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3. *On the Edge Waves of the Iturup Tsunami.*

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Abstract

Two Iturup tsunamis of 1958 and 1963 have offered a good opportunity to investigate the behaviour of edge waves on the continental shelf. Taking into account the results of a model experiment carried out lately, an attempt is made to investigate the problem by techniques of digital filtering and the Fourier transform. The complexity of the shape of the continental shelf along the Pacific coast of northeastern Japan adds difficulty to obtain the fair results such as a model experiment. The results obtained in the present work are that a dispersive wave group with the characteristics of edge waves seems to follow the direct wave but this wave group includes the wave component normal to the coast which is 1 to 3 times the wave amplitudes of edge wave mode.

1. Introduction

The earthquakes of Nov. 7, 1958 and Oct. 13, 1963 occurred off Iturup Island in the Kuril Islands. The accurate locations of epicenters of these earthquakes were at 44°18′N, 148°30′E and 43°45′N, 149°58′E respectively. The tsunamis which accompanied these earthquakes, and were observed at the Pacific coast in the northeast of Japan, seem to offer the best opportunity to examine the existence of edge waves. Because, taking the locations of the tsunami generation and propagation paths into consideration, it would be conceivable that edge waves were easily generated. From this view point, T. Hatori and R. Takahasi investigated edge waves of these tsunamis.[1),2)] However, no satisfactory resolution of this problem has been arrived at. Recently, the author and others carried out a model experiment on edge waves traveling along a curved shelf.[3)] In this paper, the existence of edge waves in the two tsunamis is discussed as compared with the results of this model experiment.

1) T. HATORI and R. TAKAHASI, "On the Iturup Tsunami of Oct. 13, 1963, as Observed along the Coast of Japan," *Bull. Earthq. Res. Inst.*, **42** (1964), 543.

2) T. HATORI, "The wave Form of Tsunami on the Continental Shelf," *Bull. Earthq. Res. Inst.*, **45** (1967), 79.

3) I. AIDA, T. HATORI, M. KOYAMA and K. KAJIURA, "A Model Experiment on Long-Period Waves Travelling along a Continental Shelf," *Bull. Earthq. Res. Inst.*, **46** (1968), 707, (in Japanese).

2. Preliminary consideration

The epicenter of the earthquake of 1958 is located on the continental shelf and that of the earthquake of 1963 at the end of the continental slope, as shown in Fig. 1. Both earthquakes are different from each other with respect to the locations of the epicenters and the characters of the earthquakes.[4] However, the records at Miyagi-Enoshima of the tsunamis which accompanied these earthquakes are very similar to each other, especially regarding the first or second wave following the initial movement of the sea surface.

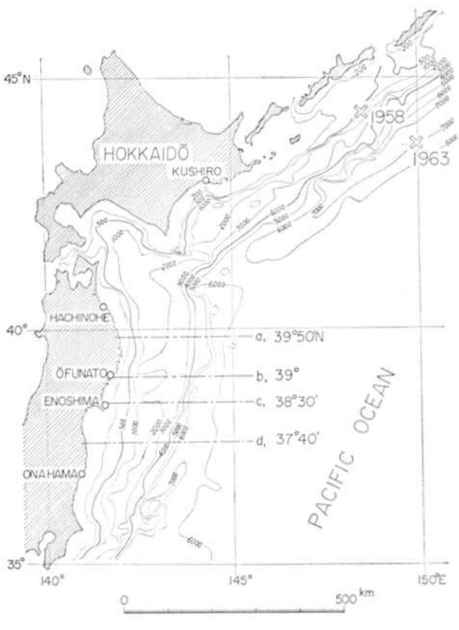

Fig. 1. Map of the sea region considered in this study. The marks ⨯ show the two epicenters of the Iturup Earthquakes. The dispersive characters of edge waves expected from four profiles marked *a*, *b*, *c* and *d* are computed.

As shown in Fig. 1, the contour lines of the sea depth extend in a south-west direction from the vicinity of the earthquake epicenters, bending the direction into almost south at the south-east offshore of Hokkaido. The contour lines are parallel to each other, except in the sea region lying between Hokkaido and Honshu where the contour line is indented deeply westward. The depth profiles normal to the shelf are considerably different from place to place. The phase and group velocities of edge waves were calculated to investigate how widely the dispersion curves vary by the difference of the depth profile. The method of calculation was the same as employed by W. Munk,[5] who studied edge waves in the California coast. In this method, the depth profile is approximated by a series of many steps. The author has once solved the problem of the shelf near Enoshima by this method.[6]

4) S. L. SOLOV'EV, "The Urup Earthquake and Associated Tsunami of 1963," *Bull. Earthq. Res. Inst.*, **43** (1965), 103.

