

5. *Estimation of Energy of Tunami and Protection of Coasts.**

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For the protection of coasts against the tunami, it is most important to know the force which acts upon the structures. From the data of the Sanriku tunami on March 3, 1933 the author here tries to estimate the force. Some ideas concerning the protection of coasts are also discussed.

Tunami at Coasts.

Periods of Oscillation of the Tunami. The modes of the tunami at the coasts are clearly shown in the records of self-recording tidal gauges.

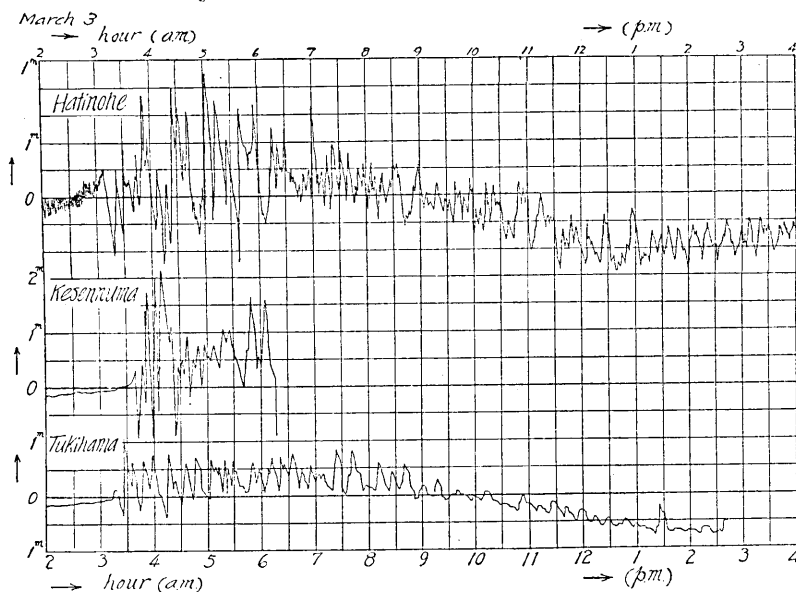


Fig. 1. Records on self-recording tidal gauges of the tunami on March 3, 1933.

* Communicated by N. Mononobe.

Three remarkable records which survived the tsunami at Sanriku coasts are shown in a same scale in Fig. 1.

Comparing the records, especially at the beginning of the oscillation, we can identify each corresponding waves in each records. The periods may be read as

Hatinohe 12 min., Kesennuma 12 min., Tukihamu 10.5 min. and the mean of these three is $2T = 11.5 \text{ min} = 690 \text{ sec.}$, T being a half period.

Heights of Tsunami at the Coasts and in the Deep Sea. The max. heights of the tsunami reached at various villages along the coasts of Sanriku may be taken as a measure of the energy there. Of some rather important villages the heights measured by the author from the mean sea level—which approximates the sea level at the beginning of the tsunami—are shown in Fig. 2. The heights of 1896 are also shown in the same figure.

These are not necessarily the heights of the wave itself, but the max. heights the water is thrown up at the coasts.

The height of tsunami seems to be rather small at its occurrence in the deep sea but coming to shallow coasts and narrow bays becomes higher and especially at the bayhead, where the energy is concentrated, it reached under circumstances as high as 30 m.

If we take that a tsunami is submitted to the laws of the trochoidal wave, the change of the height is expressed as

$$\frac{h_2}{h_1} = \left(\frac{H_1}{H_2} \right)^{\frac{1}{4}} \left(\frac{B_1}{B_2} \right)^{\frac{1}{2}}, \quad (1)$$

where h_1 and h_2 expresses respectively the heights of a wave in a bay at the sections where the depths and widths are H_1 , B_1 and H_2 , B_2 .

Change of the Height due to the Direction of Propagation. The height of a tsunami in a bay opening direct on the ocean for the epicentre is different from that of oblique one. The relation of these two was expressed experimentally by Prof. Hiroi with respect to the trochoidal wave,

$$h = h_0 \left(1 - \frac{\theta^2}{240} \right), \quad (2)$$

where h the height of a wave after the deviation, by the amount θ° , of the direction of propagation and h_0 is the original height of the wave.

The values of θ for various bays are shown in Fig. 2.

Effect of the Slope of the Sea Bed. The relation between the height

h_0 and the longitudinal slope s of the sea bed at each village at the bayhead is plotted in Fig. 3 for the tsunami of 1933 and in Fig. 4 for that of 1896.

