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STUDIES ON TSUNAMI ON THE PACIFIC COASTS OF NORTHERN HONSHÛ (I. THE MODEL EXPERIMENT OF TSUNAMI IN SHIZUKAWA HARBOUR

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§ 1. Introduction.

The Pacific coasts of Northern Honshû are known from historical times as region most frequently attacked by destructive seismic sea waves or Tsunamis. Even in recent years this district was violently damaged in 1896, 1933, etc. Although not a few papers on Tsunami in this district were published since the end of the preceding century, many problems on Tsunami were remained unsolved. As every time after destructive Tsunamis equipments for prevention from damage and harbour constructions were made in various places in this district,it is necessary to study the effects of constructions upon sea waves which invade in the bay.

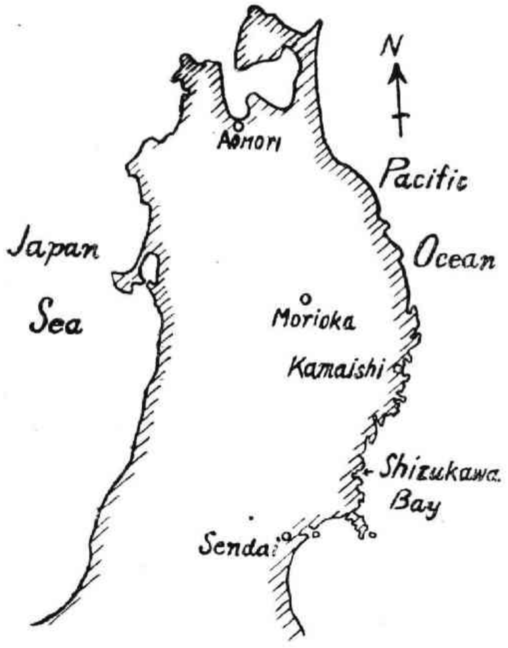


Fig. 1 Northern Honshû.

Shizukawa Bay situates at the southern part of so-called Sanriku District and communicates with the Pacific Ocean through a comparably wide mouth (Fig. 1 and Fig. 2). Shizukawa-chô which lies at the inner part of this bay was severely damaged by the Tsunami in 1896 and 1933. After the Tsunami in 1933 breakwaters were built in this harbour as shown in Fig. 4. As a first step we made a model experiment of Shizukawa

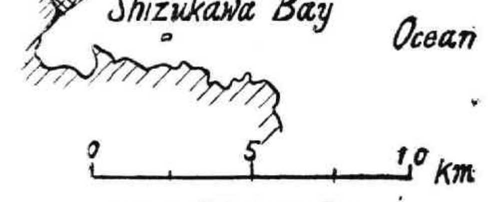


Fig. 2 Shizukawa Bay.
Cross hatching indicates the area of model.

Bay to see how these breakwaters influence the sea waves in the harbour, and then the method of prevention from damage was studied constructing some model breakwaters in the harbour.

§ 2. Method of Experiment.

In the present experiment a wooden tank was used, 240 cm long, 120 cm wide and 60 cm deep. The model of Shizukawa Harbour was put into it, the ratio of horizontal and vertical sizes of the model to the natural one being 1 : 1,500 and 1 : 125 respectively (Fig. 3). In Fig. 4 iso-bathymetric lines referred to the low water level and positions of observed points are given. The difference between the low water level and the high water level in the bay is about 180 cm and in the present experiment water was filled up to the mean sea level. Waves were generated by an iron plate which was set vertically on the opposite side of the model in the tank, by pulling or pushing it for once longitudinally. Waves thus generated and propagated in the bay were measured by small tide-gauges specially devised for this experiment as shown in Fig. 5.

Fig. 3 Model of Shizukawa Bay in the Tank. The blackened area indicates breakwaters built after 1933.