5) W. MUNK, F. SNODGRASS and F. GILBERT, "Long Waves on the Continental Shelf: An Experiment to Separate Trapped and Leaky Modes," *Jour. Fluid Mech.*, **20** (1964), 529.

6) I. AIDA, "Water Level Oscillation on the Continental Shelf in the Vicinity of Miyagi-Enoshima," *Bull. Earthq. Res. Inst.*, **45** (1967), 61.

Four profiles which marked *a*, *b*, *c* and *d* were selected for the calculation of the dispersion curve. Figure 2 shows the calculated results. The upper and lower figures show the dispersion curves of phase and group velocity respectively. This figure points out that the dispersion relation is strongly affected by the difference of the depth profile. The case of the most southern profile *d* differs from others particularly. The reason may be that in *d* profile the shelf portion shallower than 200 meters is wider than those in other profiles. The minimum group velocity appears only in the dispersion curves for cases of *c* and *d* profiles.

The response spectrum of the continental shelf in the case of normal incidence of the unit sinusoidal waves from the outer sea is also calculated for *a* and *d* profiles, as shown in Fig. 3.

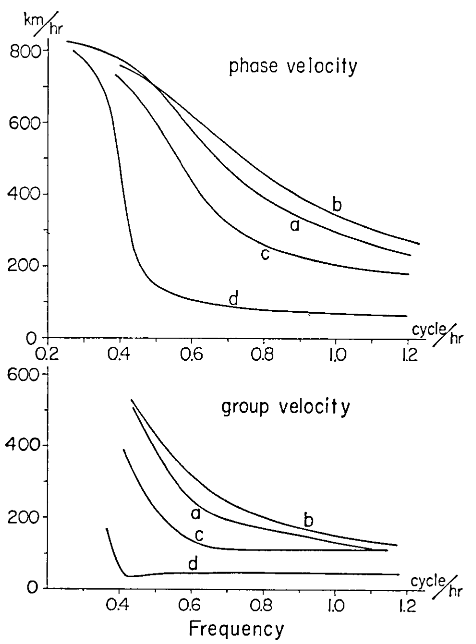

Fig. 2. Phase and group velocities of edge waves estimated from theory. The marks *a*, *b*, *c* and *d* correspond to the profiles shown in Fig. 1.

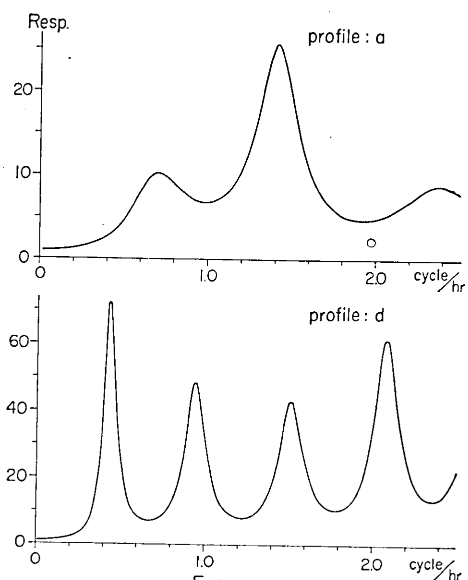

Fig. 3. Response of the continental shelf water in case of the normal incidence of waves.

3. Filtering of tsunami record

The experiment,[7] in which an aperiodic wave was given to a shelf model which has a shape of a quarter circle, shows that the wave form at the places along the coast becomes as shown in Fig. 4. Namely, the

7) *loc. cit.*, 3).

distinct dispersive wave group appeared following the direct wave. In spite of bending of the shelf, boundary waves was propagated with the character of edge wave on the average.

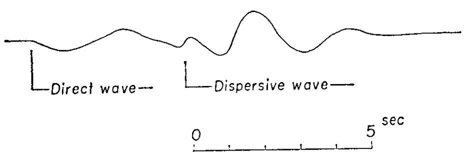

Fig. 4. Typical record observed in a model experiment.

