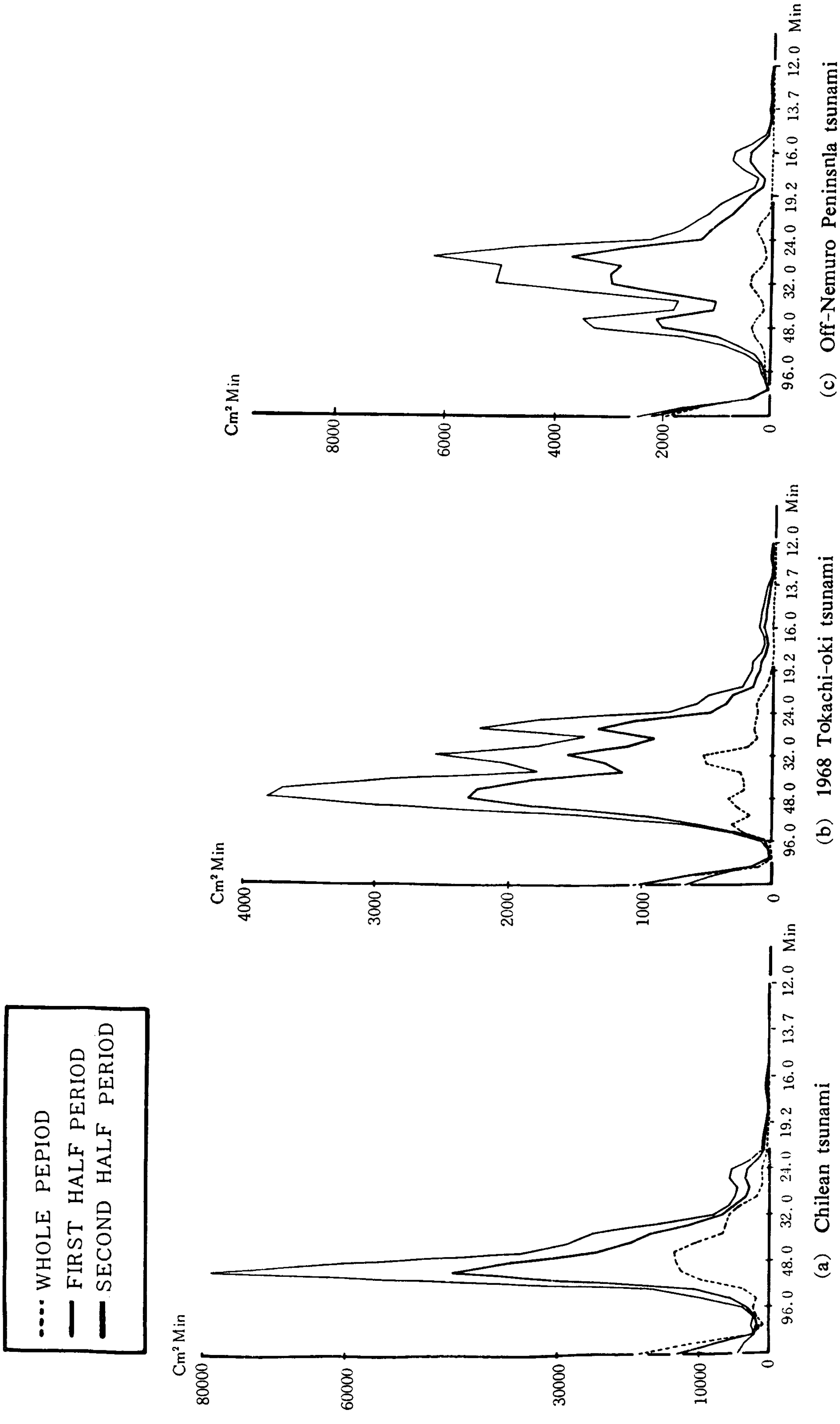


Fig. 4 Power spectrum of tsunami at Hanasaki (1968 Tokachi-oki tsunami).



(a) Chilean tsunami

(b) 1968 Tokachi-oki tsunami

(c) Off-Nemuro Peninsnla tsunami

Fig. 5 Power spectra of tsunamis at Kushiro.