This tide-gauge is composed of a fine glass rod G, a synchronous motor M and a rotating drum D driven by the motor. The length and the diameter of the glass rod are 19 cm and 1 mm respectively. One of the end of this rod was bent downwards and to float on the water a piece of cork F is attached. The glass rod was made to be able to rotate around a point on it and there a small glass mirror S is attached. C is the counter weight by which the glass rod can stand horizontally when there is no waves. In the experiment the glass rod was set nearly horizontally and the float which was attached

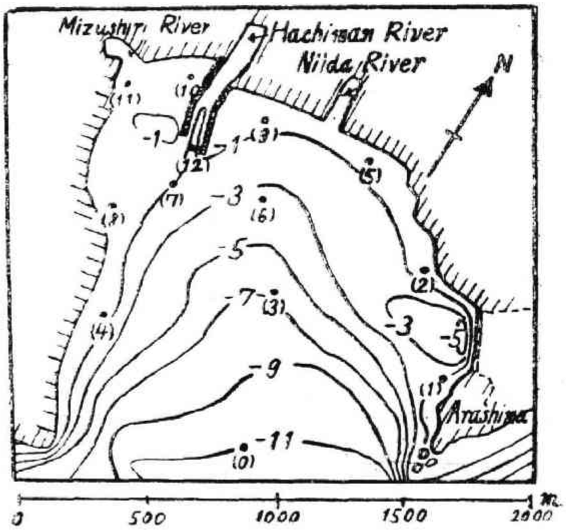


Fig. 4 Iso-Bathymetric Lines and Observed Points.

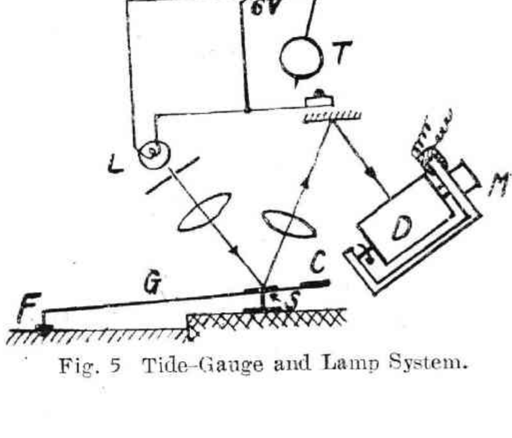


Fig. 5 Tide-Gauge and Lamp System.

to the end of the rod was placed on the water surface of the observed point. When waves invade in the bay float moves vertically together with the water beneath it and the glass rod rotates around the fixed point.

By using the lamp system shown in Fig. 5 the vertical motion of the water was recorded on the oscillograph-paper on the rotating drum. The drum revolves a turn by 20 seconds and as its diamter is 4 cm, it moves at the rate of about 6.3 mm per second. Time mark was recorded by shunting the circuit and putting off the lamp by the pendulum of the clock T every one second.

To see the effect of breakwaters built after the Tsunami of 1933 we used two models, before the Tsunami and at present, and made two similar experiments by each model. In each experiment two tide-gauges were used at the same time, one was at the centre of the mouth of the bay or at the point lettered (0) in Fig. 4 and another at each observed point. For each point two experiments were made, once by pushing and another by pulling the iron plate for once. By pushing it a wave of elevation and by pulling that of depression were generated.

Though the direction of the mouth of the model is not same as that of Shizukawa Bay as shown in Fig. 2, it is not unnatural to suppose that waves generated in the Pacific Ocean will propagate perpendicular to the mouth of the model. This is clear from the iso-bathymetric lines in the bay and by many facts experienced at the time of Tsunami in 1933. Again, waves generated by the iron plate by changing the direction of pulling or pushing by 25° from longitudinal direction of the tank were nearly same as those generated by moving it longitudinally.

In the model experiment it is very important to consider the law of similitude. When the viscosity of water is out of consideration there is one relation between ratios of the reduction of time, the vertical and horizontal sizes of the model. If we denote them by T, D and L respectively the relation between them can be given by $T = L/\sqrt{D}$. In our case as was previously stated $L = 1/1{,}500$ and $D = 1/125$, hence $T = 1/134$, that is to say the time must be reduced to 1 : 134.

§3. Results of Experiment.

Records obtained by tide-gauges are shown in Fig. 6. The number on the left-hand side of each record designates the number of the corresponding observed point. The time which is taken as abscissa and the elevation of water taken as ordinate in figures are those referred to the natural bay, that is to say the time and the elevation of water in the experiment are multiplied by 134 and 125 respectively. As the origin of the abscissa we took the time when the water at the mouth of the bay began to move vertically.