Here

h , the max. height reached by the tsunami at the villages of the bayhead.

h_0 , the max. height expected if the bay should open direct on the ocean for the epicentre of the earthquake; this is calculated from

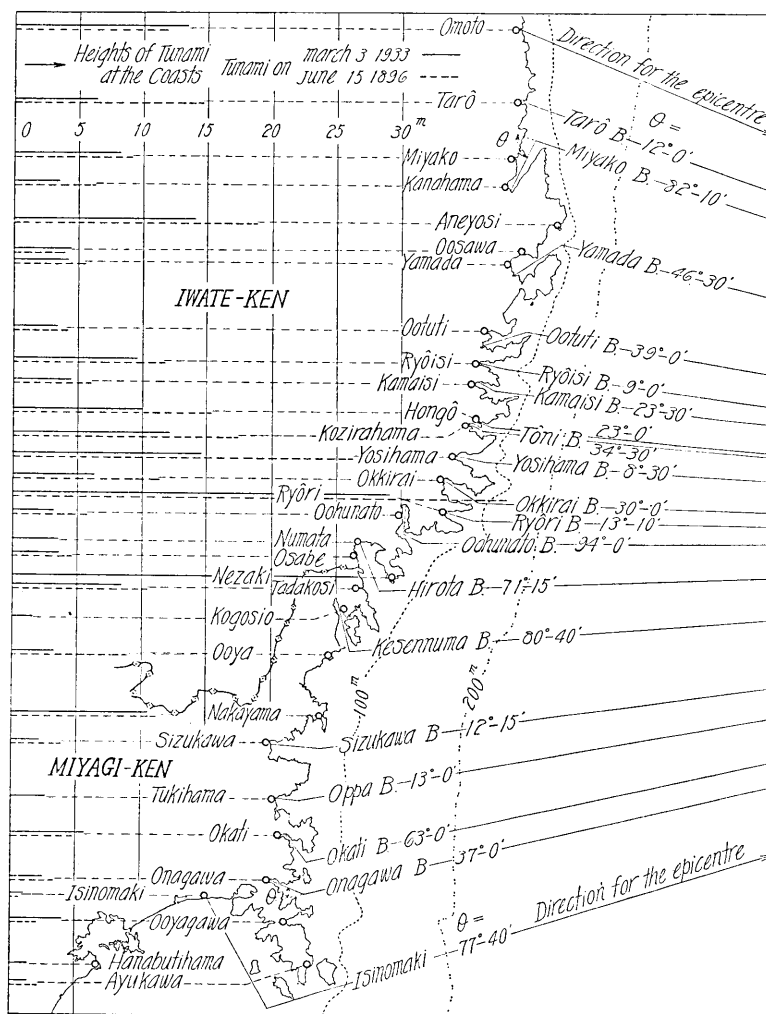
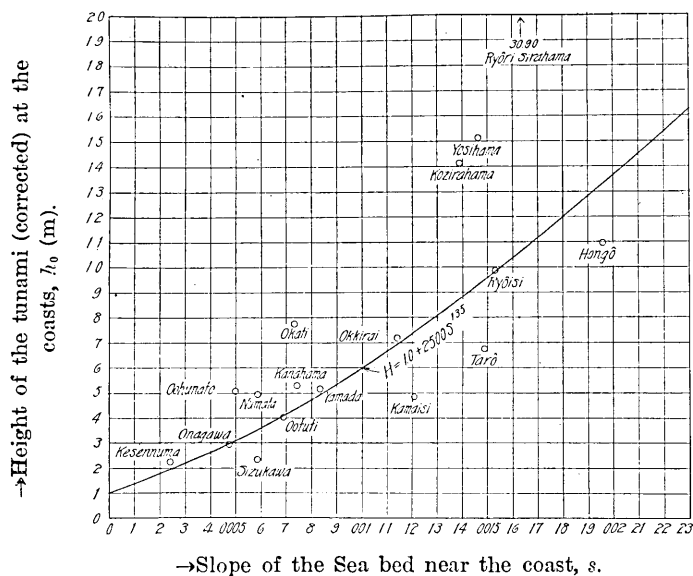
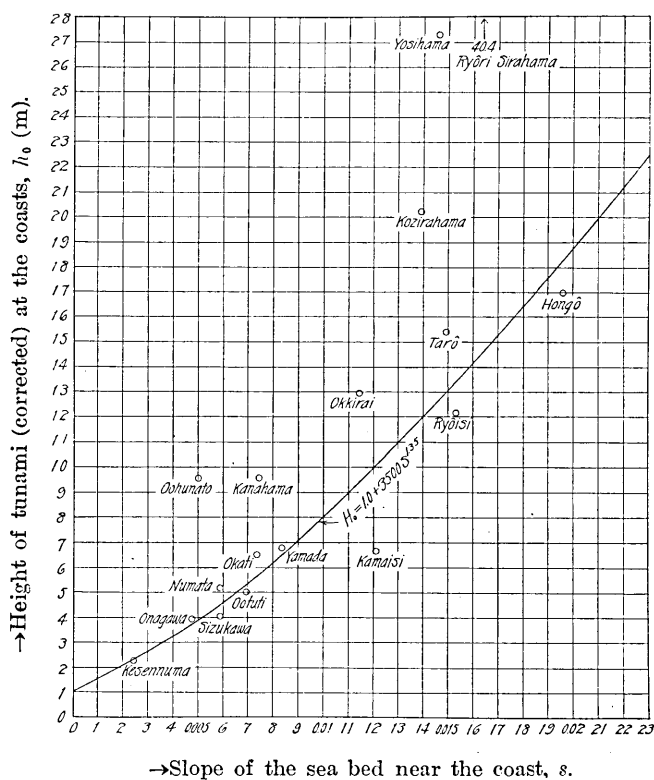


