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On Transformation of Tsunami Innundating into Osaka Bay*

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Synopsis

In order to obtain fundamental informations to establish a countermeasure against tsunamis on the coast, the authors studied on refraction of tsunamis innundating into Osaka Bay and on tsunami spectra.

The refraction of the tsunami is studied by a numerical computation for a program of refraction and diffraction of a 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.

The mareograms of the tsunamis are analyzed into spectra to find the frequency characteristics of the tsunamis and to study on transformation of the tsunamis from Pacific Ocean to the head of Osaka Bay. The result of the analysis suggests that it is necessary to be careful to study transformation of the tsunamis by the use of the refraction diagram because the tsunami is not a simple monochromatic and small amplitude wave. Remarks are given for the analyses as stochastic processes.

1. Introduction

There are various kinds of the external forces acting on the coast. The occurrence of the tsunamis are one of the remarkable phenomena in relation to the destructive suffers on the coast. And it is not yet solved the problems of the tsunamis and their countermeasures at present, even though many efforts have been concentrated to the tsunamis. On the other hand, in these years, the reclamative developements of the industrial zone 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 tsunamis in order to give any established countermeasure for them.

In this paper, at first, reviewal remarks are given. And then, a refraction characteristics of tsunami is studied by a numerical computation for Chilean Tsunami of 1960 as a small amplitude wave.

And the actual existing tsunamis are not necessarily similar to the exact small amplitude waves but the finite amplitude waves in the coastal zone. To clarify the

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nonlinearity and the nonsteadyness, tsunami spectra are studied at first as a linear transform of the mareograms of tsunamis as the stationary stochastic processes, and after that, are remarked to be studied as the nonstationary stochastic processes.

2. Reviewal Remarks

The coast of Japan had been naked to suffering by the tsunamis so that they have been given an effort to clarify the mechanisms of the tsunamis and to develope any effective countermeasure for them.

As for Kanto district and Tokyo Bay, the surveys and researches are concentrated to solve the problem refering to the historical records[1]. In the recent years, a countermeasure is introduced as a political practice refering to the results of the researches[2]. And as for Ise Bay, a similar countermeasure is filed in a report by Dr. Iida in 1975[3].

By the way, there have been no researches and surveys for Osaka Bay. It might be only one report that is related to a filing of the data and an analysis of tsunamis innundated into Osaka Bay[5]. Further detailed studies are expected in future.

Tsuchiya and Nakamura[5] filed the mareograms of the tsunamis which gave any influences to the water level in Osaka Bay in order to analyze and clarify the mechanisms of the propagations and transformations of the tsunamis. They have traced historical procedures for the tsunamis, for example, the geographical distributions of the tsunami heights, the rauf-time diagrams of the tsunami fronts, the refraction diagrams of the tsunamis and etc. They have also studied on the tsunami spectra.

The studies on the tsunamis in the past, for example, the geographical distributions of the tsunami wave heights had been studied without any consideration on dependency of the refraction diagrams. It might be caused by the difficulty of the surveys of the tsunami suffers. The authors would like to introduce the refraction diagrams to study the propagations of the wave fronts, the wave rays, the shoaling effect caused by the water depth, the transformations of the waves caused by the refraction and etc. They have concentrated especially to the transformation of the waves caused by the refraction and the shoaling.

Adding to that, a method of ocean wave spectrum is introduced into the transitional phenomena of the tsunamis to treat the tsunamis as the stationary Gaussian processes to obtain the tsunami spectra. The transformations of the tsunami spectra is also the authors' interest in this paper. The space and time transformation will be considered for the tsunami spectra.

3. Refraction Diagram

Judging from the results of the surveys, the researches[6] and the tabulated records[7][8][9] concerning to the tsunamis, it might be statistically correct that the one third of the earthquakes exceede Richter's magnitude six 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 attack the coastal zone. In Japan, the records concerning to the tsunamis can be found since the seventh century. And it is necessary in appreciation of the records to consider the accuracies of the records, the locations of the destructions and the population, the historical background and the other factors

The tsunamis which have innundated into Osaka Bay is included not only in the tabulated records mentioned above but in the records of tsunamis[10] occurred off the Aleution arc, off Alaska and off South America across Pacific Ocean to atack 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 as much as exact and to the detail as far as possible by the organized group in Japan. The refraction diagrams are drawn from the wave source to neighbour the coast of Japan by Japan Meteorological Agency, University of Tokyo and the other organizations[4].