Fig. 6 (a) are records of oscillations by waves which are generated by pushing the iron plate for once in the direction of the model and henceforth we shall call these waves thus generated as "up waves". As Fig. 6 (b) are those by waves generated by pulling the plate, we shall call these waves as "down waves". Both in (a) and (b) two records are shown for each observed point, except at the mouth of the bay. The upper is the record which is obtained by using the model of the bay at the time of the Tsunami in 1933 and the lower is that obtained by the model of bay at present.

Results deduced from these records are as follows:

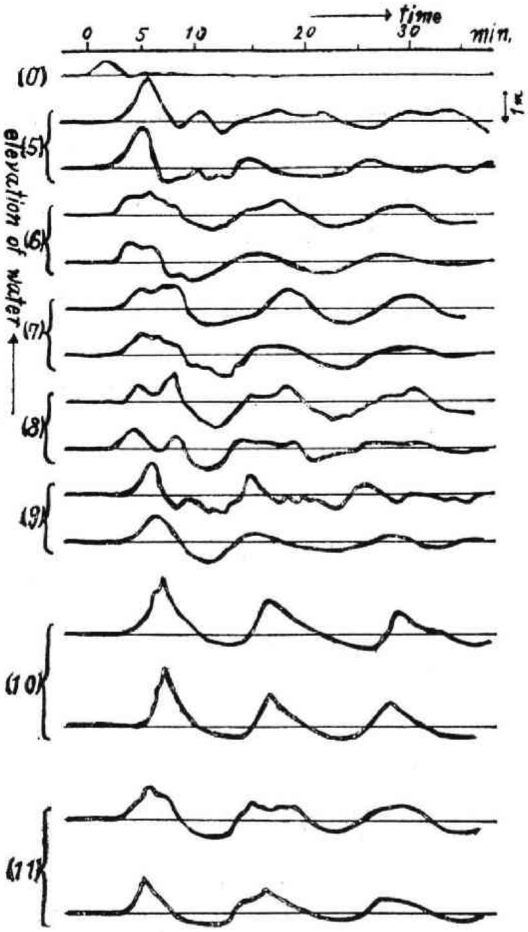


Fig. 6 (a) Oscillations at Observed Points.

(1) The maximum wave height at each observed point.

From records thus obtained the maximum wave height was evaluated for each observed point and was shown in Fig. 7 and 8. Fig. 7 is the wave height in the experiment by the model of 1933 and Fig. 8 is that at present. To compare the maximum wave height at observed points with each other, the maximum elevation or depression of the wave at the mouth was taken as the unit of wave height. In Fig. 7 and 8 two figures are written under the mark affixed to the observed point, the upper of which is the result of the experiment by the "up waves" and is the ratio of the maximum elevation at each point to that at the mouth of the bay, and the lower is the result of the down waves and is the ratio of the maximum elevation at each point to the maximum depression at the mouth. On some points only one figure is entered, as on these points distinct records of down waves were not obtained owing to the unskilfulness of the experiment.

It is easily seen from these figures that they are small in the middle and on both sides of the bay and are below two times as large as that at the mouth of the bay. In the

