CHAPTER 59

TRANSFORMATION OF TSUNAMIS IN A COASTAL ZONE

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ABSTRACT

In order to obtain fundamental informations to establish warning practices and effective countermeasures against the tsunamis on the coast, the authors have studied on refraction of the tsunamis propagating into Osaka Bay and on tsunami spectra. The refraction of the tsunami is studied by a numerical computation for a program of refraction and shoaling of small amplitude wave. An example is shown for Chilean Tsunami in 1960 to reveal that the refraction is an important factor to study on the tsunami wave height distribution along the coast of Kii Peninsula and Shikoku Island. The mareograms of the tsunamis are analyzed to obtain power spectra to study on transformation of the tsunamis from the Pacific Ocean to the head of Osaka Bay. The result suggests that it is necessary to be careful to study on transformation of the tsunamis with use of the refraction diagram because the tsunami is not a simple monochromatic and small amplitude plane wave. A brief remark is given for theanalysis of the tsunami as non-stationary process.

1. INTRODUCTION

There are various kinds of the external forces acting on the coast. The occurrence of tsunami is one of the remarkable phenomenon in relation to the destructive suffers on the coast. And it is not yet solved the protection of the tsunami at present even though many efforts have been concentrated to the tsunami. On the other hand, in these years, reclamative land use for the industrial zones and the higher utilizations of the coastal zone have become triggers to increase and spread the destructive suffers. Now, it is necessary to study and solve the problems of the tsunami in order to give any effective countermeasure for it. In this paper, at first , a reviewal remark is given. And then, refraction characteristics of tsunami is studied through a numerical computation for Chilean Tsunami in 1960 as a small amplitude wave. And the actual existing tsunamis are not necessarily similar to the exact small amplitude wave but the finite amplitude wave in the coastal zone. Tsunami spectra are studied as a linear transform of the mareogram of the tsunami as a stationary stochastic process, and after that, a remark is given to be studied it as a non-stationary process.

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2. REVIEWAL REMARKS

As for Kwanto district and Tokyo Bay, the surveys and researches have been concentrated to solve the problem(for example, since Meiji Era(Omori,1918)). In the recent years, a countermeasure is introduced as a political practice refering to the results of the researches(for example, Kawasumi,1969). And as for Ise Bay, a similar countermeasure is offered in a report by Iida(1975). By the way, there have been no researches and surveys for Osaka Bay systematically. It might be a fresh report by Tsuchiya and Nakamura(1974) that is related to a filing of the data and an analysis of the tsunamis propagated into Osaka Bay. They have focused to the mareograms of the recent tsunamis which gave any significant influences to the water level in Osaka Bay from the reports published in the past and the filed mareograms in Osaka District Meteorological Observatory in order to analyze and clarify the mechanisms of the propagation and transformation of the tsunamis. They have traced the historical procedures for the tsunamis, for example, the geographical distributions of the tsunami heights, the travel time of the tsunami fronts, refraction diagrams of the tsunamis etc. The authors have also studied on the tsunami spectra(Nakamura et al.,1976).

The studies on the tsunamis in the past, for example, the geographical distributions of the tsunami wave heights, had been studied with a little consideration on dependency of the refraction of the tsunamis. It might be caused by the difficulty of the surveys of the tsunami refractions in the past. The authors would like to introduce a refraction diagram with use of high speed electronic computer to study the propagation of the wave front, the wave ray, the shoaling effect caused by the water depth, the transformation of the wave caused by refraction etc. They have focused to study on the transformation of the wave by refraction and shoaling.

Adding to that, a method of ocean wave spectrum is introduced into the study on the transitional phenomena of the tsunamis to treat the tsunamis as a stationary Gaussian processes to obtain the tsunami spectra. The transformation of the tsunami spectra is also the authors' interest in this paper. Spacial and time dependent transformation of the waves are considered for the tsunami spectra. And a remark will be given for the tsunami spectral analysis as non-stationary process.

3. REFRACTION DIAGRAM

Judging from the results of the surveys, the researches(for example, by Iida,1956) and the tabulated catalogues(Imamura,1942; Iida et al.,1967; Soloviev and Gao,1974) concerning the tsunamis on the coast of Japan, it might be statistical expect that the one third of the earthquake exceeded Richter's magnitude $M = 6$ those of which had occured around Japan Islands has the epicenter under the sea, and the one third of the earthquakes which had occured under the sea accompanied the tsunamis to atack the coastal zone of Japan. In Japan, the records concerning the tsunamis can be found since the seventh century.

The tsunamis which have propagated into Osaka Bay are included not only in the tabulated records introduced above but in the records of the tsunamis occurred off the Aleutian arc, off Alaska and off South America propagated across the Pacific Ocean to attack the coast of Japan Islands. One of the examples is

Chilean Tsunami in 1960 which is surveyed and observed along the coast of Japan Islands exactly and in the detail as far as possible by the organized group in Japan. The refraction diagrams are drawn from the wave source in the neighbour of the coast of Japan by Meteorological Agency of Japan, University of Tokyo and the other related organizations(1961).