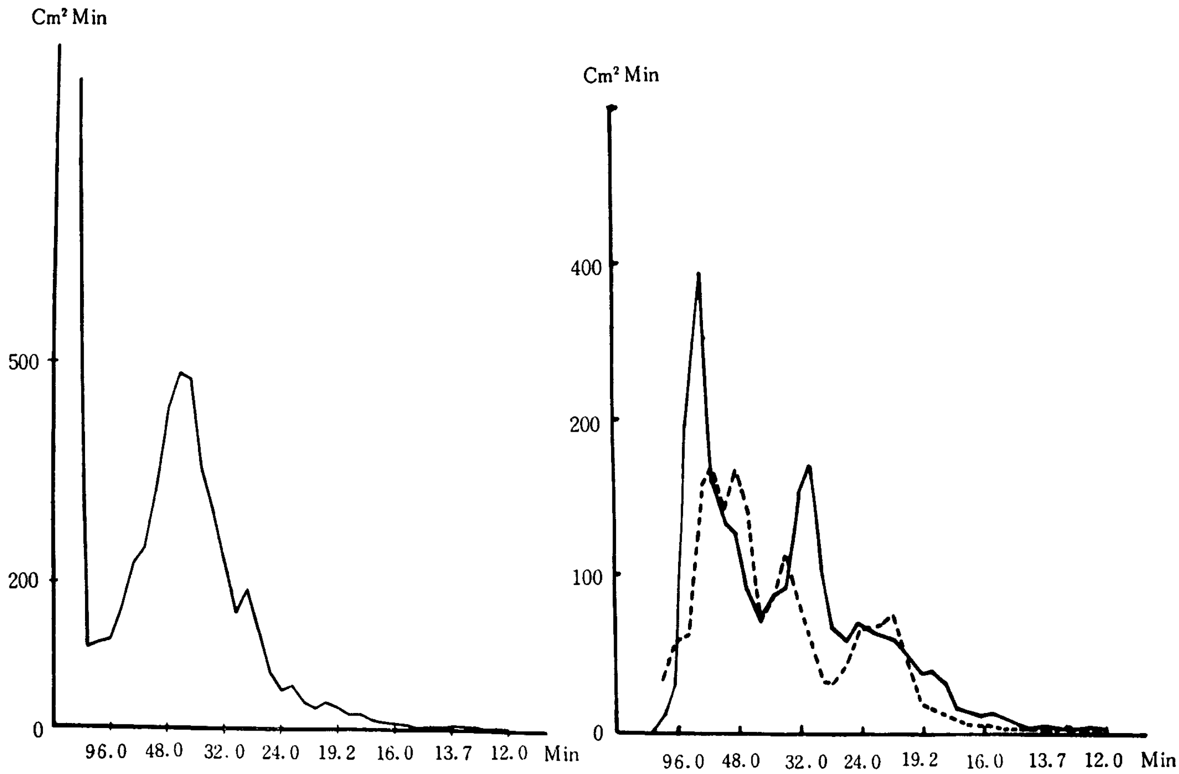
of tsunamis. Analyses are carried out by the Blackman-Tukey method for records in time intervals given in Table 4. Results of analyses are shown in Figs. 5 and 6.

As seen in Fig. 5, the spectra have three peaks at periods near 27, 32 and 48 min in every case and the largest peak elongates as the magnitude of the earthquake increases. Because spectra of the first half and the whole period are nearly similar in shape, it seems that wave motion is mainly characterized by the earlier part of the tsunami. Also, for ordinary times, small peaks of spectra are found at the same periods as in the tsunami time.

Spectra of Tomakomai are shown in Fig 7. The period of seiche on the shelf near Tomakomai as obtained from Eq. (7) is 97 min. On the other hand, the oscillation period of

Table 4 Time intervals of records used for spectral analyses (Kushiro).

