13. Seiches and Surface Waves in Ohunato Bay and two other Bays.

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On the occurrence of the recent tunami, the writer visited the Sanriku district to investigate the heights attained by the tunami in various parts of the coast. The results of these investigations are given on the maps at the end of this volume. We observe from these investigations that in some bays the tunami decreased in height as it proceeded from the mouth landward, while in others the distribution of the wave heights show quite the contrary; the tunami wave having increased in height with distance from the mouth.

Many theories have been advanced to elucidate this phenomenon. The first availed of was Green's theorem on long waves. Upon trying to apply this theory to the Sanriku bays, it is found that the wave height of the tunami becomes higher at the head of the bay than at its mouth for the reason that the bays of this region mostly get shallower and narrower towards the head. Consequently the theory conflicts with our observations, so far as these bays are concerned.

The second alternative theory was that a seiche of enormous amplitude might have been generated in the bays by the arrival of the tunami waves, especially when the period of free oscillation of the bays happened to coincide with the period of the tunami wave. It is obvious however that, if the variation of sea level had been due to seiches as supposed, the wave height must then be greater at the head of the bay than at its mouth, so that this result does not explain the facts of our observations.

The third explanation offered was that when the tunami wave rushes into a bay, its isochronal must gradually approach the form of isofathoms of the bay, since the propagational velocity of the tunami waves is proportional to the square root of the sea depth. The energy of the tunami wave which flowed through the mouth of the bay must then be so scattered along the periphery of the bay as to result in lower wave height at the bay head. This view however ignores the reflection of the tunami waves that would occur at the beach.. Moreover it is very doubtfull if such a complicated process will result in an area so narrow compared to the wave length.

The last explanation given for the phenomenon is that a tunami will decrease in height as it goes into a bay, owing to friction of the floor of the bay. Although it is true that damping of the wave height is markedly greater in a bay than in an open sea, yet how are we to account for the observed great decrease in wave height as the wave travelled from the mouth of the bay landward? If we assume the period of the tunami wave to be the same as the period of seiches in a bay, a reasonable assumption, then the decay constant must also be the same for both tunami as well as seiche, the latter being regarded here as the superposition of two wave trains progressing in opposite directions. If in a bay there should be considerable damping effect due to frictional resistances and other causes, a progressive wave must appear besides the stationary waves, with the result that there is no true nodal line for the seiches, which in reality, however, is seldom the case, so that we can safely take the damping coefficient of the tunami waves to be very small.

The preceding consideration is on the assumption that the period of tunami waves is long. If, however, surface waves of short period are superposed on the long swell of the tunami, damping must affect this surface wave to a considerable extent, and the tunami wave, which is now the sum of the long and short waves, must decrease in height as it approaches the bay head.

Actually the tunami must be composed of waves of various periods. When it approaches the mouth of a bay, all the various phenomena just considered must be brought about more or less, and the distribution of the wave height in the bay will depend only on which of the four effects above mentioned happen to prevail in that bay.

For the purpose of elucidating the foregoing questions, the writer studied the mode and the period of seiches in certain bays in the Sanriku district, as well as the growth and decay of the so-called doyô-nami (large sea swells that are caused by distant typhoons) after it has entered those bays. These observations were made during the summer of 1933, using six portable mareographs.

The mareograph consists essentially of two glass cylinders, *A* and *B*, Fig. 1, and a piece of thick-walled rubber tube *C*, which connects

A and *B* to form a U-tube. The glass cylinder *A*, which is 10 cm. long, has short thin tubes provided at both its ends. The upper thin tube is 2-branched, one branch leading to a long piece of thick-walled rubber tube *D*, and the other to a short rubber tube *F* and pinch-cock *G*. To adjust the height of the cylinder from its base, the cylinder itself (*A*) slides along its upright supporting post *E*. The lower thin tube is inserted in the bore of rubber tube *C*.

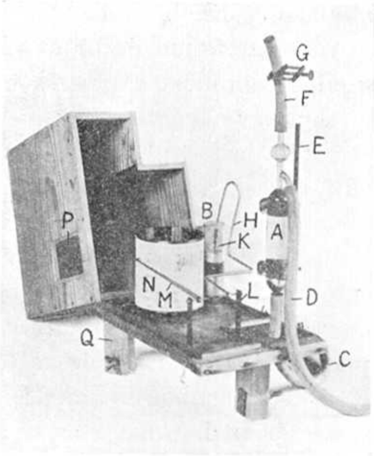

Fig. 1. The portable mareograph.

The other glass cylinder *B* is also 10 cm. long and is pinched in its lower end to fit the bore of tube *C*. The inner diameters of these two glass cylinders are exactly the same 3·0 cm.

The free end of rubber tube *D* is dropped into the sea, whose change of level is to be measured. The U-tube, consisting of *A*, *B*, and *C*, is filled with mercury to the middle of cylinders *A* and *B*. The upper half *A* and the rubber tube *D* is filled with sea water, either by suction or by pumping out the air at the upper end of tube *F*.

On the surface of the mercury in cylinder *B* is a float, a hollow glass bulb (*K*), 2 cm. in diameter, which is attached to a bent aluminium wire *H*. The glass bulb *K* and the bent aluminium wire moves on axle *L*. On this axle is also attached a lever *M* with a pen at its end, the pen pressing lightly on the record paper that is wound on a Richard clock *N*.

The distances of both the pen and the float from the axle are the same, both being 15 cm., so that the actual rise and fall of the mercury surface in cylinder *B* is recorded.

The whole is mounted on a wooden base (18 cm. × 27 cm.) The lid *P*, which is hinged to one side of the base, covers the important parts of the assembly. A glass window, which is provided on the front side of lid *P*, enables a view of the pen in motion.

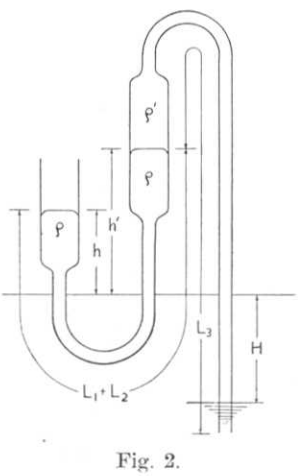

Fig. 2.

The base has three legs, *Q*'s, to which additional legs, if needed, may be attached by thumb-screw joints.

Now referring to Fig. 2, we have for the equation of motion of the liquids contained in the mareograph

$$\{\rho(L_1+L_2)+\rho' L_3\}\frac{d^2h}{dt^2}+(c_0+c_1L_3)\frac{dh}{dt}=\{\rho(h'-h)-\rho'(H+h')\}g,$$

where ρ and ρ' are the densities of mercury and sea water respectively, and c_0 is the damping coefficient due to the parts L_1+L_2, and where $H=H_0-R\cos\omega t$.

Putting

$$\frac{c_0+c_1L_3}{\rho(L_1+L_2)+\rho' L_3}=2\lambda,\qquad \frac{(2\rho-\rho')g}{\rho(L_1+L_2)+\rho' L_3}=n^2,\qquad h+h'=K,$$

$$\frac{-\rho' H_0+(\rho-\rho')K}{\rho(L_1+L_2)+\rho' L_3}g=A,\qquad \frac{\rho' Rg}{\rho(L_1+L_2)+\rho' L_3}=B,$$

we have for equation of motion

$$\frac{d^2h}{dt^2}+2\lambda\frac{dh}{dt}+n^2h=A+B\cos\omega t.$$

The solution of the above equation is then

$$h=\frac{A}{n^2}+\frac{B}{n^2}\phi\cos(\omega t-\delta)+\text{terms of free oscillation},$$

in which

$$\phi=\frac{1}{\sqrt{\left(1-\frac{\omega^2}{n^2}\right)^2+4\frac{\omega^2}{n^2}\frac{\lambda^2}{n^2}}}.$$

The mareograph, as constructed in this way, has a magnification coefficient $\frac{\rho'}{(2\rho-\rho')}=1/26{\cdot}2$ for the semi-diurnal and other tidal oscillations in which ω is very small. Moreover the mareograph is damped almost to the critical point. If however the instrument is installed where the sea is rough, it records every rise and fall of the sea surface due to the surface waves, thus frequently masking slow changes of sea level such as we wish to record. In such cases there is also the contingency that the ink in the recording pen of the instrument will be exhausted prematurely.

