4. *Abnormally High Waves, or "Tunami," on the Coast of Sanriku in Japan, on March 3, 1933.*

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Introduction.

On March 3, 1933, a train of abnormally high waves, or "Tunami," swept and wrought much havoc on the shores of Sanriku. The waves were over 20 metres in maximum height, undoubtedly generated by the "conspicuous" earthquake, of which the epicentre is determined at $\lambda=144\cdot^{\circ}6$ E, $\varphi=39\cdot^{\circ}2$ N, near the Japan Trench in the Pacific Ocean, by the Central Meteorological Observatory, and at $\lambda=144\cdot^{\circ}0$ E, $\varphi=38\cdot^{\circ}2$ N, by the Earthquake Research Institute, Tokyo Imperial University, respectively.

It was first considered that we may be able to find a clue for explaining the especially frequent occurrence of the damage of "Tunami" in these coasts from ancient time, if we investigate the statistical character of the periods of secondary undulations of bays along these coasts. The calculation was made of the periods for 45 bays, including the small bays in the open coast, among which the periods of about 10 bays were already calculated by Prof. Honda, Prof. Terada and others.[1]

Next, the relations between the heights of sea-waves and the configurations of bays, were investigated.

The data for the heights of sea-waves, were kindly placed at my disposal by Messrs. N. Nasu, R. Takahasi and others, members of the Earthquake Research Institute, and also by the Authorities of the Central Meteorological Observatory, as well as of the Public Works, Home Department.

For comparison's sake, the heights of sea-waves on June 15, 1896, were taken from the Reports of the Imperial Earthquake Investigation Committee, No. II (1896), and similarly investigated.

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[1] *Journ. Coll, Sci., Tokyo*, 24 (1908).

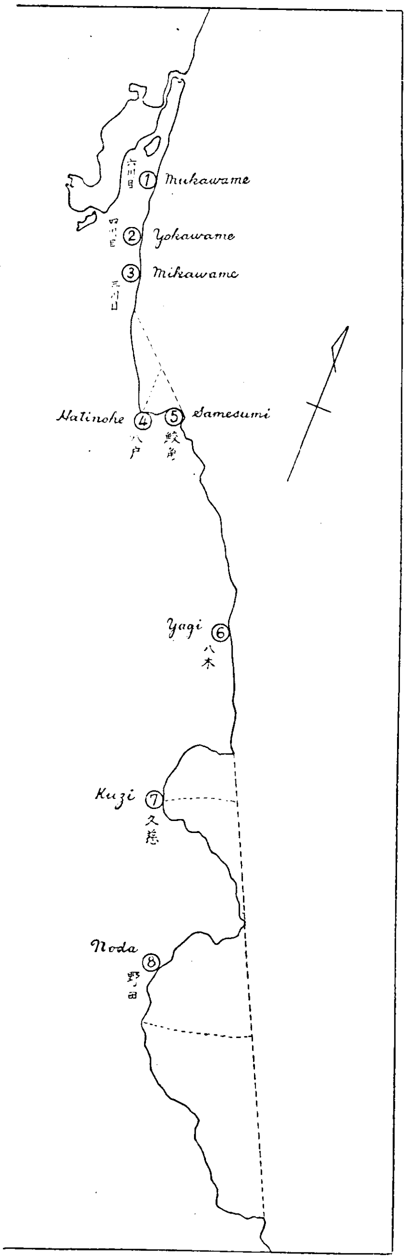
① Mukawame
② Yokawame
③ Mikawame
Hatinohe ④
八戸
⑤ Samesumi
鮫角
Yagi ⑥
八木
Kuzi ⑦
久慈
Noda ⑧
野田

Fig. 1 *a*.