Tsunami	First half period	Second half period	Whole period	Ordinary times
Chilean (1960)	18:39, 24 May -2:06, 26 May	2:09, 26 May -10:00, 27 May	18:39, 24 May -9:30, 27 May	15:03, 22 May -3:00, 24 May (Before tsunami)
Tokachi-oki (1968)	10:27, 16 May -14:24, 17 May	4:39, 17 May -8:36, 18 May	10:27, 16 May -8:54, 18 May	1:03, 20 May -12:00, 21 May (After tsunami)
Off-Nemuro Peninsula (1973)	13:33, 17 Jun. -17:30, 18 Jun.	10:33, 18 Jun. -14:00, 19 Jun.	13:33, 17 Jun. -14:00, 19 Jun.	22:33, 16 Jun. -10:12, 17 Jun. (Before tsunami)



(a) Ordinary time (Before Chilean tsunami)

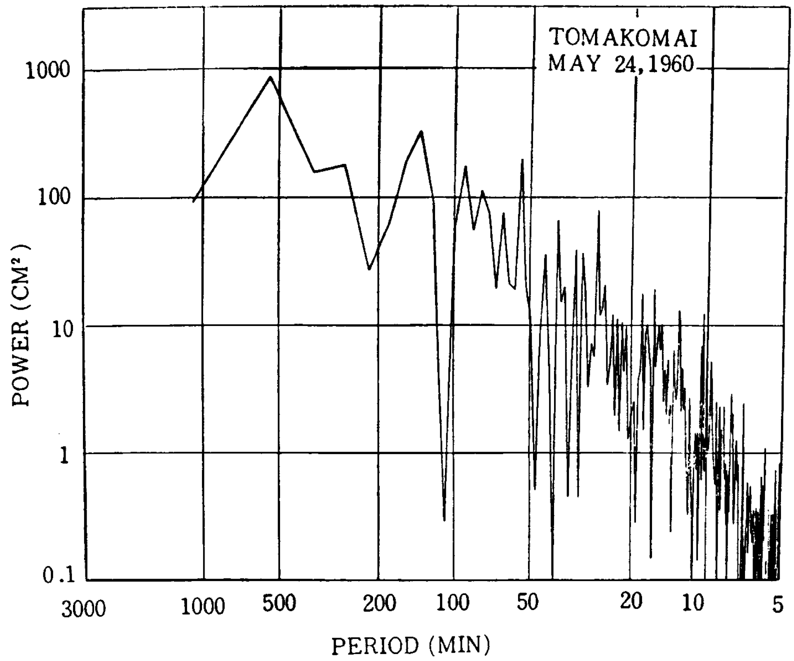
(b) Ordinary time
After 1968 Tokachi-oki tsnnami (solid line)
Before Off Nemuro Peninsula tsunami (dotted line)

Fig. 6 Power spectra of tide motions at Kushiro.

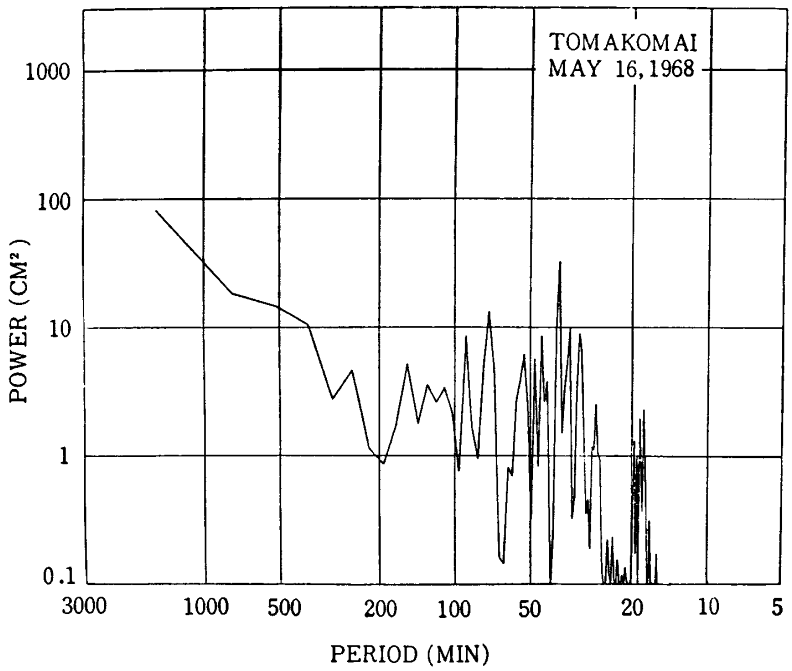
secondary undulation of Tomakomai Harbor is approximately estimated from Eq. (3) by putting $L=2800$ m, $h=9$ m for the inner port and $L=3800$ m, $h=9$ m for the sea area containing the inner and outer ports. Results of estimation for $n=1$ are $T=20$ min and $T=27$ min respectively. These values seem to correspond to periods of 90 and 24-27 min in Table 3. Other periods in Table 3 may be caused by edge waves, but it is not yet clear what is the probable cause for each peak.

