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OBSERVATIONAL STUDY ON MICROSEISMS (PART 1)

BY

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1. Introduction

For many years microseisms have been investigated by numerous scholars. But there is still lack of general agreement about the origin, the mechanism of generation and the other properties of microseisms. It is the object of this paper to solve these problems.

It has been well known that microseismic storms appear on seismograms during the passage of typhoons or cyclones. The view has often been expressed that microseisms are associated with atmospheric depressions, but recently most of investigators support the opinion that sea waves generate microseismic waves in the solid crust.

Bernard (1937) et al. found that the period of microseismic waves is about half that of the generating sea waves. Longuet-Higgins (1950) presented a significant theory for the effect at the ocean bottom of standing sea waves produced by the interference between two similar wave trains travelling in opposit directions. Such a condition as Longuet-Higgins pointed out is expected to be attained at the neighbourhood of the atmospheric low pressure center or the coast, and hence the opinion on the location of the origin of microseisms is divided into two. Although at present his theory seems most attractive, no evidence of existence of standing sea waves is observed.

From the case studies of microseismic storms, it is known that the occurrence of the peak in microseismic activity observed at an observing station does not coincide with the moment when a typhoon or cyclon approaches to the station as closely as possible, but rather is delayed, and also the occurrence of the maximum amplitude at each station seems to propagate with the velocity similar to that of progress of the typhoon or cyclone. To explain the phenomenon some of seismologists considered that the generation of microseisms is due to the swells propagated from a storm area to the coasts, and they investigated the relation between microseisms and swells. Sakata (1940) presented an excellent paper on this subject. Wadati et al. also were led to the same consideration from the existence of close relation between microseisms and swells, as observed at some stations in Japan. Santo (1959) also investigated in detail the problem by the observational data obtained at many stations in Japan during I.G.Y. period and confirmed that consideration.

One of the most effective means to investigate the origin of microseisms is a determination of arrival directions of microseismic waves. In spite of a great deal of efforts of seismologists, they did not reach the satisfactory conclusion to that investigation because of their unsuitable methods. Therefore the writer did not follow their methods, namely, the tripartite and the Lee's method, and he studied the arrival directions from the analysis of orbital motions of the earth's particles by means of vector seismographs. It became evident from these observations that the arrival directions of microseismic waves are associated with not the positions of atmospheric low pressure centers, but the coasts near the observing station. And a comprehension of the other properties of microseisms was also considerably gained, and these results appear to support the above-mentioned consideration as already pointed by the writer (1959) and (1960).

2. General features of microseismic waves observed at the Abuyama Seismological Observatory

The writer will at first refer to the general features of microseismic waves at the Observatory based upon the information deduced from the data on the waves by the precise observation during I.G.Y. period. The Abuyama Seismological Observatory is located at the position with coordinates : 34°52′N and 135°34′E, and founded on palaeozoic system.

Good care was taken in making selection of the constants of seismographs. With due consideration for ground movements with periods of 2 to 8 sec. and with amplitudes up to 7 microns, the constants of seismographs were arranged as follows.

Constants of seismographs.

Component	T_1 (sec)	T_2 (sec)	h_1	h_2	$V_{\max}$
UD	4.00	10.00	0.75	1.00	4,100
NS	4.00	10.00	0.75	1.00	3,500
EW	4.00	10.00	0.75	1.00	3,400

T_1 : Period of pendulum
T_2 : Period of galvanometer
h_1 : Damping constant of pendulum
h_2 : Damping constant of galvanometer
$V_{\max}$: Maximum magnification

Wave type

From most observations hitherto made in the world it was reported that the three components of microseismic waves possess nearly same amplitudes, and hence it has been widely accepted that microseismic waves are the Rayleigh waves. Some of seismologists, however, have considered them to be of the Love type, the Rayleigh type combined with the Love type or the Rayleigh type combined with the standing wave. The micro-

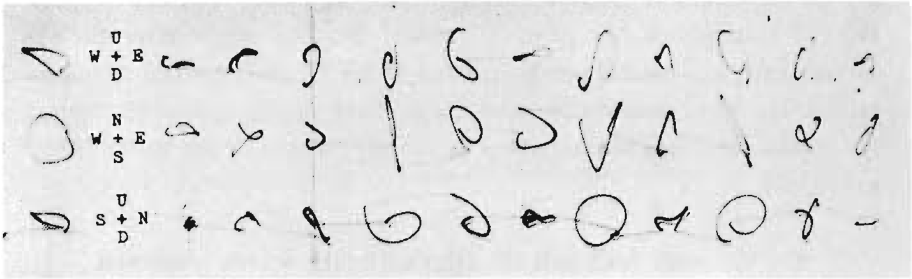

Fig. 1(1).

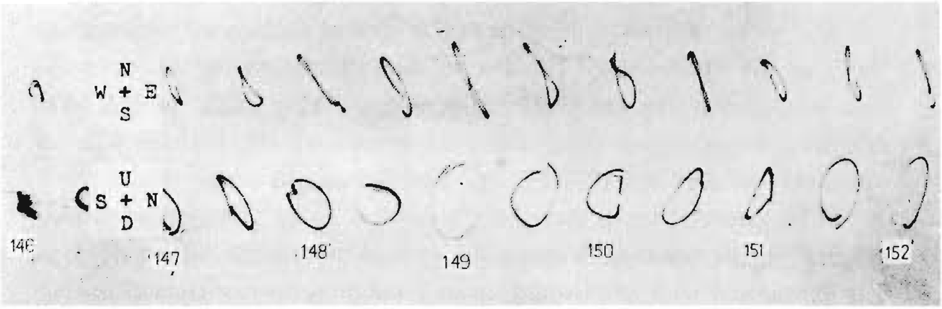

Fig. 1(2).

