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Excitation of Resonant Modes along the Japanese Coast by the 1993 and 1983 Tsunamis in the Japan Sea

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Abstract—We observed seiches at 55 ports in Japan facing the Japan Sea and obtained dominant periods from their maximum spectral amplitudes. These periods were mostly determined ranging from 10 to 40 minutes. They were compared with dominant periods of the 1993 Hokkaido Nansei-oki tsunami and the 1983 Nihonkai Chubu-oki tsunami at the same ports. As a result, relations of dominant periods between seiches and tsunamis are classified into three types. The first one is fundamental mode excitation, the second is higher mode excitation and the third is no excitation. Plotting the maximum spectral amplitude normalized at an epicentral distance of 50 km versus the ratio of the tsunami dominant period to the seiche dominant period, we obtained resonance curves having maxima at one. This fact shows a contribution of resonance to the amplification. Thus it is recognized that the dominant period of seiching is an important factor in interpreting amplification and resonance of tsunami.

Key words: Seiche, Tsunami, Japan Sea, resonant mode.

1. *Introduction*

Many tide gauge observations of tsunamis have established that the maximum tsunami amplitude rarely occurs during the first peak-trough cycle. It is difficult to understand this behavior because tsunamis are generated by fault motion with no oscillation. Accordingly, it is necessary to consider some superposition of waves to explain an amplitude increase at a later time. KATO *et al.* (1961) arrived at the idea of resonance to explain the different behavior between the 1960 Chilean tsunami and the 1933 Sanriku tsunami. ABE (2005) carried out observations of seiching at bays along the Sanriku coast, Japan, to obtain the dominant period of each observation, and constructed resonance curves by plotting the amplitude ratio between the mouth and head of each bay as a function of tsunami period normalized by seiche period. He showed that tsunami inundation heights observed at the head of bays along the Sanriku coast facing the Pacific Ocean are explained from resonance curves using the dominant periods. In contrast to the Sanriku coast, the coast of Japan bordering the Japan Sea, has a simple coastline. During the last 25 years there have

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been two large tsunamis in the Japan Sea: The 1993 Hokkaido Nansei-oki and the 1983 Nihonkai Chubu-oki tsunamis. Many tide gauge records of these tsunami are useful for analyzing tsunami amplification. In this paper I analyze the spectra of these observations to better understand the relation between tsunami amplification and seiching.

2. *Seiche Observations*

Observations of seiching at ports, including heads of bays, were conducted intermittently along the Japanese coast of the Japan Sea during the period from November 22, 2002 to December 25, 2006. Due to the simple coastline, bays are limited in number and many observation places are ports including ones facing the open sea. The fifty-five observation points distribute from Hokkaido to Kyushu in Japan as shown in Figure 1. Variations of sea level were recorded by a pressure gauge hung along the wall

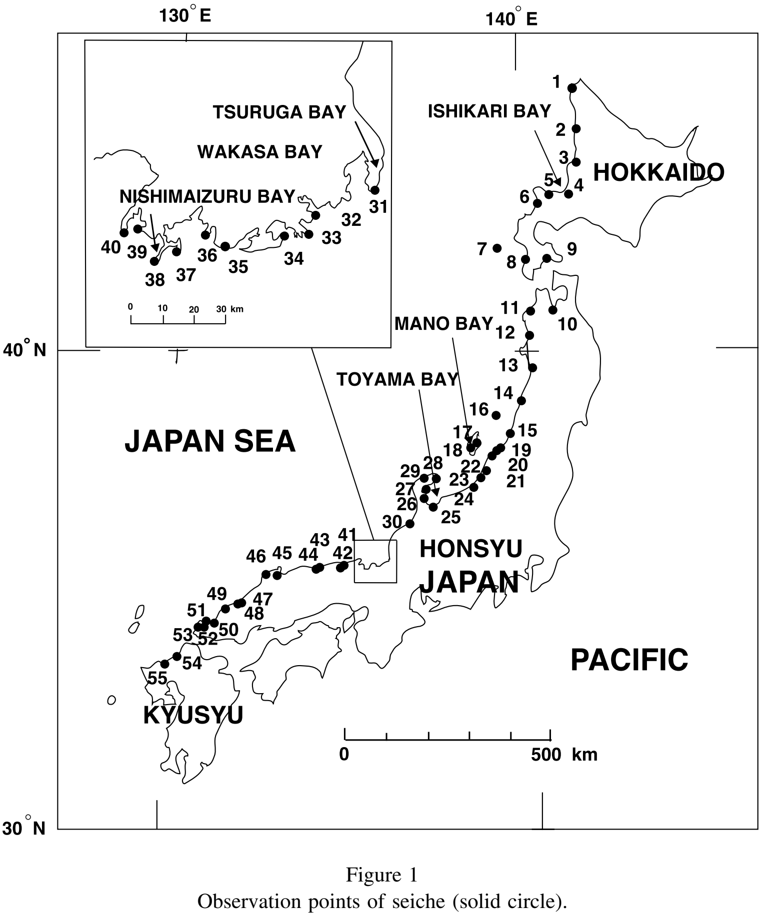

Figure 1
Observation points of seiche (solid circle).

of a quay in a port (Abe, 2005). Data were acquired for total durations of six hours with a sampling interval of one minute in comparatively calm sea conditions. The amplitude data were stored in a recorder and transferred to a computer via memory card. The time histories were transformed to smooth spectra in the frequency range of 0.06–2.4 mHz (6.9–177 min. in period).