How would these matters become in an actual tsunami? The ordinary mareograms include noises, such as seiches of the bay in which the tide station is located. The seiche periods in most bays in Sanriku district are not longer than 40 minutes. Therefore, it is considered the waves of periods of 60 minutes or more are little affected by the noise. As apparent in Fig. 2, the fundamental mode of the expected edge wave is in the range of periods longer than 60 minutes. Consequently, the digital filtering was carried out in the frequency band from 60 minutes to 180 minutes in order that an object in the present problem was confined to the period longer than 60 minutes.

The original record of the Iturup tsunami of 1958 at Onahama is shown in the lowest part of Fig. 5. This record includes the large

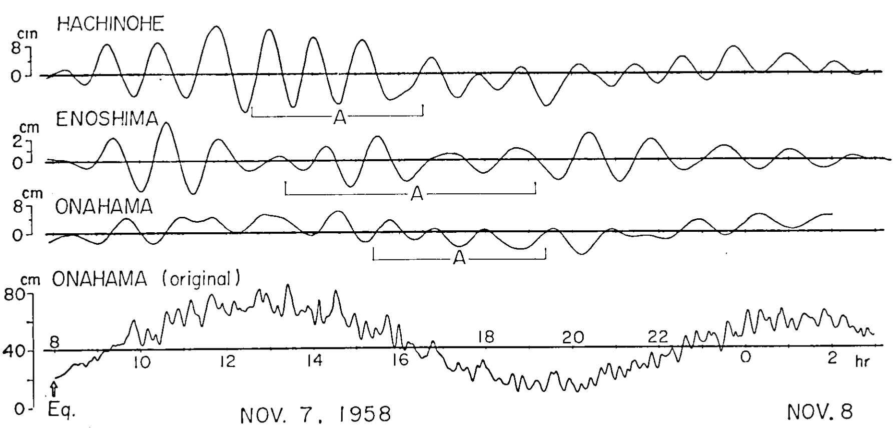

Fig. 5. Filtered and non-filtered records of the Iturup tsunami of 1958. Marks A show dispersive wave groups following the direct waves.

quantity of comparatively short period noises. Thus, it is utterly impossible to correspond the wave phases of stations with each other. However, the filtered records of this tsunami at Hachinohe, Enoshima and Onahama, shown in the upper part of Fig. 5, are considerably simplified. In the record at Enoshima, it is seen that, after the direct waves with two or three crests, a comparatively distinct wave group with several crests appears and the periods of the waves become successively longer. This wave group is labelled *A*. In the record at Onahama, the waves which are considered to be the same as *A* group are smaller in amplitude than at Enoshima, but the dispersive character of waves is apparent. At Hachinohe, although the separation of this dispersive wave group from direct waves is not so apparent, the periods of several waves following the direct waves are successively lengthened.

In the case of the tsunami of 1963, the records of five stations; three stations as already mentioned and other two stations Kushiro and Ofunato, were filtered, and the results are shown in Fig. 6. The filtered