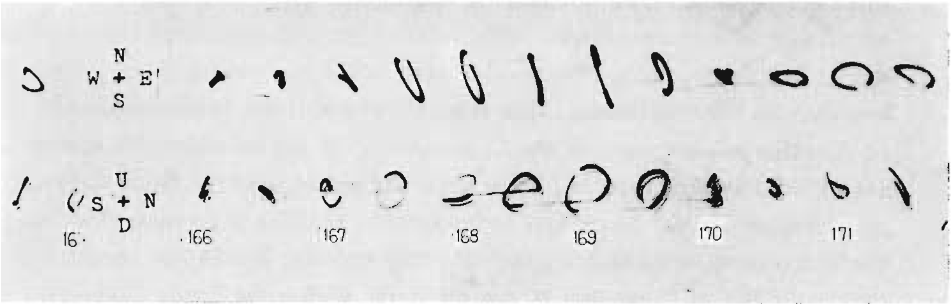

Fig. 1(3).
Fig. 1. Examples of seismograms.

seismic waves observed at the Abuyama Seismological Observatory appear to be of the Rayleigh type, as shown in Fig. 1, which is the example of seismograms obtained by the vector seismographs. In fact the vector seismographs recorded frequently the waves of the typical Rayleigh type, but on the other hand, recorded little the Love or standing waves, apart from a few waves regarded as apparent Love waves or standing waves produced by superposition of several waves propagated from various directions.

Amplitude

The ground amplitude and the wave period by which the writer will investigate microseisms in following pages were measured according to the Instruction Manual of Seismology for I.G.Y.

Fig. 2 shows the frequency distributions of ground amplitudes in

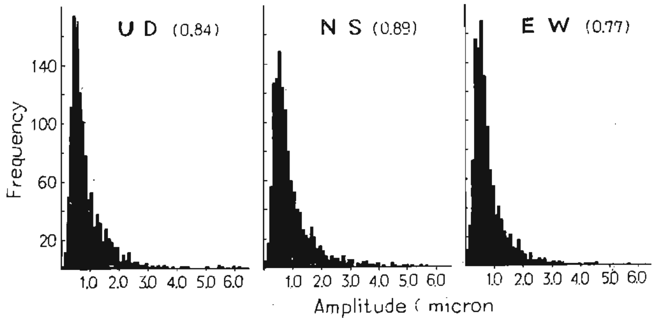

Fig. 2. Frequency distributions of the amplitude of microseismic waves. The numerals show mean values of amplitudes in each component.

three components. The numerals in the figures give the mean values of amplitudes in each component. The value in vertical component is similar to that in NS-component, whereas the value in EW-component is somewhat less than in NS-component. This tendency of amplitude is observable also on the other seismographs of the Observatory. If the microseismic waves are of the Rayleigh type and come from the coasts near the Observatory, this tendency should be natural and resanable, as there is no coast close to the Observatory in its easterly and westerly regions, but in the northerly region the Sea of Japan and in the southerly region the Pacific Ocean are comparatively close to the Observatory.

Period

Frequency distributions of wave periods are shown in Fig. 3. The numerals in the figures give the mean values of periods in each component. They are approximately equal to half the mean period (8.2 sec.) of about four thousand sea waves in the westerly Pacific Ocean observed by L. Paris. There are two groups with the respective maximum of frequency in the distributions. The group whose peak is at the period of 4 sec. is what you call microseisms. Another group with the peak of 2 sec. has been observed at various stations during the passage of cold fronts. Lynch (1952) studied this 2-second microseisms observed at New York by using the tripartite observation. The results obtained by his investigation indicate that the Great Lake is probably the source of generation of the 2-second microseisms. This sort of microseisms will be referred afterwards.

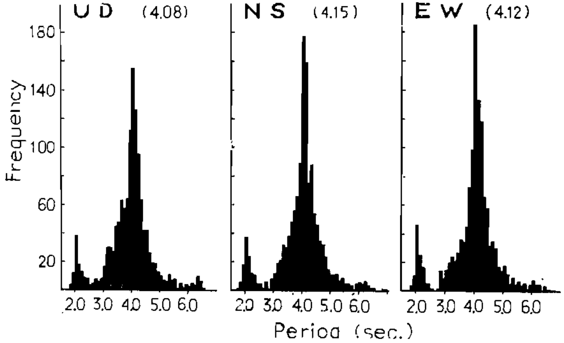

Fig. 3. Frequency distributions of the period of microseismic waves. The numerals show mean values of periods in each component.

3. Variation of the amplitude and the period of microseismic waves during microseismic storms

When typhoons or cyclones are passing near an observatory, micro-

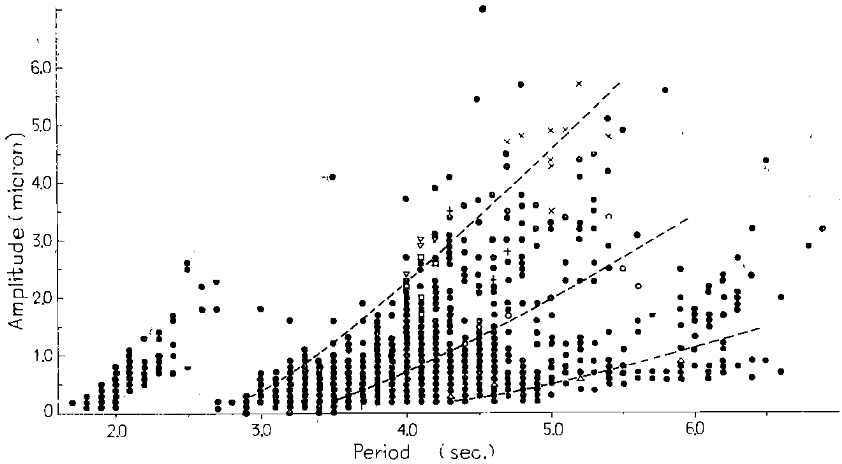

Fig. 4. Ralation between amplitudes and periods of microseismic waves.