In this section, Chilean Tsunami in 1960 is taken in the tsunamis innundated into Osaka Bay, because the details and the accuracy of the data and the records for Chilean Tsunami in 1960 are reliable and abundant more than the other tsunamis.

In order to find the process of the innundation of Chilean Tsunami in 1960, a schedule is arranged to draw a refraction diagram from off Nankaido (in 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 Japan Meteorological Agency, 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 tsunamis innundating into Osaka Bay. For a convenience of analyses, the wave heights are assumed to be same along the initial line introduced above as the boundary for the in-put.

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 effect of the water depths and of the refraction following Snell's law as in geometrical optics. This manual method has been widely utilized for studying of the propagation of the tsunami fronts[9]. As the first step, the wave fronts are drawn time to time successively, 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 separation of the neighbouring two wave rays for a linear theory.

On the other hand, a method to use a 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 and diffraction of waves, which is prepared by Worthington and Herbitch[11] in Texas A and M University.

In order to practice the computation, the areas are taken as shown in Fig. 1. 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 (ca 160 Km square). And the wave front is assumed initially to propagate perpendicular to the

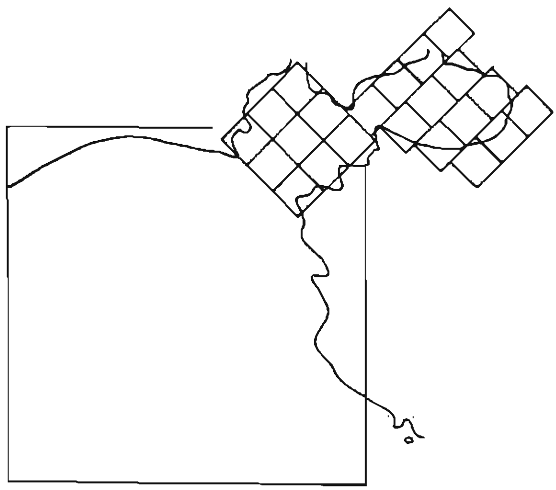

Fig. 1 Zoning of the areas for computations of the refraction of the tsunami

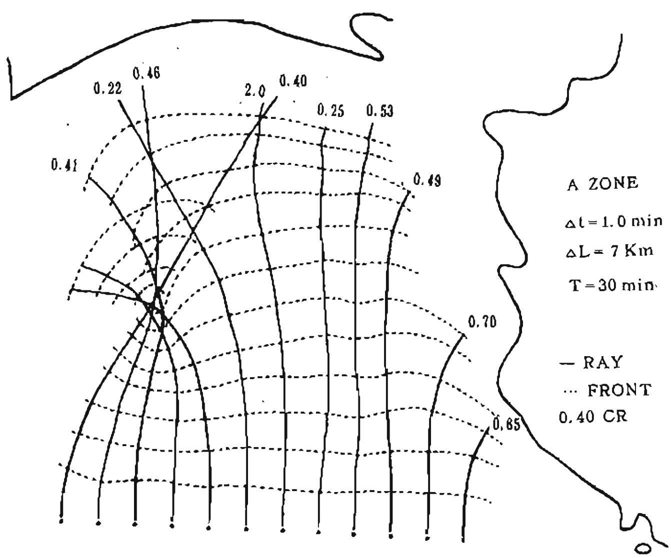

Fig. 2 Refraction diagram of simulated Chilean Tsunami in 1960 by a computer

initial line, which is taken to approximate 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 are given by an interporation

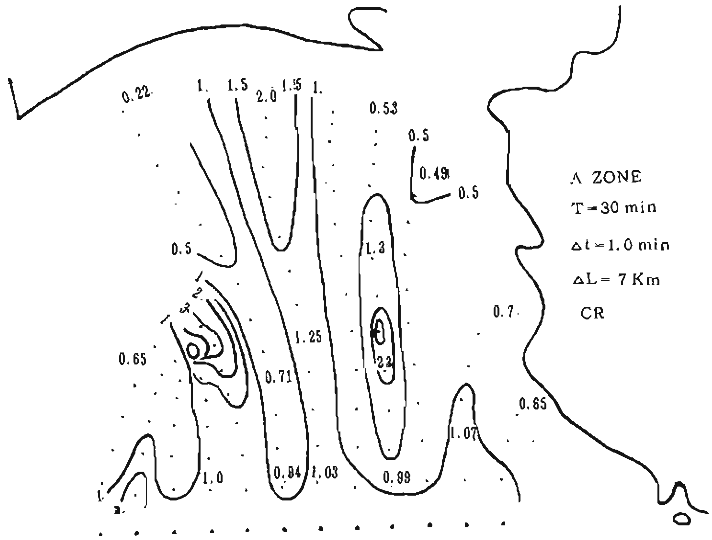

Fig. 3 Wave height distribution of simulated Chilean Tsunami in 1960 by a computer

from the nautical charts published by Hydrographic Office, Maritime Safety Agency of Japan.