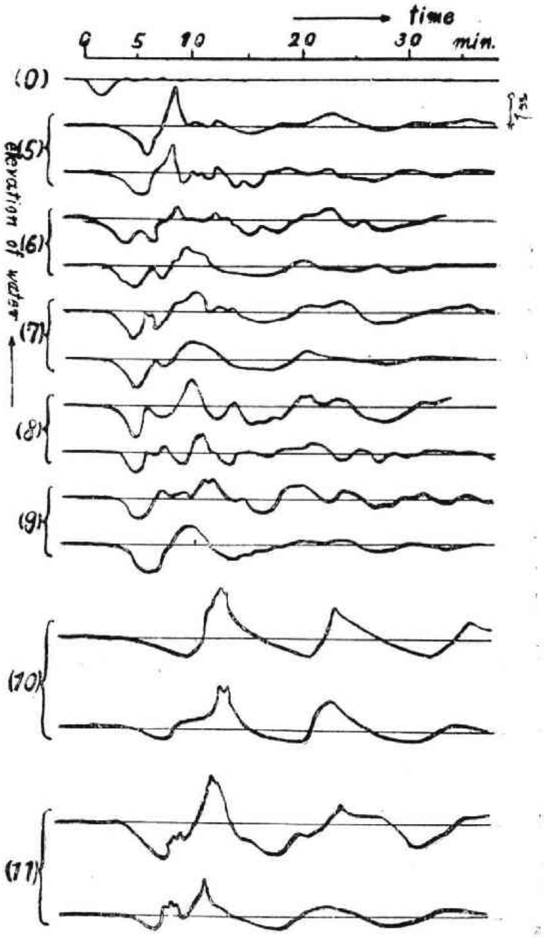


Fig. 6 (b)

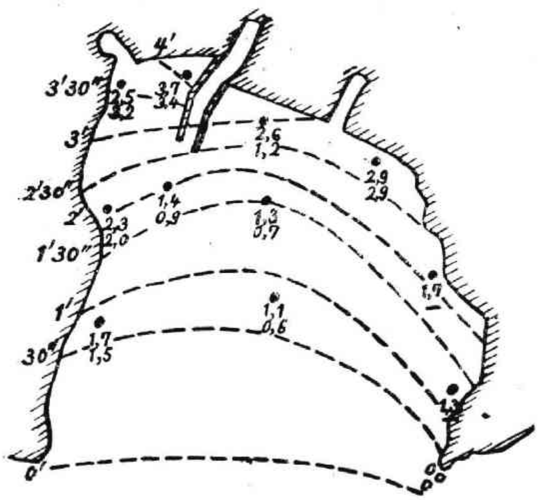


Fig. 7 Maximum Wave Height and the Travel Time of the First Crest Obtained by the Model of the Bay in 1933.

inner part of the bay wave height increases rapidly. Especially at the innermost part it becomes as large as about four times as that at the mouth.

In fact at the time of Tsunami in 1896 and 1933 waves gathered there and invading in the Hachiman River the water flooded over the town. When we compare Fig. 7 with Fig. 8 it will be found that by the aid of breakwaters built after 1933 the wave elevation was lowered in the harbour (observed point (9)) and the eastern side of it (observed point (5)). However on the contrary near the mouth of the Hachiman River (observed point (10)) it looks like to be raised a little. In consequence of this experiment it is clear that any adequate equipments should be constructed there for prevention from damage.

(2) Travel time of the first crest of waves.

Observed travel time of the first crest of the "up waves" was shown in Fig. 7 and 8 by dotted lines. Time was measured from the time when the first crest passed the mouth of the bay in the model and it was shown on the left side of each curve. Also these were referred to the natural bay and were obtained by multiplying by 134 to the observed time. From these figures we shall be able to presume the direction of the wave propagation in the bay. It takes about 4 minutes for the wave to arrive at the innermost part from the mouth and it is nearly equal to the time required to the travelling of a long wave as calculated from the depth of the sea. For "down waves" it was about 1.25 times longer.

(3) Wave form in the bay.

To see the wave form in the bay we made three longitudinal sections of waves in the bay as illustrated in Fig. 9. Fig. 9 (a) is the cross section from the centre of the mouth (observed point (0)) to the front of the quay-wall (observed point (9)) through observed point (3) and (6). Fig. 9 (b) and (c) are those from the mouth to the innermost part of the bay (observed point (10) and (11)) through (7) and (8). Fig. 9 (a) was obtained