seismic waves grow in amplitude and their period changes in the wide range. There are many reports of these variations, but they gave the explanation only for the case of the individual storm. The writer studied these variation in detail during I.G.Y. period and could give the plausible explanation of them. Since microseismic waves resemble in appearance in three components, hereafter they will be stated only in NS-component. Fig. 4 shows the relation between ground amplitudes and wave periods of microseisms. The points are scattered, but they have the tendency that the amplitude is larger for a longer period as pointed out by most of seismologists. To investigate this problem more precisely than made hitherto, the writer gave attention for the case of the individual storms. The symboles excepting the solid circles in Fig. 4 show the waves whose forms are remarkably regular in appearance in all seismogrms. They fall into three groups as indicated by the broken curves, that is, the group laid along the abscissa (A), near the middle region (B) and near the upper limit of the scattered points (C). Then the writer made a comparison between those three groups and the meteorological conditions corresponding to the times when the three groups were observed. Fig. 5, 6 and 7 are the weather charts corresponding to the times when the waves expressed by the symbols of open triangles (△), open circles and crosses were observ-

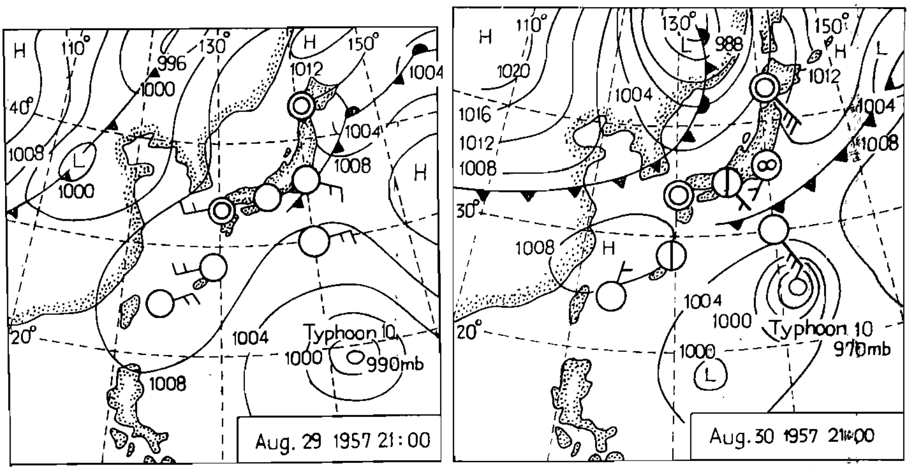

Fig. 5. Weather charts at the time when the waves expressed by symbols of open triangles (△) in Fig. 4 were observed.

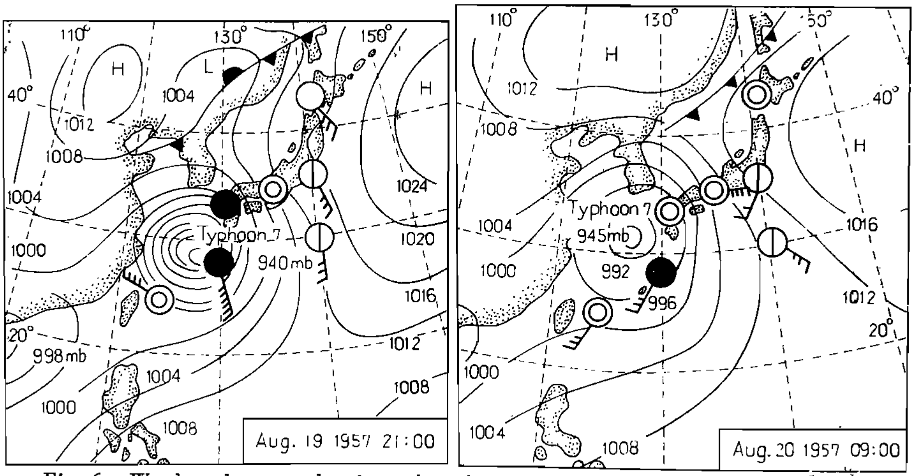

Fig. 6. Weather charts at the time when the waves expressed by symbols of open circles in Fig. 4 were observed.

ed respectively.

The first group (Fig. 5) was observed at the time when the typhoon was far distant from the Observatory, the second (Fig. 6) during its presence at a moderate distance and the third (Fig. 7) on its passing near the Observatory. From this fact the following inference may be drawn. Sea waves generated in a typhoon area have the wave height and period depending on the scale of typhoon. After leaving the generating area they

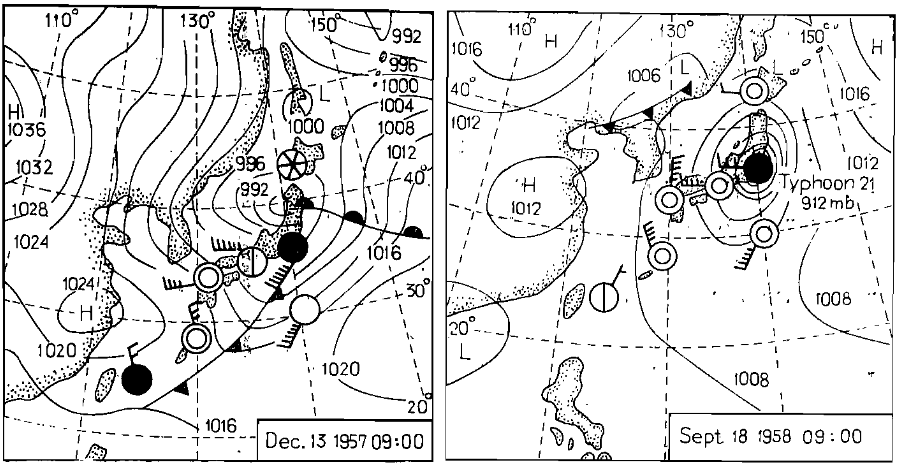

Fig. 7. Weather charts at the time when the waves expressed by symbols of crosses in Fig. 4 were observed.