The results of the computations are shown in Fig. 2 and 3. In the computations, the period of the wave is taken to be 30 min. In Fig. 2, the wave rays and the wave fronts in the step of 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 in the each computations of the wave rays. As the resultant of the refraction coefficient and the shoaling factor, a measure of the wave transformation in height is obtained as shown in Fig. 3. In Fig. 3, the curves are characterized by a parameter to indicate the relative wave height refering to the initial wave height.

Before the second step of the computation, the twenty two small areas of the square (ca 15 Km square) with the mesh points 25×25 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. For the practical computation, one of Yamaguchi's modified program of Texas A and M University is also utilized[2], when one of the authors, Tsuchiya 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 first step of the computation, it is easily found that the wave front needs more than twelve min to travel from off Kushimoto to the entrance of

Kii Channel, if the given wave front behaves similar to the tsunami. And that, the wave rays passing Kii Channel are only two or three rays not far from the coast in Fig. 2. The wave rays far from the coast atack the coast of Shikoku, on the way to which the wave rays are strongly refracted by the effect of the water depth distribution in the area of the large square. The wave rays in Fig. 2 are quite similar to that in the refraction diagram obtained by Nakamura manually[13].

In these computations, the wave height and direction are assumed to be same along the initial line. Through the successive computations, the wave heights are obtained on the wave rays in 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. 4 refering to the results of the computations. 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

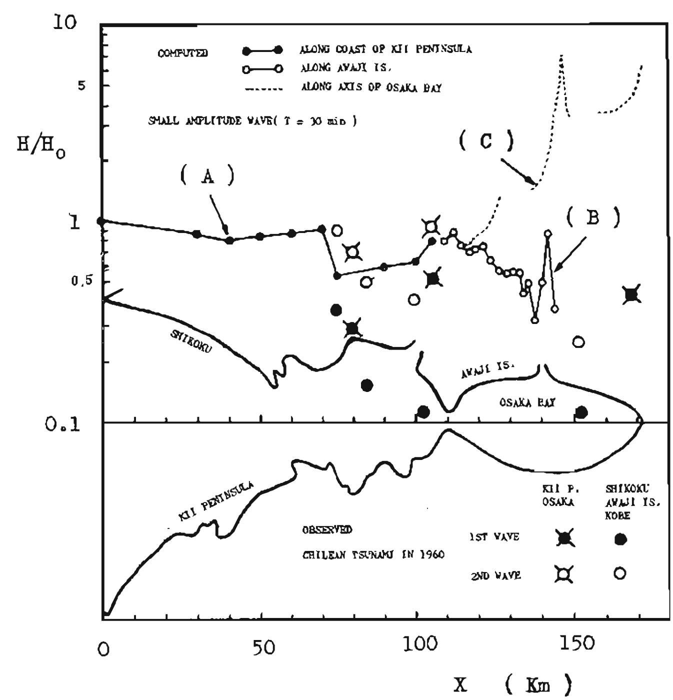

Fig. 4 Transformation of simulated tsunami in wave height by a computer along the coast from Pacific Ocean to Osaka Bay

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 (in the region of $0 < x < 110$ Km), the observed wave heights are much smaller than the computed ones and the second wave heights are fairly good in agreement between the observations and the computations.