In this section, Chilean Tsunami in 1960 is taken as an example in the tsunamis propagated into Osaka Bay, because the details and the accuracy of the data and the records of Chilean Tsunami in 1960 are reliable and abundant in comparison to the other tsunamis.

In order to find the process of the propagation of Chilean Tsunami in 1960, a schedule is arranged to draw a refraction diagram from the Pacific Ocean to Osaka Bay by a numerical computation and a manual drawing. For a convenience of practice, the authors refered to the refraction diagram of Chilean Tsunami in 1960 by Meteorological Agency of Japan, in which the location of the tsunami front just arrived at the south of Shionomisaki is taken as a boundary to start the computation and to draw the refraction diagram of the tsunami propagating into Osaka Bay. A schematical topography from the Pacific Ocean to Osaka Bay is shown in Fig.1. And for a convenience of analysis, the wave heights are assumed to be same along the line which is introduced above as the boundary for the in-put data.

The manual drawing of the refraction diagram is obtained under the assumption of the tsunami as a long wave and with the considerations of the effects of the water depth and of refraction. This manual method has been widely utilized for studying on the propagation of the tsunami fronts and for estimation of the source areas of the tsunamis. As the first step to construct a refraction diagram the wave fronts are drawn time to time successively at a given time step, after that the wave rays are drawn as the orthogonals to the wave fronts. And the wave transformation in height may be estimated to apply Green's formula to the water depth and the width of the neighbouring two wave rays for a linear theory.

On the other hand, a method to use a high speed electronic computer is introduced to obtain the refraction diagram of the tsunami. In this case, the tsunami is assumed to be a small amplitude wave to apply the computer program for refraction of wave, which is developed by Worthington and Herbich(1970) in Texas A and M University.

In order to practice the computation, the areas are taken as shown in Fig.2. Initially the wave front is assumed to be located on the line stretching toward southwest from off Kushimoto. The line forms a part of the large square(about 160 km square). And the wave front is assumed initially to propagate perpendicular to the initial line, which is taken to approximate to a line corresponding to a wave front of Chilean Tsunami in 1960 off Nankaido at a certain time.

For the first step of the computation, the large square is devided to form a mesh with the points of 15 × 16, in which the water depth is given by an interporation from the nautical charts published by Hydrographic Office, Maritime Safety Agency of Japan.

The results of the computations are shown in Figs.3 and 4. In the computations, the period of the wave is taken to be 30 min. In Fig.3, the wave rays and the wave fronts at every one minute are shown by the solid lines and the dot lines respectively. The refraction coefficient and the shoaling factor are obtained at the same time at the each step of the computations. Relative wave height is also obtained by a product of the refraction coefficient and the shoaling factor. The result is shown by curves in Fig.4, which are characterized by a parameter to indicate the relative wave height refering to the initial wave height.

After the computation in the first area, the twenty two small areas of square (about 15 km square) with the mesh points 25 $\times$ 25 are considered to practice the successive computations from the open ocean to Osaka Bay under the consideration of the availability of the computer at the Data Processing Center of Kyoto University. The wave directions of the last steps in each area are the next initial data of the wave directions as the in-put data. For the practical computation, one of the authors, Tsuchiya, has insisted not to fail the generality of the small amplitude wave in the application of the computing program to the tsunami so that no approximation and no simplification of the equations are considered except the numerical truncations even if the cpu time in the computation is elongated.

As the result of the computation in the first area, it is easily found that the wave front needs more than twelve minutes to travel from off Kushimoto to the entrance of Kii Channel, if the given wave front behaves similar to the tsunami. And, only two or three rays initiated not far from the coast in Fig.3 are passing Kii Channel. The wave rays far from the coast atack the coast of Shikoku Island, on the way to which the wave rays are strongly refracted by the effect of the water depth in the area of the large square. The wave rays in Fig.3 are quite similar to those in the refraction diagram obtained by Nakamura(1974) manually.