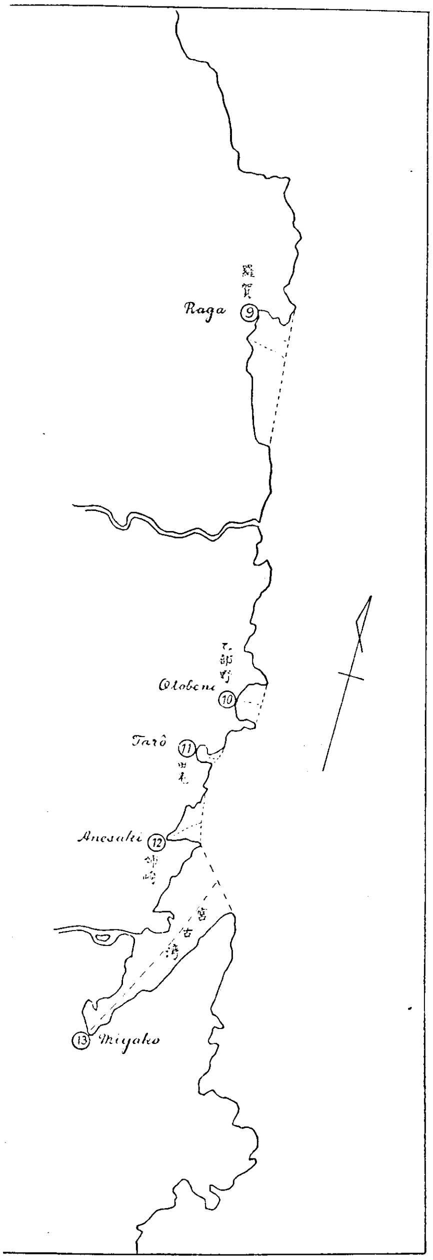
羅賀
Raga ⑨
Otobeni ⑩
Tarô ⑪
田老
Anesaki ⑫
姉崎
宮古湾
⑬ Miyako

Fig. 1 *b*.

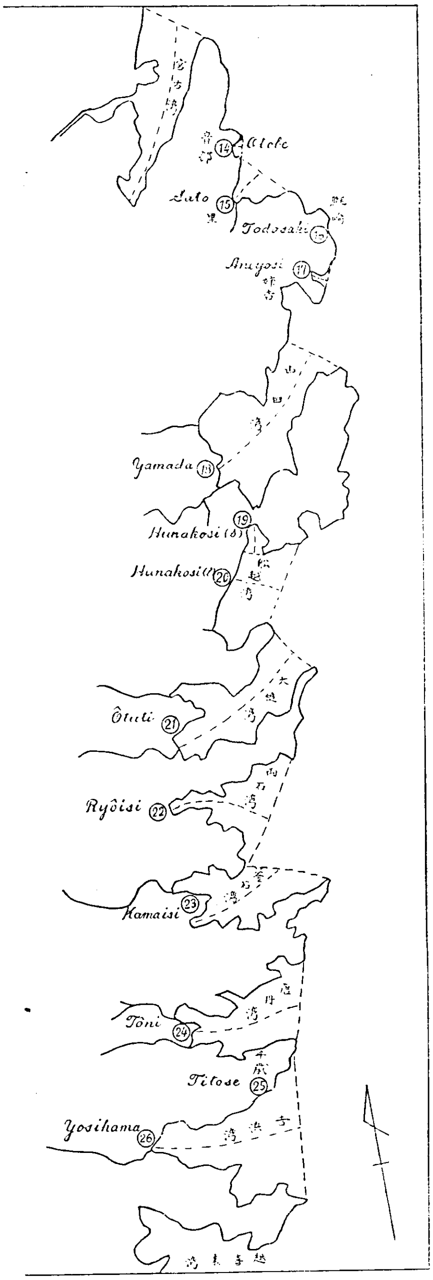
Atete 14
Sato 15
Todosaki 16
Anyosi 17
Yamada 18
Hunakosi (S) 19
Hunakosi (N) 20
Ôtuti 21
Ryôisi 22
Kamaisi 23
Tôni 24
Titose 25
Yosihama 26

Fig. 1 c.