In Osaka Bay, the observed wave height is a few but seems to be good in 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 anomarous, which might be caused by the given conditions and the matching conditions in the computer program through the successive computations. As the results of the computation practices, the authors have awared that it is necessary to effort to avoid the unstable results appearing in the computation of the very long period waves in the very shallow waters. The undesirable curve C might be obtained by the computation without the effort mentioned above. In the next step in the successive computation, the initial wave direction is constant along the initial wave front of the next area. This initialization is essential in the computations by the use of the computer program developed by Worthington and Herbitch. The undesirable result might be partly caused by this forced initialization in the successive computations from the view point of physical characteristics and conditions of the wave refraction. Adding to that, the approximation of the tsunami as the small amplitude wave might be acceptable only for the first and the second waves but the following tail of the

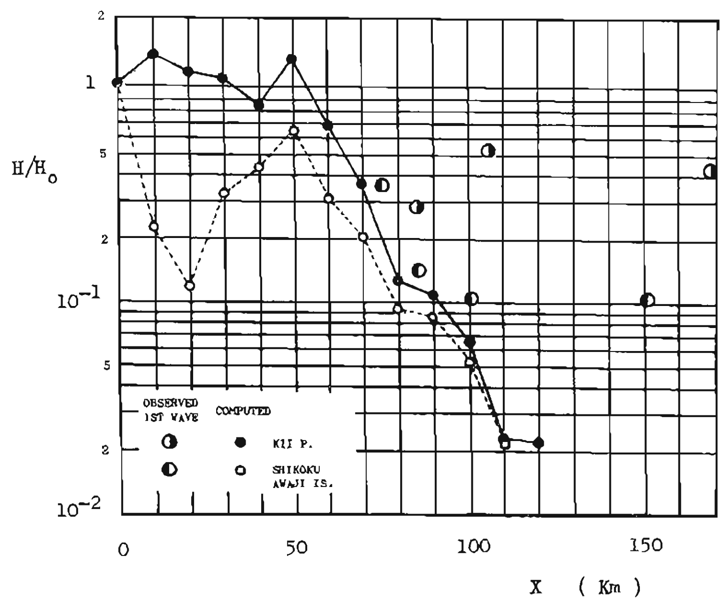

Fig. 5 Transformation of simulated tsunami in wave height by manual drawing along the coast from Pacific Ocean to Osaka Bay

tsunami when the observed data are compared to the computed wave heights because the computations do not include the reflection of the waves on the coast.

The numerical wave height estimations from the refraction diagrams obtained by the manual are shown in Fig. 5. In Fig. 5, the estimated wave heights are in good agreement to the observed data except those in Osaka bay.

Judging from these refraction diagrams and the analyses, 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 results from the refraction diagram obtained by the manual. It is necessary to consider not only a simple rauf-time of the tsunami for a glance but the wave rays or the effects of the refractions when the arrival time of the tsunami on the coast is discussed.

There have been obtained 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 taken as the references, 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 wave fronts as the initial data are different from the locations of the wave sources. And the essential remarks are that the tsunamis are the phenomena of transitional rather than the long wave or the small amplitude wave, so that the discrepancy is more or less inevitable between the computed results and the observed data of the wave heights. The wave patterns of the tsunamis are not necessarily periodical, so that a technique of frequency analysis or spectrum analysis should be also introduced to study the mechanisms 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 included 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 usefull in studying the frequency characteristics of the tsunami.

The introduction of the spectrum analysis in the problem of tsunamis might be by Dr. Takahashi[14)15)] who had been in Earthquake Research Institute. His contributions should be appreciated by not only his followers but those who study tsunamis. And recently, the records of tsunamis have been compiled at International Tsunami Information Center (ITIC) to offer the records as well as the informations and contributions of the latest tsunami spectra analyzed by the use of fast Fourier transform (FFT)[18)]. As mentioned by Kajiura in the discussion of Tsunami Symposium in Moscow, 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[17)] and he had been hoped to have a chance to cooperate in a study on tsunami spectra.

In this paper, the records are selected to study 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 the transformations of the tsunami spectra with the propagations of the tsunamis from the open ocean to Osaka Bay. To start the analyses, the elevations of the water surfaces are read from the mareograms of the tsunamis in a certain constant step or a constant time interval. The discrete values of the elevations in a tsunami are assumed to be a stationary Gaussian stochastic process and trated to analyze by Blackman-Tukey's method which has been widely utilized for spectrum analysis of ocean waves.

(1) Time Dependency of Tsunami Spectra

As mentioned above, the stationary Gaussian process is the necessary assumption in the spectrum analysis of the tsunamis. When the assumed process is sure, the length of the data for the analysis might not affect the pattern of the tsunami spectrum. The freedom of the data should be also considered statistically through the analysis. The time dependency of the used data length in the analysis might show that the process is not ergodic.