3. *Observed Spectra and the Dominant Periods in the Seiche*

The dominant period T_0 is defined as the period of the maximum amplitude in the seiche spectrum for each observation point. The numbers corresponding to observation points are indicated in Figure 1. Examples of obtained spectra are shown in Figure 2. These are characterized by a single peak and referred to here as ‘single-peak’ spectra. A single-peak spectrum is defined as containing no second peak in amplitude higher than one-third of the maximum level, so that the dominant period is clearly defined. Eleven observation points are included in this category as shown in Figure 2, and occupy 20% of all the observation points. Most of these observation points are in large bays such as Ishikari, Toyama and Wakasa. This is not the case, however, for Sakata (No.14), Naoetsu (No.23), Kanazawa (No.30) and Sawada (No.18). The former three points are in comparatively large ports and the last one is on a beach at the head of Mano Bay. The dominant period for the single-peak spectra is always longer than 33 minutes. The rest of the observations are characterized as ‘multiple-peak’ spectra. The multiple-peak spectra were observed at open coasts, small islands or asymmetrical bays. Six examples of multiple-peak spectra are shown in Figure 3, in which Haboro, Fukuoka are on the open coast, Awashima is on a small island and Ryotsu, Toyama, Sakaikou are in asymmetrical bays. Dominant periods are also defined for the multiple-peak spectra. Hereafter, the dominant period of the seiche spectrum is called the seiche period.

A histogram of the observed seiche periods is shown in Figure 4. The seiche period varies from a minimum value of 7.1 minutes at Aomori port (No. 10) to a maximum value of 167 minutes at Tsuruga port (No. 31). The most frequently occurring range for the seiche period was 10–20 minutes, which accounted for 25% of all the data. The number of observation points with seiche period ranging from 10 to 40 minutes reaches 31 and corresponds to more than half, 56%. It forms an approximately continuous distribution as shown in Figure 4.

4. *Dominant Periods of the 1993 and 1983 Tsunamis*

The 1993 Hokkaido Nansei-oki tsunami and the 1983 Nihonkai Chubu-oki tsunami are treated for comparison. The former was caused by the Hokkaido Nansei-oki earthquake, registering a magnitude of 7.8, and the latter was caused by the Nihonkai

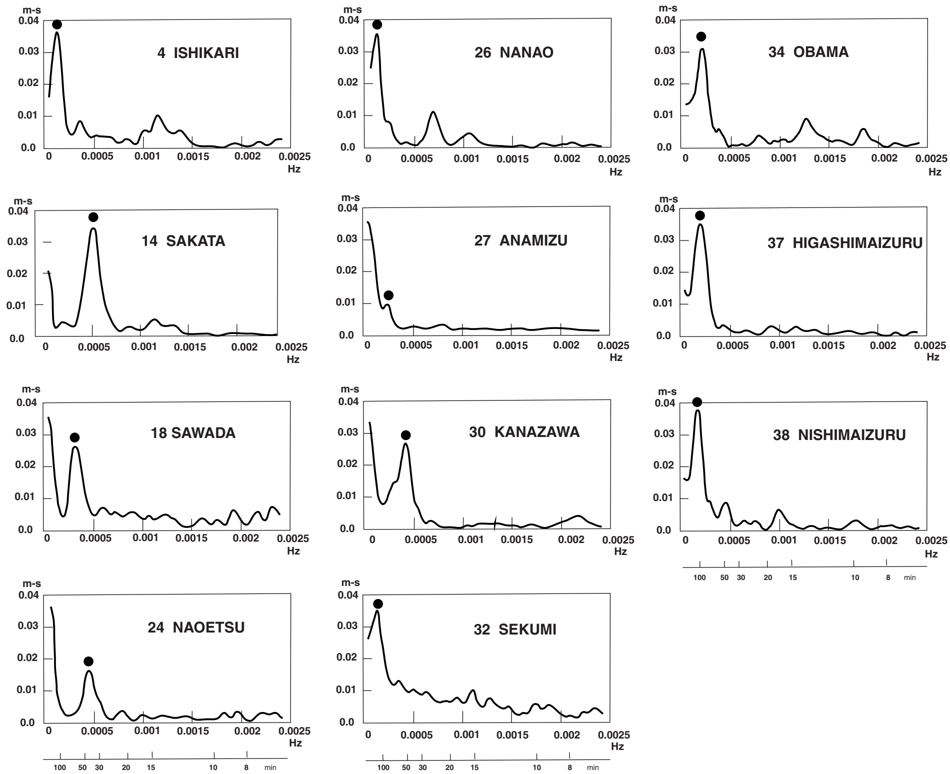

Figure 2
Amplitude spectra of single-peak seiche. The dominant periods are indicated by solid circles.