To avoid these objections the rubber tube D (Fig. 1) is narrowed by a pinch-cock and the mareograph is damped sufficiently to suppress the traces of the disturbing waves. In these cases of excessive damping, the terms of the free oscillation of the above expression becomes approximately

$$Pe^{-\frac{n^2}{2\lambda}t}.$$

If in this case the sea level, which is here assumed to be very calm, is suddenly lowered by unity, or the instrument is raised by unity, the instrument records a decrement curve. If we denote by T the time spent by the instrument in recording half of the final variation $1/26{\cdot}2$, we have

$$\frac{1}{2}=e^{-\frac{n^2}{2\lambda}T}, \qquad 4\frac{\omega^2}{n^2}\frac{\lambda^2}{n^2}=\frac{\omega^2T^2}{0{\cdot}480},$$

and

$$\phi=\frac{1}{\sqrt{\left(1-\frac{\omega^2}{n^2}\right)^2+\frac{\omega^2T^2}{0{\cdot}480}}}.$$

The value of the reducing factor ϕ as the function of ω and T is given in Fig. 3. We can obtain therefore the height of sea waves even with these excessive dampings, provided we know the value of T and the period of the surface wave under consideration.

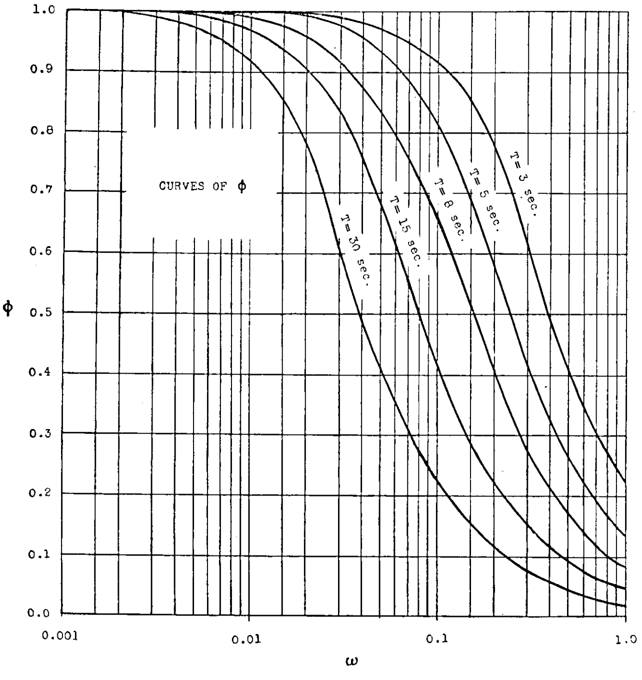

Fig. 3.

Whenever a mareograph was installed on a wild sea coast the value of T was measured by inserting the free end of the rubber tube D in

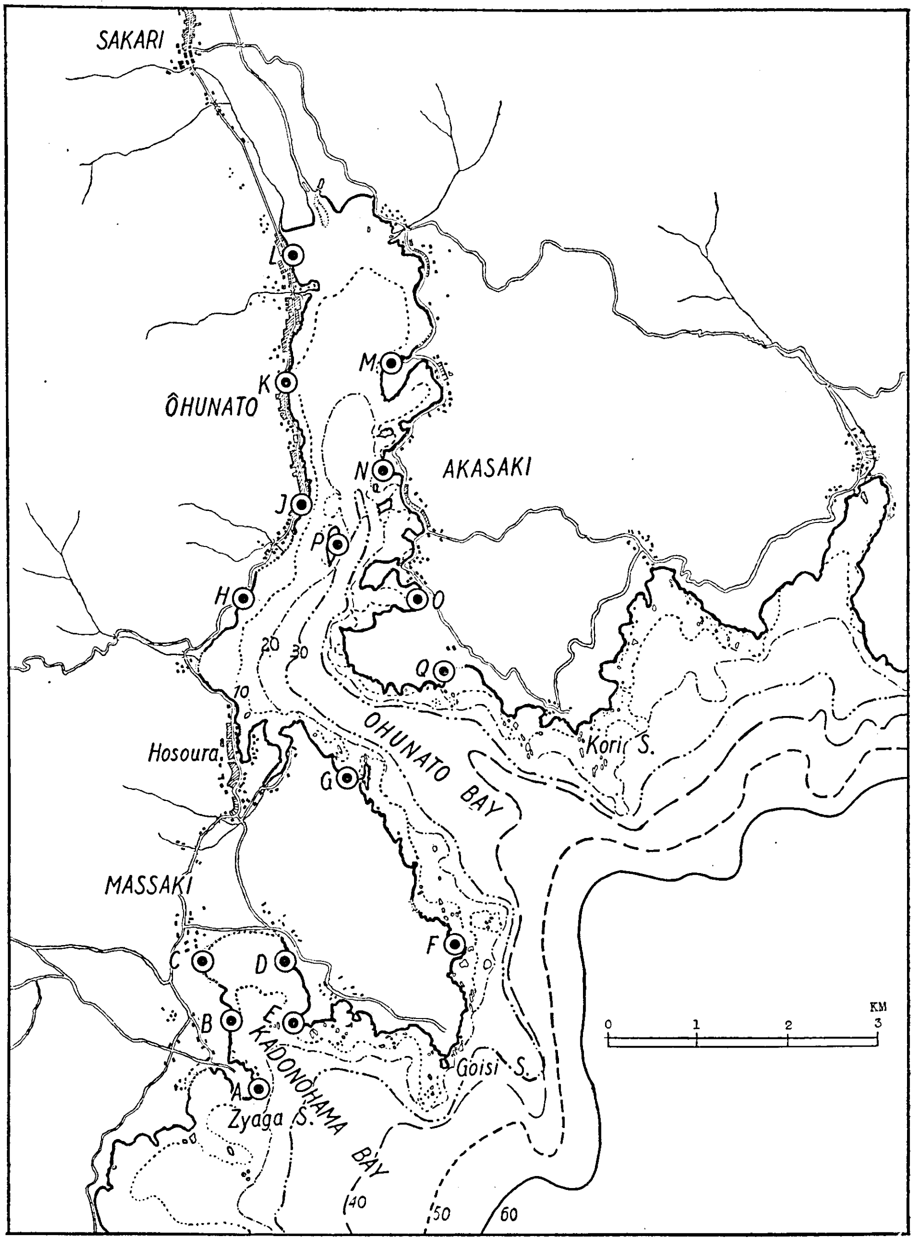
SAKARI
L
K
ÔHUNATO
M
N
AKASAKI
J
P
H
O
Q
20
30
10
Hosoura
OHUNATO BAY
Kori S.
G
MASSAKI
F
C
D
B
E
KADONOHAMA BAY
Goisi S.
A
Zyaga S.
40
50
60
KM
0
1
2
3

Fig. 4.

a bottle of sea water and raising it 1 meter, while the mean period of the surface waves was measured with a stop-watch.

We selected the bays of Ohunato, Ryôri, and Kadonohama for our observations. These bays are typical of the three shapes, the long and narrow, the triangular, and the rectangular.