In this article, the records of tsunamis in 1944 at Osaka and in 1960 at Kushimoto. The mareograms are read in the step of each three minutes to give the time series of the water level as shown in Table 1 (the fifth column). 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 with the consideration of freedom (the sixth column) by the successive folding of the original data.

As for the tsunami caused by the earthquake off Nankaido at Osaka, the spectrum analysis is carried out for the data length (T) of 2. 5, 5 and 10 hours for the initial length of the tsunami record to show in Fig. 6. In Fig. 6, it is easily found

Table 1 Numbers 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)

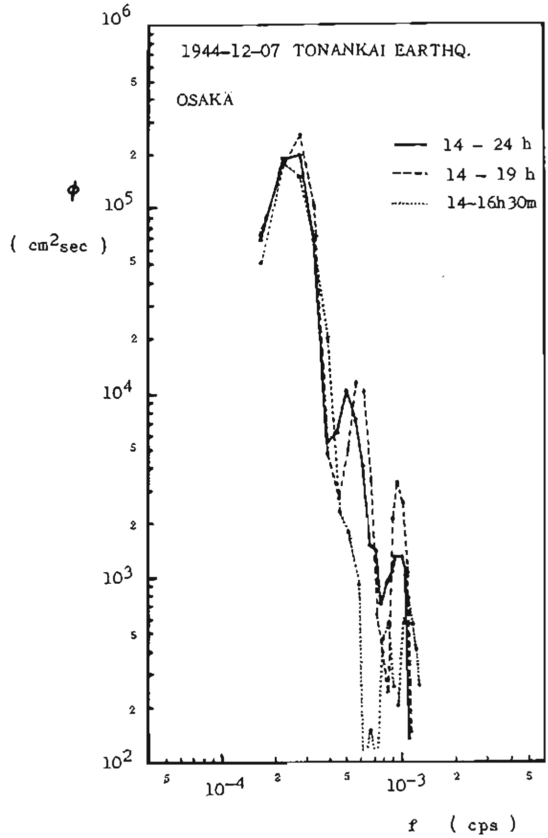

Fig. 6 Tsunami spectrum as a function of time elapse at Osaka for the Earthquake off Tonankai in 1944

that the initial stage (T=2.5 hours), the principal peak of the spectrum is at the period of ca 70 min ($f=2.2\times10^{-4}$cps), and the other peaks are smaller than one hundredth of the principal peak. When the longer data is considered (T=5 hours), the second and the third harmonics of the principal peak become significant which might be caused by the shoaling effect. The wave might be transformed into a nonlinear wave. The longest data (T=10 hours) gives the power spectrum with the less significant higher harmonics which might show that the energy of the wave is decreasing. The principal peaks of the three are quite similar and a little variation to give the similar patterns of the power spectra except the details of the patterns for the significant higher harmonics.

And for Chilean Tsunami in 1960 at Kushimoto, the three kinds of the data lengths are considered, i. e., the length (T) of 3, 6 and 12 hours for the data originated at the time three hours before the arrival of the tsunami. The obtained power spectra are shown in Fig. 7. The power of the spectra after the arrival of the

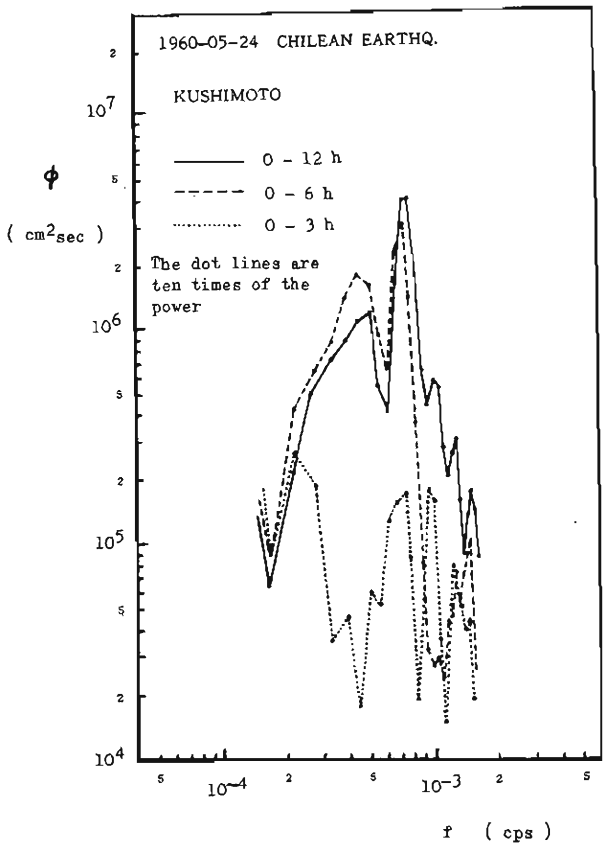

Fig. 7 Tsunami spectrum as a function of time elapse at Kushimoto for the Earthquake off Chilean in 1960