The harbor of Muroran is located near the mouth of the Uchiura Bay (Fig 1), so that the tsunami motion may be influenced by seiche in the bay.

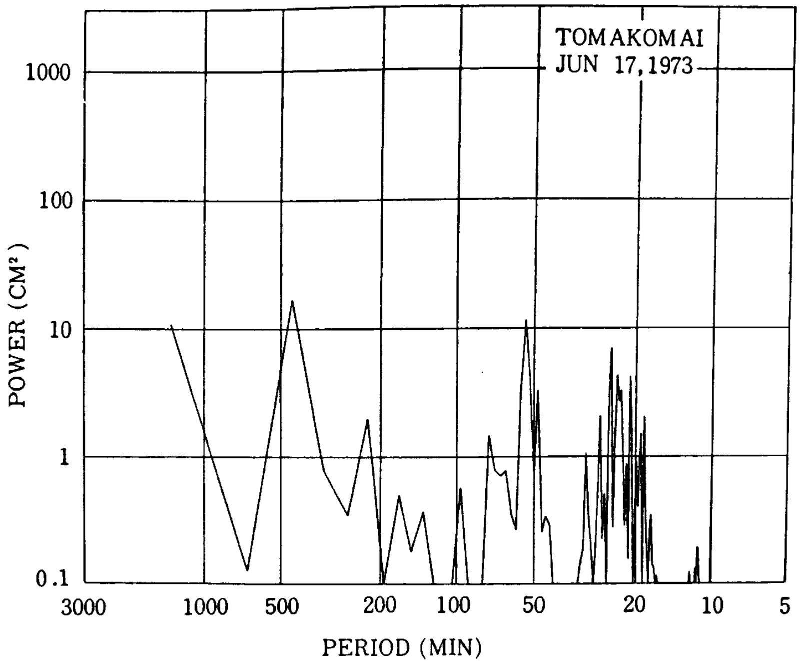
According to Kashiwamura[11], when values of L and h are given as $L=45$ km (the distance from Muroran to Yakumo) and $h=80$ m (mean depth of the Uchiura Bay), the



(a) Chilean tsunami



(b) 1968 Tokachi-oki tsunami



(c) Off-Nemuro Peninsula tsunami

Fig. 7 Power spectra of tsunamis at Tomakomai.

period of seiche in the bay is approximately estimated as $T=54$ min and this value coincides with the observed periods 53–58 min in the later parts of tsunamis.

Spectra and predominant periods of tide motion in Muroran Harbor are shown in Fig. 8 and Table 3. On the other hand, estimated periods are as follows;

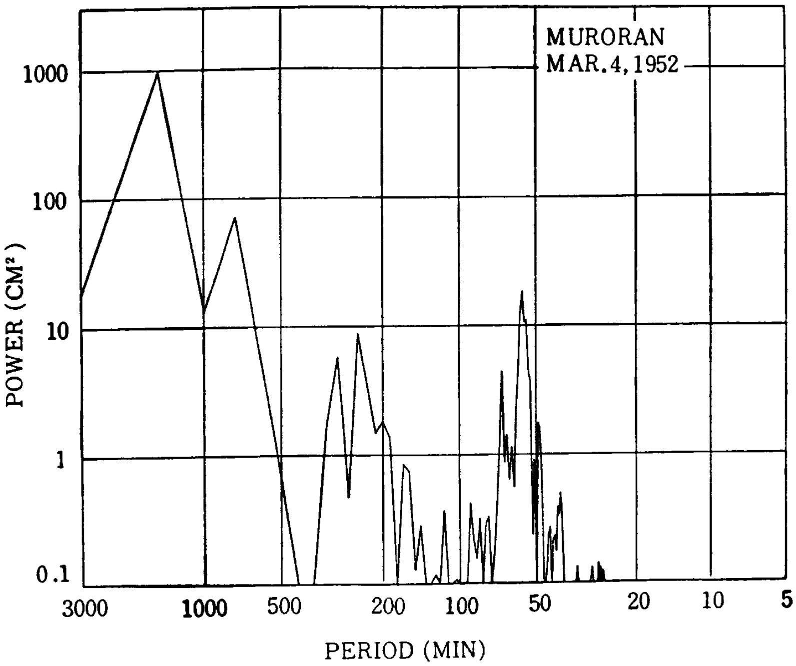
$T=202$ min for seiche on the shelf near Muroran
$T=64$ min ($m=1$, $n=0$) for seiche of the bay in E-W direction
$T=54$ min ($n=2$) for secondary undulation of the bay in S-N direction

