CHAPTER NINE

BAYWATER RESPONSE TO TSUNAMIS

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ABSTRACT

To investigate the transient characteristics of the tsunami-induced oscillations, records of tsunami caused by the Off-Miyagi earthquake in June, 1978 were analysed on the basis of theories on stationary and non-stationary stochastic processes. The stationary spectra show the average feature of the phenomenon. Discrepancies, however,are recognized between the first half oscillations and the second half oscillations during the tsunamis. Besides, the energy densities of non-stationary spectra do not always indicate stationary value at the periods which correspond to the predominant ones of the stationary spectra. These suggest that tsunami-induced oscillations are translative.

1.0 INTRODUCTION

Tsunami waves are basically generated by dislocation of sea-bottom in earthquakes of magnitudes of over 6.5. Waves which attack the coast give greater height as the magnitude of an earthquake increases. Such waves are still in the dispersive process even at the coastline, because the source regions of tsunamis which attack the Japan Island are usually at the western slope of the Japan Submarine Trench and the distance to the coast is nearly the same order of the breadth of the source. Moreover, these waves are transformed by reflection and refraction superimposed by shelf resonance and the edge waves to give complicated dynamic phenomena near-coast offshore region(Iwasaki(4)).

Dynamic phenomena such as baywater oscillations have been of considerable interest to coastal engineers in relation to engineering evaluation of structures against tsunami disaster. Many researchers have treated them so far, both theoretically and experimentally. Consequently, the understanding of the response of water bodies to external disterbance has progressed greatly. However, less attension has been paid on the investigations based on the actual tide gauge records, because of the limited amount of the tide gauge stations and tide gauge records available in ordinary bays. So that the detailed behaviours of actual bay oscillations were not so well investigated and the verification of experimental or numerical results by observed data is often hindered.

Then, the transient process of baywater response to tsunamis should be investigated based on the observation data, which is the object of this study.

2.0 OUTLINE OF THE OFF-MIYAGI TSUNAMI IN JUNE, 1978

The Sanriku Coast is the name of the coast which is situated in the northeastern part of the mainland of Japan facing the Pacific Ocean and stretching from 38°N to 41.5°N in latitude. Although this coast is famous

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by the inundation of tsunamis and a lot of tsunamis attacked there in the past, there were only three cases for which scientific records were obtained among those which originated off this coast and severe damage. They were the Sanriku Tsunami in 1896, the Sanriku Tsunami in 1933 and the Tokachi-oki Tsunami in 1968. Thus, data acquisition of tsunami waves is not easy, because earthquakes of magnitude of over 7.0 are very much seldom.

In 1978, small tsunamis were caused by an earthquake of the magnitude of 7.4 which originated off the coast of the Miyagi Prefecture, the southernmost part of the Sanriku Coast, at 17:14 on June 12. Its source was reported to be at 142°14'E longitude, 38°10'N latitude and about 25 km deep. According to records of the present tsunamis, the initial motion of tsunamis was in the upward direction at the whole stations in the Sanriku Coast, suggesting the uplift of the sea-bottom in the tsunami source area. The tsunami source area which was estimated by using the adverse refraction diagram was reported by Iwasaki and Mano(5) as shown in Fig. 1, of which the longer axis of 65 km lies in the E-W direction and the shorter one of 50 km lies in the N-S direction, roughly along a bathymetric line of 600 m deep.

As to the Miyagi district, Hatori(3)reported two historical tsunamis as shown in Fig.1. These tsunamis caused by the earthquakes of magnitude of 7.5 and 7.4, respectively, whose seismic intensities were inferred from old documents. The present area of aftershocks coincided with the wave source area of the historical tsunami caused by the earthquake on October 21, 1861. This historical tsunami caused waves of 3 to 4 m high at Ryori near Ofunato Bay. However, wave heights of the present tsunamis were small in compare with those in 1861. The maximum height was only about 1.22 m at Onagawa Bay and about 1.18 m at Kesennuma Bay in the north of the Miyagi Prefecture. Generally speaking, historical tsunami were generated at the similar locations to the source regions of recent tsunamis. Then, the area in the sea near the Miyagi district may still be considered a region of relatively high tsunami risk, because no conspicuous tsunami has been generated in this region since 1861, as pointed out by Hatori(3).

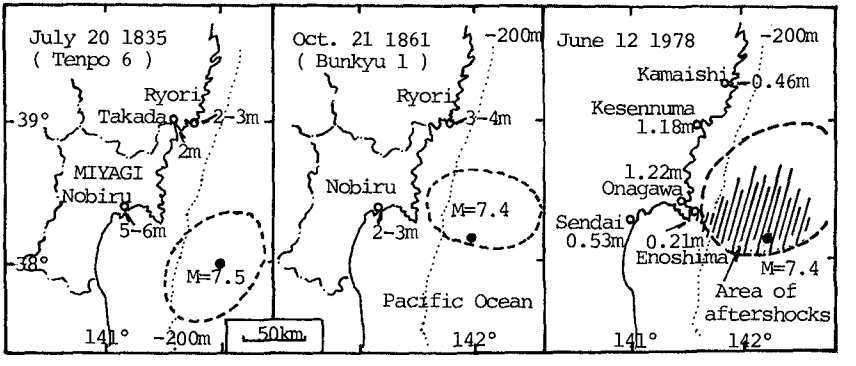


Fig. 1 Tsunami heights and tsunami source areas of the 1835 Tenpo and the 1861 Bunkyu earthquakes inferred from old documents by Hatori (3), and the tsunami source area caused by the Off-Miyagi Earthquake in 1978 as defined by Iwasaki and Mano(4).