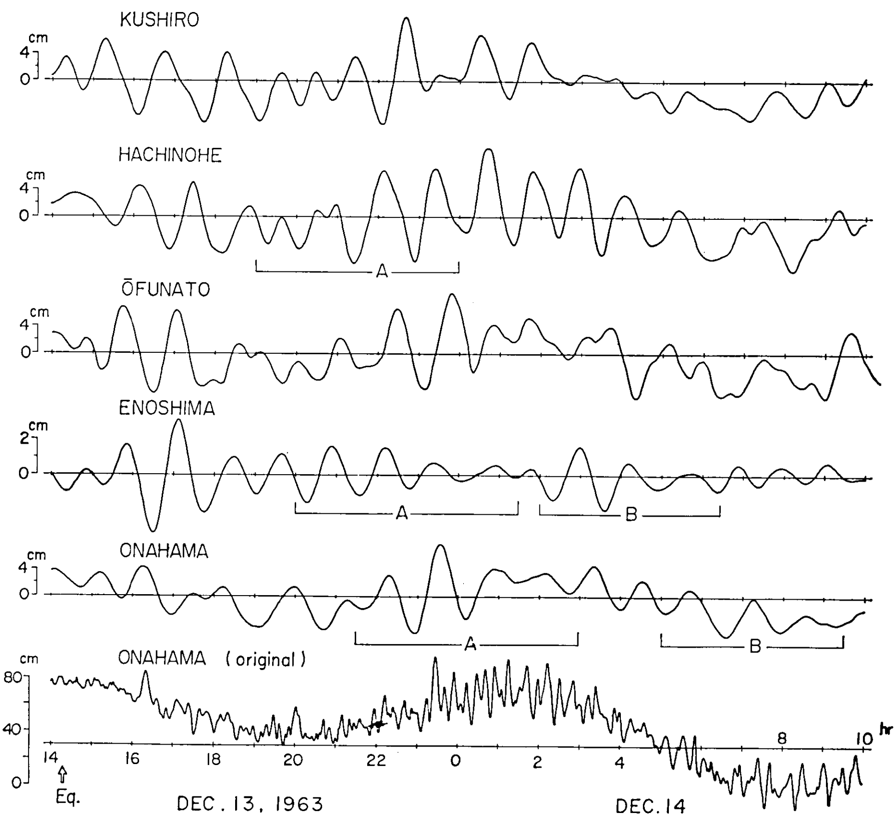

Fig. 6. Filtered and non-filtered records of the Iturup tsunami of 1963. Marks *A* and *B* show dispersive wave groups following the direct waves.

records at Enoshima are closely similar to the one of 1958 and the coherence between the filtered records of both tunamis is calculated to be 0.75 to 0.77 at 70 to 80 minutes of periods, showing the comparatively high values. At Hachinohe, however, the difference of wave form between both tsunamis is apparent, and the coherence between both records has a low value of 0.47 at 70 munites of periods. The coherence at

Onahama is a medium value, being 0.57 at 70 minutes of period. The difference of coherences, between both tsunami records according to the location of observing station, seem to be related to the path of the wave propagation, since the tsunami generating areas are very close to each other as seen in Fig. 1.

On the records of Enoshima and Onahama shown in Fig. 6, remarkable wave groups following the direct waves may be recognized. These groups occupy the same situations as *A* groups in Fig. 5, therefore they are considered to be similar to *A* wave group of the tsunami of 1958. Moreover, the similar forms of the waves are continued behind *A* group, this group being labelled *B*. At Hachinohe and Ofunato, although the wave forms are rather similar to each other, *A* wave group is not evident.

The travel time graph may be drawn by means of the investigation of the correspondence of the crests or the troughs of wave records at various stations. However, the record at Kushiro is hardly related to the other station records and also the accuracy of the travel time graph is not enough to discuss the wave dispersion, even in the region southward from Hachinohe. If the propagation velocities of the maximum amplitude waves were determined, they are 42 km/h for *A* group and 60 km/h for *B* group. These values nearly correspond to the minimum group velocity of about 45 km/h, for the profile *d* which represents the depth profile in the middle point between Enoshima and Onahama.

Although *A* wave groups of these filtered records are not so remarkable as the dispersive waves with the character of edge wave observed for the case of a model experiment mentioned above, it is considered that the character of the travel time and dispersion of waves are approximately the same as the case of the model experiment.

4. Analysis of the dispersive wave group

For *A* or *B* wave groups, the Fourier analysis is carried out and the mean phase velocity between the observing stations is computed for each component. The analysis is made for the non-filtered original record.

Figure 7 shows the results, in which the triangular marks in the upper part show the phase velocities obtained from the analysis between Hachinohe and Enoshima for the tsunami of 1958 and the circular marks in the lower part show the ones between Enoshima and Onahama for the tsunami of 1958 and of 1963. Theoretical dispersion curves of phase velocity of the edge wave are shown by the solid lines in the figure. The profile *a* is the middle point between Hachinohe and Enoshima, and