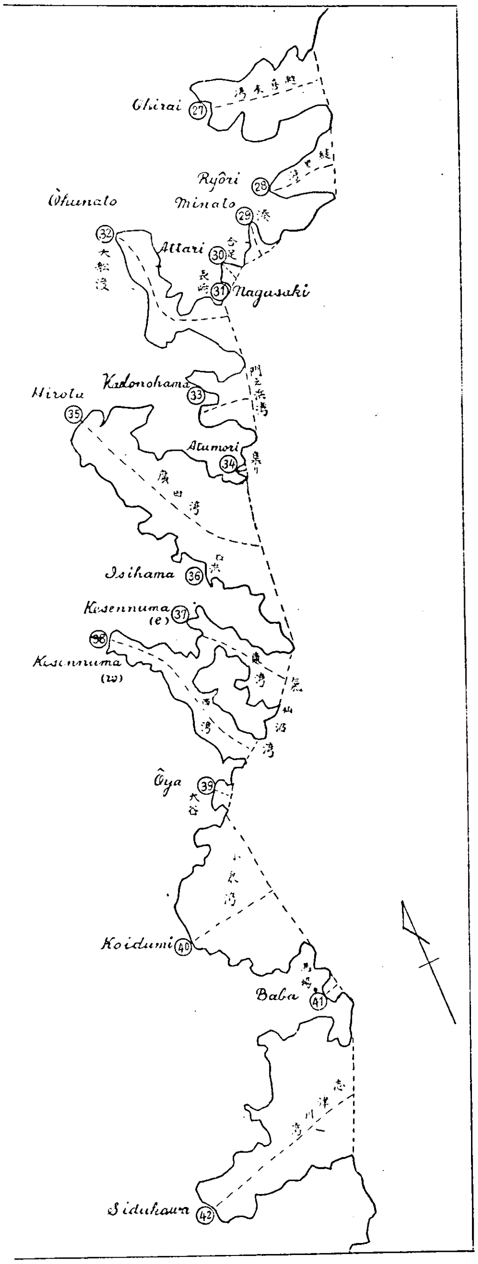
Okirai 27
Ryôri 28
Minato 29
Ôhunato 32
Attari 30
Nagasaki 31
Kadonohama 33
Hirota 35
Atumori 34
Isihama 36
Kesennuma (e) 37
38
Kesennuma (w)
Ôya 39
Koidumi 40
Baba 41
Siduhawa 42

Fig. 1 d

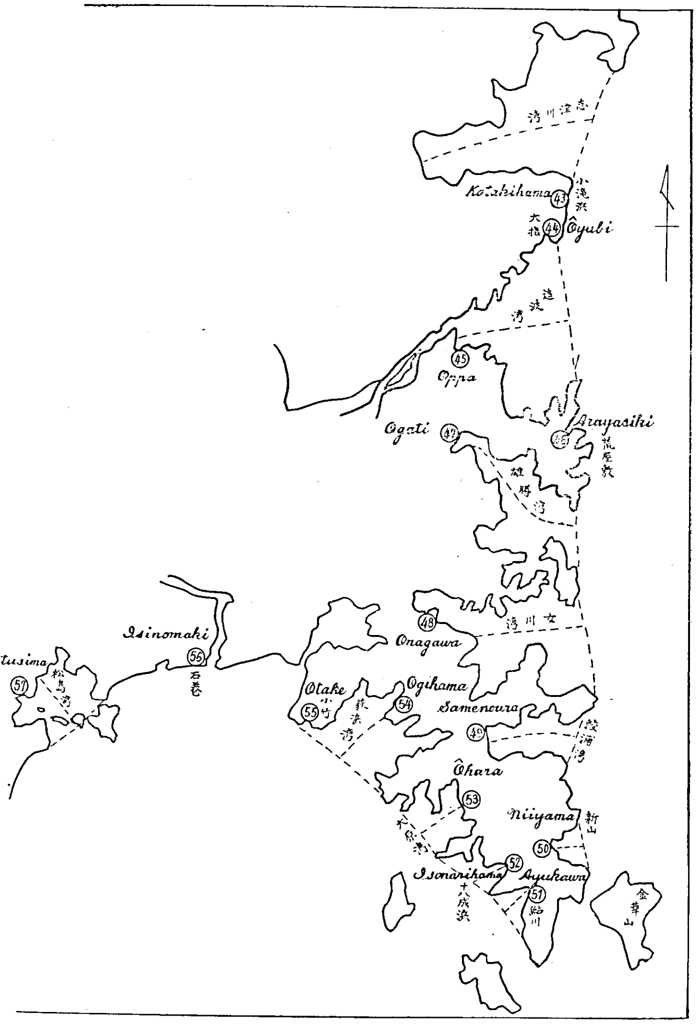

Fig. 1 *e*.