Fig. 2. Height of the tsunamis at Sanriku coasts.

Fig. 3. Relation between h_0 and s according to the tsunami of 1933.Fig. 4. Relation between h_0 and s according to the tsunami of 1896.

h and eq. (2).

s , mean slope of the sea bed near the coast, represented by H/l .
where

H , the depth of the sea at the mouth of the bay.

l , the length of the bay along its centre line.

The plots in these figures do not come in a curve, being affected by other configurations of the bays, but from the figures it may be concluded that for the places of larger s , h should be the greater. They may be roughly expressed as

$$h_0 = 1.0 + 2500 s^{1.35} \text{ for the tsunami of 1933.}$$

$$h_0 = 1.0 + 3500 s^{1.35} \text{ ,, ,, ,, 1896.}$$

Estimation of Forces from the Damages.

(i) *Sea Wall at Yosihama and several other Embankments.* The sea-wall which had the section as shown in Fig. 5 and a length of 420 m. had been constructed to prevent future tsunami after the great one in 1896 at Yosihama, where the disaster was said to be one of the greatest.

With the tsunami of this year the seawall was swept flash from the bottom as shown in Fig. 7 in the Plate. The height submerged by the tsunami at this coast was 14.6 m. From the nature of the materials the horizontal force nec-

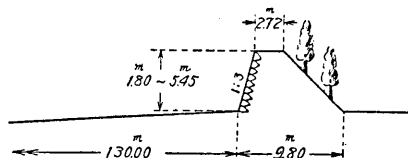


Fig. 5. The section of Yosihama sea wall which was swept away by the tsunami.

essary to shear off the wall is calculated as $p_h = 12$ tons per sq. m. of its vertical projection. As the tsunami occurred this time in the midnight of cold winter, the surface of the wet earth is expected to be in frozen condition. If we take the depth as 15 cm from the surface, this value

Earth embankments at	Dimensions of Walls			Height of Tsunami over the base of the walls (m)	Remarks
	Heights (m)	Base Widths (m)	p_h (t/m ²)		
Yagi	3.9	15.4	smaller than 16.5	4.0	Survived The tsunami swept away
Okkirai	1.0	5.5	larger than 5.6	5.0	
Noda	0.6	1.0	smaller than 4.0	1.4	Survived
Numata	0.6	0.4	smaller than 1.2	1.0	Survived

becomes $p_h = 20.2 \text{ t/m}^2$.

For several other earth embankments at different villages the values of p_h are calculated in the above table.

These values may be taken as measures of the forces at those villages.

(ii) *Displacement of Stones.* The tunami had carried large stones, the max. one amounting to 27 tons in weight, on the shore from the sea bed. The forces p_h required to move the stones at various places are calculated as follows.