3.0 STATIONARY CHARACTERISTICS OF THE BAYWATER RESPONSE TO TSUNAMIS

3.1 Stationary Spectrum of Oscillation by Tsunamis

Onagawa Bay and Kesennuma Bay were selected for the analysis of gauge records, because the tsunami heights at two bays were relatively high in compare with those of other stations in the Sanriku Coast. Besides, Onagawa Bay was just located near the present tsunami source area and Kesennuma Bay was just opened to that. In Onagawa Bay, there are a tidal gauge station at the head and a tsunami observatory of the Earthquake Research Institute, University of Tokyo, at Enoshima Island offshore of the bay. In paticular, Enoshima data may be used to estimate the spectral characteristics of wave offshore. In Kesennuma Bay, there is a big island inside the bay, so that the bay is almost like a long and narrow bay.

Table 1 shows the general discription of wave data and Fig. 2 shows the time sequence records of water level, namly tsunami waves, which were deduced from gauge records by subtracting meteorological tides estimated by the moving average method. Wave data at Onagawa and at Kesennuma were divided into two parts, "before the tsunamis" and "after the tsunamis". Furthermore, data after the tsunamis were divided into "first half" and "second half" for the spectral analysis on the basis of stationary stochastic process.

Spectrum is a widely used idea for presenting the constitution of a given time series. Wave oscillations originated in the open sea or induced within the bay are, in fact, typical time series in nature. There are several methods which can be used to estimate the spectrum of the stationary band-limited time series. The " Maximum Entropy Method " as introduced by Burg(2) is used here. This method is very convenient for the analysis of tsumani waves, because it can produce a highly resoluted spectrum with accurate frequencies and power estimates, even for the observed time series with very few samples.

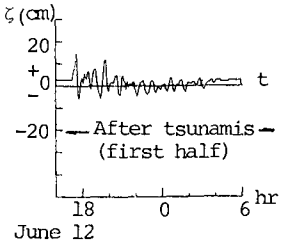
For a given stationary time series,the maximum entropy power spectrum is defined by the following power spectrum, S(f), which maximizes the entropy of the given time series:

$$S(f)=\frac{\Delta t\sigma_{M+1}^{2}}{\left|\sum_{m=0}^{M}\gamma_{m+1,K+1}\exp(i2\pi fm\,t)\right|^{2}} \qquad (1)$$

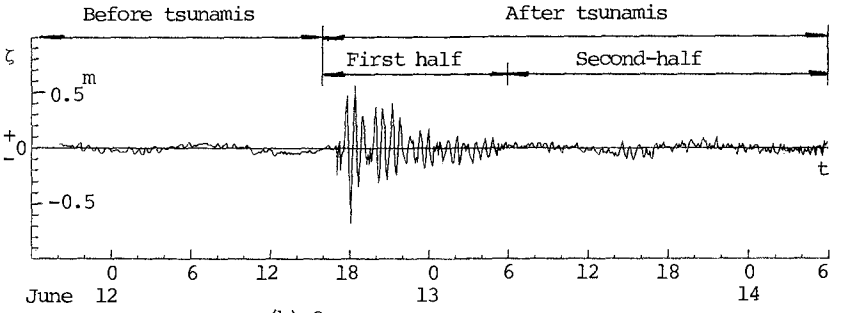
Hereafter, S(f) is called MEM-spectrum, where σ_{M+1}^{2} and $\gamma_{m+1,K+1}$ are the variance of prediction errors and the prediction error filter for the filter number K+1, respectively. M is the number of the maximum correlation lag, and f is the frequency. The actual time step, Δt, was determined by the chart speed of tide gauge. Since Δt was selected as 5 min, the maximum frequency available is 1/15(HZ), that is, the minimum period available is 15 minutes here. The frequency range was, then,

Table 1 Tide gauge stations and analysis data

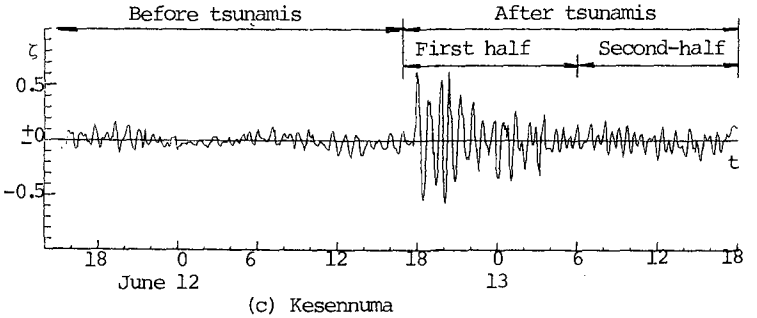
Bay	Onagawa				Kesennuma		
Tide gauge station	Enoshima	Onagawa			Kesennuma		
Time origin (t=0)	After the tsunami	Before the tsunami	After the tsunami: First half data	After the tsunami: Second-half data	Before the tsunami	After the tsunami: First half data	After the tsunami: Second-half data
June, 1978, JST	12th 16:00	11th 18:00	12th 16:00	13th 6:00	11th 14:00	12th 17:00	13th 6:00
Sampling time (Δt)	5 minutes	5	5	5	5	5	5
Number of data (N)	169	265	169	289	324	156	145
Number of filters(K)	15	20	15	20	20	14	14