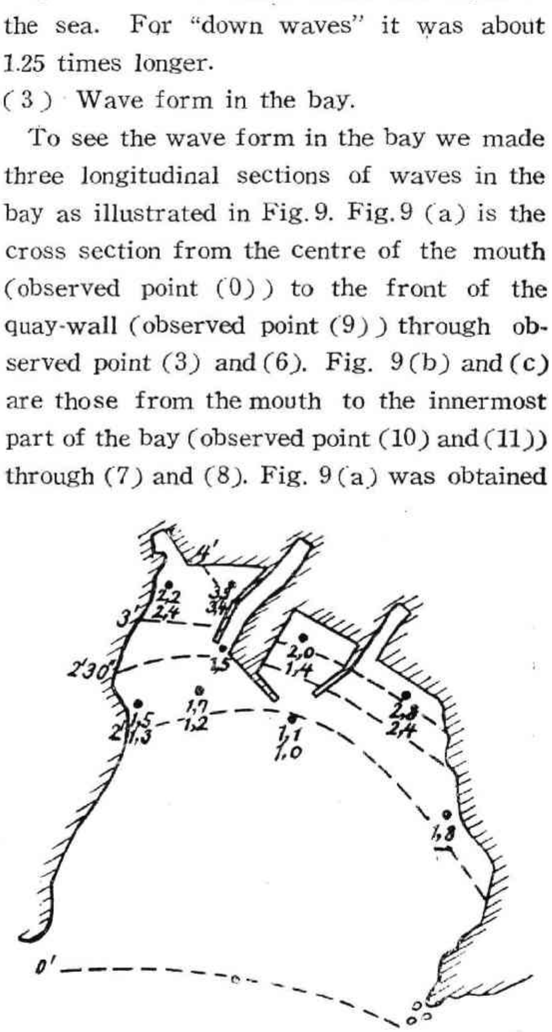


Fig. 8 Maximum Wave Height and the Travel Time of the First Crest Obtained by the Model of the Bay at the Present State.

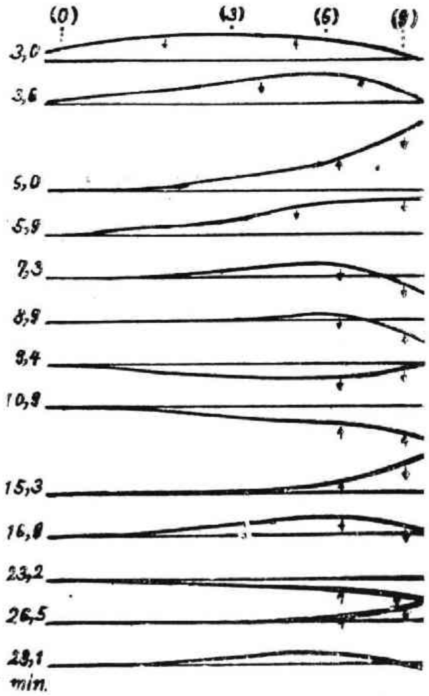


Fig. 9 Longitudinal Cross Sections of Waves in the Bay.
(a) Cross Section from (0) to (9) in the Case of Up Waves in 1933.

from the experiment of "up waves" using the model of the bay in 1933, (b) and (c) were from experiments of up and down waves using the model of the bay at the present state respectively. In these fiigures the left-hand side corresponds to the mouth and the opposite side to the inner part of the bay. The numbers in brackets shown on the upper part of each figures indicate the number of the observed point, and the number on the left-hand side is the time which each wave is required to form, measured from the time when the water on the mouth of the bay begins to move.

From these figures it will be found that the progressive wave invaded in the bay transforms gradually to the stationary wave which is damped by the effect of the viscosity of water and the friction on the sea bed. This transformation is particularly distinct in Fig. 9 (b) and (c). This stationary wave form is nothing but the secondary undulation excited in the bay.

(4) Period of the secondary undulation.

Oscillations in the bay consist of the forced oscillaiton which is generated by external forces or by invading waves and the free oscillation, the latter is due to the secondary undulation induced by the forced oscillation. In our experiment the incident wave was nearly a solitary wave on the mouth of the bay, hence the free oscillation predominated as the time elapsed. The period of the secondary undulation was obtained from record by tide-gauges and estimated as 11.8 minutes. On the other hand the period deduced from the depth of the sea