Chubu-oki earthquake, having magnitude of 7.7. Both of these tsunamis impacted the coast as waves higher than 10 meters spread throughout the Japan Sea. The marigrams were collected from thirty tide stations and the amplitude spectra were obtained for six hours from the origin times. These tsunami waveforms were corrected for the response of the tide gauges using recovery times measured by SATAKE *et al.* (1988). For tide stations without such data, an average recovery time of 269 s was applied as used by ABE (2003). The dominant period T_t is defined as the period of the maximum amplitude of the tsunami spectra, using the same method as used for the seiche observations. The tide stations used are shown in Figure 5.

5. *Comparison of Spectra between Tsunami and Seiche*

The spectra of tsunamis observed at each tide station are compared with the spectrum of the seiche that was observed nearest the tide station in the same bay or

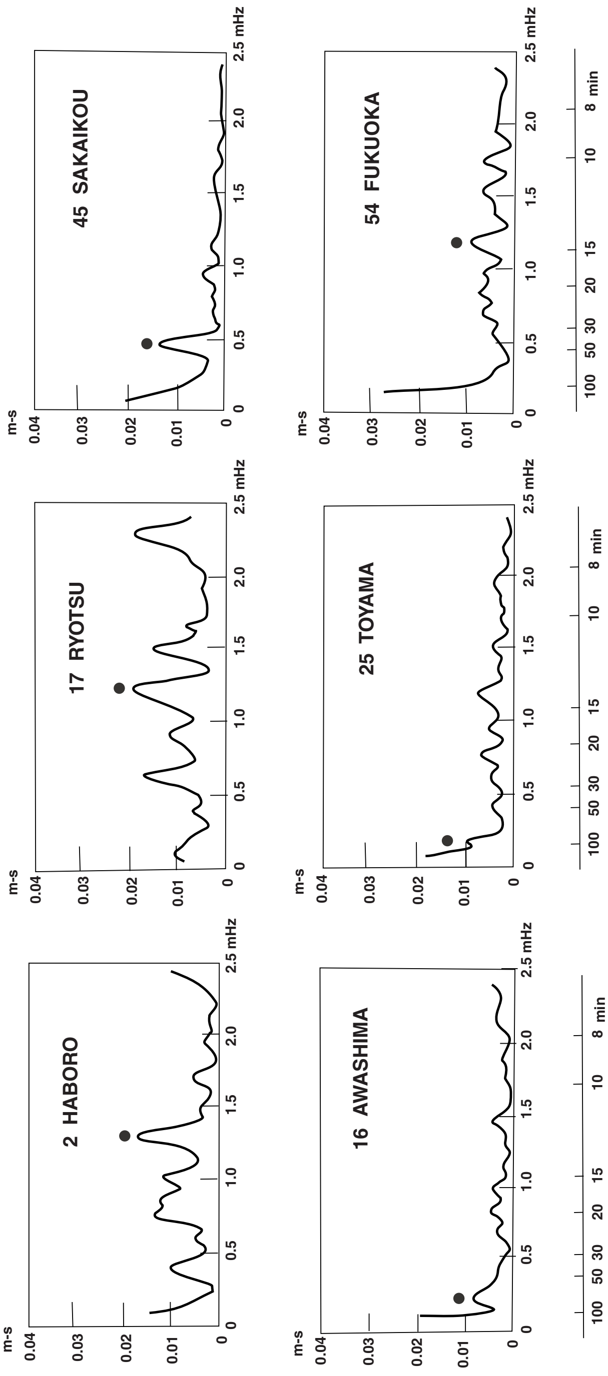

Figure 3
Example of multi-peak seiche spectra. The dominant periods are indicated by solid circles.

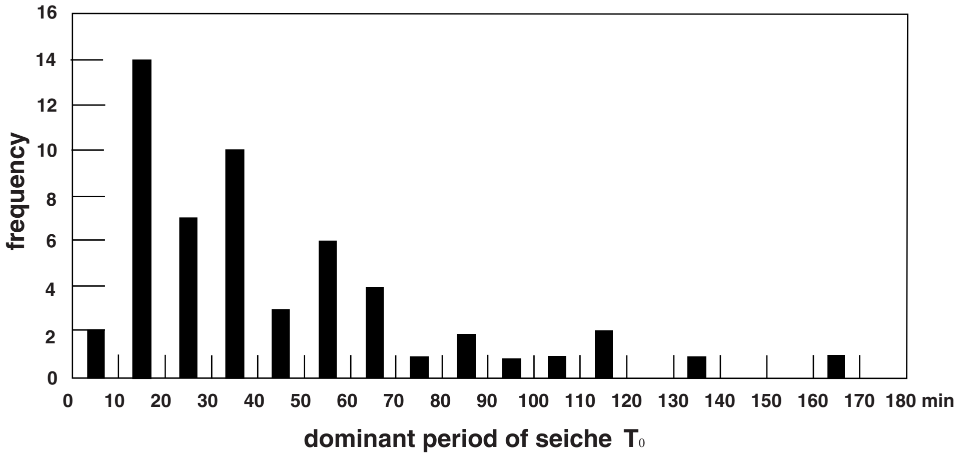

Figure 4
Histogram of dominant periods observed in seiche.