The observations lasted during the period from Aug. 8 to Aug. 22, 1933, a period chosen because of the typhoons that often pass over the adjacent seas of Japan and cause those huge swells already mentioned. In these cases seiches are also excited, frequently to large amplitudes, these bays. Unfortunately, however, no typhoon appeared in the neighbourhood of Japan during the period of our observation, so that our observations were not so comprehensive as we had wished them to be.

In Fig. 4 and Fig. 5 are given the forms and the depths of these three bays, as well as the positions of our observing stations, the last shown by double rings lettered *A*, *B*, *C*, etc. The first simultaneous observation was made at stations *A*, *B*, *C*, *D*, and *E* on the shore of Kadonohama bay. The second simultaneous observation was made at stations *F*, *G*, *H*, *J*, *K*, *L*, all of which lie on the western shore of Ohunato bay, while the third was made at *L*, *M*, *N*, *O*, *P*, *Q*, which lie along the eastern shore of the same bay. The fourth and the final simultaneous observationl was made at *R*, *S*, *T*, situated along the southern shore of Ryôri bay.

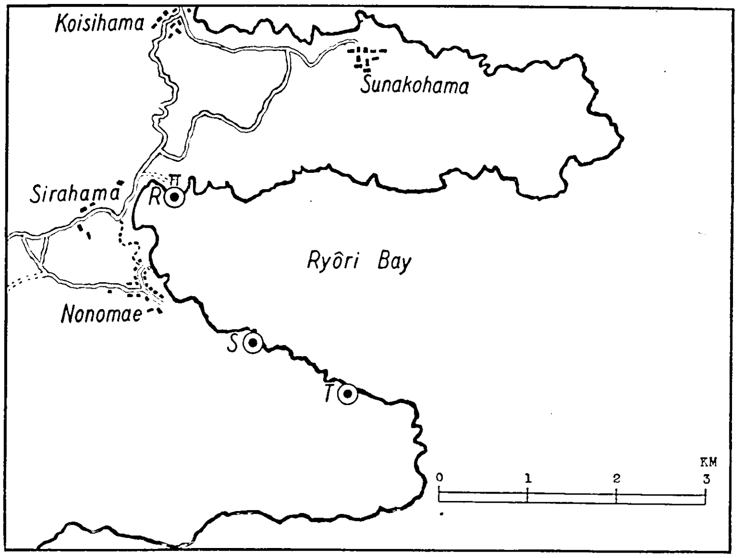

Fig. 5.

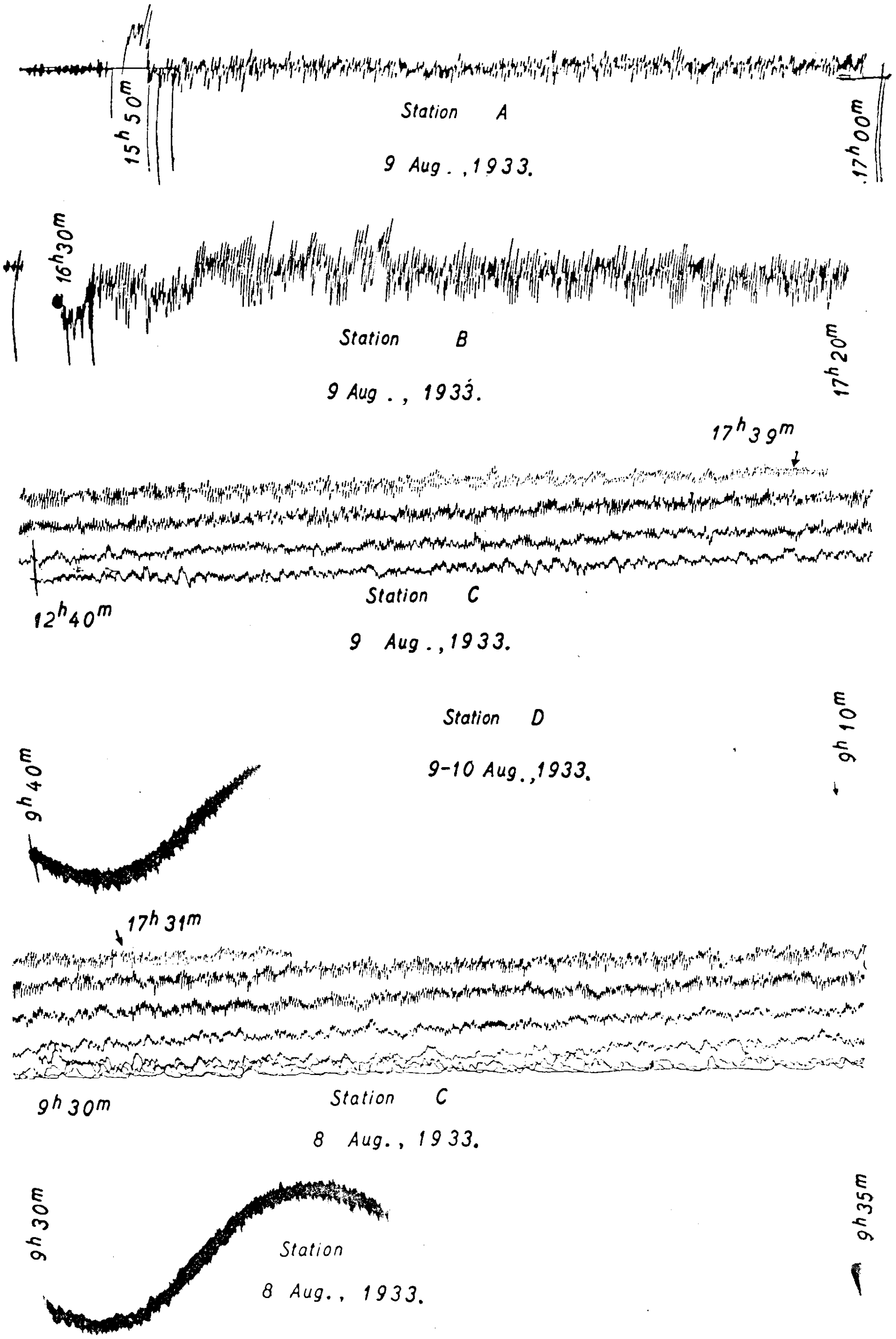
15h 50m
Station A
9 Aug., 1933.
17h 00m
16h 30m
Station B
9 Aug., 1933.
17h 20m
17h 39m
Station C
9 Aug., 1933.
12h 40m
Station D
9-10 Aug., 1933.
9h 40m
9h 10m
17h 31m
9h 30m
Station C
8 Aug., 1933.
9h 30m
Station
8 Aug., 1933.
9h 35m

Fig. 6.