and $T=32$ min ($n=3$) for secondary undulation of the bay. These values seem to correspond respectively to periods 230–250, 65, 56–59 and 39 min in Table 3. What kind of oscillation corresponds to the long period of 300 min is not yet clear.

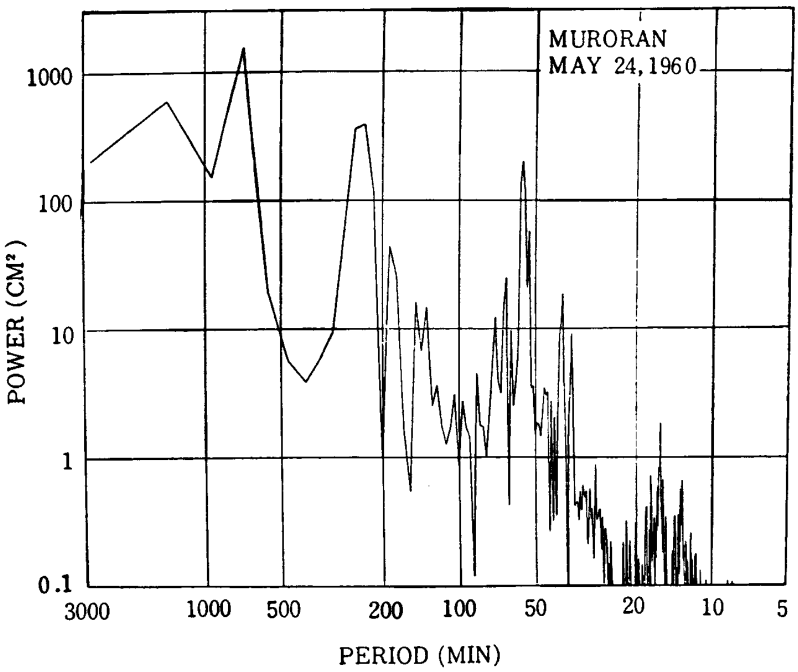
As shown in Table 3, predominant periods of 26–29, 34, 45–48, 55–58 and 131 min were caused by every tsunami at Hakodate. In the Chilean tsunami, oscillations of about 131 min period were also found in tsunami records at Aomori in Honshu. Tide motions of these periods may correspond to seiches in large sea areas in the Tsugaru Straits[12].

In order to consider the characteristics of tsunami motion in Hakodate Harbor, spectral analyses were made for tsunami and for ordinary times. Analyses of records shown in Table 5 were carried out by the Blackman-Tukey method and the results are shown in Figs. 9 and 10.