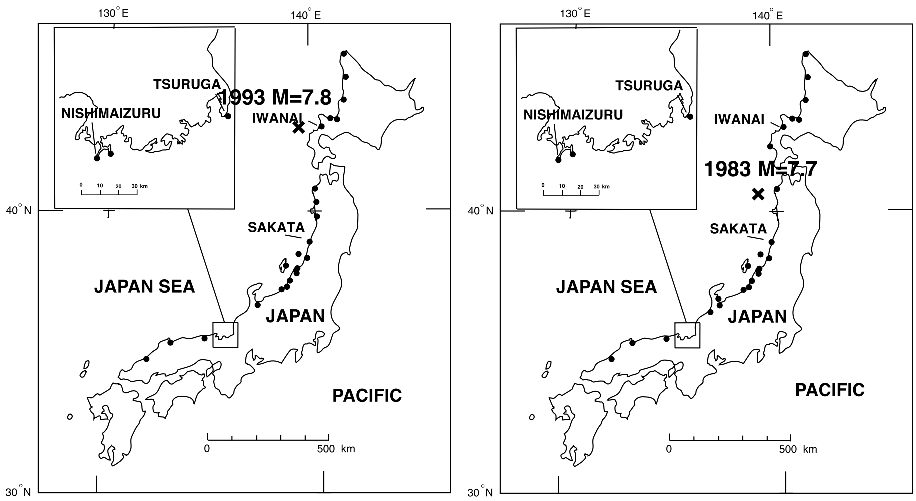

Figure 5
Tide stations at which dominant periods of tsunami were observed. Left: 1993 tsunami. Right: 1983 tsunami.

port. Four examples are shown in Figure 6. The first case is for Iwanai tide station and the seiche at Iwanai port (No. 6). The tsunami amplitude is as large as ten times that of the seiche and the period component consists of two or three peaks in contrast to the isolated peak of the seiche. A dominant period of 23 minutes of the 1993 tsunami is almost equal to the seiche period of 21 minutes, a difference of only 2 minutes. Since the seiche period is approximately the fundamental mode of the bay (ABE, 2005),

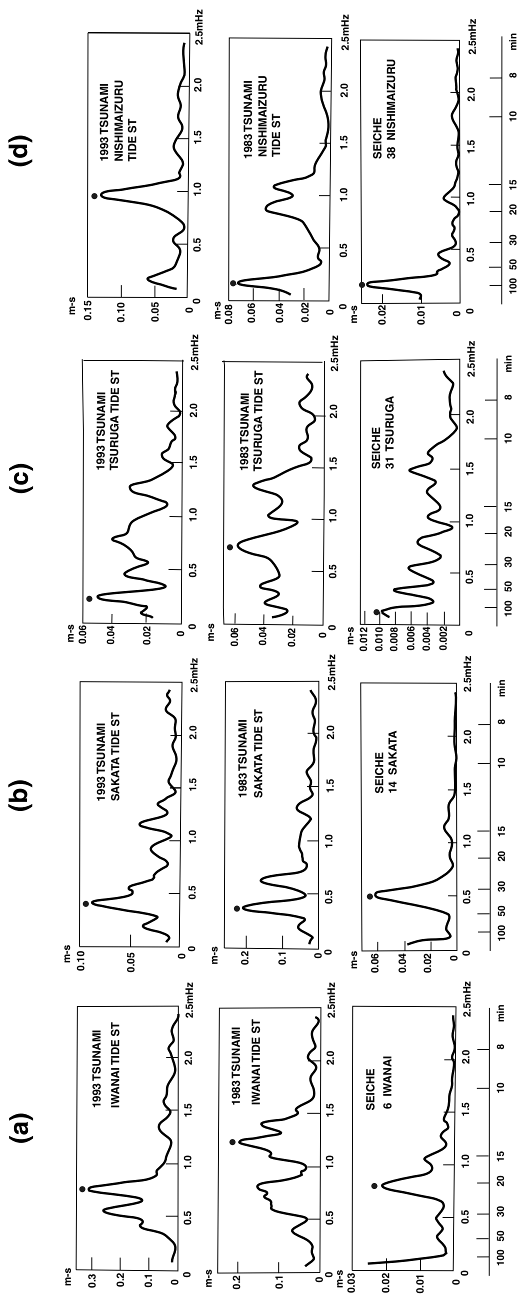

Figure 6
Amplitude spectra of tsunamis and seiche. From top to bottom: 1993 tsunami, 1983 tsunami and seiche. (a) Iwanai, (b) Sakata, (c) Tsuruga, (d) Nishimaizuru. Dominant periods of tsunamis and seiche are indicated by solid circles.

this indicates that the 1993 tsunami excited the fundamental mode with a node at the head of the bay. The spectrum for the 1983 tsunami also has a peak at the natural period, even though the maximum amplitude was observed at 14 minutes period. This again suggests that the fundamental mode was excited by the tsunami incident to Iwanai.