propagate through the open sea to the coasts as the swell, and generate the microseismic waves in the neighbourhood of the coasts. The oceanography suggests that the swell decreases in height and its period becomes long with propagating of the swell. Therefore the amplitude and the period of microseismic waves depend on the scale of typhoon and the distance of propagation of the swell.

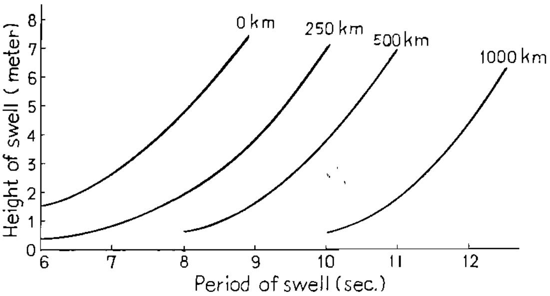

Fig. 8. Distance (km) from which swell comes as functions of height and period of swell at end of distance of decay.

Fig. 8 shows the relation between the wave height and the period of swells at the end of distance of decay given by Sverdrup and Munk (1947). A similarity between Fig. 4 and 8 is very noticeable and this is one of the probable proofs that the microseismic waves may be generated by the swell propagated from a typhoon area to the coasts. Accordingly the scale of typhoon (wind velocity in generating area, duration of wind and so on) and the decay distance of the swell, that is, the distance from the typhoon to the coast near the station, may be estimated by using Fig. 4 from the amplitude and the period of the microseismic waves at the Observatory. There is another group of waves with the period of 2 sec. in Fig. 4. This group also has the tendency growing in amplitude with an increase of the wave period and the slopes by which those two groups are enveloped resemble closely. But the group with the period of 2 sec. is lacking in points along the abscissa. Accordingly it is supposed, that the 2-second microseisms are probably generated by the sea waves that the local winds due to the cold front produce in the neighbourhood of coasts, while the 4-second microseisms are generated by the swell propagated from the disturbance source far away from coasts.

Apart from the general discussion of the amplitude and the period of microseismic waves as described above, the writer will turn to the discussion on the individual character of them referred to the two kinds of storms, e.g., the cyclone in winter season and the typhoon in summer season.

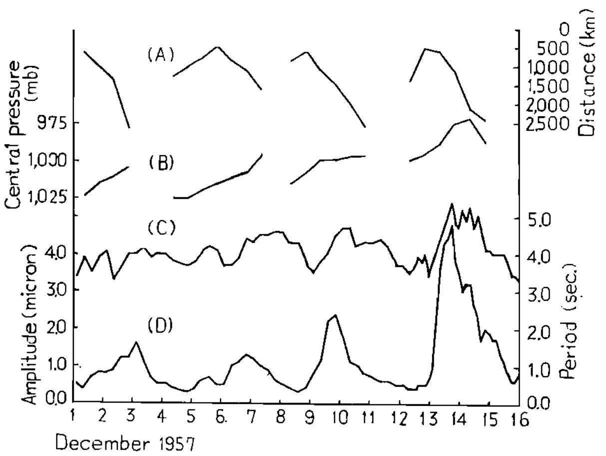

Fig. 9. Variations of distance from the Observatory to center of depression (A), central pressure of depression (B), periods (C) and amplitudes (D) of microseismic waves.

Fig. 9 shows the variation of the amplitude and the period of microseismic waves generated by cyclones in winter season, the central pressure of depression and the distance from the Observatory to the center of depression. And Fig. 10 shows the variation of microseismic waves

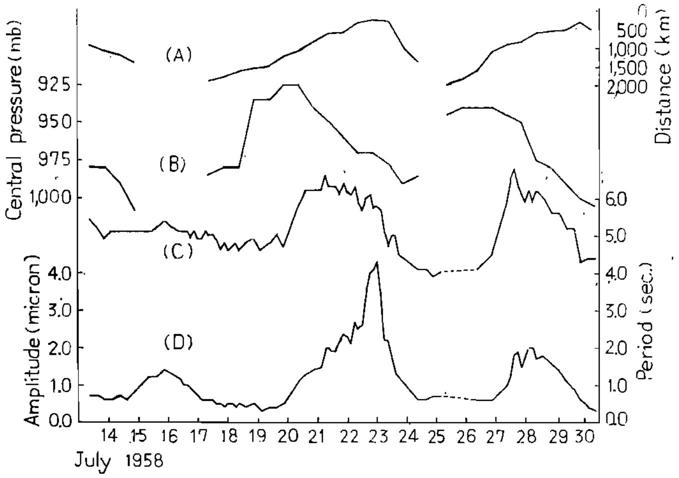

Fig. 10. Variations of distance from the Observatory to center of typhoon (A), central pressure of typhoon (B), periods (C) and amplitudes (D) of microseismic waves.