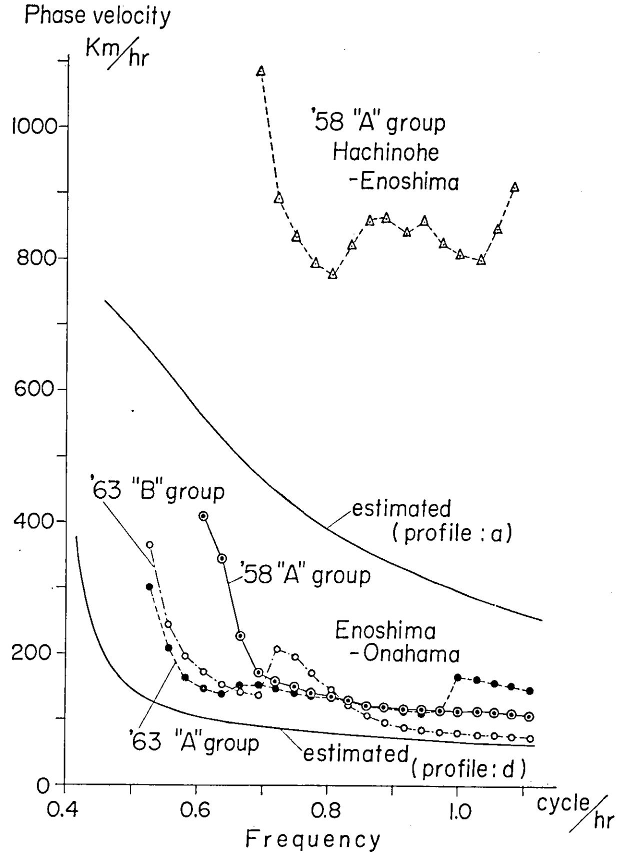

Fig. 7. Phase velocity obtained by the Fourier analysis of the dispersive wave group. The estimated dispersion curves are drawn to compare with the observation.

the profile *d* between Enoshima and Onahama. In this figure, the values obtained from the observation reach 1.5 or 2 times the calculated values. If there was a wave component oscillating normal to the shore, it is expected that the apparent phase velocity becomes faster than the theoretical value taking only a trapped mode into account, and a similar effect has been experienced in our model experiment. Therefore, an attempt is made to separate the wave components propagating along the shelf and oscillating normal to the shore.

As shown in Fig. 8, it is supposed that there are two points St. 1 and St. 2 at a distance 2Δ along the shelf. If the amplitudes of the wave component propagating along the shelf, which are hereafter called the progressive wave, are a_{p1} and a_{p2} and the amplitudes of the wave component oscillating normal to the shore, which are hereafter called the standing wave, are a_{s1} and a_{s2}, at two points St. 1 and St. 2,

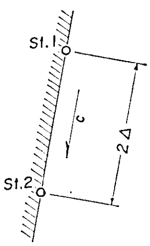

Fig. 8.

respectively, the wave of the angular frequency ω observed at St. 1 may be expressed by

$$a_1 = a_{p1} \cos\left(\omega t - \frac{\omega \Delta}{c}\right) + a_{s1} \cos(\omega t + \varphi_1),$$

where c is the phase velocity of edge waves with angular frequency ω. In the same manner, the wave observed at St. 2 is expressed by

$$a_2 = a_{p2} \cos\left(\omega t + \frac{\omega \Delta}{c}\right) + a_{s2} \cos(\omega t + \varphi_2).$$

φ_1 and φ_2 are phases.

Since the observed values are only a_1 and a_2, assumptions are made to solve the problem: The progressive wave does not attenuate for the distance between two stations, i.e. $a_{p1} = a_{p2} = a_p$, and the amplitudes of the standing waves in two stations are equal to each other and phases are coincident, i.e. $a_{s1} = a_{s2} = a_s$, $\varphi_1 = \varphi_2 = \varphi$. With $a_s/a_p = S$, we have

$$a_1 = a_p \sqrt{\left(\cos\frac{\omega}{c}\Delta + S\cos\varphi\right)^2 + \left(\sin\frac{\omega}{c}\Delta - S\sin\varphi\right)^2} \cos(\omega t - \delta_1),$$

and

$$a_2 = a_p \sqrt{\left(\cos\frac{\omega}{c}\Delta + S\cos\varphi\right)^2 + \left(\sin\frac{\omega}{c}\Delta + S\sin\varphi\right)^2} \cos(\omega t + \delta_2),$$

where,

$$\delta_1 = \tan^{-1}\frac{\sin\frac{\omega}{c}\Delta - S\sin\varphi}{\cos\frac{\omega}{c}\Delta + S\cos\varphi},$$

and

$$\delta_2 = \tan^{-1}\frac{\sin\frac{\omega}{c}\Delta + S\sin\varphi}{\cos\frac{\omega}{c}\Delta + S\cos\varphi}.$$

Therefore, from the observed values of the amplitude ratio $|a_2|/|a_1|$ and the phase difference $\delta = \delta_1 + \delta_2$, S and φ may be obtained by assigning the phase velocity c.