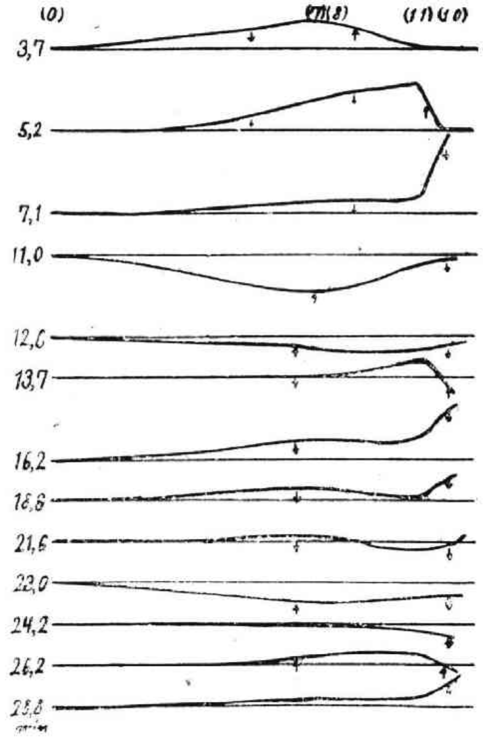


Fig. 9 (b) Cross Section from (0) to (10) in the Case of Up Waves at the Present State.

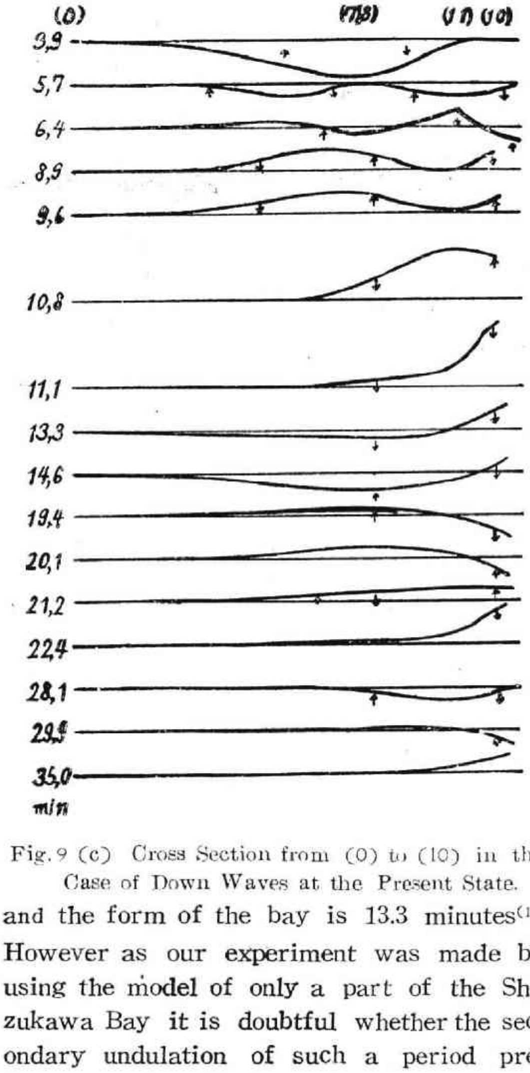


Fig. 9 (c) Cross Section from (0) to (10) in the Case of Down Waves at the Present State.

and the form of the bay is 13.3 minutes(1). However as our experiment was made by using the model of only a part of the Shizukawa Bay it is doubtful whether the secondary undulation of such a period predominates virtually in the bay.

(5) Tne effect of viscosity.

As was previously stated the wave in the bay is damped gradually. From records by tide-gauges we can see that the height of the crest of the wave decreases exponentially with time. As an empirical formula we obtained

$$h = h_0 e^{-0{\cdot}039t},$$

where h is the height of the crest at time t (sec), h_0 is that at $t = 0$, that is to say when the elevation of water is largest. The above formula refers to the model, but for the natural bay it becomes

$h = h_0 e^{-0{\cdot}017t}$, where t is meseaured in min.