In these computations, the wave height and direction are assumed to be uniform along the initial line. Through the successive computations, the wave heights are obtained on the wave rays at each step of one minute. The estimated wave height distribution along the coast of Kii Peninsula from Kushimoto to Osaka is shown by the curve A in Fig.5. The absissa is a convenient distance from Kushimoto and the wave height refered to that at Kushimoto is the ordinate. The curve B is the estimated wave height distribution obtained by the computations along Awaji Island. And the curve C is the wave height distribution estimated along the axis of Osaka Bay from Tomogashima Passage to Osaka. The dots and circles are the observed heights of the first and the second wave respectively. The simple dots and circles are the data along the coast of Shikoku, Awaji Island and Kobe. The crossed dots and circles are the data along the coast of Kii Peninsula. For the region from the open ocean to Tomogashima Passage($0 \leq x <$ 110 km), the observed wave heights are much smaller than the computed ones and the second wave heights are fairly good correspondence to the computations. In Osaka Bay, the observed wave height is a few but seems to be good agreement to the computed wave height distribution along Awaji Island(curve B). Although, the computed wave height along the axis of Osaka Bay(curve C) cannot be expected as an actual phenomenon. The curve C is anomalous as an actual trend, which might be caused by the given conditions and the matching conditions in the computer program through the successive computations. The authors have been aware of that it is necessary to effort to avoid the unstable results appearing in the computation of the long period waves in the very shallow water. At the cross point of the wave rays, the computed wave height is anomalously large as far as the computation is refered to the linear theory of wave refraction. In the successive computation, the initiative of the wave direction is essential. And this might be a cause of an undesirable result. Adding to that, it is necessary to remark that no reflection is considered through the computation.

Judging from these refraction diagrams and the analysis, the wave height of Chilean Tsunami might be not so large as the computed results along the axis of Osaka Bay and not so small as the expected results from the hand written refraction diagram. It is necessary to consider not only a simple travel time of the tsunami for a glance but the wave rays or the effect of refraction when the arrival time of the tsunami at the coast is discussed.

There have been obtained and collected the records of the tsunamis caused by the earthquake off Tonankai in 1944, off Nankaido in 1946, off Alaska in 1964, off Aleutian arc in 1965, Hiuganada in 1968 and the others. Even when these records are only reliable ones, the authors may expect that the wave height at the head of Osaka Bay cannot be larger but much smaller than the wave height at Kushimoto.

It is necessary to remark that the initial wave front is different from the exact location of the wave source. And the essential remarks are that the tsunamis are the phenomena of transitional rather than a linear long wave or a small amplitude wave, so that the discrepancy is more or less inevitable between the computed results and the observed wave heights. The tsunamis are not necessarily periodical, so that frequency analysis or spectrum analysis should be also introduced to study on the mechanism and the characteristics of the tsunamis.

4. TSUNAMI SPECTRA

The concept of the tsunami spectrum might be originated and introduced to detect what component of frequency is dominant in the mareogram including a tsunami. When the water level as a time series is assumed to be a stationary Gaussian process, the method of the spectrum analysis might be useful in studying the frequency characteristics of the tsunami.

The introduction of the spectrum analysis in the problem of the tsunamis might be carried out at first by Takahashi(1961a,b). And recently, the records of the tsunamis in the world have been compiled at International Tsunami Information Center(for example, ITIC,1975) to offer the records as well as the informations and contributions of the latest tsunami spectra analyzed with use of Fast Fourier Transform(or FFT). As mentioned by Kajiura, it is essential to study what length of the data is necessary in obtaining the tsunami spectrum. On the other hand, one of the authors, Higuchi had ever analyzed the mareograms of Chilean Tsunami in 1960 by the use of periodgram(Higuchi,1963) and he had been desired to have a chance to cooperate in a study on tsunami spectra.

In this paper, the records are selected so as to study on tsunami spectra for the significant four examples, i.e., the tsunamis caused by the earthquakes off Tonankai in 1944, off Chile in 1960, off Alaska in 1964 and off Aleutian arc in 1965. In this section, the focus is to study on the transformations of the tsunami spectra through the propagations of the tsunamis from the open ocean to Osaka Bay. Before start of analysis, the elevation of the water surface is read from the mareograms of the tsunamis at a certain constant step or a constant time interval. The discrete values of the elevations in a tsunami are assumed to be a time series of a stationary Gaussian process and treated to analyze by Blackman-Tukey's method which has been widely utilized for the spectrum analysis of ocean waves.

5. TIME DEPENDENCY OF TSUNAMI SPECTRA

When the assumed stationary process is sure, the length of the data for the analysis might not affect the form of the tsunami spectrum. The freedom of the data should be also considered statistically through the analysis. The time dependency of the data length in the analysis might show that the assumption is not suitable. In this section, the two tsunamis in 1944 at Osaka and in 1960 at Kushimoto are taken up for the analysis. The mareograms are read at the step of every three minutes to give a time series of the water level(cf. Table 1). The analysis is followed as that for ocean waves so that the number of the data is taken to be six hundred or much more under the consideration of freedom by the successive folding of the original data(see the sixth column in Table 1).

As for the tsunami caused by the earthquake off Nankaido at Osaka, the spectrum analysis is carried out for the data length of 2.5, 5 and 10 hours of the tsunami record to showthe spectra in Fig.6. In this figure, it is easily found that the principal peak of the spectrum is at the period of near 70 min($f = 2.2 \times 10^{-4}$ cps) for the initial stage of 2.5 hours, and the other peaks are smaller than one hundredth of the principal peak. For the longer data of 5 hours and 10 hours, the second and the third harmonics of the principal peak become significant which might be caused by shoaling effect or the other effects. And the wave might be transformed into a nonlinear wave in the shallow water. The longest data(10 hours) gives the power spectrum which have the less significant higher harmonics to show that the energy of the wave is decreasing with the time elapse. The principal peaks of the three are quite similar and a little variation to give the similar form of the power spectra except the details of the forms for the significant higher harmonics.