Figures 9 and 10 are the results obtained from the data of Enoshima and Onahama in case of the tsunami of 1958. The spectral amplitude, the amplitude ratio $|a_2|/|a_1|$ and the phase difference δ are shown in this order from the top in Fig. 9. S and φ determined from these data are shown in Fig. 10. In the lowest part of the figure, the separated spectral amplitude of the standing wave a_s and of the progressive wave a_p are shown. The dotted curve in the figure is the response spectrum of the shelf as calculated in Fig. 3, which is expected for the shelf with the depth profile at the middle point between Enoshima and Onahama.

Comparing the response (dotted line) with the components of the standing waves a_s (thick line), the general appearance, on the whole,

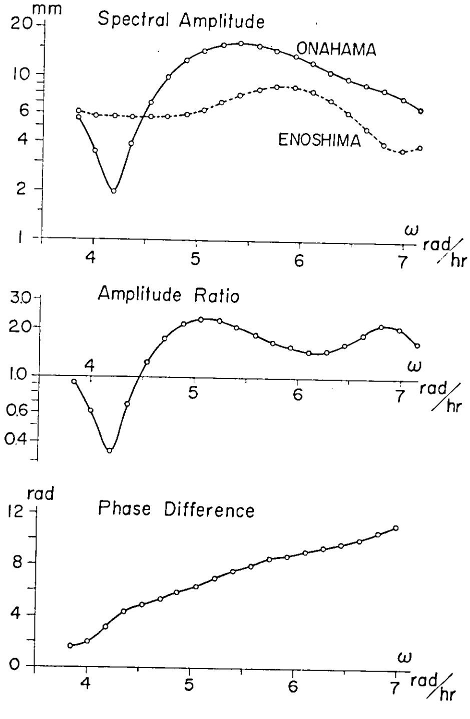

Fig. 9. Results of the Fourier analyses of the records observed at Enoshima and Onahama in case of the Iturup tsunami of 1958.

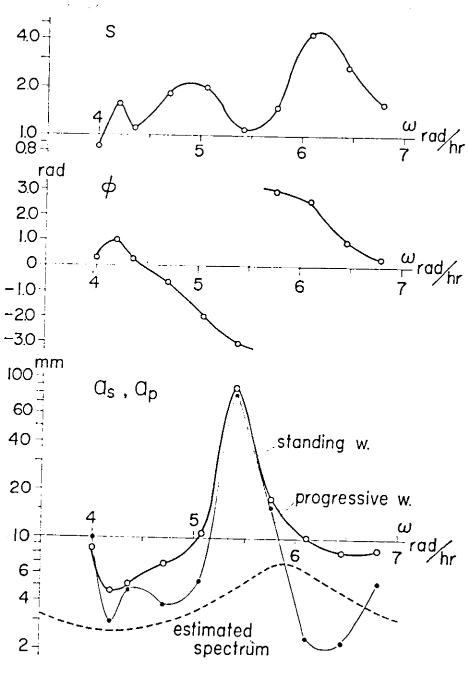

Fig. 10. Separation of the component of the oscillatory wave a_s normal to the shore and the progressive wave a_p along the shelf, with regard to Enoshima and Onahama in the tsunami of 1958. S shows $|a_s|/|a_p|$ and φ is the phase difference of two components.

seems to be fairly well coincident. The value for $\omega=5.4$ rad/h does not coincide with calculated response. However, by means of the present brief method, it is considered to be very difficult to make the actual value coincide with the theoretical value. Because, at the point in question, the phase angles of a_s and a_p become nearly inverse to each other. According to the result, the amplitude of the wave component propagating along the shelf is nearly equal to that of the wave component oscillating normal to the shelf in the part of comparatively long periods and is a half to one third in the part of short periods.