	Weight of Stones (t)	p_h (t/m ²)	Heights of Tunami (m)
Hiraiga	27.3	larger than 2.2	10.3
Kozirahama	15.0	larger than 2.2	16.3
Ryôri-Sirahama	8.0	larger than 1.0	25.0
Kuzi	6.0	larger than 1.0	7.9
Yosihama	2.7	larger than 1.2	14.6
Hirota-Atumari	2.6	larger than 1.0	26.7

(iii) *Breaking-off of Trees.* Large trees which were broken off—as shown in Fig. 8 in the Plate—were taken up as a measure. By calculation it was found that the trees—the diameters of the trunks of which were amounted 30 cm or more—may be broken off by rather low pressures caused by the flow of water 2 m/sec. or less.

Protection of Coasts.

Force to be expected. Assuming the tunami as a long trochoidal wave, the velocity of motion of the particles and the pressure caused by it may be calculated by the following formulas,

$$\left. \begin{aligned} r &= \frac{r'_0}{\sinh \frac{\pi H}{L}} \cosh \frac{\pi}{L} (H-c); & r' &= \frac{r'_0}{\sinh \frac{\pi H}{L}} \sinh \frac{\pi}{L} (H-c), \\ v_h &= \frac{\pi}{T} r; & b_0 &= \frac{\pi r_0 h_0}{4L}; & \omega &= \sqrt{g \left(H + \frac{h_0}{2} \right)}, \\ p_h &= n \frac{\gamma v_h^2}{2g} \text{ taking } n=4 \text{ according to Prof. Lira } p_h=0.2\gamma v_h^2, \end{aligned} \right\} \quad (3)$$

where

r and r' , horizontal and vertical diameter respectively of the orbit of motion of a particle of the depth c from the surface.

r_0 and r'_0 , those of a surface particle.

v_h , max. horizontal velocity of a particle.

b_0 , difference of heights of the centre of the orbit of a surface particle and the water surface.

h_0 , height of a wave. L , a half wave length $= \omega T$.

ω , propagation velocity of the wave.

T , a half period. H , depth of water.

p_h , pressure caused by v_h when the motion is suddenly stopped.

γ , unit weight of water.

n , a constant dependent on the conditions of collision.

In the following calculation it was assumed that $T=345$ sec. and h_0 is 3 m. at the depth of 100 m. and varies with the depth by the equation (1).

H (m)	h (m)	ω (m/sec)	L (m)	$r_0=r$ (m)	v_h (m/sec)	p_h (t/m ²)
100	3.00	31.5	10900	52.1	0.48	0.05
50	3.58	22.4	7775	88.5	0.81	0.13
30	4.06	17.7	6115	135.0	1.23	0.30
20	4.50	14.8	5090	182.0	1.66	0.55
10	5.34	11.1	3845	327.0	2.98	1.78
5	6.36	9.0	3094	630.0	5.73	6.57

Though the height becomes larger as the depth decreases but under a certain depth the trochoidal wave motion cannot be maintained and breaks down. With such a long wave as the tsunami the "breaking" seems to occur when $h_0 = \frac{H}{2}$. When it breaks the falling velocity from

h_0 (m)	v_h (m/sec)	p_h t/m ²	v_0 m/sec.	v_r (m/sec)	p_r (t/m ²)
2	4.33	3.75	5.42	6.94	9.63
4	6.26	7.84	7.65	9.89	19.56
6	7.58	11.49	9.39	12.07	29.14
8	8.85	15.66	10.84	13.99	39.16
10	9.91	19.64	12.12	15.66	49.04

the crest combined with v_h causes a great pressure. This is depended on the depth where the "breaking" takes place and for various h_0 the pressures are calculated in the above table.

Here v_r is the max. falling velocity from the crest $v_r = \sqrt{2g\left(\frac{h_0}{2} + b_0\right)}$

$$v_r = \sqrt{v_h^2 + v_0^2}$$

p_r , the pressure caused by $v_r = p_r \div 0.2 v_r^2$.

p_r is the max. pressure intensity to be expected for relatively small area where "breaking" takes place, but not the value to be taken as a uniform load in the design of the breakwater; actual uniform pressure being nearly equal to p_h .

As can be seen from the table above, the pressures are largely depended on the depth where breaking takes place. This can be determined locally by the relative investigation of H and h_0 and according to $H = \frac{h_0}{2}$.

After the "breaking", the water runs up the shore as a "flow", and in general, gradually decreasing its velocity. Therefore the pressure exerted by the flow generally decreases as the distance from the line of breaking increases.