And for Chilean Tsunami in 1960 at Kushimoto, the three kinds of the data lengths are considered, i.e., 3, 6 and 12 hours for the data originated at the time three hours before the arrival of the tsunami. The spectra are shown in Fig.7. The power of the spectra after the arrival of the tsunami are ten times at least comparing to that before the arrival of the tsunami as a whole of the frequency. The spectra after the arrival of the tsunami have the two peaks at the periods of 40 min and 23 min(that is, $f = 4.4 \times 10^{-4}$ cps and 7.4×10^{-4} cps) respectively. In these two pesaks, the one for the period of 23 min is fairly sharp and significant in the three spectra. This peak might be formed by the local resonant oscillation excited by the energy supply from the incident wave. The tsunami might be characterized by the peak at the period of 40 min in Fig.7. After the arrival of the tsunami, the form of the spectra show the dependency of the analyzed data lengths to give significant higher harmonics. The existence of these higher harmonics suggests that the waves are transformed into the nonlinear waves or affected by the water depth to appear so called shoaling effect.

In the mareogram, the tsunami and tides are recorded in a superposed form.

When the focus is at the problem of the tsunami, the components except the tsunami should be treated as a back ground noise. In the spectrum, the components except the tsunami are taken to be the back ground spectrum as is considered by Munk, Snodgrass and Miller(1962). In Fig.7, the power spectrum before the arrival of the tsunami may correspond to the back ground spectrum mentioned above. When the principal peak and the pattern of the power spectrum are refered to discuss the frequency characteristics, and when the principal peak is sharp with a narrow band width, the assumption might be acceptable that the tsunami is similar to the monochromatic waves as is considered in the refraction diagram. Judging from Figs.6 and 7, the above assumption should be a fairly rough assumption. This assumption might be sufficient for only the initial part of the tsunami as considered in the refraction diagram.

6. TSUNAMI SPECTRA FROM OPEN OCEAN TO OSAKA BAY

In this section, the transformation of the forms of the tsunami spectra is considered from the Pacific Ocean to Osaka Bay for the significant tsunamis listed up in Table 2 except the tsunami caused by Hiuganada Earthquake in 1968. In order to obtain the tsunami spectra of each stations, the data are treated and processed in similar manner as done for Figs.6 and 7. For the convenience of a glance to detect the transformation of the tsunami spectra, the distance from Kushimoto is taken as the ordinate and the abscissa is taken as frquency to form a diagram with a parameter of power density for each tsunami respectively. The obtained results are shown in Figs.8, 9, 10 and 11 for each tsunami respectively.

One of the example is Fig.8 which is for Tonankai Earthquake in 1944, the mareograms are obtained only at Shimotsu and Osaka so that the detail cannot be detected. The increase of the power density with the distance is easily found in the lower frequency region in Fig.8. And the principal peak(at $f = 9 \times 10^{-4}$ cps) in Kii Channel decreases in Osaka Bay down to less than one tenth and the incidence of the wave induces the local other oscillations.

As for Chilean Tsunami in 1960, as is shown in Fig.9, the frequency at the principal peak of the spectra is almost uniform from Kii Channel to Osaka Bay except Kushimoto. The local effect in the spectra might be characterized by the higher harmonics. The peak of $f = 8 \times 10^{-4}$ cps at Kushimoto may be caused by the effect of the local topography as mentioned for Fig.6. In case of the propagation, the reflection and refraction might cause the significant transformation of the tsunami for the tail part. The peak of $f = 3 \times 10^{-4}$ cps suggests that a oscillation is induced and formed to locate the node at Tomogashima Passage and the loops at the head of Osaka Bay and the mid Kii Channel. This oscillation is easily found by a glance of the diagram as shown in Fig.9. And the trend shows that the power density for the higher frequency region decreases gradually with the distance.

The other examples similar to Chilean Tsunami in 1960 are the tsunamis in 1964 and 1965, which are analyzed and shown in Figs.10 and 11. The wave sources are in each cases far from Japan and the waves come to Japan across the ocean. And the analyses of these tsunamis suggest that the tsunami wave heights and the power density of the tsunami spectra depend on the locations of the wave sources and the paths of the wave rays as well as the magnitude of the waves at the source areas.

The above results are obtained from the tsunami spectra obtained by Blackman-Tukey's method which has been widely utilized in the spectrum analysis of the ocean waves. Exactly speaking, it is necessary to remark that all phenomena of the tsunamis are transitional and to consider to treat the tsunamis as nonstationary processes. The appreciation of the tsunami in the scope of the nonstationary stochastic process might be an important and interesting problem to be solved as remarked by Nakamura(1975).