(a) Enoshima



(b) Onagawa



(c) Kesennuma

Fig. 2 Time sequence records of water level deduced from tide and tsunami gauge records.

divided into 100 unites, which enabled the calculation of MEM-spectrum. The number of filter terms was tentatively selected by the "Final Prediction Errors Standard", and the optimal one was decided so that the spectrum would include the first mode which had been estimated by a preliminary test with fewer filter terms.

Fig. 3 shows the MEM-spectra of Onagawa Bay, where the broken line was derived from the first half data after the tsunamis at Enoshima near the bay mouth and chain line is the one at Onagawa in the bay head. In this spectra, ordinate of S(f) is normalized such that 100 and 1 are the reference maximum and minimum values of spectra. According to the results of Onagawa, there are four predominant oscillation modes during the tsunamis. Their periods are 41, 32, 18 and 13 minutes. The oscillation of 41 min is the basic mode along the bay axis, whose node exists near bay mouth. The oscillation with the period of 18 min is corresponding to the first longitudinal mode, whose node exists near the branched bay at the bay head as reported by Aida(1). The oscillation with the period of 13 min may be corresponding to the second lateral mode between two branched bays. Spectra of Enoshima show four peaks at the period of 43, 26, 18 and 12 minutes. The predominant oscillation period 43 min shows that the water oscillation at Enoshima, although the tide gauge station is considered to be located at the open sea,is affected by the existence of Onagawa Bay. The oscillation of rather longer period is evidently reflecting the effect of the continental shelf off Onagawa Bay. Enoshima is located at the mouth of Onagawa Bay and was just on the edge of the present tsunami source area. So, the spectra at Enoshima may provide information on the waves in the tsunami source area. The oscillation of the period of 26 min seems to be related to the waves in the present tsunami source area. However, further data and considerations are needed to specify it. The oscillation energy is developed mainly with respect to the basic mode. Their magnitudes at the bay head are much higher than those at the bay mouth.

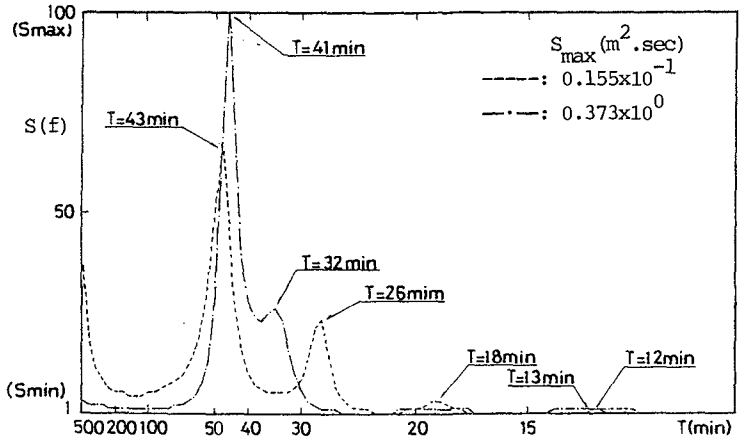


Fig. 3 MEM spectrum of Onagawa Bay, where the broken line is derived from the first half data after the tsunami at Enoshima, and the chain line at Onagawa.

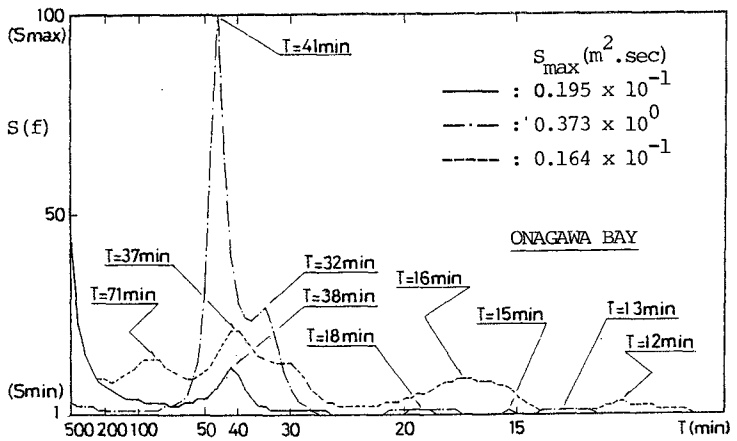
Fig.4 shows the MEM-spectra at Onagawa and Kesennuma. The spectra at Onagawa show the several predominant oscillation periods of 38, 27, 18 and 15 minutes for the wave data before the tsunamis invade; for the first half data after the tsunamis, those of 41, 32, 18 and 13 minutes; and for the second half data after the tsunamis, those of 37, 30, 16 and 12 minutes, respectively. The oscillation of 38 min is the basic mode along the bay axis and the oscillation period of 18 min is corresponding to the first longitudinal mode.The oscillation with the period of 15 min is corresponding to the first lateral mode.It represents the interaction of oscillations in two branched bays, named Onagawa Harbour and Gobaura Bay, and may be considered a lateral oscillation between these two bays. By the intrusion of tsunamis,the basic mode with the period of 38 min in ordinary times before the tsunamis is slightly shifted to the longer period range, 41 min, in the first half of the tsunamis; and to shorter period range, 37 min, in the second half of the tsunamis,suggesting that the position of node moves toward the open sea; and moves back into the bay during the tsunamis. The oscillation energy is especially amplified in the basic mode in the first half of tsunamis. One of another tipical facts is that rather remarkable rise in the spectrum is recognized at around 71 minutes in the final stage, evidently reflecting the effect of the continental shelf off Onagawa Bay.