The similar analysis between Hachinohe and Enoshima is carried out. Figure 11 is the results of Fourier analyses for the records of these stations, Fig. 12 showing S, φ, a_s and a_p obtained by the present method. However, in this case, the complete solution was not obtained for the part of $\omega=5.5$ rad/h or more. Therefore, here is shown an approximate solution by the dotted line. Although, in the lowest part of Fig. 12, the response spectrum estimated from the depth profile of the shelf at the middle point between Hachinohe and Enoshima is added with the dotted

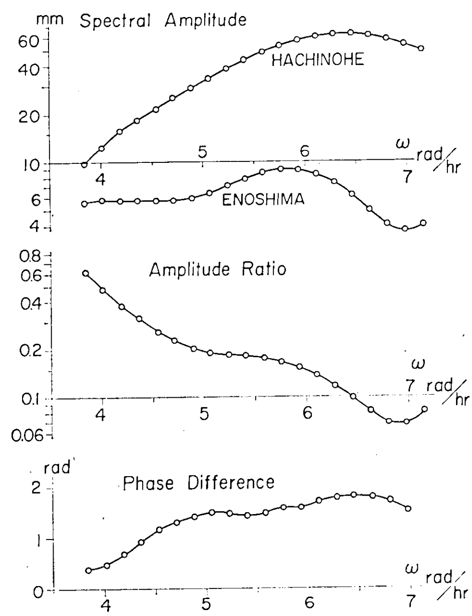

Fig. 11. Results of the Fourier analyses of the records observed at Hachinohe and Enoshima in case of the Iturup tsunami of 1958.

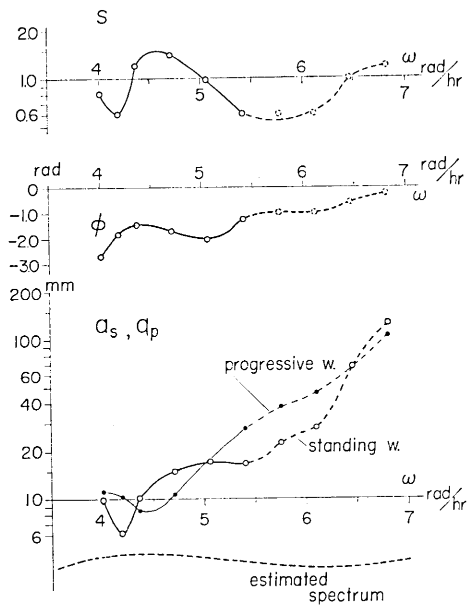

Fig. 12. Separation of the component of the oscillatory wave a_s normal to the shore and the progressive wave a_p along the shelf, with regard to Hachinohe and Enoshima in the tsunami of 1958. S shows $|a_s|/|a_p|$ and φ is the phase difference of two components.

curve, it does not coincide with the standing wave amplitude obtained from the observation except that the values of a_s in the comparatively long period part are of the same order as those obtained for Enoshima and Onahama. This may indicate that, as for the behaviour of waves between Hachinohe and Enoshima, the assumptions used in the present analysis may not be reasonable.

5. Synthesis of wave form by means of Fourier transform

If there were waves propagated with the dispersive character of edge waves, it is possible to compose the wave form in a station from the Fourier spectrum of waves in another station. Similar analysis for the elastic surface waves of earthquake was made, for instance by Y. Satô[8].

An attempt to verify the usefulness of this method is made for waves observed in the model experiment. The wave forms at observing points at the distance of 160, 200 and 280 cm from the wave source are calculated from the Fourier spectrum of waves observed at the point 360 cm from the source, based on the dispersion relation of phase velocity expected from a theory. The results are shown in Fig. 13. For the attenuation factor for waves, the average value obtained in the experiment is adopted. In Fig. 13, it may be said that the calculated wave, shown in the uppor side of each position, simulates very well the observed wave shown in the lower side.

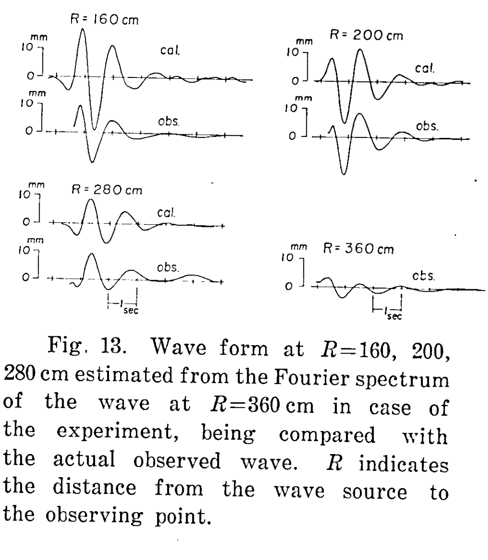

Fig. 13. Wave form at R=160, 200, 280 cm estimated from the Fourier spectrum of the wave at R=360 cm in case of the experiment, being compared with the actual observed wave. R indicates the distance from the wave source to the observing point.