7. CONCLUSIONS

The authors have analyzed the tsunamis propagating into Osaka Bay in order to study the transformation of the tsunamis through the propagation. (1) At first, Chilean Tsunami in 1960 is taken to study on the wave height distribution along the coast from Kushimoto to Osaka(from the Pacific Ocean to the head of Osaka Bay) in a fairly good correspondency between the refraction diagrams which are obtained by the numerical computations and the manual drawings. The observed wave height along the coast seems to fit well to the computed ones for the initial part of the tsunami, especially for the second wave, except along the axis of Osaka Bay. (2) he tsunamis are analyzed to study the tsunami spectra as a tool to reveal what are the peak frequencies of the tsunamis and what are the induced local oscillations with the consideration of the above refraction diagrams. An oscillation is found by the spectrum analyses of the tsunamis on the frequency-distance diagram with a parameter of the power density to form an oscillation with a node at Tomogashima Passage and two loops at the head of Osaka Bay and at the mid Kii Channel. (3) Adding to the above, it might be necessary to develope a study of tsunami spectrum as a nonstationary stochastic process in relation to the generating processes of the tsunamis.

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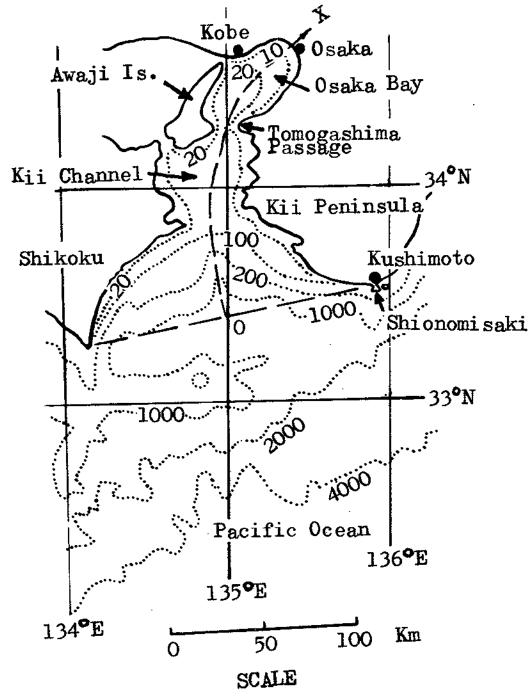

Fig.1 Area of the problem: from the Pacific Ocean to Osaka Bay

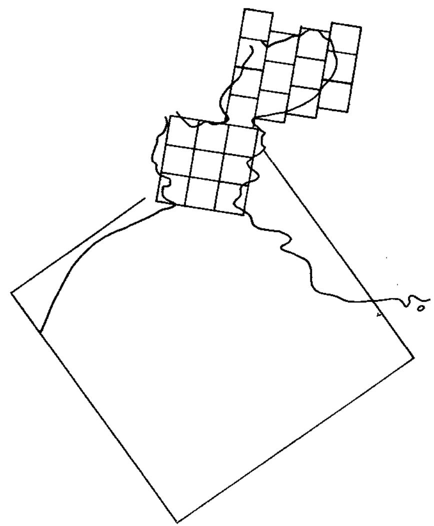

Fig.2 Zoning of the areas for computations of the refraction of the tsunami

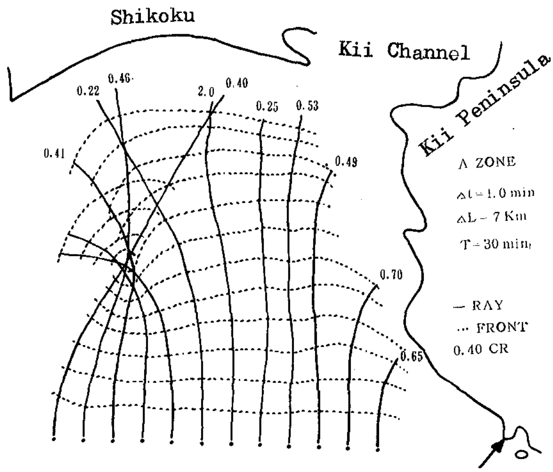

Fig.3 Refraction diagram of simulated Chilean Tsunami in 1960 by a computer

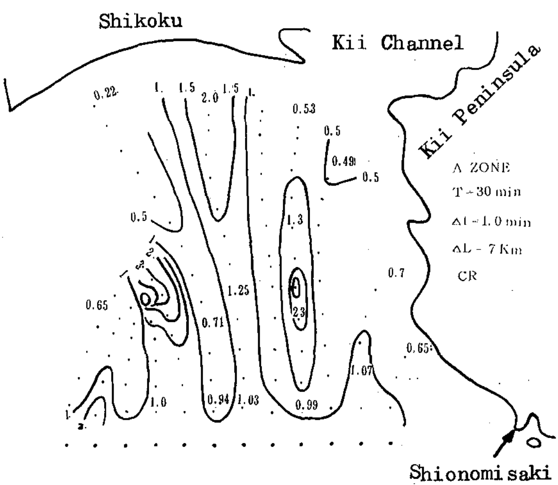

Fig.4 Wave height distribution of simulated Chilean Tsunami in 1960 by a computer