generated by typhoons in summer season, the central pressure of typhoon and the distance from the Observatory to the center of typhoon. It is marked by three noticeable differences between those two variations. The first is that the wave period in winter is shorter than in summer, that is to say, in winter the period variates centering around about four seconds, and in summer around about five seconds. The second is the marked growth of the amplitude against the gradual growth of the period in winter, while in summer the growth of the amplitude is similar to that of the period. The third is that the fall of growth of the amplitude is earlier than that of the period in winter and it is the opposite in summer. Since the seasonal wind stirs mainly the Sea of Japan in winter and the typhoon carries swells from a distance to the Pacific coasts in summer, the disturbance source in winter is not so far as the occasion of the typhoon. Accordingly the wave period in winter is shorter than in summer when the microseismic waves are produced by the swell with a longer distance of propagation, and it rises not frequently above five seconds. In winter season a low pressure produced in the south-westerly ocean off Japan passes over the Sea of Japan with developing its energy, as the variations of the central pressure of depressions and the distance from the Observatory to the center of depressions are indicated in Fig. 9, and hence the microseismic amplitude increases rapidly and its period increases moderately by the decrease of the distance of propagation of swells and the development of the storm energy. When the disturbance source is going away, the amplitude decreases by the increase of the distance of propagation of swells and the period increases furthermore by the development of the storm energy and the increase of the distance of propagation of swells.

On the other hand the energy of a typhoon produced on the southerly Pacific Ocean far off Japan at first increases with the northward approaching of the typhoon as shown in Fig. 10. Therefore the microseismic waves generated by the typhoon grow gradually in amplitude and period owing to the increase of the storm energy which is expected to be powerfull enough to exceed the opposite effect due to the decrease of the distance of propagation of swells. As the typhoon approaches considerably near Japan, the energy begins to decrease. Then the wave period of microseisms also begins to decrease owing to the decrease of the energy of typhoon and the diminishing of the distance of propagation of swells, wherease the amplitude rises still owing to the diminishing of the distance of propagation of swells. It has been hitherto considered that the wave period of microseisms should be associated with the depth of the ocean where a disturbance source exists. But this offers a striking contrast with the result, as above mentioned, that the dependency of the wave period on the energy scale of the disturbance source and the distance from the disturbance source to the coast near the observation point is obviously proved from the writer's observation. As seen on the figures of Santo's paper (1959), the variations of the amplitude and the period of microseismic waves depend a little on the location of the observing station, though the amplitude is influenced by the vibrational properties of the ground and the period by the instrumental constants of seismographs. From this fact, it may be accepted that the observational data of most of stations located at least in Japan may yield the same results as the above one deduced from the observation of the Abuyama Seismological Observatory alone. The wave period of about 4 sec. which predominates in microseisms observed in most of stations of the world, has been frequently regarded as being due to the vibrational properties of the ground. However, if it is so, the fact that there is no maximum peak of the amplitude corresponding to the period of 4 sec. can not be accepted without contradication (see Fig. 4).

4. Tripartite observation

The tripartite observation also was carried out during I.G.Y. period, but the satisfactory result was not brought. The positions of three points of observation are shown by A, B and C in Fig. 11. The instruments used in this observation are the vertical electromagnetic seismographs which were adjusted to the following constants : the period and the damping constant of pendulum are 4.0 sec. and 0.65, the period and the damping constant of galvanometer are 10.00 sec. and 1.00 and the magnification is about 4,000. As the side-lengths of the tripartite net were not sufficiently long notwithstanding the serious attention for the coincidence of constants of the three seismographs, the considerable error was unavoidable. The velocities of propagation and the arrival directions gained by the observation were scattered in the wide range. The relation between velocities and periods is shown in Fig. 12. About half of the numbers of velocities computed are above 3 km/sec, and they are excluded from Fig. 12 because they are of unreliable accuracy. The open circles show the values of the waves which have regular sinusoidal

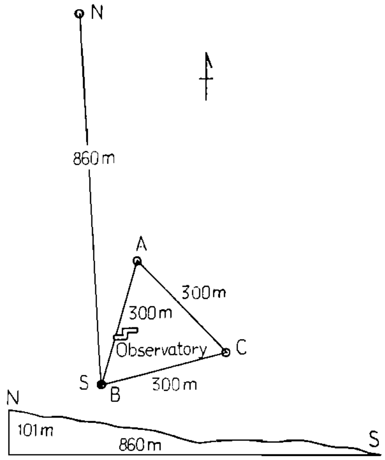

Fig. 11. Positions of observation.

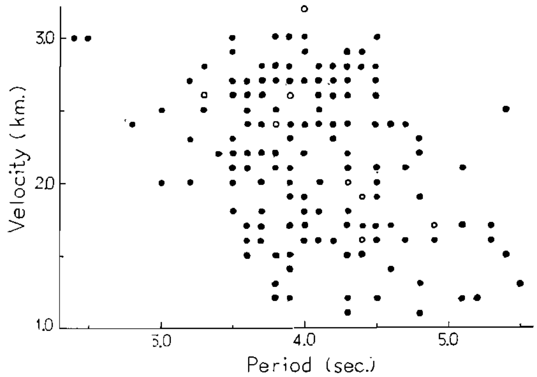

Fig. 12. Relation between velocities and periods of microseismic waves.