tsunami are ten times at least of 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 ca 40 min and 23 min ($f=4.4\times10^{-4}$ cps and 7.4×10^{-4} cps) respectively. In these two peaks, the one for the period of ca 23 min is fairly sharp and significant before and after the arrival of the tsunami. This peak might be formed by the local resonative oscillation agitated by the energy supply from the incident wave. The tsunami might be characterized by the peak at the period of ca 40 min in Fig. 7. After the arrival of the tsunami, the patterns of the spectra show the dependency of the analyzed data lengths to give several 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 mareograms, the tsunamis and the tides are recorded in a superposed form. When the focus is at the problem of the tsunamis, the components except the tsunamis should be treated as a back ground signal. In the spectra, the components except the tsunamis are taken to be the back ground spectra as considered by Munk, Snodgrass and Miller[18]. 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 tsunamis are similar to the monochromatic waves as considered in the refraction diagram.

Judging from Fig. 6 and 7, the above assumption should be a fairly rough assumption. This assumption might be sufficient for only the initial part of the tsunamis, as considered in the refraction diagram.

(2) Tsunami Spectra from Open Ocean to Osaka Bay

Tsunami spectra in this paper are obtained under an assumption that the tsunamis are approximately the stationary Gaussian processes, even though the phenomena of the tsunamis are transitional.

In this article, the transformation of the patterns of the tsunami spectra is considered from 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 for Fig. 6 and 7. The tsunami spectra are shown in the diagrams to relate the power density and frequency.

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 absissa is taken as the frequency to form a diagram with a parameter of power density for each tsunamis respectively. The obtained results are shown in Fig. 8, 9, 10 and 11 for each tsunamis 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 detaile cannot be

Table 2 Numbers of data used for study local transformation of tsunami spectra

EARTHQUAKE ACCONPANIED 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=180km)	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)

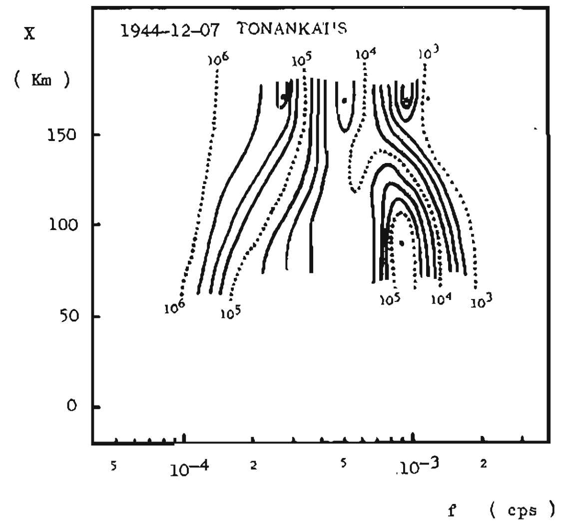

Fig. 8 Local transformation of tsunami spectra with distance for the Earthquake off Tonankai in 1944

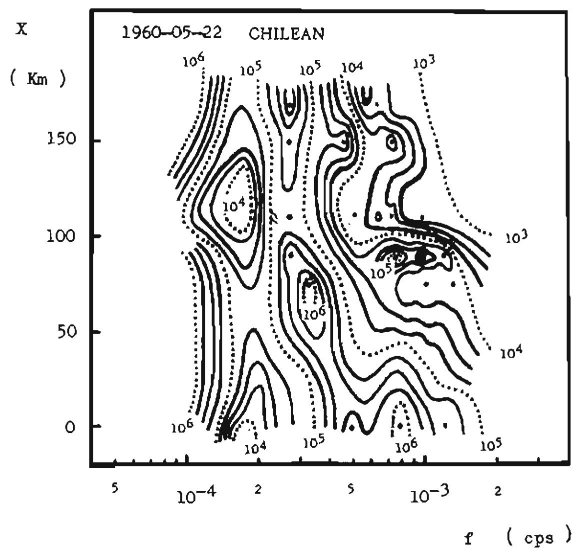

Fig. 9 Local transformation of tsunami spectra with distance for the Earthquake off Chile in 1960

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 $f=9\times10^{-4}$ cps) in Kii-Channel decreases in Osaka Bay down to less than one tenth and induces the local other oscillations.