Method of Investigation and Results.

1. Frequencies of Periods of Secondary Undulations.

We have calculated the periods of all the possible mode of secondary undulations of all conspicuous bays in the coast of Sanriku, of which situations, shapes and sizes are given in the annexed maps, Fig. 1, applying the ordinary formula, $T=\frac{4l}{\sqrt{gh_m}}$, where l is the length of the bay, h_m, the mean depth, and g, the acceleration due to gravity, and the frequency of periods falling in successive 5 minutes intervals, was counted and plotted as ordinate, the minutes of the intervals being taken as abscissa, as shown in Fig. 2 *a*.

A remarkable maximum of frequencies of periods takes place at the intervals between 20 and 25 minutes, and a second maximum, between 5 and 10 minutes respectively. This seems to show that there is a characteristic arrangement of many bays with nearly equal periods. This fact may be considered as a hint for the explanation of unusual frequency in these districts of the damages due to " Tunami ". It may be supposed that these bays are tuned for resonance with the proper periods of the sea-waves advancing from the epicentre in the ocean.

If we take also the small bays in the open coast together, the second maximum shown in the above figure (*a*), becomes very remarkable of which the period is nearly the thirds of the longer, as shown in Fig. 2 *b*.

This latter fact may be explained, if we assume that there is a structural unit in the topographical feature of the surface crust, i.e., if the period of secondary undulation be chiefly determined by the length of bay, the square root of the mean depth being nearly equal, the length of bay may be said to be either equal to or three times as that of this unit.

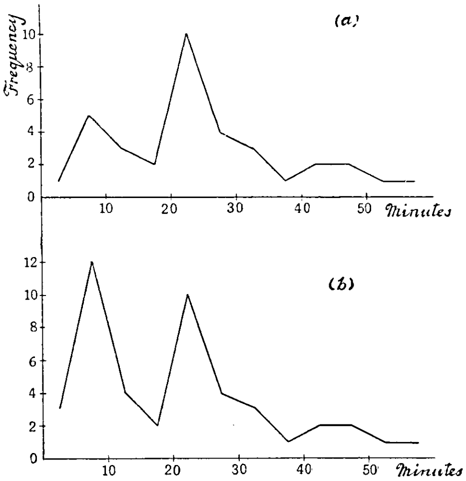

Fig. 2. Frequency of the periods of secondary undulations of bays in the coast of Sanriku.
(*a*) Conspicuous bays only.
(*b*) Including also the small bays in the open coast.

2. Relations between the Heights of Sea-waves and the Configurations of Bays.

If we assume the period, T, of secondary undulation be constant, then the relation between the mean depth and the length of bay will be expressed by the parabola, $l^2=\frac{T^2}{16}gh_m=kh_m$. An *xy*-diagram was constructed with h_m and l as ordinate and abscissa respectively, and every bay was plotted on this diagram as shown in Fig. 3, *a*, *b* and *c*, in which the arrow shows the direction perpendicular to the mouth of bay and the affixed number with bracket shows the mean height of sea-waves in metres, observed at several stations about the end of each bay, corrected for the distance from the epicentre, assuming that the height of sea-wave is inversely proportional to the square root of the distance, for which the distance to the bay of Yamada, the nearest station, 226 km., was taken as unity. The number without bracket in Fig. 3, 4, 5, 6, shows the stations, which are shown in Table I.

The bays, in which the sea-waves reached over 10 metres are distinguished by the marks ◉, and those which had the height of sea-waves less than 5 metres, by △. Moreover, the height of sea-wave, of which the reliability is comparatively great, as judged from the agreement of