As to Kesennuma Bay, three remarkable peaks were noticed at 52, 33 and 19 minutes in the spectra derived from data before the tsunamis; Two remarkable peaks were noticed at 50 and 32 min in the first half data after the tsunamis; and at 59 and 30 minutes in the second half data after the tsunamis. The largest period is corresponding to the basic oscillation mode of the bay whose node exists near the bay mouth, and the others are related to the oscillations near the bay head. However, the response features are different from the ones of Onagawa Bay. In the first stage of tsunami times, the mode at the period of 19 min disappears and the others are slightly shifted to shorter periods of 50 and 32 min. The energy of the basic oscillation is especially developed in this stage. It can be said that the location of the node of the basic mode moves into the bay and moves toward the open sea by the intrusion of the tsunamis.

3.2 Numerical Analysis

In contrast to the spectral analysis of the observed wave data, a theoretical investigation on the resonant oscillation in Onagawa Bay would be done in this study. Through this investigation, a discrete set of natural oscillation modes of Onagawa Bay and the corresponding relative wave heights at every point inside the bay are estimated, from which the system function of the baywater oscillation system can then easily be found. Furthermore, on the basis of the power spectrum of the waves observed at Enoshima near the bay mouth, the response power spectrum at various sites inside the bay can also be estimated.

Records of wave gauge set in bays show very much different behaviour in each locality where the gauges are set. It is the influence of the local features, the transient nature of the incident waves and the bay dynamics. From the foregoing statement, a simple concept is realized that the occurance of the baywater oscillations, at least, is concerned with two parameters; one is the natural periods of the bay, the other is the period range of the incident waves. For the case of a long and narrow bay, only longitudinal oscillations are importance. Then, the natural period of the first mode of free oscillation on continental shelves or bays is



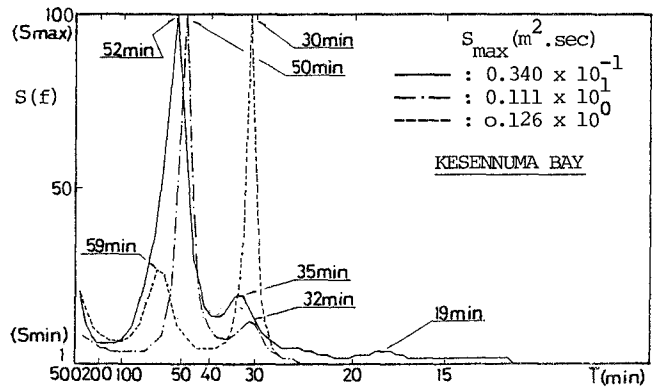


Fig. 4 MEM spectra at Onagawa and at Kesennuma, where the solid line is derived from data before the tsunami; the chain line is derived from first half data; and the broken line from second-half data after the tsunami.

calculated by $T=4\ell/60\sqrt{gh}$ (min.), where h and ℓ are the average depth and length. However, tsunami-induced oscillations in bays are different from the free oscillations. They should be considered as forced oscillations. In this study, the basic equation used to analyse numerically this problem is the Helmholtz equation, which describes the spatial variation of the linear oscillation in a bay; that is,

the long wave equation for periodic waves is

$$\frac{\partial}{\partial x}\left(h \frac{\partial \zeta}{\partial x} \right) + \frac{\partial}{\partial y}\left(h \frac{\partial \zeta}{\partial y} \right) - \frac{1}{g} \frac{\partial^2 \zeta}{\partial t^2} = 0 \qquad (2)$$

where ζ is the surface elevation, g is the acceleration of gravity. To obtain a solution of the steady oscillations for the bay, we assume that the induced wave oscillation is a simple harmonic; that is,

$$\zeta(x,y,t)=A(x,y)\exp(i\sigma t) \qquad (3)$$

where σ is the angular frequency. Then, the long wave equation is converted to the well-known Helmholtz equation;

$$\frac{\partial}{\partial x}\left(h \frac{\partial A}{\partial x} \right) + \frac{\partial}{\partial y}\left(h \frac{\partial A}{\partial y} \right) + \frac{\sigma^2}{g} A = 0 \qquad (4)$$

To solve this equation is then equavalent to finding out the unknown function A(x,y). In this study, one of the numerical methods, that is, " Finite Element Method " is used to solve that equation. Then, the solution of the Helmholtz equation is finally converted to the problem of solving an eigen-value system given by

$$[\,K\,]\,\{A\} - \lambda[\,M\,]\,\{A\} = 0 \qquad (5)$$

with the boundary conditions of $A=A_0$ at the entrance of the bay and $\frac{\partial A}{\partial n} = 0$ at the rigid boundary, where $\lambda=\sigma^2$, $\{A\}$: unknown node value vector, $[K] = \sum_{k=1}^{m} [K]^{(k)}$: the stiffness matrix, $[M] = \sum_{k=1}^{m} [M]^{(k)}$: the mass matrix.