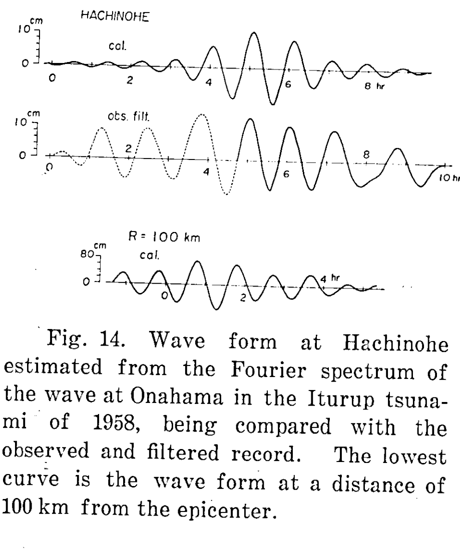

Fig. 14. Wave form at Hachinohe estimated from the Fourier spectrum of the wave at Onahama in the Iturup tsunami of 1958, being compared with the observed and filtered record. The lowest curve is the wave form at a distance of 100 km from the epicenter.

In other words, it is certain that edge waves are propagating along the shelf in the case of our experiment. How would the actual tsunami behave in comparison with the experiment? For the Iturup tsunami of 1958, the wave form at Hachinohe is estimated, using the wave spectrum at Onahama, as shown in the upper part of Fig. 14. Comparing this wave with the filtered wave of the observed record shown at the lower side, the good coincidence as in the experiment can not be recognized.

8) Y. Satô, "Analysis of Dispersed Surface Waves by means of Fourier Transform II," *Bull. Earthq. Res. Inst.*, **34** (1956), 9.

Extending the estimation up to the position near the wave source ($R=100$ km), the wave form is more diffused, which is unreasonable.

6. Conclusion

For the tsunamis generated off Iturup Island, a considerably distinct wave group following the direct wave is observed in the vicinity of Enoshima and Onahama. These waves include the component, propagating along the shelf with the character of edge wave. The amplitude of this component is a half or a quarter of a whole wave amplitude. However, it is hardly considered that these edge waves are propagated from the vicinity of tsunami origin. A more reasonable consideration may be that the mode of edge wave is generated when a wave train of the tsunami enters the shelf obliquely near northeastern Japan.

The author wishes to express his sincere thanks to Professor K. Kajiura for his helpful advice. All the numerical computations were made by utilizing the facilities of the computer center of the University of Tokyo.

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3. エトロフ津波のエッヂウェーブについて

地震研究所　相　田　　勇

1958 年および 1963 年のエトロフ島沖の地震に伴った津波は，その波源の位置から見て，日本の東北地方太平洋岸で edge wave が観測されることが期待され，すでに 2, 3 の報告がなされている．しかし未だ完全な結論が出たとはいえないので，最近筆者等が行った水理模型実験の結果などを参照して，edge wave の存在について検討することとした．

先づ実際観測された津波の記録をディジタルフィルターして見ると，直接波の到着後しばらくして，分散性の波群が見出される．これは比較的波源に近い観測点で，模型実験の場合に認められることと一致する．

次にこの波群についてフーリェ解析を行なって位相速度を求めたが，これは陸棚の断面から計算される理論的な edge wave の位相速度よりかなり速い値を示す．模型実験の場合にも，この様なことが，棚に直角な成分の波の効果として指摘されたが，観測点の少い実際の津波の場合は，この成分を分離することは困難である．ここでは極めて簡単な方法で棚に直角方向の成分を分離して見ると，宮城江の島，小名浜の付近で棚に沿って進行する波の 1～3 倍に達すると推定される．

又 edge wave の特性を持った波が伝播している場合，或る点で観測された波のフーリェスペクトルから任意の点の波形の合成が出来る筈である．模型実験の場合について，これを試みると，波形の合成値と，観測値とはよい一致を示す．しかし実際の津波についてはよい結果が得られない．

以上を総合して，波源のすぐ近くから edge wave として棚の上を伝播して来ると考えるより，観測点付近の棚に津波が斜に入射するために edge wave の mode が観測されると考える方が適当である．