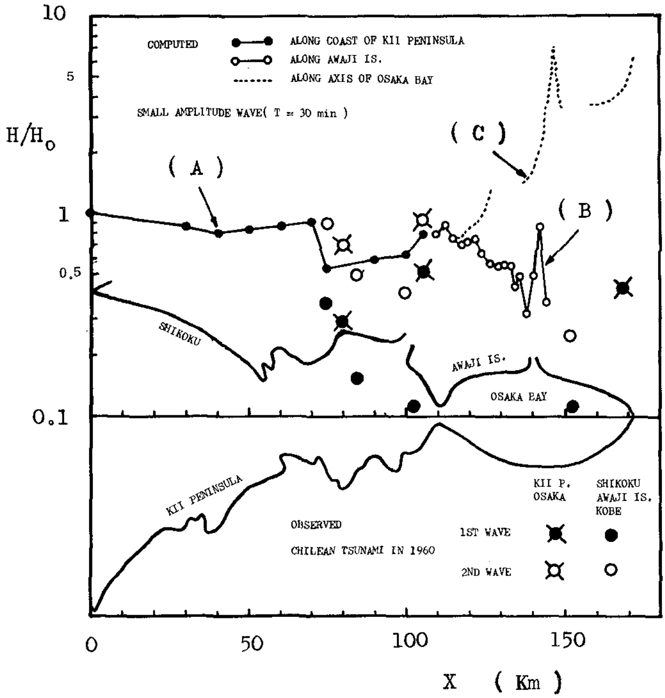

Fig.5 Transformation of simulated tsunami in wave height by a computer along the coast from the Pacific Ocean to Osaka bay

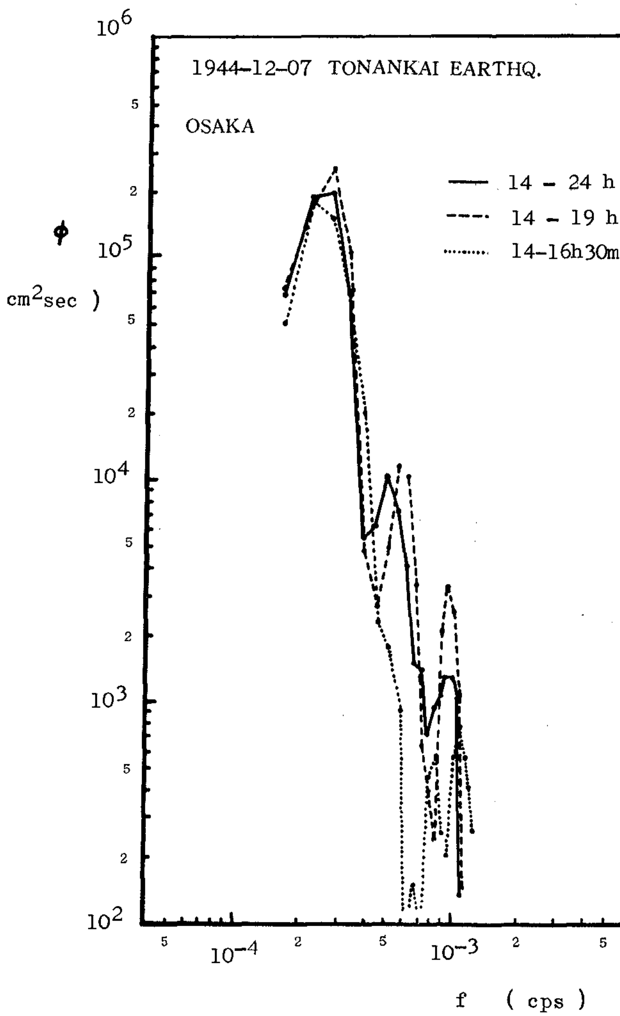

Fig.6 Tsunami spectrum as a function of time elapse at Osaka for the Earthquake off Tonankai in 1944