The solution domain defined in this study covers not only the confined water area, but also some area of open sea. In fact, the seaward boundary of the domain is just located at the edge of the bay mouth and the width of the extended part is almost the same as that of the confined part. The domain was divided into 98 triangular elements with 71 nodes. According to the above definition of the solution domain, the seaward boundary is assumed to be the entrance and all the others are taken as rigid boundary.

Next, from the Fourier analysis, we know that

$$S_y(f) = |H(f)|^2 S_x(f) \qquad (6)$$

where H(f) is the Fourier transform of the impulse response function of a given system; $S_x(f)$ and $S_y(f)$ are the power spectrum functions of the input x(t) and the output y(t), respectively. Then, the output power spectrum can easily be computed if the input power spectrum and the system function are given. An example of the system functions of Onagawa Bay referred to Enoshima has been computed and the power spectrum of the waves observed at Enoshima has also been estimated as shown before.

Fig. 5 shows examples of the system function and the power spectrum estimated in this way. From this figure, it can be seen that the oscillations of natural mode theoretically obtained for Onagawa Bay are those with the periods of 38.5, 14.8, 9.0 and 7.9 minutes. Among them, the oscillations with the periods of 38.5 and 14.8 min are almost the same as the predominant oscillations of the first half after the tsunami records of Onagawa. The system functions say that oscillations on the bay and harbour cause greatly the amplification of oscillation energy at the bay head. Table 2 is the summary of the results of spectral analyses and numerical analyses on the stationary characteristics of the tsunami-induced oscillations, including the results reported by Aida(1).

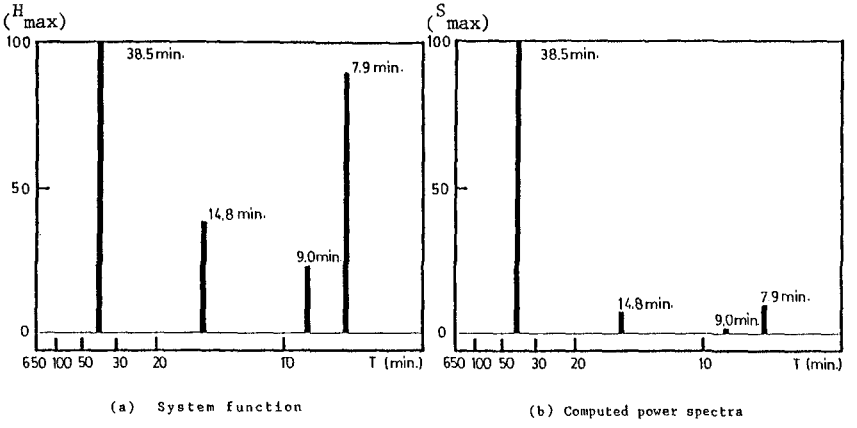


Fig. 5 System functions and computed power spectra at Onagawa in Onagawa Bay.

Table 2 Periods of oscillations in Onagawa and Kesennuma bays

Bay	Tide gauge station		Period (minutes)										
			Oscillation on continental shelves					Oscillation in bay					
			NE	ENE	E	ESE	SE	F		L_1	T_1	L_2	T_2		
Onagawa		Observation (Long-period waves)*	98-120					36.0		18.1	14.4	12.8	10.0	9.0	8.0
		Numerical model*						40.7		18.1	14.0	12.1	10.0	9.0	8.0
	Enoshima	Observation (Tsunamis) After tsunamis First half						43	26	18		12			
	Onagawa	Observation (Tsunamis) Before tsunamis						38	27	18	15				
		After tsunamis First half						41	32	18		13			
		Second half	71					37	30		16	12			
		Numerical model						38.9			14.8			9.0	7.9
		Seiche: $T=4\ell/60\sqrt{gh}$ (min.)	97	76	77	83	89								8
Kesennuma	Kesennuma	Observation (Tsunamis) Before tsunamis						52, 35, 19							
		After tsunamis First half						50, 32							
		Second half						59, 30							
		Seiche: $T=4\ell/60\sqrt{gh}$ (min.)	152	-	72	-	80								
Remarks		*; and F: fundamental mode; L_1, L_2: longitudinal 1st and 2nd modes; T_1, T_2: lateral 1st and 2nd modes [after Aida(1)].													

3.3 Amplification Factor

Fig. 6 shows the amplification factors at various sites within Onagawa Bay relative to Enoshima, which are directly estimated through the computation by using the numerical model based on finite element method as a set of natural oscillation modes and corresponding relative wave height vectors. The amplification factor at the period of 38.5 min is corresponding to the basic mode of the bay and the part at the period of 7.9 min is respect to the harbour resonance. However, values of the amplification factors seem to be large.