The second example is that of the Sakata tide station and Sakata port (No. 14). The dominant periods of the 1993 tsunami and the 1983 tsunami are 40 and 44 minutes, respectively. On the other hand the seiche period of Sakata port is 33 minutes. These spectra are dominated by energy at periods of 20 minutes or more. It is interesting that the dominant period of 40 minutes in the 1993 tsunami recorded at Sakata is almost equal to twice the dominant period observed at the Iwanai tide station for the same tsunami, and the dominant period of 44 minutes in the 1983 tsunami is almost equal to three times the dominant period at Iwanai tide station for the same tsunami. The fact that the ratio is integer suggests that the observed periods have the same origin.

The third case is that of Tsuruga tide station and Tsuruga bay (No. 31). The spectra of the tsunamis at Tsuruga have many peaks with an irregular interval. On the other hand the seiche observed there consists of many peaks with an almost regular interval. It is classified as a multiple peak spectrum as described above. This bay is asymmetrical in shape, with a dominant period of 167 minutes having the longest period of the peaks in the seiche spectrum. The multiple peaks are related to the higher modes. The dominant periods of the 1993 tsunami and the 1983 tsunami are 64 and 22 minutes, respectively, which correspond to higher modes identified in the seiche spectrum.

The fourth case is that of the Nishimaizuru tide station and Nishimaizuru bay (No. 38). It is noted that the tsunami spectra are represented by two peaks at 17 and 93 minutes period. The 17-minute peak dominated in the 1993 tsunami but the 93-minute peak dominated in the 1983 tsunami. The seiche period of 93 minutes is represented as a single peak as shown in Figure 2. It coincides with the dominant period of the 1983 tsunami. On the other hand 17 minutes dominated in the 1993 tsunami. The two modes correspond to the fundamental and a higher mode, as suggested by the latter as about one fifth the period of the fundamental mode.

6. Correlation between Seiche Period and Tsunami Dominant Periods

At the same port and bay the dominant periods of tsunamis are compared with the seiche period. The correlations are shown in Figure 7. In the figure, straight lines of 1:1, 1:3, 1:5 and 1:7 as the ratio of tsunami dominant period to seiche period are indicated. Since the seiche period probably is that of the fundamental mode at a bay or port, dominant periods of tsunami for 1:1 are the fundamental modes. When we approximate a bay or port as a rectangular bay of length L and sea depth h, we obtain a resonance period T_n from Merian's formula as follows:

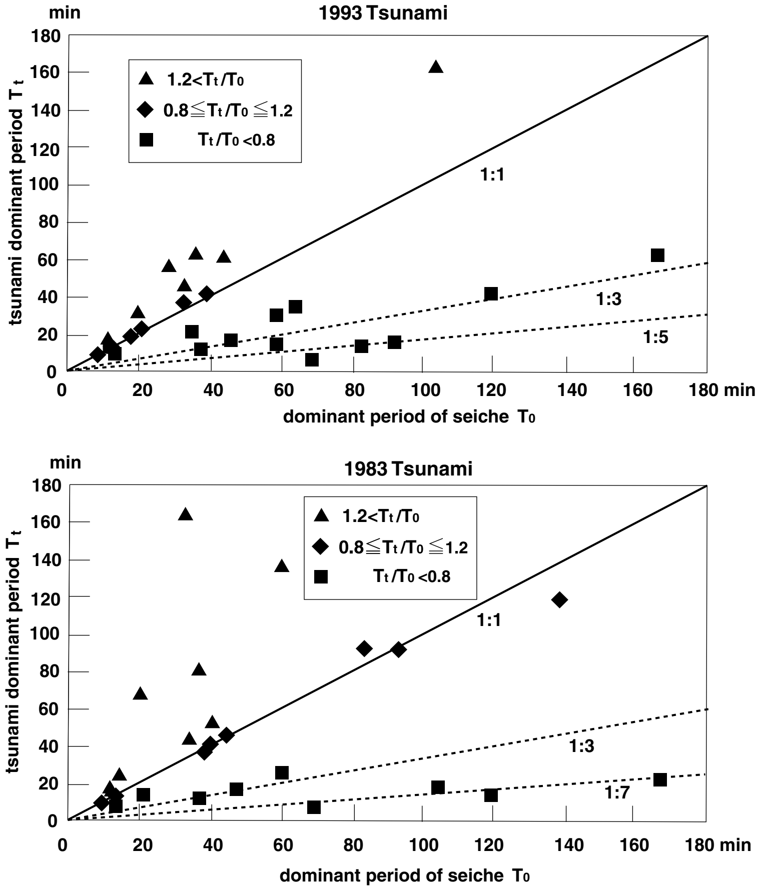

Figure 7
Correlation relation of tsunami dominant period to dominant period of seiche. Groups I, II and III are shown with diamond, rectangle and triangle, respectively. Top: 1993 tsunami. Bottom: 1983 tsunami.