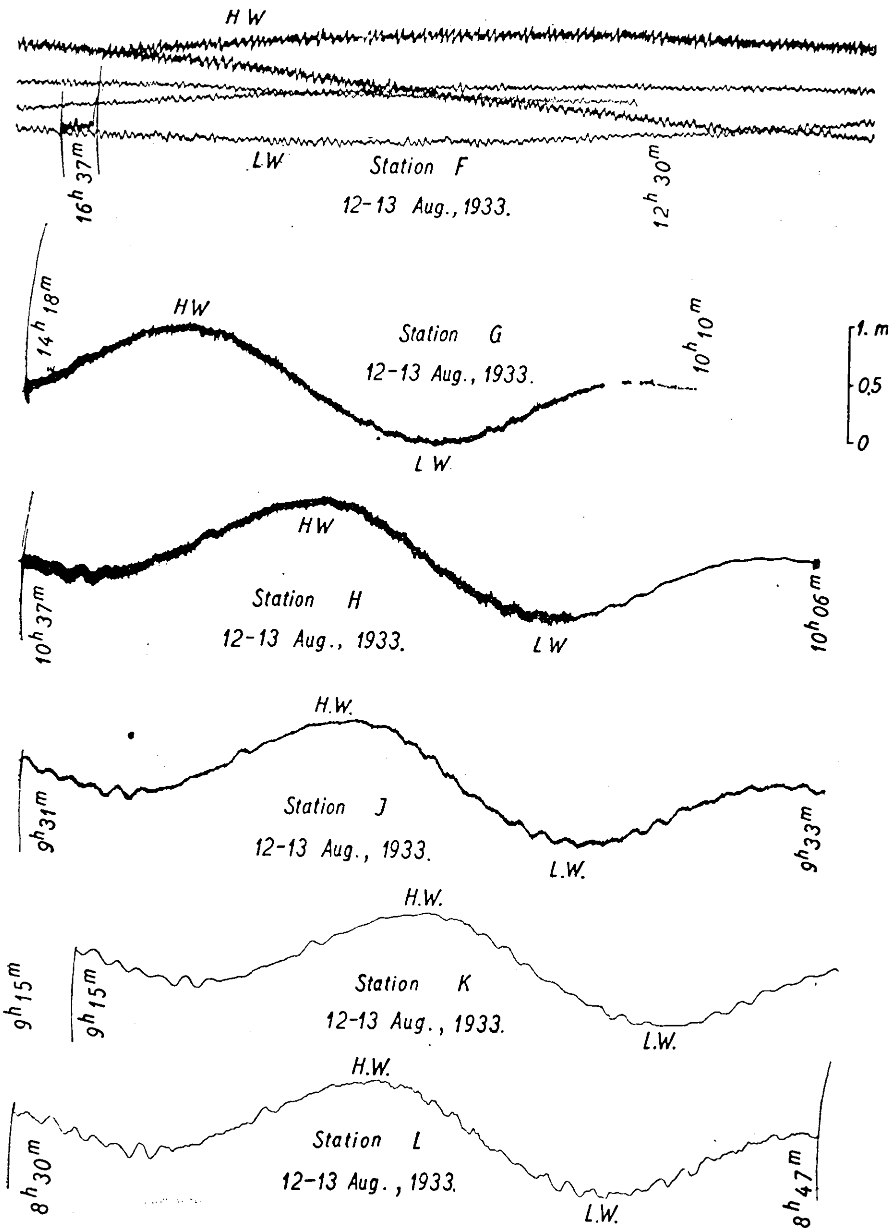
H W
L W
Station F
12-13 Aug., 1933.
16h 37m
12h 30m
14h 18m
HW
Station G
12-13 Aug., 1933.
10h 10m
L W
1. m
0.5
0
HW
Station H
12-13 Aug., 1933.
10h 37m
L W
10h 06m
H.W.
Station J
12-13 Aug., 1933.
9h 31m
L.W.
9h 33m
H.W.
9h 15m
9h 15m
Station K
12-13 Aug., 1933.
L.W.
H.W.
Station L
12-13 Aug., 1933.
8h 30m
L.W.
8h 47m

Fig. 7.

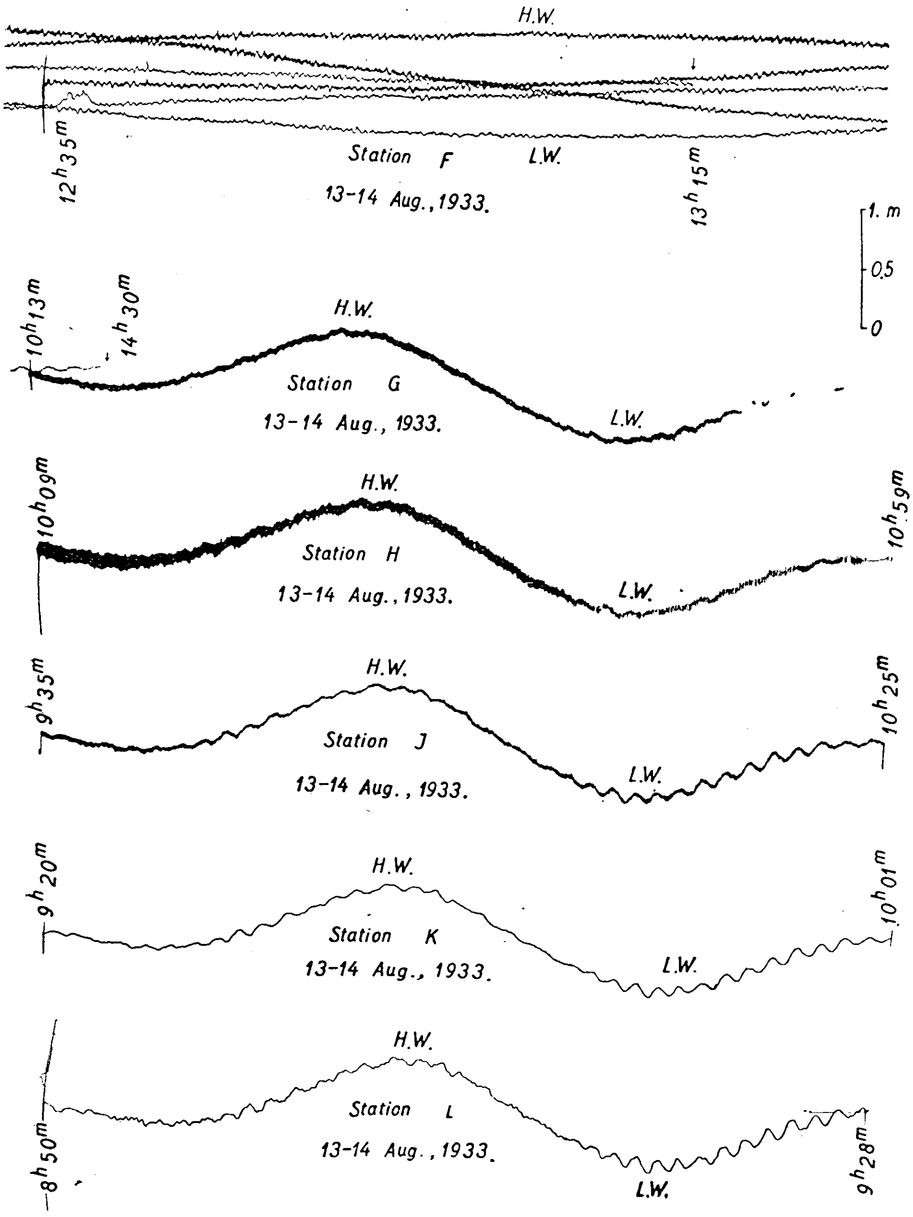
H.W.
12h35m
Station F
L.W.
13-14 Aug., 1933.
13h15m
1. m
0.5
0
10h13m
14h30m
H.W.
Station G
13-14 Aug., 1933.
L.W.
10h09m
H.W.
Station H
13-14 Aug., 1933.
L.W.
10h59m
9h35m
H.W.
Station J
13-14 Aug., 1933.
L.W.
10h25m
9h20m
H.W.
Station K
13-14 Aug., 1933.
L.W.
10h01m
H.W.
Station L
13-14 Aug., 1933.
8h50m
L.W.
9h28m

Fig. 8.