Then, the amplification factor at Onagawa relative to Enoshima(i.e. bay head vs. bay mouth) was computed from the MEM-spectrum at Enoshima ,$S_E(f)$, and at Onagawa, $S_o(f)$, with the assumption of no reflection at the bay mouth; that is,

$$R(f) = \sqrt{\frac{(1+\mu)\, S_o(f)}{S_E(f)}} \qquad (7)$$

where μ=0 (without reflection). The results are shown in Fig.7 and Table3 , from which the amplification factors estimated from the MEM-spectrum in this way seem to be explained, to a reasonable degree, by the relative tsunami heights obtained from the tsunami records which are shown in Table 4. They are very much dependent on the oscillatory periods.

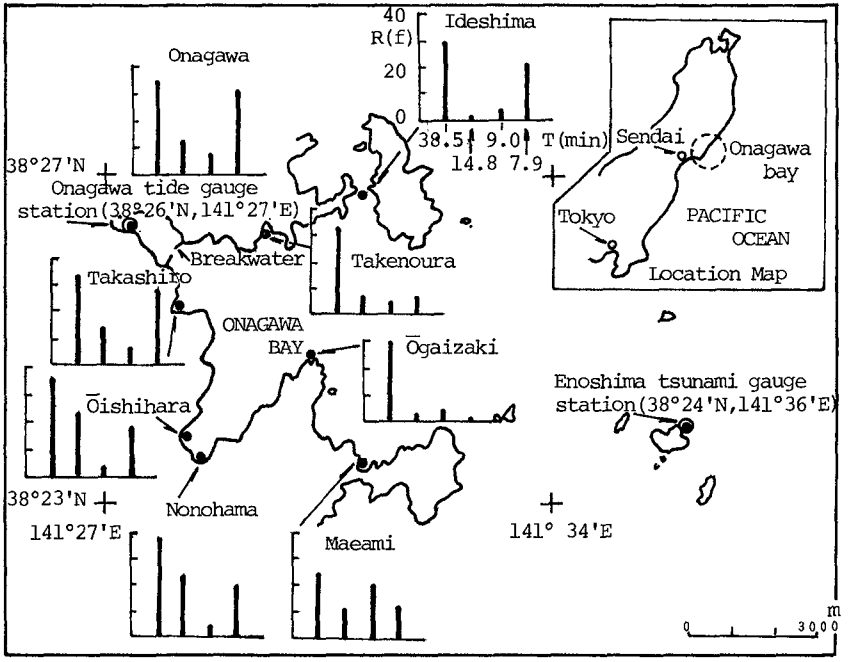


Fig. 6 Amplification factor at various sites within Onagawa Bay relative to Enoshima.

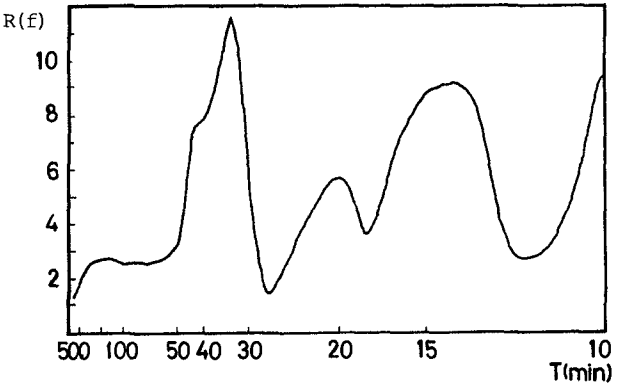


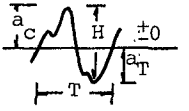
Fig. 7 Amplification factor at Onagawa (bay head) vs. Enoshima (bay mouth), which is derived from the MEM-spectra for the first half data after the tsumamis.

Table 3 Amplification factor at Onagawa relative to Enoshima, for predominant periods of oscillations derived from MEM-spectra.

	F							L_1		T_1	L_2	
Period(min.)	45	43	42	36	32	29	26	19	18	15	13	12
Amplification factor	2.3	5.1	7.3	8.8	11.5	6.2	1.4	5.2	3.9	8.7	8.0	3.0

Table 4 Relative tsunami heights at Onagawa vs. Enoshima [from tide gauge records].

	Zero upcrossing waves					
	$\frac{(a_c)_O}{(a_c)_E}$	$\frac{(a_T)_O}{(a_T)_E}$	$\frac{(H)_O}{(H)_E}$	Period(min.) $(T)_E$	Period(min.) $(T)_O$	Remarks
1st wave	3.1	12.5	5.8	35	40	
2nd wave	8.0	17.5	10.1	50	35	$(\ )_O$:Onagawa
3rd wave	3.6	2.7	3.2	50	55	
4th wave	3.3	10.3	4.7	30	35	$(\ )_E$:Enoshima
5th wave	7.2	7.0	7.1	55	40	
6th wave	8.2	12.0	9.3	25	40	
7th wave	14.5	2.8	6.1	55	40	
8th wave	4.0	3.5	3.7	45	50	
9th wave	5.7	6.0	5.8	30	40	
10th wave	-	8.5	13.0	20	30	



Water bodies on the continental shelf and in a bay usually oscillate by themselves. Such water oscillations are excited more by tsunami. The mechanisms of the wave amplification have been mainly considered to be energy concentration and resonance. The former has been discussed by Green's law and as to the latter, there are many solutions of the steady state oscillations for bays with various topography. However, as I was saying just now, the results are still unreliable enough to apply to the tsunami-induced oscillations, because of their transient characteristics as pointed out by Mano(7).