One of the present authors(2) has obtained a formula expressing the elevation of waves in a rectangular bay of uniform depth, taking the effect of viscosity into consideration. In the bay this is given by

$$\eta = \frac{2H\sqrt{gD}}{L} \sum_{s=0}^{\infty} \frac{1}{B_s^2 - \alpha^2} \sin \frac{s + \frac{1}{2}}{L} \pi x$$
$$\times \left[B_s \left(1 + f_s \frac{B_s^2 + \alpha^2}{B_s^2 - \alpha^2} \right) \sin \left(\alpha t - \frac{2B_s \alpha f_s}{B_s^2 - \alpha^2} \right) \right.$$
$$- \alpha e^{-B_s f_s t} \left(1 + \frac{2B_s^2 f_s}{B_s^2 - \alpha^2} \right) \sin \left\{ B_s t \right.$$
$$\left. \left. - B_s f_s \left(t + \frac{2B_s}{B_s^2 - \alpha^2} \right) \right\} \right]$$

where D and L are depth and the length of the bay respectively, ν is the coefficient of viscosity, x is the distance measured from the mouth towards the closed end of the bay, g is the acceleration of gravity,

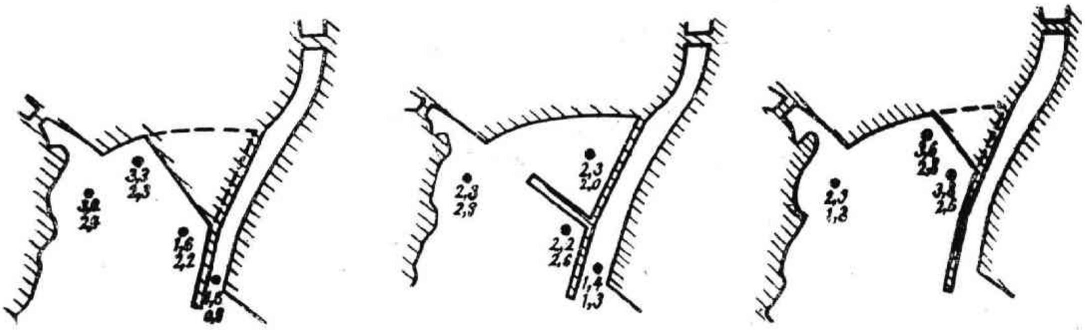
$$B_s = \sqrt{gD} \left(s + \frac{1}{2} \right) \pi / L,$$

$$f_s = \frac{1}{2D} \sqrt{\frac{\nu D}{\sqrt{gD}\,(2s+1)\pi}},$$

$s = 0, 1, 2, \cdots$. In obtaining this formula it was assumed that at the mouth of the bay the elevation of water is given by

$$\eta = H \sin \alpha t.$$

In the above formula the first term in braces expresses the forced oscillation and the second term expresses the free oscillation. The term $\alpha e^{-B_0 f_0 t} \sin B_0 t$ corresponds to the secondary undulation considered in our experiment. Comparing the above formula with our experimental result we can evaluate the value of the coefficient of viscosity ν as 0.15 cm^2/sec. When the law of similitude is satisfied the values of f_s must be equal both for the model and the natural bay. From this relation and the value of ν in the case of model, the coeffi-



(a) (b) (c)

Fig. 10 Model Breakwaters for Prevention from Damage.

cient of viscosity of the sea water becomes to 17 cm^2/sec.

As the result of observations in the Japan Sea a relation was obtained between the coefficient of eddy viscosity and the velocity of the sea current V. It was ex pressed as

$$\nu = 4 + 2.6 \times 10^{-1}V + 3.2 \times 10^{-3}V^2,$$

where V is measured in cm/sec. If we adopt 32.6 cm/sec as the mean value of V which is estimated from the experiment, ν becomes 15.9 cm^2/sec in the natural bay. This value is nearly equal to the value 17 which was obtained assuming that the law of similitude is satisfied, and this means that the law is satisfied fairly good in our experiment even when the effect of viscosity is taken into consideration.

§ 4. Methods of Prevention from Damage.

As was previously stated near the mouth of the Hachiman River the elevation of water becomes largest. Therefore we made three experiments on the method of the prevention from damage by Tsunami, constructing three model breakwaters at different positions in the north-western part of the bay. They are shown in Fig. 10 (a), (b) and (c). Of these breakwaters one which was built as shown in Fig. (a) was most effective, but even by the breakwater in Fig. (b) the wave at the innermost part of the bay can be fairly lowered. The breakwater shown in Fig. (c) is completely useless unless it is sufficiently tall and strong.

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