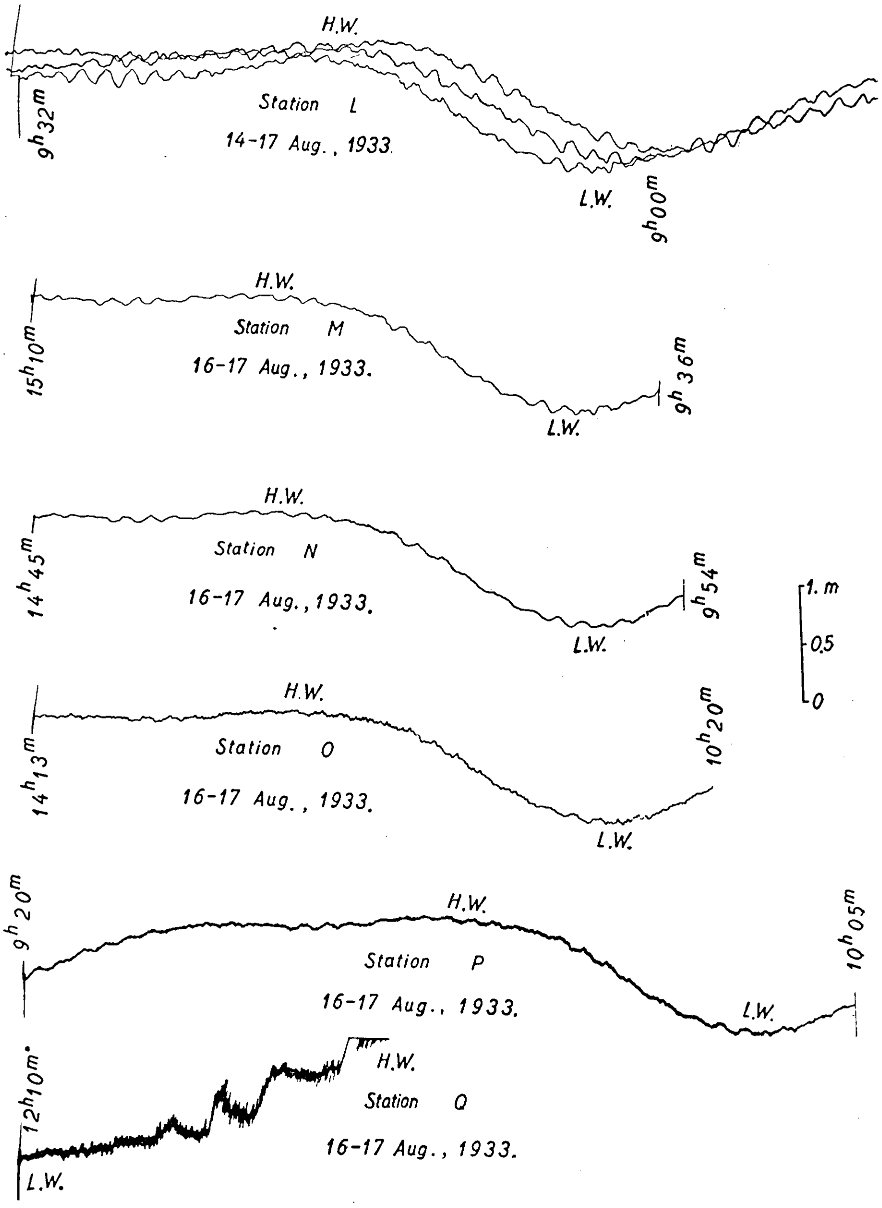
H.W.
Station L
14-17 Aug., 1933.
9h32m
L.W.
9h00m
H.W.
Station M
16-17 Aug., 1933.
15h10m
9h36m
L.W.
H.W.
Station N
16-17 Aug., 1933.
14h45m
9h54m
L.W.
1. m
0.5
0
H.W.
Station O
16-17 Aug., 1933.
14h13m
10h20m
L.W.
9h20m
H.W.
Station P
16-17 Aug., 1933.
10h05m
L.W.
12h10m
H.W.
Station Q
16-17 Aug., 1933.
L.W.

Fig. 9.

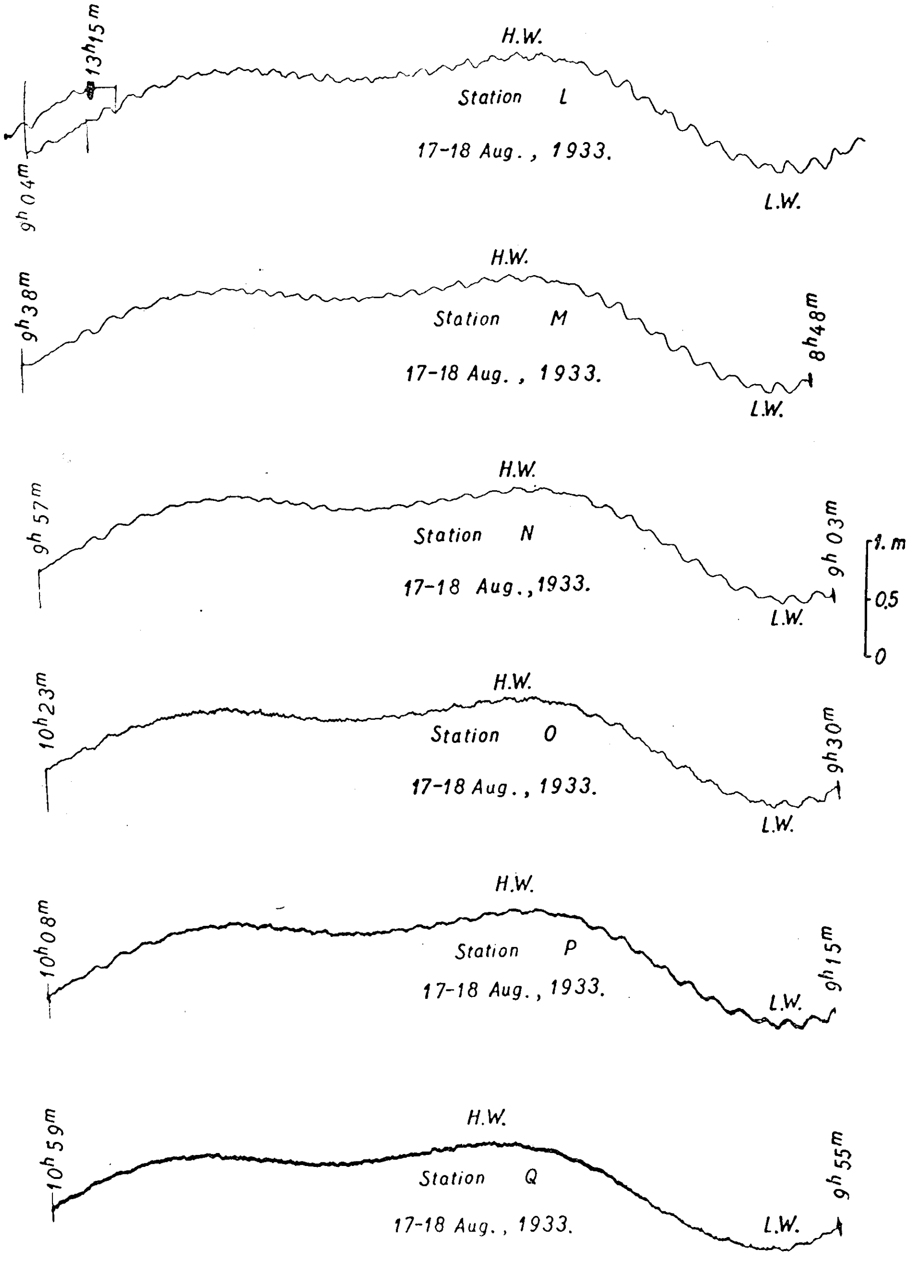
13^h15^m
H.W.
Station L
17-18 Aug., 1933.
9^h04^m
L.W.
H.W.
9^h38^m
Station M
17-18 Aug., 1933.
8^h48^m
L.W.
H.W.
9^h57^m
Station N
17-18 Aug., 1933.
9^h03^m
L.W.
1. m
0.5
0
H.W.
10^h23^m
Station O
17-18 Aug., 1933.
9^h30^m
L.W.
H.W.
10^h08^m
Station P
17-18 Aug., 1933.
9^h15^m
L.W.
H.W.
10^h59^m
Station Q
17-18 Aug., 1933.
9^h55^m
L.W.