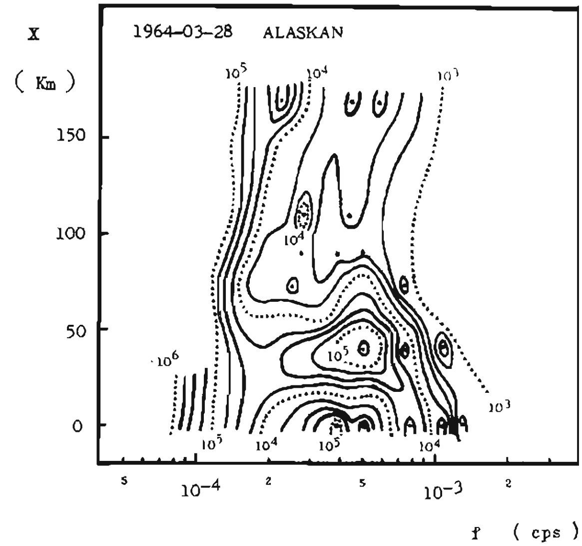

Fig. 10 Local transformation of tsunami spectra with distance for the Earthquake off Alaska in 1964

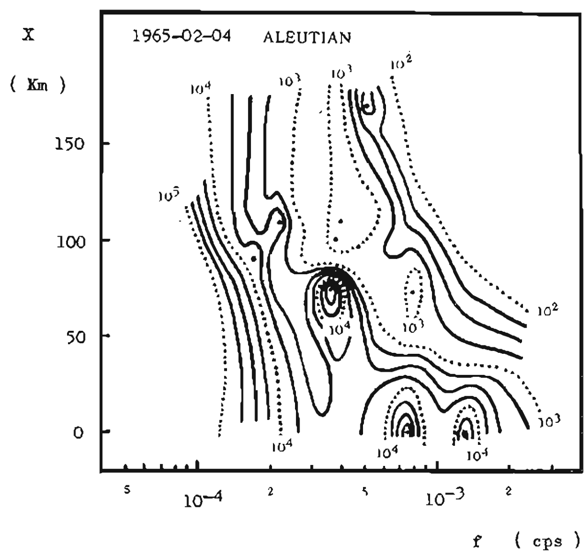

Fig. 11 Local transformation of tsunami spectra with distance for the Earthquake off Aleutian arc in 1965

As for Chilean Tsunami in 1960, as is shown in Fig. 9, the frequency at the principal peak of the spectra is almost same from Kii-Channel to Osaka Bay except Kushimoto. The local patterns of the spectra might be characterized by the higher harmonics. The peak of $f=8\times10^{-4}$ cps at Kushimoto may be caused by the effect of the local topography as mentioned for Fig. 6. In case of the innundation of the tsunamis from the open ocean to Osaka Bay, the tsunamis propagates and reaches to the coast or shore line to reflect and to induce oscillations, which cause the significant transformation of the bottom feel tsunamis for the tail part of the tsunamis. The peak of $f=3\times10^{-4}$ 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 of Kii-Channel. This oscillation is easily found by a glance of the expression as given 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, those of 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 much as the magnitude of 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 the all phenomena of the tsunamis are transitional and to consider to treat the tsunamis as a 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.

5. Conclusions

The authors have analyzed the tsunamis innundating into Osaka Bay to study the transformation of the tsunamis through the propagation.

(1) At first, Chilean Tsunami in 1960 is taken to study the wave height distribution along the coast from Kushimoto to Osaka (from Pacific Ocean to the head of Osaka Bay) in a fairly good agreement by use of the refraction diagrams which are obtained by the numerical computations and the manual drawing. The observed wave heights 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) The 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 of Kii-Channel.

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.

Acknowledgement

In this study, the authors have owed to refer to the records and data wich are systematically filed by Mr. K. Onishi and Mr. H. Sato of Osaka District Meteorological Observatory. And Prof. K. Kajiura, Drs. T. Hatori and I. Aida of Tokyo University are cordially acknowledged for them to show us the data and reports and to give us valuable suggestions.

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