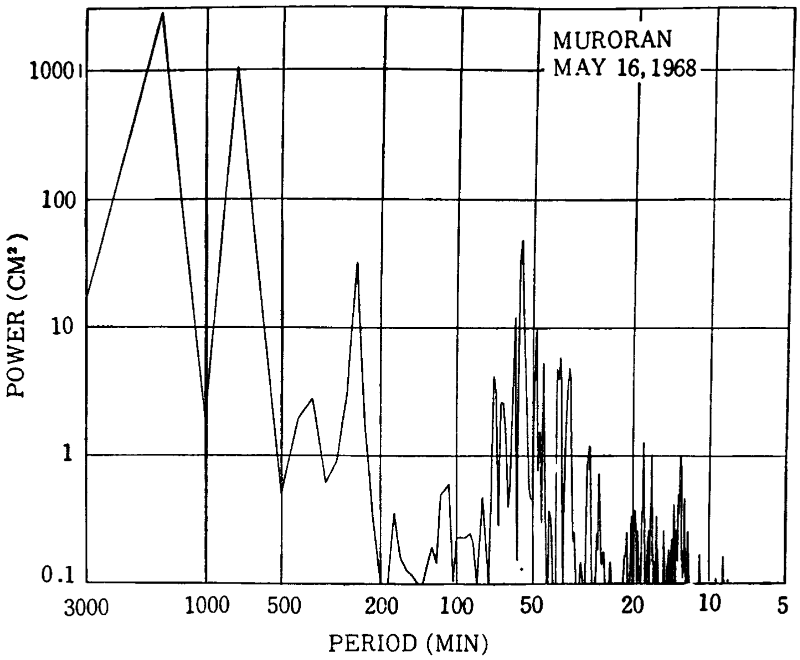
As shown in these figures, the spectra have three peaks at periods of 120-160, 53-60 and 25-27 min both at tsunami and ordinary times. In tsunami times, peaks are amplified and the largest peak of the whole period elongates as the magnitude of the earthquake increases. In the same tsunami, however, the period of the largest peak changes with the passage of time. For instance, although the largest peak was at a period of 160 min in the earlier part of the Chilean tsunami, it moved to 53 min in the middle part and again to 160 min near the end of the tsunami period.