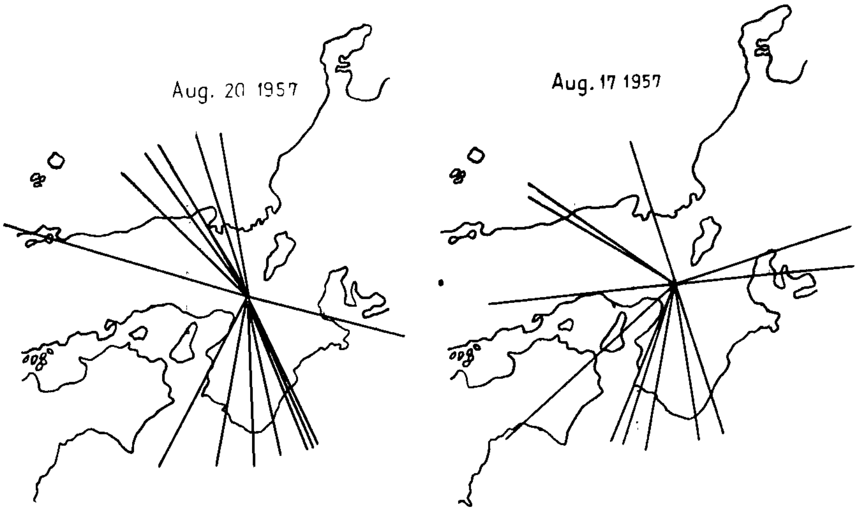

Fig. 13. Arrival directions of microseismic waves measured by tripartite method.

forms and whose periods are identical within 0.1 seonds at three points of observation. The arrival directions of individual waves are shown in Fig. 13. The directions are considerably scattered, but it may be seen that they point toward mainly the Sea of Japan and the Pacific Ocean. And we notice the tendency that the velocity increases with the decrease of the period. Ikegami and Kishinouye (1951) also indicated this tendency in their paper, but the subject does not bear further discussions because of the insufficient accuracy of the observation. As Don Leet (1949) discusses, many microseismic waves coming from various directions are superposed and the each phase of the superposed waves differs at different points of observation. Therefore it stands to reason, that the values of velocities and arrival directions of microseismic waves are scattered in wide range, if they are computed from the phases selected at will in the tripartite method. The writer can hardly avoid the conclusion from his observation that the tripartite measurement is not effective to the determination of the velocity and the arrival direction of microseismic waves.

5. Observation by vector seismographs

From the above mentioned observations it is a natural inference that the microseismic waves are generated by swells propagated from the disturbance source to the coasts near the observing station. But this inference was not drawn from the direct observation of the origin of microseisms. It seems most important to the writer that the arrival direction of microseismic waves is clearly observed, if the best results are to be obtained for the investigation of the origin of microseisms. For this purpose, the writer adopted the analysis of the orbital motions of waves. The orbital motions analyzed hitherto by many seismologists were found to be so complicated that any usefull information might not be deduced. To overcome this difficulty the writer made newly vector seismographs. The seismograms recorded at the Abuyama Seismological Observatory were also considerably complicated, but their orbital motions brought out the various significant facts. The recording system of orbital motions is shown Fig. 14.

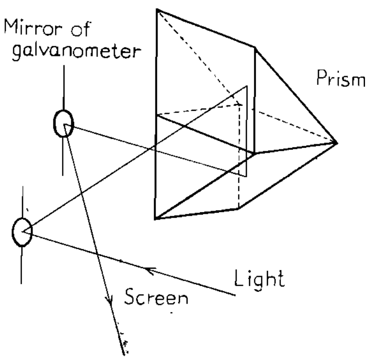

Fig. 14. Recording system of orbital motions.

The seismographs using for the routine observation during I.G.Y. period were turned to immediate account for this purpose, and hence the constants of seismographs are the same as on the occasion of the routine observation. Three orbital motions in UD-EW, UD-NS and EW-NS planes were simultaneousely recorded on the same recording paper which runs during 1 sec. and stops during about 4 sec. Examples of the seismograms are shown in Fig. 1. The single wave of the Rayleigh type is frequently observed, but the Love wave or the standing wave is scarcely present. Only a few of the later two wave types may be considered to have been accidentally produced by the superposition of waves coming from various directions. On comparing the seismograms of ordinary seismgraphs with those obtained by vector seismographs, it may be readily understood that even if the vertical amplitude is small and the horizontal amplitude is considerable or even if they are the opposite on the ordinary seismographs, it is in consequence of the superposition of waves. Accordingly the microseismic waves are regarded as the Rayleigh waves in the following discussions.

Frequency distributions of arrival directions

The longer axis of the elliptical orbits of ground particles in the horizontal plane was used for the study on the direction of approach of microseismic waves by Donn (1954), Strobach (1955) and others, but their inferences are insufficient for lack of the records in the vertical component. The writer picked out such waves that their orbits are nearly linear in the horizontal plane and elliptic in the two vertical planes for making the frequency distributions of arrival directions. The distributions were directly drawn on the charts which were divided radially into thirty-six round the Observatory. Fig. 15 shows the distribution on the occasion of the microseisms generated by the typhoon No. 6 in 1959 and the travelling path of the typhoon is shown in Fig. 16.

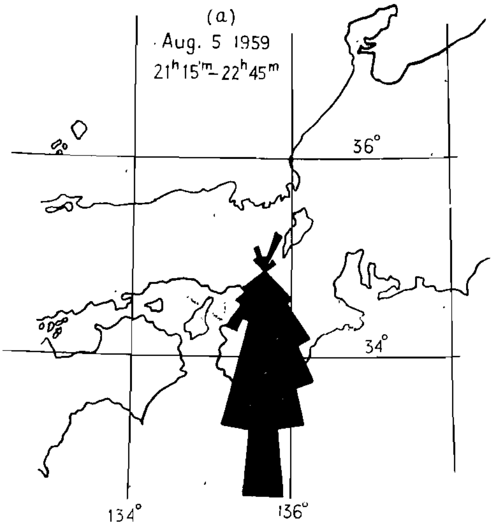

Fig. 15(a).

Fig. 15(b).

Fig. 15(c).