4.0 NON-STATIONARY CHARACTERISTICS OF THE BAYWATER RESPONSE TO TSUNAMI

Through the results of stationary spectrum, discrepancies were recognized between the first half oscillations and the second half oscillations. It will suggest that the further advanced considerations on the characteristics of the baywater oscillations due to tsunamis will be needed. Then, in order to investigate a non-stationary stochastic time series, a so called " instantaneous Fourier spectrum " was used, which represents the constitutions of the given time series at each time steps. The definition and the estimation scheme of the instantaneous Fourier spectrum which adopted in this study are as follows:

Let x(t) be a given non-stationary time series, and let $y_n(t)$ be outputs through a series of system functions $H_n(f)$. In linear systems, the following relationship is well known(Papoulis(8)).

$$Y_n(f) = H_n(f)\, X(f) \qquad (8)$$

where X(f) and $Y_n(f)$ are the Fourier transform of the input x(t) and the outputs $y_n(t)$ of the system, respectively. Taking inverse transforms of these separated transform functions, $Y_n(f)$, respectively, the outputs are then derived as

$$y_n(t) = \int_{-\infty}^{+\infty} X(f) H_n(f) \exp(i2\pi ft)\, df \qquad (9)$$

This set of time functions referred to different frequency indicates the components of the given time series at every time step. The envelpoe of these time functions is, then, defined as the instantaneous Fourier spectrum, F(f,t), in this study(Kamiyama(6)).

To estimate this instantaneous Fourier spectrum, the system function with the Gaussian type is assumed here, i.e.,

$$H_n(f) = \exp\left(-\alpha \frac{f-f_n}{f_n} \right)^2 \qquad (10)$$

Because the parameter α and the band width of the frequency Δf_n can not be determined uniquely, values of α and Δf_n were chosen as 50 and 0.15, respectively, after the several trial tests. Furthermore, the numerical Fourier integration were carried out based on the well known " fast Fourier transform method ".

Fig. 8 shows the instantaneous Fourier spectra at Enoshima in Onagawa Bay. According to the results,oscillation in the period range between 43 and 49 min, in which the basic oscillation mode of the bay is included, are at first excited remarkably. As time was elapsed, the energy was slightly transferred to shorter spectrum bands. Spectra in the period bands between 25 and 35 min are also developed, which corresponds to the waves in the present tsunami source area. The energy densities depend on the oscillatory periods. However, they do not always keep the constant.

Fig. 9 shows the instantaneous spectra at Onagawa. It is quite natural that the energy density before the tsunamis invade is very small. However, the oscillation energies are excited remarkably by the intrusion of the tsunamis. In the first half after the tsunamis, two remarkable oscillations around 39 to 43 minutes and 33 minutes are noticed in which the natural period of the bay is included. After that, at the 3rd wave, the above two remarkable oscillation modes become much more clear with the center periods at 31 and 41 minutes, respectively. And at the 4th wave, the oscillation becomes simple with the center period of 41 min. The oscillation energies in the range between 31 and 41 minutes occupy the major portion of baywater oscillations, and the period of these oscillation modes changes slightly with the lapse of time, which suggests the energy transfers among these modes. And the results agree with the ones of the stationary spectra.

Fig.10 shows the instantaneous Fourier spectra at Kesennuma. Although the spectral energies in the period range 45 and 51 min are excited by the intrusion of tsunamis, the oscillatory mode is relatively simple. The predominant oscillation with the center period at 53 minutes is noticed, which is corresponding to the basic mode of the bay. However,as time was elapsed, the energy is gradually transferred to shorter spectrum band and the oscillations are superimposed to give complicated spectra.

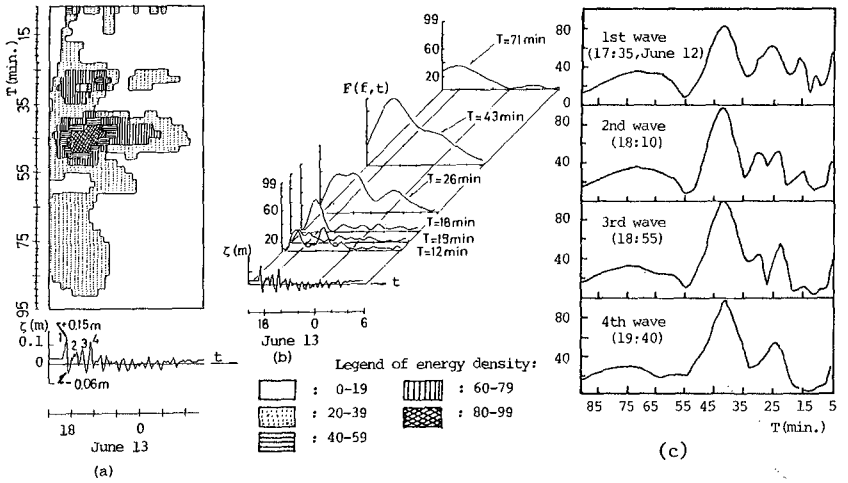


Fig. 8 (a) is energy densities in contour plotted by elapsed time t and periods T(min.). Values of energy density function F(f,t) were normalized 0(minimum) to 99(maximum). (b) is the time history of instantaneous Fourier spectra plotted for the predominant periods of oscillation in the stationary spectra. And (c) is the instantaneous spectra at 4 instants selected from the time sequence records of water level, which correspond to from the 1st wave to the 4th wave.