Fig. 10.

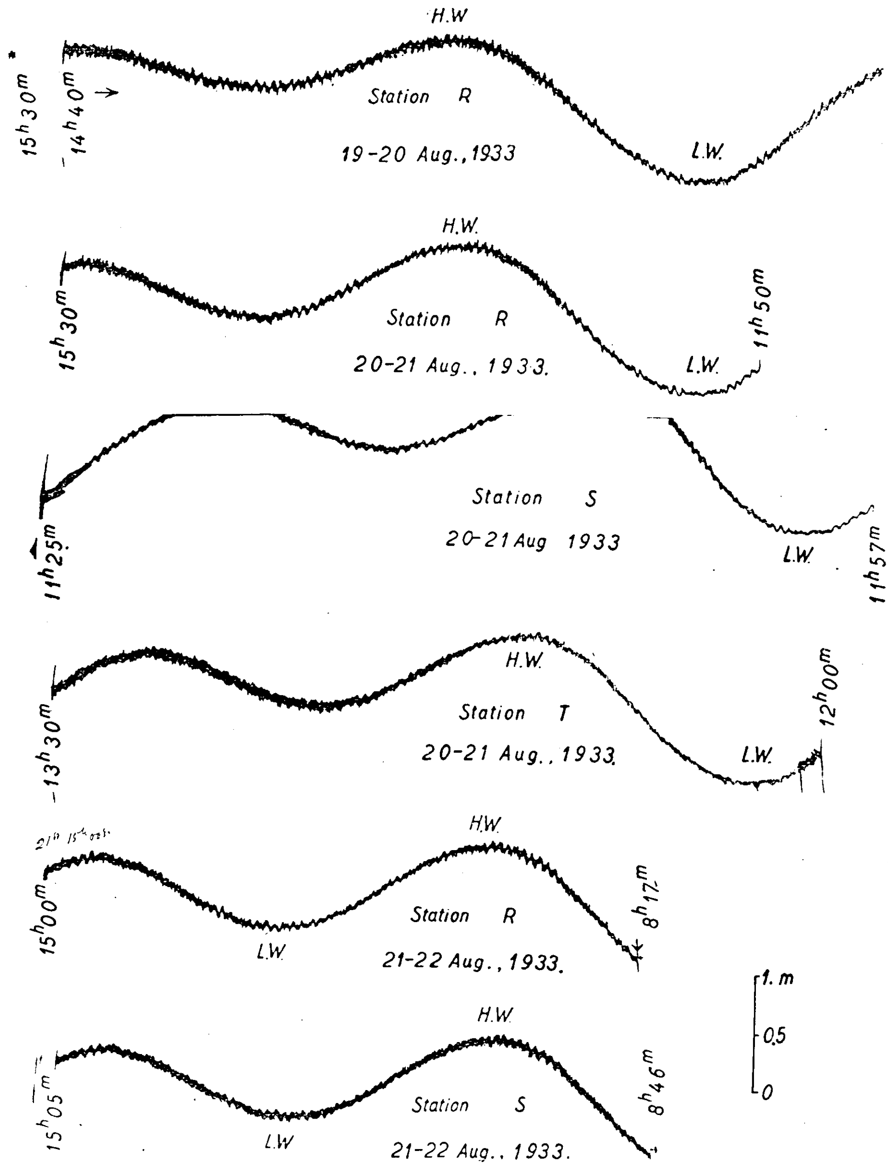
H.W
15h 30m
14h 40m
Station R
19-20 Aug., 1933
L.W.
H.W.
15h 30m
Station R
20-21 Aug., 1933.
L.W.
11h 50m
11h 25m
Station S
20-21 Aug 1933
L.W.
11h 57m
H.W.
13h 30m
Station T
20-21 Aug., 1933.
L.W.
12h 00m
H.W.
15h 00m
L.W.
Station R
21-22 Aug., 1933.
8h 17m
1. m
0.5
0
H.W.
15h 05m
L.W.
Station S
21-22 Aug., 1933.
8h 46m

Fig. 11.

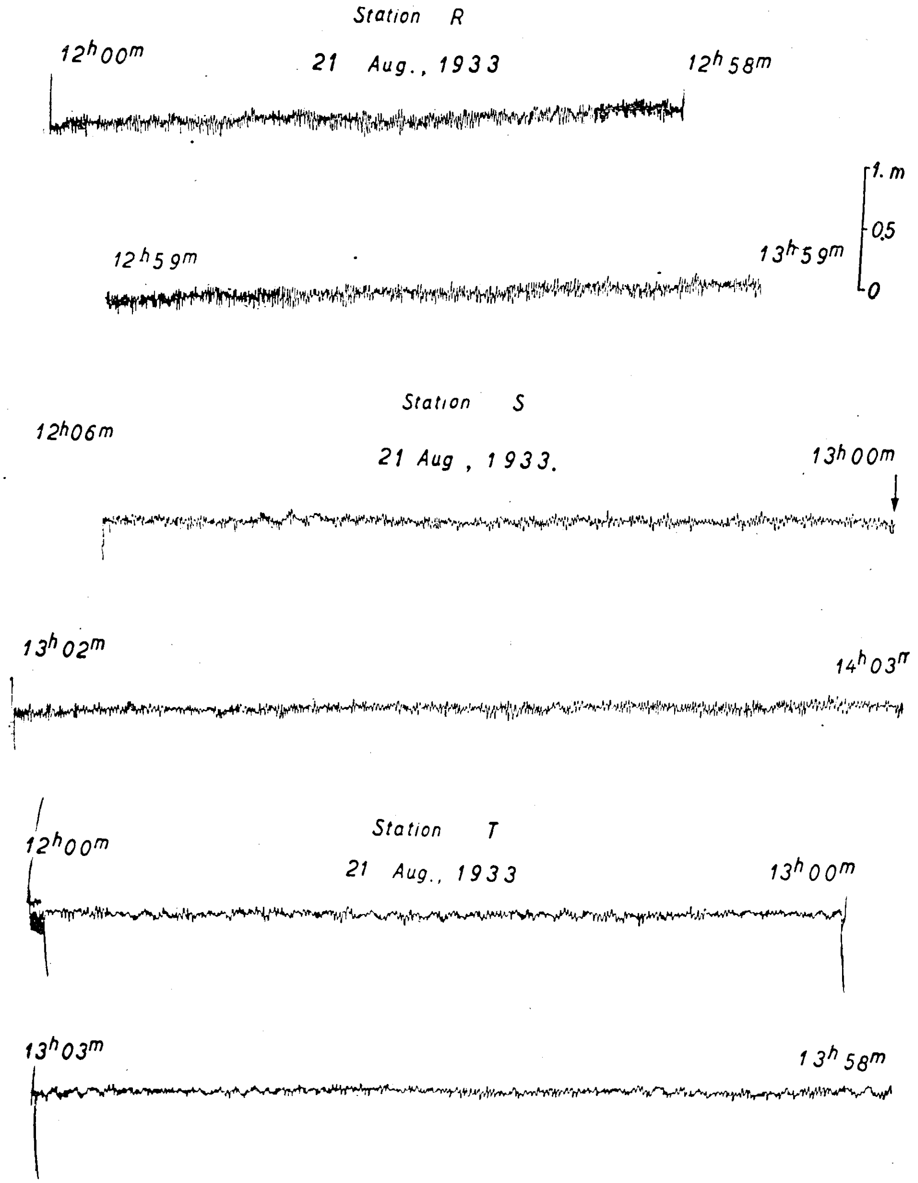
Station R
12h00m
21 Aug., 1933
12h58m
1. m
0.5
0
12h59m
13h59m
Station S
12h06m
21 Aug, 1933.
13h00m
13h02m
14h03m
Station T
12h00m
21 Aug., 1933
13h00m
13h03m
13h58m

Fig. 12.