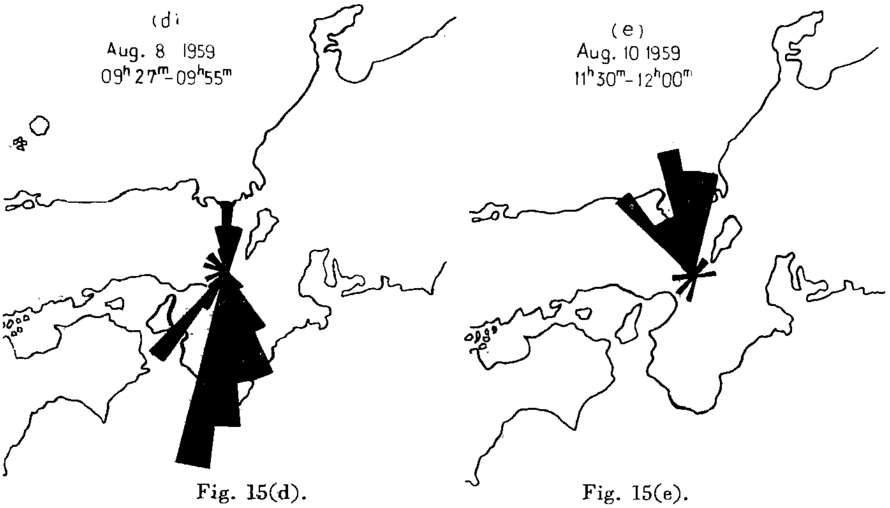

Fig. 15(d). Fig. 15(e).

Fig. 15. Frequency distributions of arrival directions of microseismic waves.

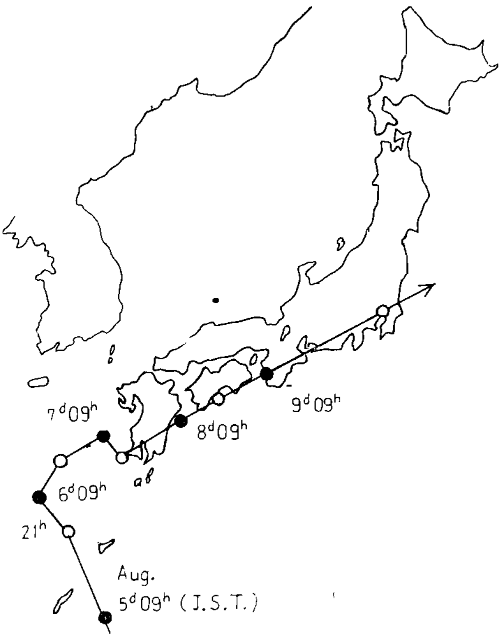

Fig. 16. Travelling path of the typhoon No. 6 in 1959.

When the center of the typhoon was passing off the south-west coast of Kyushu the microseismic waves come to the Observatory mainly from the Pacific coasts as shown in (a), (b) and (c) of Fig. 15, and their directions of propagation do not point toward the center of the typhoon. As the typhoon did not yet stir up the Sea of Japan, the waves appearing to come from the coasts of the Sea of Japan are scarcely found. When the typhoon passed through Kyushu and went on off the east coast of Kyushu, the distribution is (d) of Fig. 15. It is similar in appearance to (a), (b) and (c), and the arrival directions do not point toward the center of the typhoon. When the center of the typhoon went on into the Pacific Ocean on Aug. 10, the distribution is shown in (e) of Fig. 15. In this case the Sea of Japan was stirred up and in the southern ocean off the Kii Peninsula swells went down considerably, and hence most of the arrival directions point toward the Sea of Japan. In winter season the seasonal winds blow hardly over the Sea of Japan and the surge is raised, whereas the Pacific Ocean remains comparatively calm. Therefore the frequency distributions of the propagating direction of microseismic waves pointed mostly toward the coasts of the Sea of Japan as shown in Fig. 17. When the disturbance sources are in the Sea of Japan, the prevailing direction of propagation is somewhat westerly shifted from the due north direction having the shortest distance of the wave propagation, and the frequency distribution is roughly in inverse proportion to the distance from the Observatory to the land shelf. When the disturbance sources exist in the Pacific Ocean, the prevailing direction is southerly, in whose direction the distance of propagation is longest, and the frequency has the tendency to decrease in proportion to the distance from the Observatory to the coast. This is

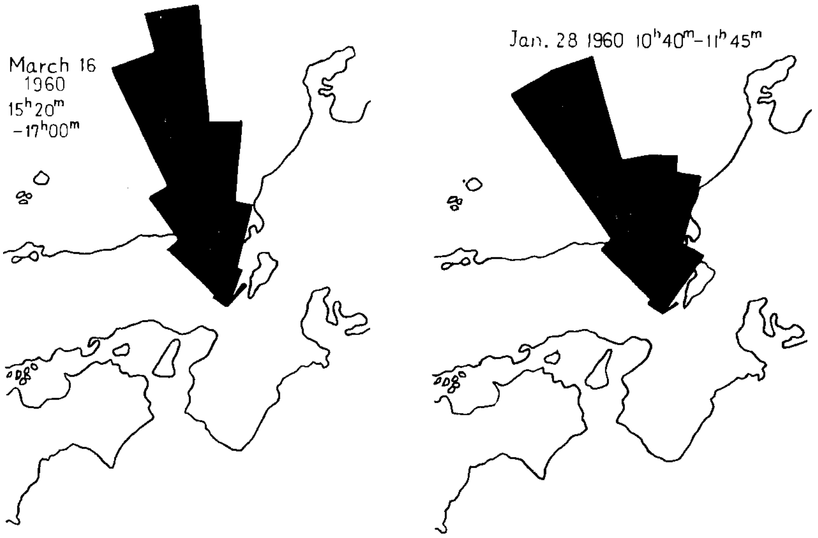

Fig. 17. Frequency distributions of arrival directions of microseismic waves.

probably due to the position of the typhoon where the typhoon does not send swells to the south-easterly coast of the Kii Peninsula. The frequency distribution is found to be rather dense in the direction of Osaka Bay. These waves coming from that direction may be not considered to be generated at Osaka Bay separated almost from the open sea. They are supposed to be the waves propagated from Tosa Bay, because their periods are similar to that of the waves coming from the other directions. In the direction of Wakayama the frequency is minimum without any exception in all distributions. This is the most interesting fact, and if we take up a pursuit of this fact, the origin of microseisms may be found soon unexpectedly. The frequency distribution shown in Fig. 18 was obtained on the waves of the typical Rayleigh form selected among the all waves observed by vector seismographs. This figure also shows that all directions point toward the coasts with two exceptions and the frequency is minimum in the direction of Wakayama district.