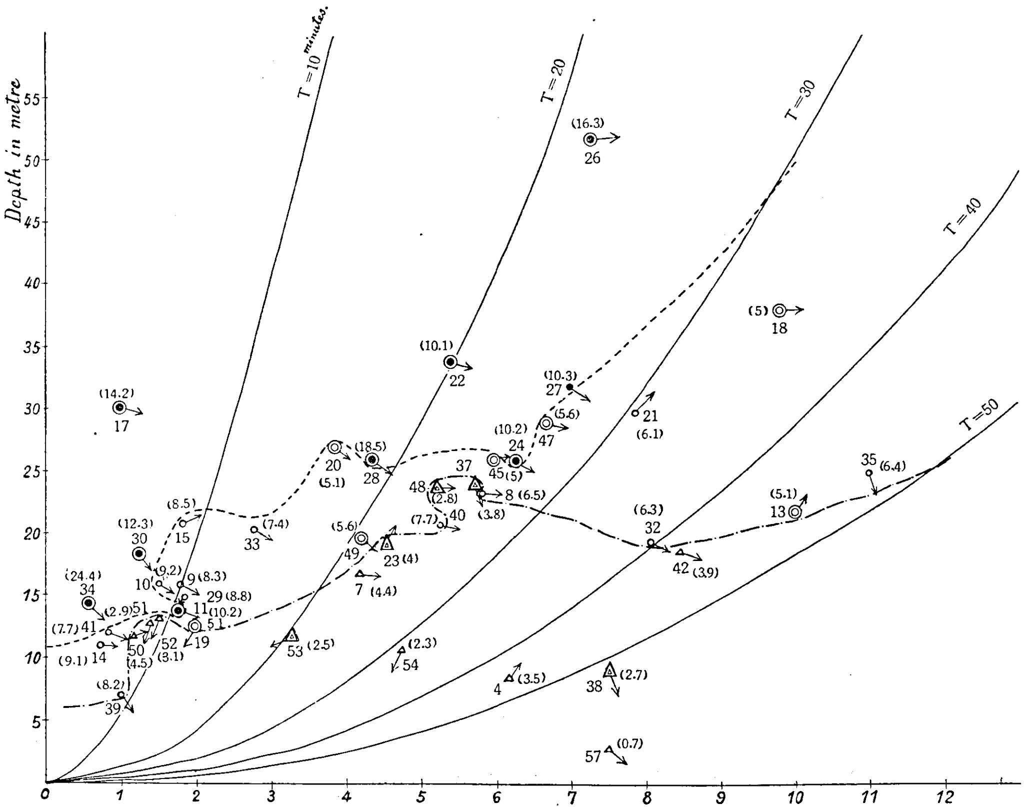

Fig. 3 *a*. Wave height, given by Earthquake Research Institute. N-direction is taken upward.

the values by different authorities, is distinguished by ⊙, ◎ or △.

In these diagrams, we can draw approximately a boundary curve separating the bays with sea-waves over 10 metres, which seems to run across the curves of T=constant. Also another boundary curve may be drawn between the bays with above and below 5 metres of "Tunami."

It may be said that abnormally high waves such as over 10 metres generally take place in deeper bays, and comparatively low waves such as less than 5 metres, are frequent in shallower bays.

The fact that both the cases of "Tunami" in 1933 (Fig. 3, *a*, *b*) and in 1896 (Fig. 3, *c*), have given the similar results, might have some definite meaning to be still investigated.