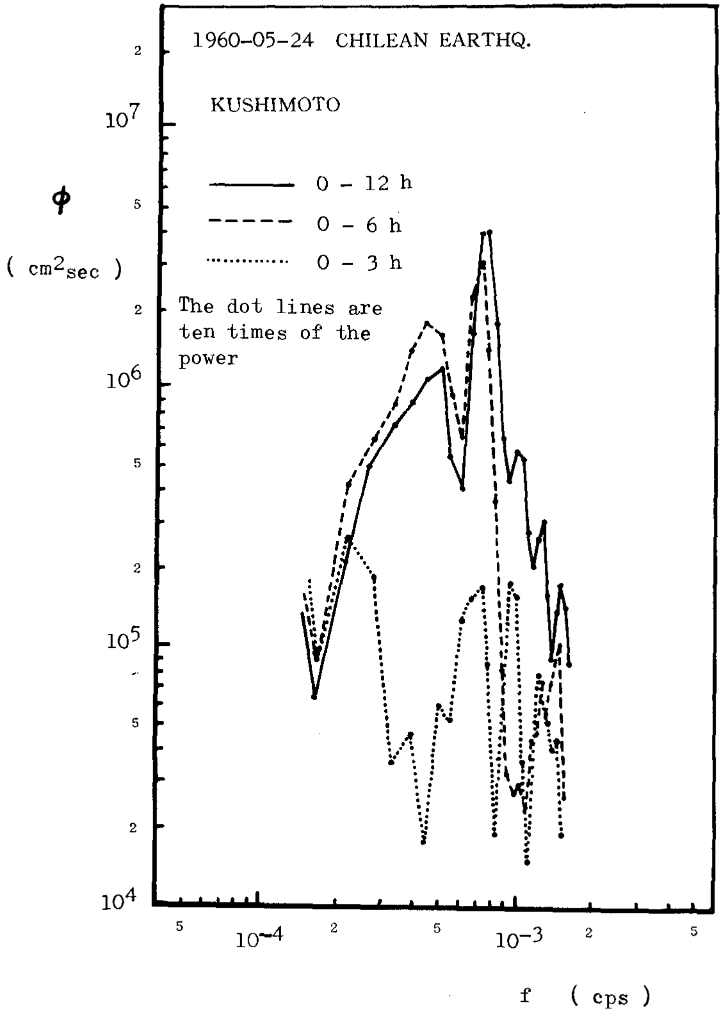

Fig.7 Tsunami spectrum as a function of time elapse at Kushimoto for the Earthquake off Chile in 1960

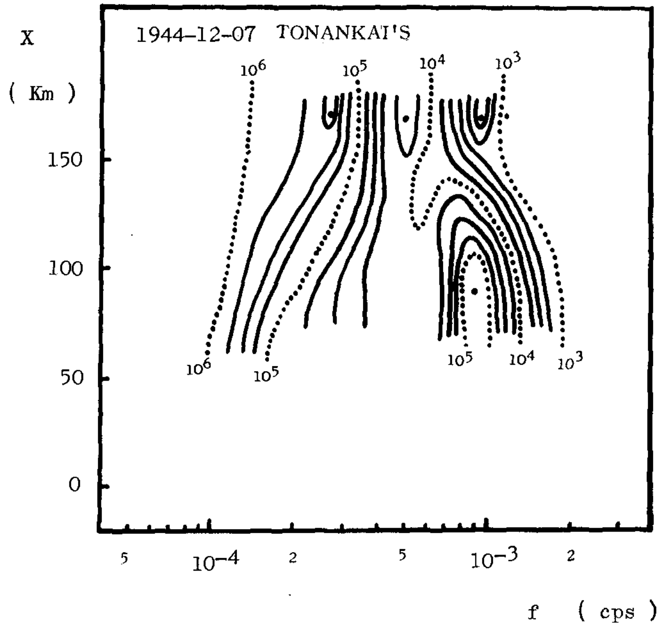

Fig.8 Local transformation of tsunami spectra with distance for the Earthquake off Tonankai in 1944

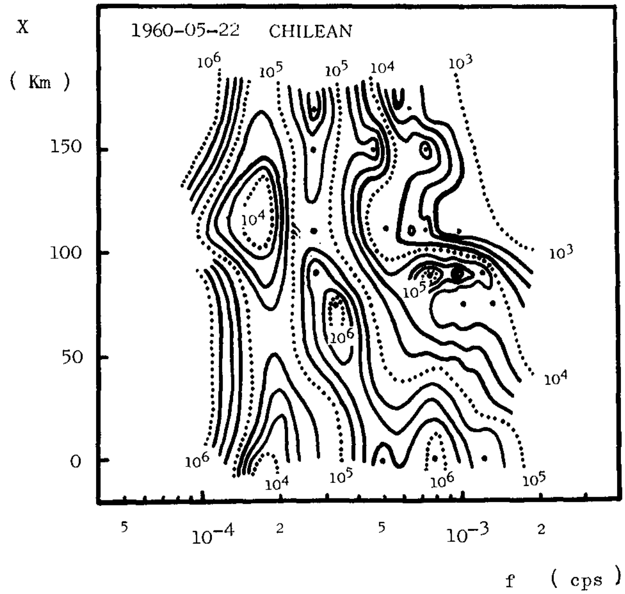

Fig.9 Local transformation of tsunami spectra with distance for the Earthquake off Chile in 1960