The shores of Kadonohama and Ryôri bays mostly consist of almost vertical cliffs, in many places inaccessible, except for the innermost parts of the bays where there are narrow sand beaches. In these circumstances, the number of stations that could be utilized for a simultaneous observation was restricted.

The results of the observations are given in Figs. 6–12, which are photographic reproductions of the observational records obtained. Particulars of all the observing station are given in the following Table.

Table I.

Station	Place	Period of Observation	Half-time (T)	Speed of Recording Drum
A	Zyaga Saki, Kadonohama	Aug. 9-10	9 sec.	One rev. per 1 hour; 1 day
B	—	Do.	5	1 hour; 1 day
C	Baisin, Kadonohama	Aug. 8-10	5	1 hour; 1 day
D	Nakai, Kadonohama	Do.	6	1 day
E	Tatega Saki, Kadonohama	Aug. 9-10	11	1 day
F	Kaisima, Ohunato	Aug. 12-15	12	4 hours
G	Nagaiso, Ohunato	Do.	14	1 day
H	Marumori, Ohunato	Do.	7	1 day
J	Simohunato, Ohunato	Do.	4	1 day
K	Nagaisawa, Ohunato	Do.	—	1 day
L	Kakenosita, Ohunato	Aug. 11-18	—	1 day
M	Bentenzima, Ohunato	Aug. 16-18	—	1 day
N	Kuinazima, Ohunato	Do.	—	1 day
O	Takonoura, Ohunato	Do.	—	1 day
P	Sangozima, Ohunato	Do.	3	1 day
Q	Senmaru, Ohunato	Do.	11, 20	1 day
R	Sirahama, Ryôri	Aug. 20-22	21	1 hour; 1 day
S	Yokonuma, Ryôri	Aug. 20-21	18	1 hour; 1 day
T	Myôzin, Ryôri	Do.	19	1 hour; 1 day

Ohunato Bay. We will first describe the results obtained from observations made at Ohunato bay. As may be seen in Fig. 4, Ohunato bay is roughly 9 km. long and 1·3 km. wide, the mean depth being 23 m. The medial line of the bay changes its direction by about 90° half way from the mouth to the head. The shores along the northern half of the bay are mostly of gentle slope, and densely inhabited, while the shore along the southern half of the bay consists mostly of cliffs.

As will be seen in Figs. 6-12, seiches are clearly observed in this bay, though, owing to decrease in their amplitudes, they are liable to be masked by surface waves at points near the mouth.

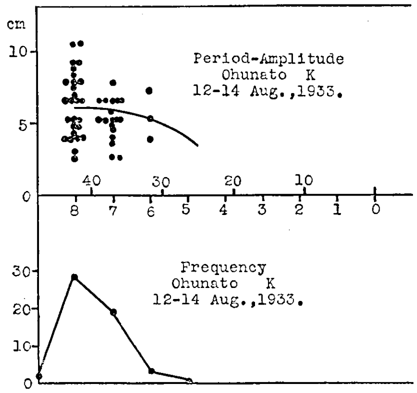

Fig. 13.

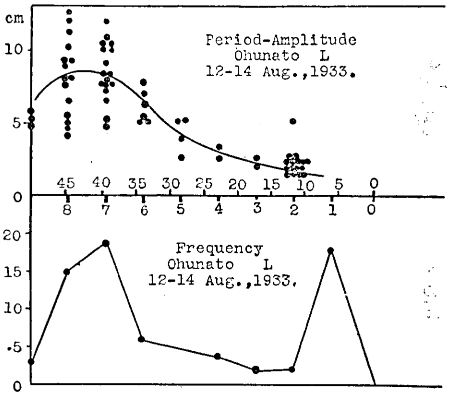

Fig. 14.

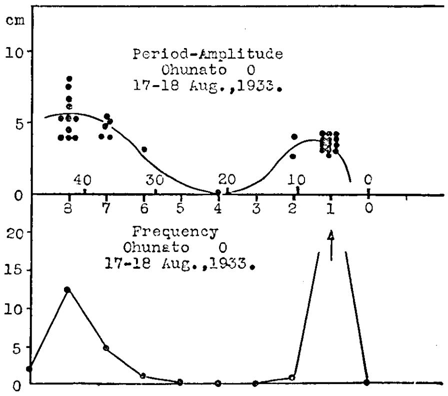

Fig. 15.

In Figs. 13-15, which are amplitude-period diagrams and frequency diagrams plotted on the basis of Figs. 6-12, we can see that there are two seiches of different periods in the bay. In one of them the period varies widely, the average however being 40 min., while the amplitudes vary with the period. The other has a period of 8 min.[1] Taking the amplitude (that at the head of the bay being taken as unity and with due consideration of their phases) of these seiches as ordinate and the distance from the head of the bay along the medial line as the abcissa, we get Fig. 6c. According to this diagram, the seiche with a period of 40 min. is the fundamental oscillation of the bay, while that with a period of 8 min. is the fifth harmonic. The movement of the nodal line due to the horn-shaped mouth of the bay is probably what causes the period of the fundamental oscillation to vary.

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[1] These periods of seiches are in fair agreement with those reported by K. Honda and others in the *Pub. Earthq. Inv. Comm.*, 26 (1908).

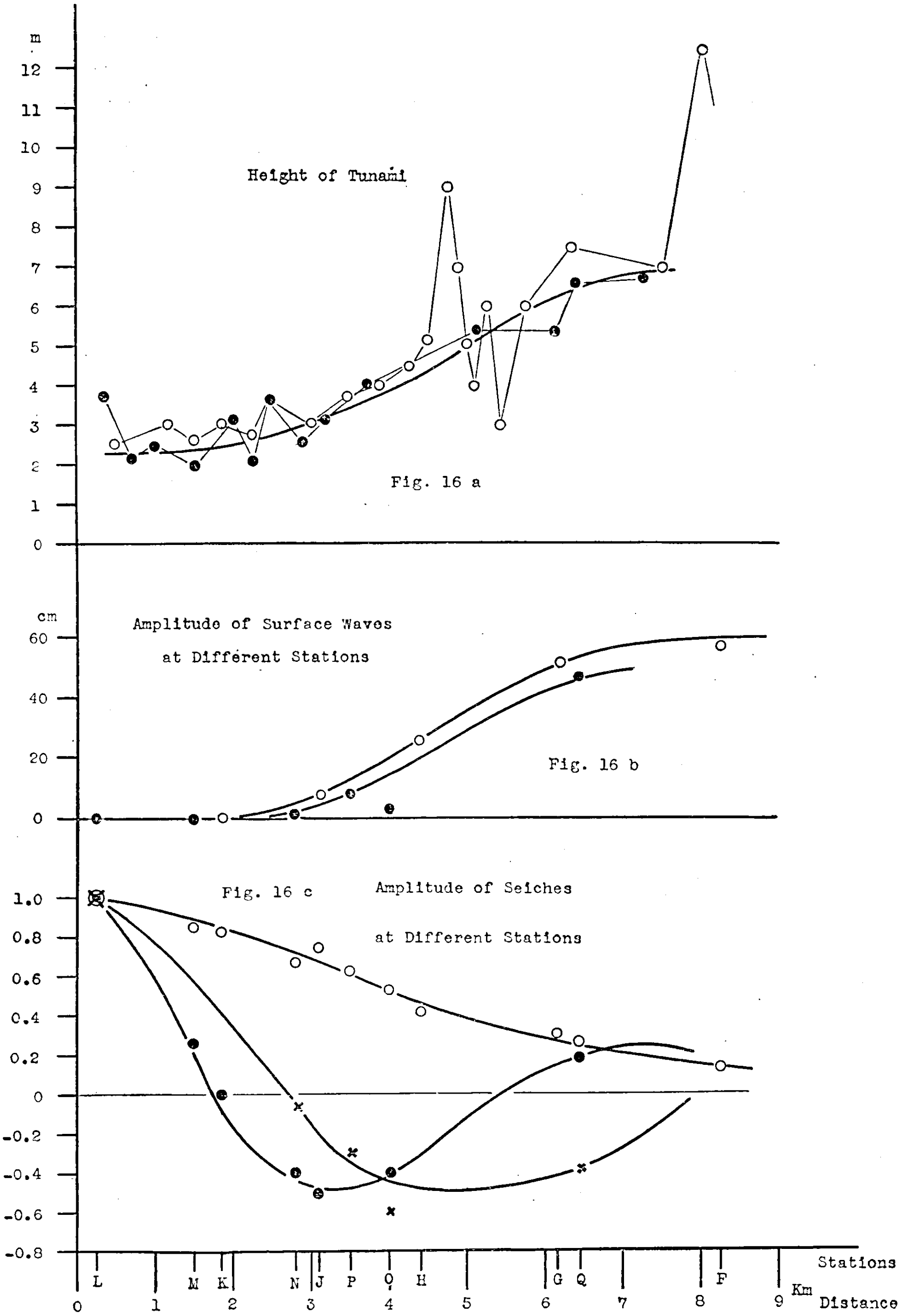
m
12
11
10
9
8
7
6
5
4
3
2
1
0
Height of Tunami
Fig. 16 a
cm
60
40
20
0
Amplitude of Surface Waves at Different Stations
Fig. 16 b
1.0
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
Fig. 16 c
Amplitude of Seiches at Different Stations
L
M
K
N
J
P
O
H
G
Q
F
Stations
0
1
2
3
4
5
6
7
8
9
Km
Distance