$$T_n = \frac{4L}{(2n+1)\sqrt{gh}},$$

in which g is the gravitational acceleration at the Earth's surface and n is an integer. Assuming the seiche period as the fundamental mode we will obtain the periods of higher modes as

$$T_n = \frac{T_0}{2n+1}.$$

Thus the higher mode is represented as the ratio of odd numbers such as 1:3,1:5,1:7, etc.

It is observed that most of the tsunami dominant periods are explained as being the fundamental mode (seiche period) and a higher mode in the area T_t / $T_o \leqq 1.2$. In this area the tsunami was trapped in the bay or port and proper oscillations were excited. On the other hand in the area T_t / T_o > 1.2 this trapping did not occur and the tsunami period has no particular relation to the seiche period. The long-period components were observed at tide stations distant from the epicenter.

For example the longest-period peak in the 1983 tsunami spectra is observed at Wakkanai (No. 1 in Fig. 1) being located at the northern tip of Hokkaido. The location relative to the epicenter shows an oblique incidence, which is not favorable for exciting secondary seiche undulations (e.g., NAKAMURA and WATANABE, 1961). Thus, we can classify all the data into three groups, as indicated in Figure 7. One is a group of fundamental mode excitation around the line of 1:1. Another one is a group of higher mode excitation around lines of 1:3, 1:5 and 1:7. The rest comprise a group corresponding to no excitation of proper oscillations. Assuming an error of 20% for the 1:1 line we obtain 7 and 9 tide stations for the 1993 tsunami and the 1983 tsunami, respectively. They correspond to 27% and 33%, respectively, of the observations. This is the first group (Group I). The second group is defined as tide stations having dominant periods smaller than the lower limits to the 1:1 line. Twelve and nine tide stations belong to this group for the 1993 and 1983 tsunamis, respectively (Group II). The third group is defined as tide stations for the periods larger than the upper limit of the first group. It consists of 7 and 9 tide stations for the 1993 tsunami and the 1983 tsunami, respectively (Group III). The classifications are shown in Figure 7 using three different symbols.

In the distribution we can notice a critical transition from the fundamental mode to higher modes in the 1993 tsunami and identify the critical point at 40–44 minutes of tsunami dominant period. The existence of this transition implies that the 1993 tsunami has most of its energy confined to a period range shorter than this critical value. The one observation that does not fit this interpretation is the Toyama tide station, which has a dominant tsunami period of 167 minutes. In contrast, it is concluded that the 1983 tsunami consists of a broader spectrum of energy that extends to periods longer than 119 minutes.

The different character of modal excitation for the two tsunamis is illustrated in the histogram of Figure 8. The ratio of higher mode to fundamental mode excitation is 1.7 and 1.0 for the 1993 tsunami and the 1983 tsunami, respectively. Excitation of higher modes is larger in the 1993 tsunami. It suggests that the former is more dominated by short-period energy in comparison with the latter.

7. *Resonance*

The dominant period ratio T_t / T_0 is defined as the dominant period of tsunami T_t relative to the seiche period T_0. The normalized amplitude of the tsunami dominant period is also defined as the amplitude at the epicentral distance of 50 km, reduced by a formula which has amplitude inversely proportional to the square root of the epicentral distance, i.e., it is assumed that tsunami amplitude decreases due to geometrical spreading. The normalized amplitude is plotted against the dominant period ratio for both tsunamis as shown in

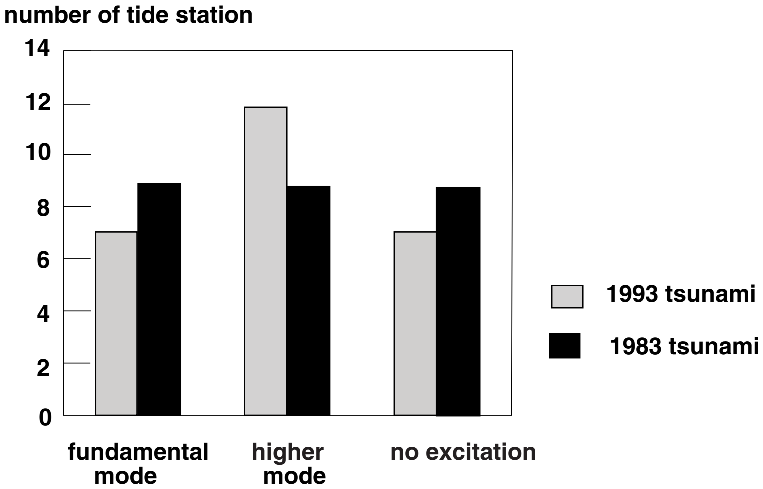

Figure 8
Histograms of mode excitation in the 1993 and the 1983 tsunamis.