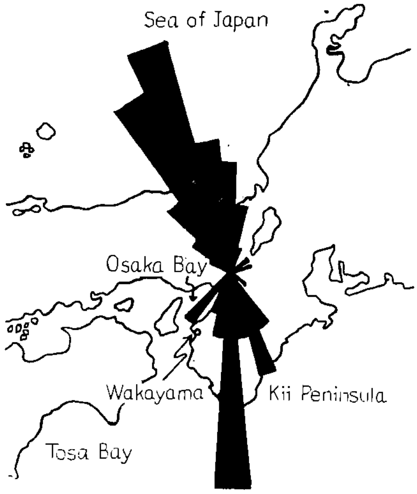

Fig. 18. Frequency distribution of arrival directions of microseismic waves having the pure Rayleigh type.

6. Progression of microseismic waves and their wave velocity

For the purpose of investigating whether the waves of the Rayleigh type selected to make the frequency distributions are progressive or not, the observation by ordinary seismographs at the two points were carried out simultaneously with the observation by vector seismographs. The positions of the two points are shown by N and S in Fig. 11, and the instruments used for this purpose are NS-component seismgraphs with the same constants as those of the vector seismographs. The arrival directions were measured on the vector seismographs and the differences

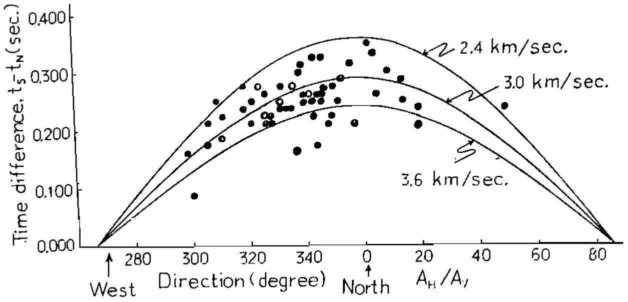

Fig. 19. Differences of the arrival times of microseismic waves at the two points of observation versus the arrival directions.

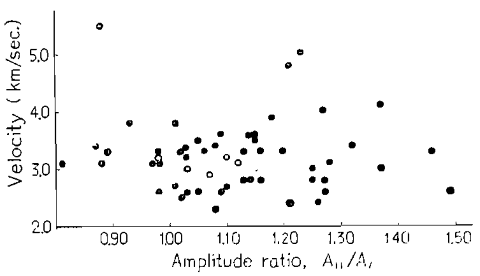

Fig. 20. Wave velocity as a function of the amplitude ratio of horizontal to vertical component.

of the arrival times of microseismic waves were read from the seismographs of the two points of observation. These relations are plotted in Fig. 19. The three sinusoidal curves in the figure show the relations between the arrival directions and the differences of arrival times at the two points computed for the waves of the velocities of 3.6 km/sec, 3.0 km/sec and 2.4 km/sec. The points are scattered. But they are on the whole distributed between the two curves showing the velocities of 2.4 km/sec and 3.6 km/sec, while the velocities observed by tripartite measurements are widely scattered. The open circles in the figure show only the waves with the orbital motions of the typical Rayleigh form. These points are plotted along the curve of 3.0 km/sec. Fig. 20 shows the wave velocity as a function of the amplitude ratio of horizontal to vertical component, which was deduced from the analysis of orbital motions. The wave velocity, especially for the waves of the typical Rayleigh form, is not scattered so much within the range of the ratio of 0.8 to 1.2. Accordingly the wave of the typical Rayleigh form may be considered to be the single wave, and there is little doubt that they progress with the velocity of about 3 km/sec.

7. Summary

1) The microseismic waves are undoubtedly of the Rayleigh type. Even though vertical ground motions are small as compared with horizontal motions, it is in consequence of superposition of waves coming from various directions.

2) Vertical ground motions are nearly equal in mean amplitude to horizontal motions. The mean amplitude in NS component is slightly larger than in EW component, because the Rayleigh waves approach from the northerly or southerly directions in which the origins of generation of microseisms exist.

3) The mean period of microseismic waves is nearly equal in each component, and it is about 4.1 sec. This period is approximately equal to half the mean period of swells in the westerly Pacific Ocean.

4) There are the predominant period of 2 sec. beside of 4 sec. in the frequency distribution of the period. The 2-second microseisms are associated with the local wind blowing at the time of the passage of cold fronts.

5) The amplitude and the period of microseismic waves depend on the scale of the disturbance source and the distance of propagation of swells from the disturbance source to the coast near the station.

6) The tripartite observation does not give the satisfactory results.

7) The wave velocity is about 3.0 km/sec.

8) The arrival directions observed by the vector seismgraphs indicate decidedly that the microseismic waves propagate from the coasts. The observation by vector seismographs is one of the most effective means to investigate the microseisms.

9) All results of the writer's investigations show that microseisms are generated by swells propagated from the disturbance source to the coasts near the observatory.

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