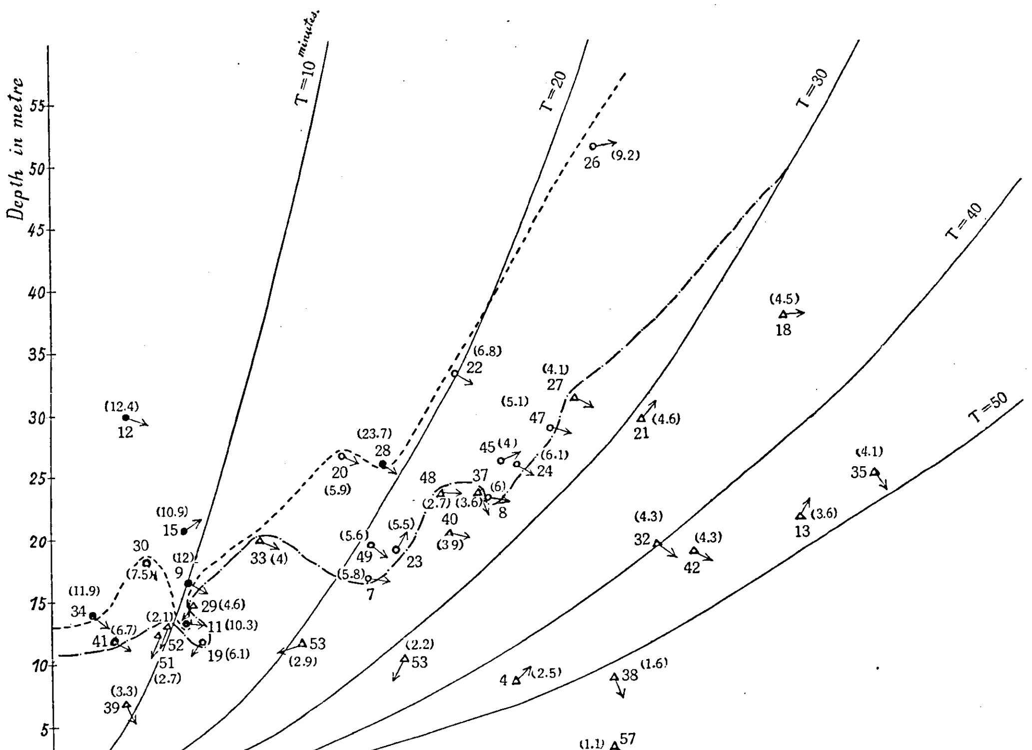

Fig. 3 *b*. Wave height, given by Central Meteorological Observatory. N-direction is taken upward.

By all means, the depth of bay is an important factor governing the height of sea-wave. This is not, however, the sole factor to be considered, but the period of oscillation of bay must be taken as another important ractor. The importance of the latter may be shown in the cases of Yamada and Hirota, which had smaller height of sea-waves than expected from the depth of bays, in comparison with the other bays. They might have had much higher sea-waves than this time (1933) and the preceding one (1896), if the periods of sea-waves were more than 35 minutes and resonated with the proper periods of oscillations of these bays.

Again, in the extreme case, even when the period of oscillation is very short, that is when $l \fallingdotseq 0$, which corresponds to the case in which the sea-wave has arrived at the coastal cliff, the height of sea-wave may have the possibility to grow above 10 metres, if the depth of bay is more than 10 metres, as may be judged from Fig. 3.