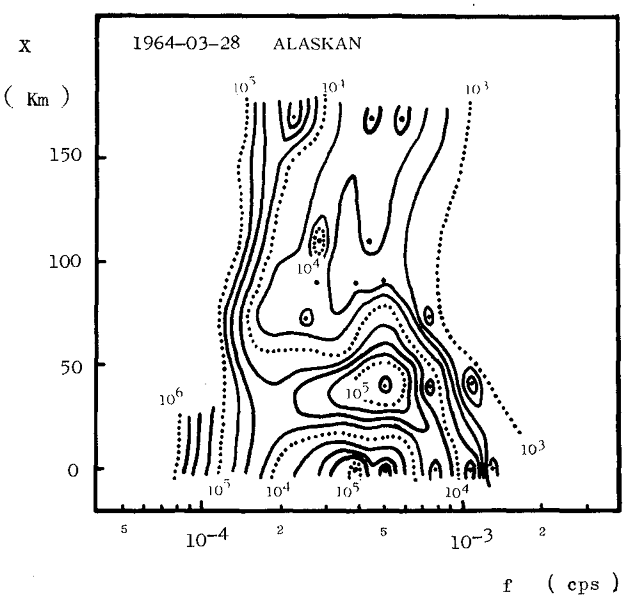

Fig.10 Local transformation of tsunami spectra with distance for the Earthquake off Alaska in 1964

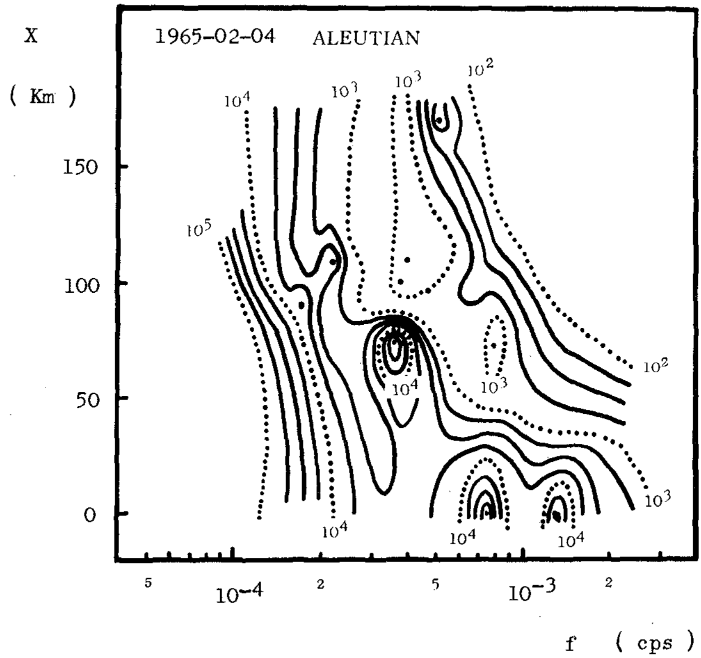

Fig.11 Local transformation of tsunami spectra with distance for the earthquake off Aleutian arc in 1965

Table 1 Number of data used for power spectral analyses of tsunamis

LOCATION	TIME	EARTHQUAKE	TIME STEP	ORIGINAL NUMBER OF THE DATA	NUMBER OF DATA USED FOR ANALYSIS	NUMBER OF FOLD
OSAKA	14–24(10 hs)	TONANKAI	3 min	N_0 = 200	N = 600	(2)
	14–19(5 hs)			100	600	(5)
	14–16h30m(2.5 hs)			50	600	(11)
KUSHIMOTO	0–12(12 hs)	CHILEAN	3 min	240	720	(2)
	0–6 (6 hs)			120	600	(4)
	0–3 (3 hs)			60	600	(9)

Table 2 Numbers of data used to study on local transformations of tsunami spectra

EARTHQUAKE ACCOMPANIED WITH TSUNAMI	1944–12–07 TONANKAI	1960–05–22 CHILEAN	1964–03–28 ALASKAN	1965–02–04 ALEUTIAN	1968–04–01 HIUGANADA
LOCATION	NUMBER OF DATA (NUMBER OF FOLD)				
OSAKA (X = 180 km)	400 (1)	340 (1)	720 (0)	680 (0)	–
KOBE (170)	–	480 (1)	–	–	–
SUMOTO (110)	–	480 (1)	680 (0)	482 (1)	–
NUSHIMA (85)	–	–	670 (0)	–	–
KOMATSUJIMA (75)	–	480 (1)	500 (1)	319 (1)	230 (2)
WAKAYAMA (90)	–	–	480 (1)	480 (1)	–
SHIMOTSU (70)	290 (2)	450 (1)	–	560 (1)	–
MORI (40)	–	–	540 (1)	–	–
KUSHIMOTO (0)	–	480 (1)	480 (1)	681 (0)	230 (2)