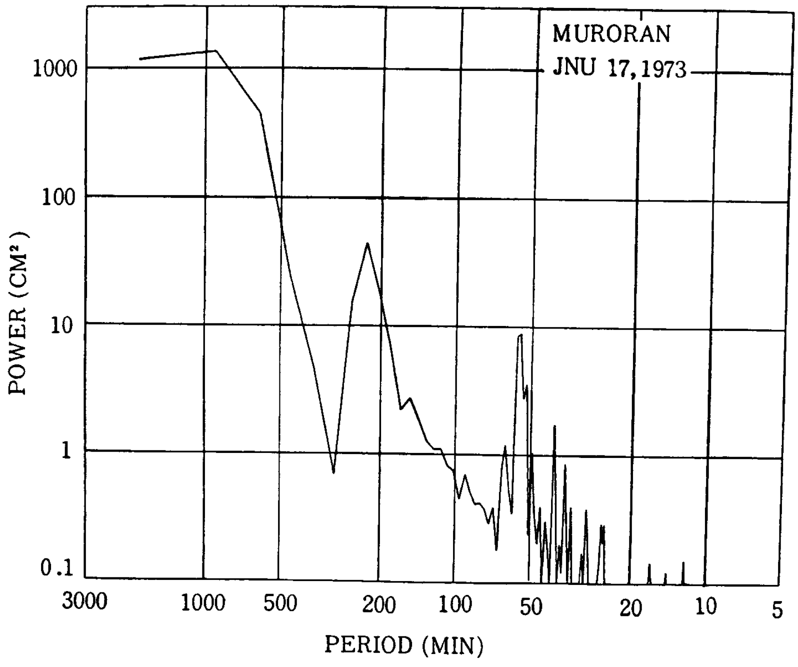
(a) 1952 Tokachi-oki tsunami



(b) Chilean tsunami

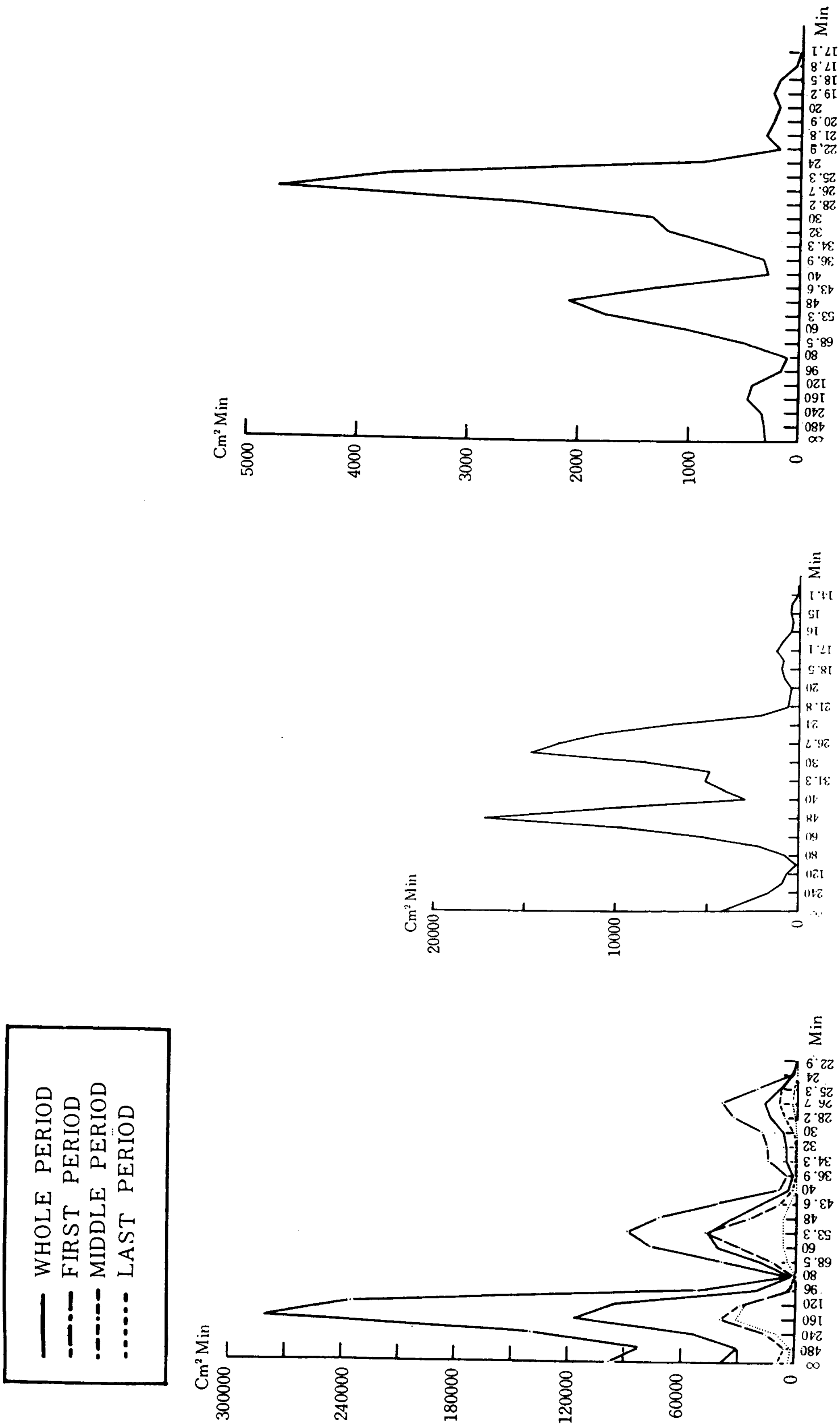


(c) 1968 Tokachi-oki tsunami



(d) Off-Nemuro Peninsula tsunami

Fig. 8 Power spectra of tsunamis at Muroran.