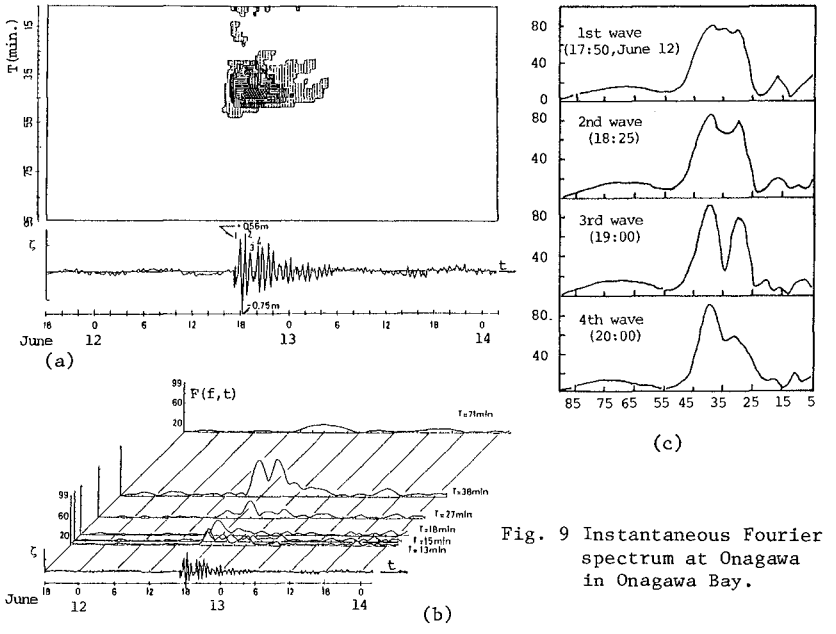


Fig. 9 Instantaneous Fourier spectrum at Onagawa in Onagawa Bay.

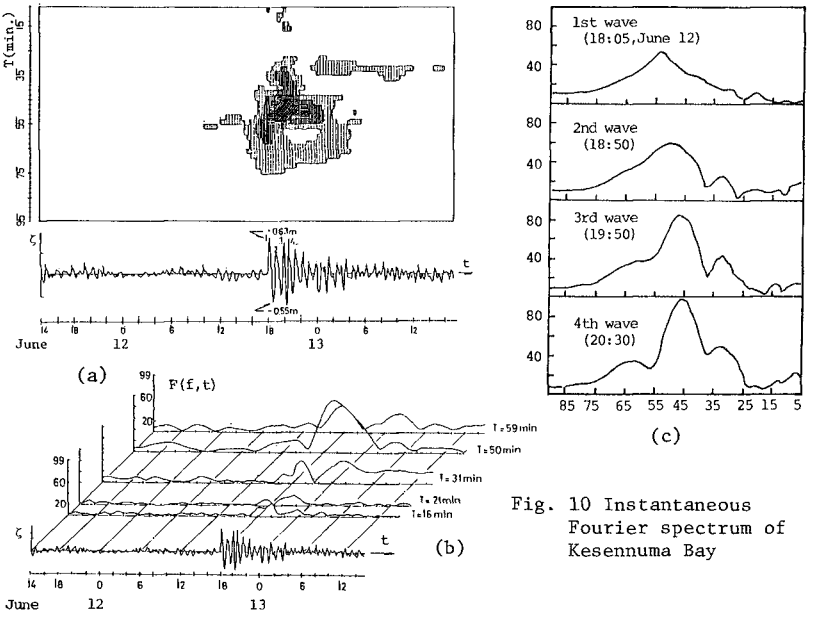


Fig. 10 Instantaneous Fourier spectrum of Kesennuma Bay

5.0 CONCLUSIONS

Stationary and non-stationary characteristics of tsunami-induced oscillations in bays were mainly investigated on the basis of records of tsunami caused by the Off-Miyagi earthquake in June, 1978. The estimated stationary spectra show that the main part of the oscillation energy is included in the basic mode and the secondary mode of oscillations based on the locality of bays, including the effect of continental shelf. The predominant period of these modes shifts to longer and/or shorter period ranges with the lapse of time, suggesting that the position of node moves toward the open sea and moves back into the bay during the tsunamis. The energies of non-stationary spectra do not always indicate stationary value at the periods which correspond to the predominant ones of stationary spectra, because of the transient characteristics of tsunami waves. Then, the results of the steady state oscillations are still not reliable enough to apply directly to the tsunami-induced oscillations.

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