Figure 9. It is found that data concentrate around 1 in the abscissa and the maxima occur near one in both cases. This result was expected from the concentration around lines 1:1 as shown in Figure 7. The concentration around 1 and the amplitude increase at 1 supports the idea that the amplification of the tsunami is caused by a resonance due to local bathymetry. An exceptional observation is the large amplitude of the 1993 tsunami observed at Nishimaizuru. This may be due to some unknown mechanism such as focusing. The fact that the maximum in the resonance curve appears at 1 implies that the fundamental mode is more important than higher modes in the amplification.

8. *Discussions*

Honda *et al.* (1908) also estimated dominant periods of seiche records near some of the observation points used in the present study. According to them they are as follows: 22.6 min (Niigata); 11.6–12.4, 14.5–17.2, 22.0–25.5, 30–35.8, and 43 min (Kashiwazaki); 37.6 min (Naoetsu); 12.5–16.4, 21.9, 28.0–33.0, and 81.5 min (Wazima); 56.7 and 62.7–67.7 min (Tsuruga); and 11.9–12.9 min (Tonoura). In our study, the corresponding dominant periods were observed to be as follows: 44 min (No. 21 Niigata westport), 46 min (No. 23 Kashiwazaki), 38 min (No. 24 Naoetsu), 30 min (No. 29 Wazima), 167 min (No. 31 Tsuruga) and 13 min (No. 47 Tonoura). At Naoetsu, Wazima and Tonoura our result agrees with that of Honda *et al.* (1908). At Niigata our period of 44 min is almost twice their result of 22.6 min, and at Tsuruga our result of 167 min is about three times their result of 56.7 min. The fact that the dominant period ratios were integers suggests that Honda *et al.* (1908) observed higher mode excitation.

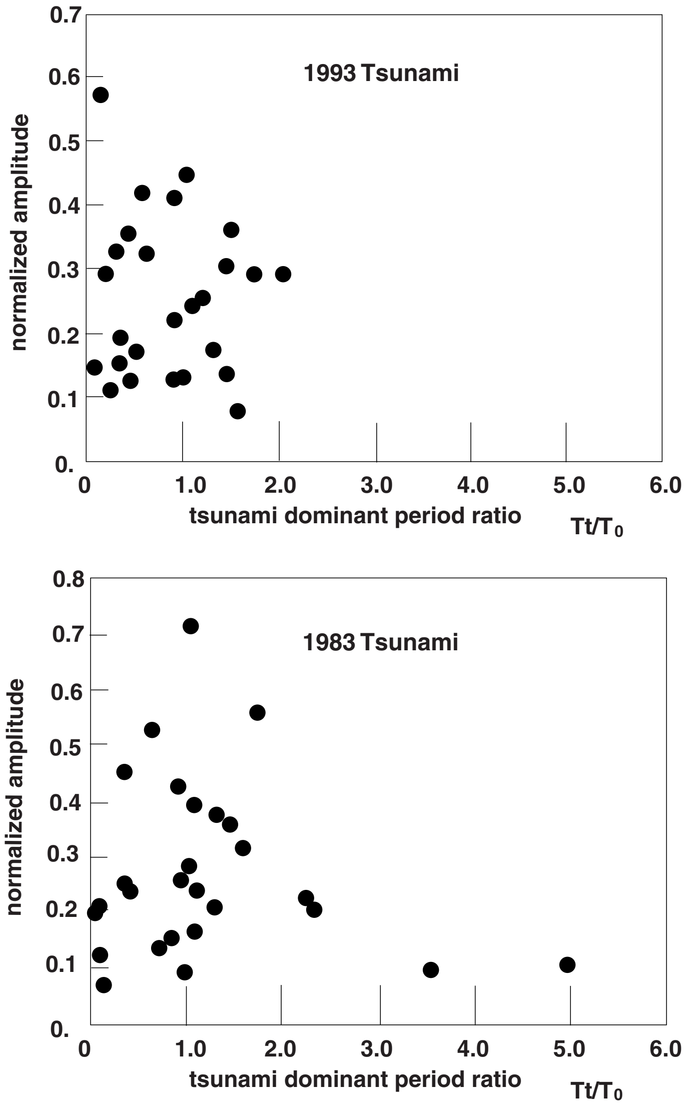

Figure 9
Normalized maximum spectral amplitude versus the dominant period of tsunami relative to seiche period in the 1993 tsunami (top) and the 1983 tsunami (bottom).