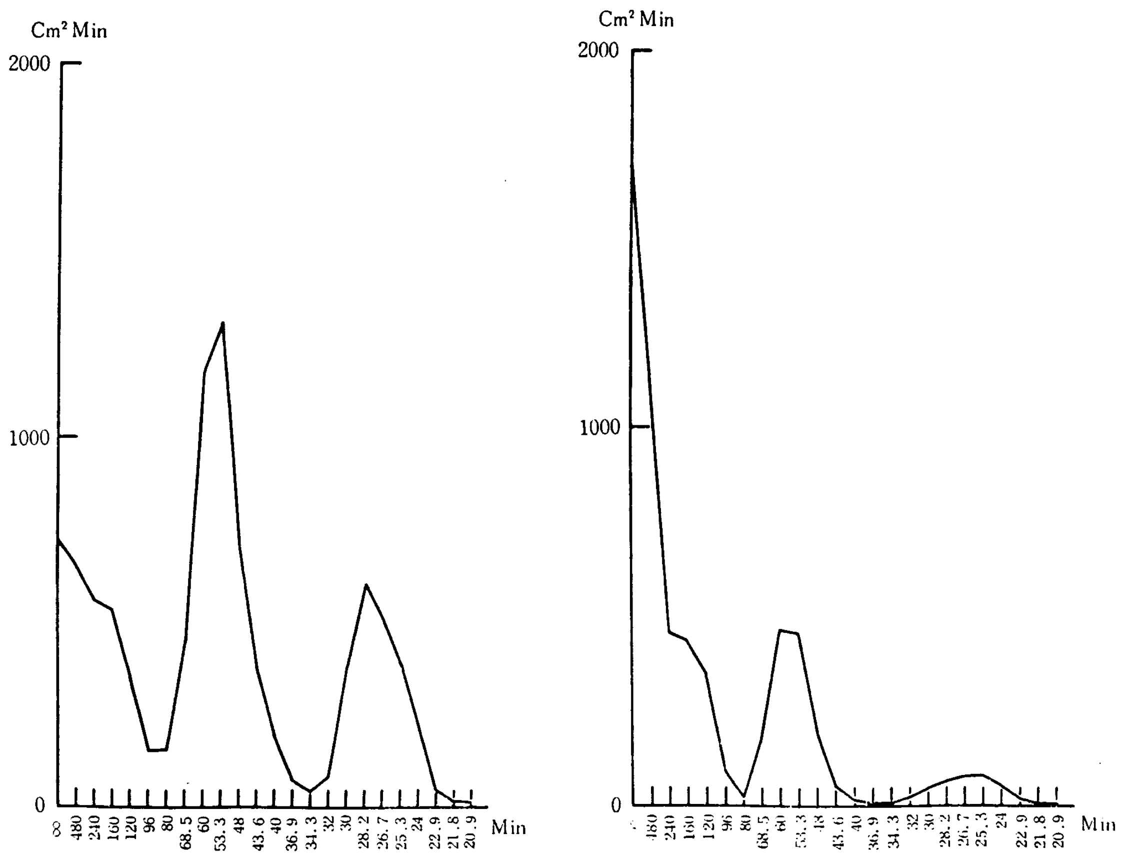


(a) Chilean tsunami

(b) 1968 Tokachi-oki tsunami

(c) Off-Nemuro Peninsula tsunami

Fig. 9 Power spectra of tsunamis at Hakodate.



(a) Ordinary time
(Before Chilǝan tsunami)

(b) Ordinary time
(Before Off-Nemuro Peninsula tsunami)

Fig. 10 Power spectra of tide motions at Hakodate.

Table 5 Time intervals of records used for spectral analyses (Hakodate).

Tsunami	Tsunami time	Ordinary times
Chilean (1960)	the whole period (11:00, 24 May-18:00, 27 May) First, Middle and last period (length of each period is one third of the whole period)	01:45, 23 May -03:36, 24 May (Before tsunami)
Tokachi-oki (1968)	10:51, 16 May-9:00, 17 May	
Off Nemuro Peninsula (1973)	14:51, 17 Jun.-16:00, 18 Jun.	23:59, 15 Jun. -02:02, 17 Jun. (Just before tsunami)

4. CONCLUSION

From spectral analyses of tide gauge records in Tokachi-oki (1952, 1968), Chilean (1960) and Off-Nemuro Peninsula tsunami (1973) observed at Hanasaki, Kushiro, Tomakomai, Muroran and Hakodate, local characteristics of tsunamis were examined. At Kushiro and Hakodate, analyses for tsunami and ordinary times were made and time dependency of tsunami motion was obtained.

According to the results of these analyses, peaks of spectra are amplified in tsunami times and the largest peak elongates as the magnitude of the earthquake increases.

At each harbor, tsunami motion is greatly influenced by seiche and edge waves on the continental shelf. Predominant periods are also caused by seiche in the harbor at Tomakomai and oscillation in the Uchiura Bay at Muroran. At Hakodate, predominant periods seem to correspond to seiche in the large sea areas.

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