Breakwater. One of the functions of the breakwater is considered to "break" the tsunami at a pretty distance from the coast, so that the energy is much diminished by the friction of the sea bed, as the effects of the friction of the sea bed is far larger after "breaking" than before. For this purpose it must be constructed pretty far from the coast, accordingly at a large depth and this calls for a large cost. But according to the result of the experiment the wall at a large depth seems to give little effect on the height of the tsunami at the shore. Therefore

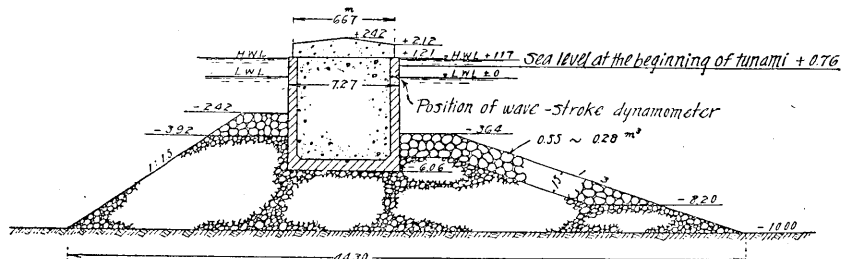


Fig. 6. The pressure of the tsunami was measured by a wave stroke dynamometer at the low water level of the breakwater at Hatinohe Harbour.

it is not advisable that for this sole purpose this type of breakwater is constructed. In general we must be satisfied by taking into consideration the force of the tsunami in constructing the breakwater for harbour facilities.

The force which acts on the vertical front surface of a breakwater is expected nearly equal to p_h and on the horizontal top surface p_v of the preceding paragraph.

A breakwater of Hatinoh Harbour which has the section as shown in Fig. 6 was attacked by the tsunami—the height and period are shown in Fig. 1; max. height $h_0=3.2$ m and $T=360$ sec.

The record of the wave-stroke dynamometer which was set at the spot shown in Fig. 6., showed after the tsunami $800 \text{ \#}/\square'$. as the max. pressure.

According to the formulas (3)

$$H=4.4 \text{ m.}, r=318 \text{ m.}, r'=1.34 \text{ m.}, v_h=2.78 \text{ m/sec.}, p_h=1.55 \text{ t/m}^2.$$

at the depth of the dynamometer. The static pressure is $p'=wh=2.73 \text{ t/m}^2$. The pressure expected is $1.55+2.73=4.28 \text{ t/m}^2$, where the measured value $800 \text{ \#}/\square'$. is equivalent to 3.92 t/m^2 .

Another use of the breakwater is to kill near coast the energy of the "flow". For this purpose the breakwater is built in shore near the coast or on shore. The top level of this type must be higher than the mean sea level for example by 3 m. or more. The force which acts on the breakwater for this use is calculated taking into consideration the distance from the line of "breaking" and the depth where it breaks. The configuration of the breakwater must be most carefully determined as it gives great effect on the structures near it.

Groves of Trees. For the coast where less energy of the tsunami is expected, groves of trees along the coast will be effective to lessen the damage. Under larger energies the trees will be broken off and give another damage due to the drifting lumbers. The author would insist that the prevention by groves is effective where the velocity of flow is about 2.0 m/sec. or less.

Retaining Walls and some other Means. Masonry retaining walls, earth embankments and concrete buildings along the coast diminish the energy and lessen damages of the backward houses and other structures. But this also can be said where the energy is rather small.

An example of the earth embankment which was most effective is shown in Fig. 9 in the Plate. The village Yagi had suffered enormous

damages by the tsunami of 1896, but later the railway embankment was built along the shore and the damages of this time were exceedingly smaller.

Fig. 10 shows an example of the failure of a concrete retaining wall which shows the overturning effect of the tsunami.

For the places where the energy is so large that the height of it is 30 m. or more there seems no means to prevent the damage. The only means to be free from it is to select the residential site at the elevated ground where it does not reach.

5. 津 浪 の 勢 力 と 防 禦

内務省土木試験所 松 尾 春 雄

昭和8年3月3日の三陸津浪に依る被害状況より海岸各地に於ける勢力の推定を試み次に土木工作物に依り將來の被害の輕減を圖らんとする場合その強度を如何程にすべきかに就て概算を試みた。

[H. MATSUO.]



Fig. 7. Sea wall at Yosihama was swept flash from the bottom.

[B. E. R. I., Suppl. Vol. I, Pl. I.]



Fig. 8. Trees at Ryôri-Sirahama were broken off near the ground



Fig. 9. Railway embankment along the shore at Yagi was effective to eliminate the damage.



Fig. 10. Concrete retaining wall was overturned towards the front. (Yagi)