NAKANO and UNOKI (1962) studied seiche observed at tide stations around Japan. They identified undulations that accompanied storm surge, tsunami and meteorological disturbances, etc., from tide gauge records for intervals of one month to 26 years. In their results they listed frequently observed periods as follows: 26–27, 38, and 45–55 min (Wakkanai); 18–22 and 42–60 min (Miyazu); 40, 45, 50, 55, 60, 70 and 80 min (Sakaikou);

and 11–12 min (Tonoura). Our result is as follows: 33, 52, 36 and 13 min for Wakkanai (No. 1), Sakaikou (No. 45), Miyazu (No. 40) and Tonoura (No. 47), respectively. There is a maximum difference of 5 minutes between them, which seems insignificant when we consider that measured seiche periods are subject to some variation (see below).

RABINOVICH (1997) proposed a method to separate source spectra of tsunami from observed tide gage spectra using the background spectra observed before the tsunami arrival. He approximated the tsunami spectrum observed at a tide station as a multiple of source spectrum and background spectrum. Our result shows that the dominant period of the seiche is reproduced in tsunamis at many tide stations. According to his approximation this may be explained by the generated tsunami having energy at periods similar to the seiche periods.

ABE (2007) estimated tsunami source lengths for the 1993 tsunami and the 1983 tsunami by analyzing the first wave. Assuming a sea depth of 2500 and 2000 m he obtained the lengths of 169 and 126 km for the 1993 and 1983 tsunami, respectively. We can calculate the period from the wavelength and the long-wave velocity. Assuming the length to be one wavelength and the same sea depths used by ABE (2007), we obtain periods of 18 and 15 min for the 1993 and 1983 tsunamis, respectively. These values are in the range of the most frequently appearing dominant periods, as described in Section 3. This is in agreement with the amplification resulting from resonance.

AIDA *et al.* (1975) observed seiche at Onagawa Bay in northeast Japan and investigated its change with time. They found that the seiche energy is mainly in the fundamental mode, whose period varies seasonally from 37 to 42. Their result implies that we should adopt at least 5 minutes as the potential error in our measurements of dominant period. This amounts to 14% in the relative error. We conservatively assumed 20% relative error in our classification of mode excitation. It should be noted, however, that this reflects seasonal variation and its geographic variability in addition to measurement error.

9. Conclusion

Seiches were observed at fifty-five observation points consisting of ports and bays facing the Japan Sea along the Japanese coast, and the dominant periods (resonant periods) were determined from the maximum spectral amplitudes. Most of the seiche periods are found to range from 10 to 40 minutes. They are compared with dominant periods of the 1993 and 1983 tsunamis observed at the same ports on tide gauges. The result shows that resonant oscillations of ports or bays, including the higher seiche modes, were excited by the tsunami. Where no excitation of resonant oscillation occurred, this is explained as being due to oblique incidence. The fact that the amplification as a function of the ratio of tsunami and seiche dominant periods attains its maximum at a ratio of one indicates resonance between tsunami and bay or port. The dominant seiche period is therefore an important factor to consider in interpreting tsunami amplification.

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REFERENCES

ABE, K. (2003), *Source model of a small tsunami accompanied with a volcanic earthquake at Kouzu-shima on July 1, 2000*, Zisin *2*, *56*, 181–187 (in Japanese).

ABE, K. *Tsunami resonance curve on dominant periods observed at bays*. In *Tsunamis: Case Studies and Recent Developments* (ed. K. Satake) (Springer Publishing 2005) pp. 97–113.

ABE, K. (2007), *Phase representing source lengths of tsunami in tide gauge records*, Pure Appl. Geophys. *164*, 453–463.

AIDA, I., KOYAMA M., DATE D. and S. SAKASHITA. (1975), *Long-period waves in the vicinity of Onagawa Bay (III)—Time change of the seiche characteristics in the bay*. J. Oceanog. Soc. Japan *31*, 61–70.

HONDA, K., TERADA, T., YOSHIDA, Y., and ISITANI, D. (1908), *The secondary undulations of oceanic tides*, J. Coll. Sci., Imper. Univ. Tokyo, *24*, 1–110.

KATO, Y., SUZUKI, Z., NAKAMURA, K., TAKAGI, A., EMURA, K., ITO, M., and ISHIDA, H. (1961), *The Chile tsunami of 1960 observed along the Sanriku coast of Japan*, Sci. Rep. Tohoku Univ., Ser. 5, Geophys. *13*, 107–125.

NAKAMURA, K. and WATANABE, H. (1961), *Tsunami forerunner observed in case of the Chile tsunami of 1960*, Report on the Chilean Tsunami, Field Investigation Committee for the Chilean Tsunami, pp. 82–99.

NAKANO, M. and UNOKI S., (1962), *On the seiches (The secondary undulations of tides) along the coasts of Japan*, Records of Oceanographic Works in Japan, No. 6, 169–214.

RABINOVICH, A. B. (1997), *Spectral analysis of tsunami waves: Separation of source and topography effects*, J. Geophys. Res. *102*(C6), 12663–12676.

SATAKE, K., OKADA, M., and ABE, K., (1988), *Tide gauge response to tsunamis: Measurements at 40 tide stations in Japan*, J. Mar. Res. *46*, 557–571.

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