Fig. 16.

The third harmonic of the oscillation of the bay seldom seems to occur. It was observed only once during the period of our observations. This is probably due to the large resistance to this mode of oscillation caused by the shallow and narrow sea near the nodal line (between stations M and N) of the oscillation.

The heights of the surface wave observed at different stations are plotted in Fig. 16b. These heights were calculated from the breadth of the curves shown in Figs. 6–12 and the half-time of the marcographs, using the formula for ϕ already given. The period of the surface waves as actually measured at each station ranged between 8 sec. and 10 sec.

Referring to the same figure, we see that the surface wave does not decrease in height until the bay bends its direction NE-ward, when the height begins to decrease rapidly and almost disappears at station M.

This decrease is probably due to the fact that in the southern half of the bay the increase of wave height owing to narrowing of the bay cancels the decrease due to the friction, while in the other half of the bay which is comparatively narrow and shallow, the friction is very great.

We shall plot in Fig. 16a the heights of tunami as observed at a number of points on the shore of Ohunato bay. These heights were investigated by G. Nishimura, T. Takayama, and the writer. In the Figure, the black circles represent heights observed at the eastern shore of the bay, while the plain circles are those observed at the western shore. The heights of tunami, as seen in the figure, clearly decreases with distance from the mouth of the bay to its head.

Now the gradual rise of sea level when the tunami arrives is everywhere the same, provided the period of the tunami greatly exceeds the period of the bay, whereas a decrease in the period of the tunami always causes the sea level to be higher at the bay head than at the mouth. The height of the tunami as observed at Ohunato bay cannot therefore be explained merely by gradual elevation of sea level.

The heights of the tunami as measured by G. Nishimura and others are heights of traces of the inundation left on the walls of houses, on cliffs, etc. It does not always mean that the general sea level gradually rose to that height by the arrival of the tunami. Since there are generally waves on any sea surface, there is no reason to believe that these surface waves did not exist in the case of this tunami. On the contrary, we must think rather that the tunami is accompanied by large surface waves.

Now in regard to the matter of the wave heights of tunami, let us assume that the height of the tunami (about 2 m.) observed at the innermost part of the bay is due solely to the gradual elevation of sea level. There are two reasons for making this assumption: firstly, the sea is always very calm in this part of the bay, and secondly, it has been reported by an eyewitness that the tunami was neither a bank of water nor a rolling wave, but a gradual increase of sea water.

Then the observed height of the tunami, subtracted by 2 m., may be regarded as the approximate height of the tunami due to the waves of short period. In support of this consideration we find that the manner in which this part of the tunami decreases in height is quite similar to that in which the surface waves decrease in height as revealed by the present mareographic observations. The slopes of the two curves given respectively in Fig. 16a and in Fig. 16b are expressible by the same function $Ae^{-0.6x}$, x being the distance in km.

The heights of tunamis that we have measured are then the sum of the height of the surface waves and the height to which the general sea level had risen, whence it follows that not only the general rise of the sealevel, but the extent to which the surface waves rise is also of fundamental importance.

Kadonohama Bay. We could not make a comprehensive observation of this bay owing to conditions being unfavourable for the installation of our mareographs. As may be seen in Figs. 6–12, the seiches do not show distinctly in this bay, though some oscillations are traceable. One of their periods range from 3·6 min. –4·9 min., while that of the other two were 12 min. and 17 min. respectively. The first two of these oscillations probably belong to the seiches of Kadonohama bay proper, while the last one belongs to a seiche of the bay of which the Kadonohama bay is a branch.

The height of the surface waves was greatest in the middle of the bay, though the differences were not marked.

As we have no detailed data in regard to the height of the tunami on the shore of this bay, we cannot compare it with the results obtained by the present mareograph observation.

Ryôri Bay. As the northern shore of this bay was almost inaccessible owing to the cliffs there, stations were put up at the bay head and on the south shore. Results of the observation are given in Figs. 6–12. Seiches are not conspicuous in this bay, though the periods were found to be 18 min., 12 min., and 2 min. Owing to the triangular shape of this bay, the period of the seiches seems to be irregular.

The height of the surface waves was greater at the head of the bay than at the mouth, as may be noticed from the records of simultaneous observations given in Figs. 5-12.

The height of the tunami was enormous at the bay head, amounting to 23 m. above mean sea level, while it was only a few meters at the mouth. This must partly be due to the fact that the height of the surface waves increases with distance from the mouth landwards, and partly to the effect as expected from Green's theorem.

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13. 大船渡灣及び其他の灣に於ける靜振と海波（概要）

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津浪が灣内に進入した場合に，津浪の高さは或灣に於ては灣口に於て低く灣奥に於て高いのに反し他の灣では灣口に於て高く灣奥に於て低いといふ事實がある．

此の事實に對する說明を得る一助として，著者は大船渡灣，綾里灣及び門ノ濱灣の3灣に於て靜振及海波の觀測を爲した．此等の灣は夫々其の形が細長いもの，三角形なるもの，及び矩形なるものゝ代表として撰んだのである．觀測は主として6臺の携持用檢潮儀を用ひた同時觀測である．

携持用檢潮儀は第1圖に示してある様なものであつて，此によつて潮汐，靜振及海波を同時に記錄する事が出來る．

觀測の結果は第5圖乃至第12圖に示してある．觀測の結果に依れば，大船渡灣の靜振の周期は40分及び8分であり，綾里灣の靜振の周期は18分，12分及び2分，門の濱灣のは4分，12分及17分であつた．

尙海波の高さが灣奥に行くに從つて減少又は增大する模様を調べて，此れを我々が調査した津浪の高さの灣内に於ける分布と比較して見ると，第16圖 *a* 及 *b* に示した如く兩者は全然同じ變化の有様である事が判るのである．

從つて我々が調査して來た津浪の高さなるものは長周期の波による海面の緩昇の外に，普通の海波と同程度に短周期の波の高さを含むで居り，且其れが重要なる部分を占めてゐる事が結論されるのである．