We have also drawn xy-diagrams with the wave heights above cited,

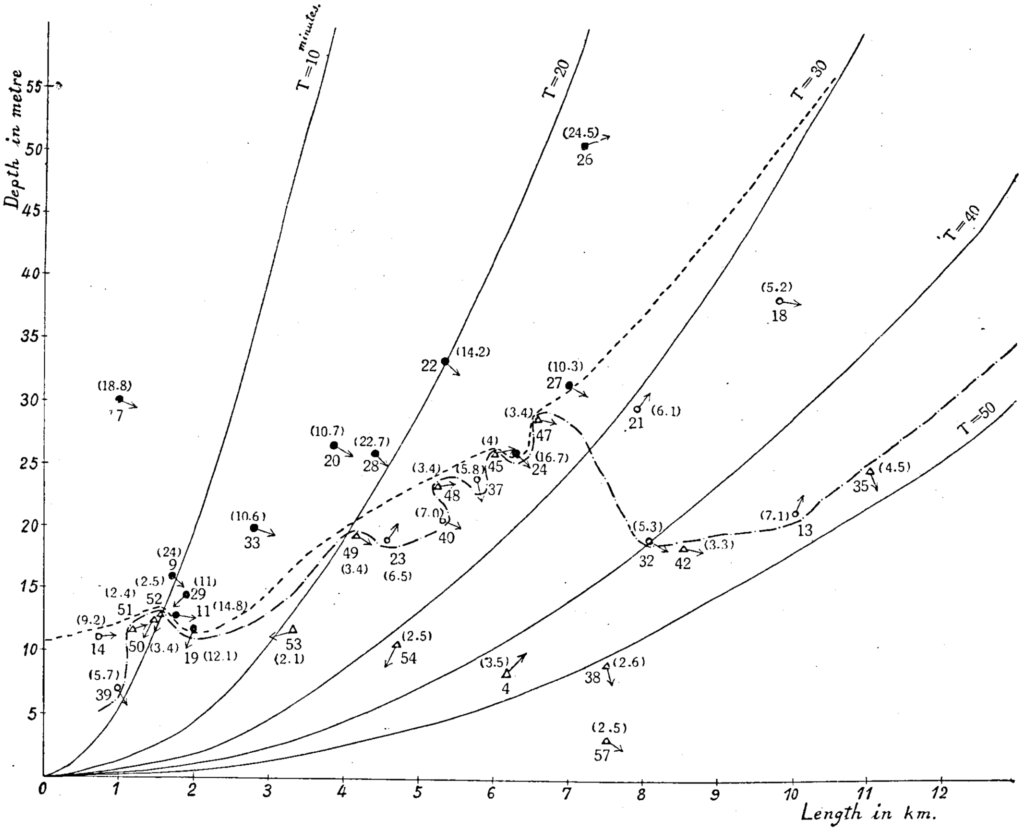

Fig. 3 c. Wave height, in 1896.
N-direction is taken upward

TABLE I.

1.	Mukawame 六川目	2.	Yokawame 四川目	3.	Mikawame 三川目
4.	Hatinohe 八戸	5.	Samesumi 鮫角	6.	Yagi 八木
7.	Kuzi 久慈	8.	Noda 野田	9.	Raga 羅賀
10.	Otobeno 乙部野	11.	Tarô 田老	12.	Anesaki 姉崎
13.	Miyako 宮古	14.	Otobe 音部	15.	Sato 里
16.	Todosaki 魹崎	17.	Aneyosi 姉吉	18.	Yamada 山田
19.	Hunakosi(s) 船越 (小)	20.	Hunakosi(l) 船越 (大)	21.	Ôtuti 大槌
22.	Ryôisi 兩石	23.	Kamaisi 釜石	24.	Tôni 唐丹
25.	Titose 千歳	26.	Yosihama 吉濱	27.	Okirai 越喜來
28.	Ryôri 綾里	29.	Minato 湊	30.	Attari 合足
31.	Nagasaki 長崎	32.	Ôhunato 大船渡	33.	Kadonohama 門之濱
34.	Atumori 集	35.	Hirota 廣田	36.	Isihama 石濱
37.	Kesennuma(E) 氣仙沼 (東)	38.	Kesennuma(W) 氣仙沼 (西)	39.	Ôya 大谷
40.	Koidumi 小泉	41.	Baba 馬場	42.	Sidukawa 志津川
43.	Kotakihama 小瀧濱	44.	Ôyubi 大指	45.	Oppa 追波
46.	Arayasiki 荒屋敷	47.	Ogati 雄勝	48.	Onagawa 女川
49.	Samenoura 鮫浦	50.	Niiyama 新山	51.	Ayukawa 鮎川
52.	Isonarihama 十八成濱	53.	Ôhara 大原	54.	Ogihama 荻濱
55.	Otake 小竹	56.	Isinomaki 石巻	57.	Matusima 松島

as ordinates, and the proper periods of undulations of bays as abscissae, respectively, as shown in Fig. 4, *a*, *b*, *c* and *d*. A general tendency may be seen, that the wave height decreases as the period increases. This fact may probably be explained as follows:—

Though the energy distribution of propagating sea-waves as a function of the wave-length or the period cannot be very simple, it may be considered to decrease with the wave-length, at least above a certain value of the latter.

Even if the energy distribution is assumed constant for all wave lengths, the bays of small proper periods, or rather their extreme case, the cliffs on the open coast, reflect waves of all wave lengths without much dissipation so that the height of wave will reach twice that of the incident wave, while on the contrary, the bays of longer proper periods will only select such waves which are in tune, and resonate to them, while the others are more or less dissipated due to the frictional effects.

On the other hand, the bays of longer periods, which generally correspond to large values of lengths, will absorb the energy of propagating sea-waves, in travelling a longer distance, more than the bays of smaller periods.

Consequently, the heights of waves will decrease with the increase of the periods of undulations of bays.

Next, the V-shaped bays such as Ryôri and Atumori have had extremely high sea-waves, nevertheless no sensible correlation could be found between the heights of sea-waves and the values of A/b, statistically, where A is the area of the bay calculated with planimeter and b, the breadth of the mouth of the bay.

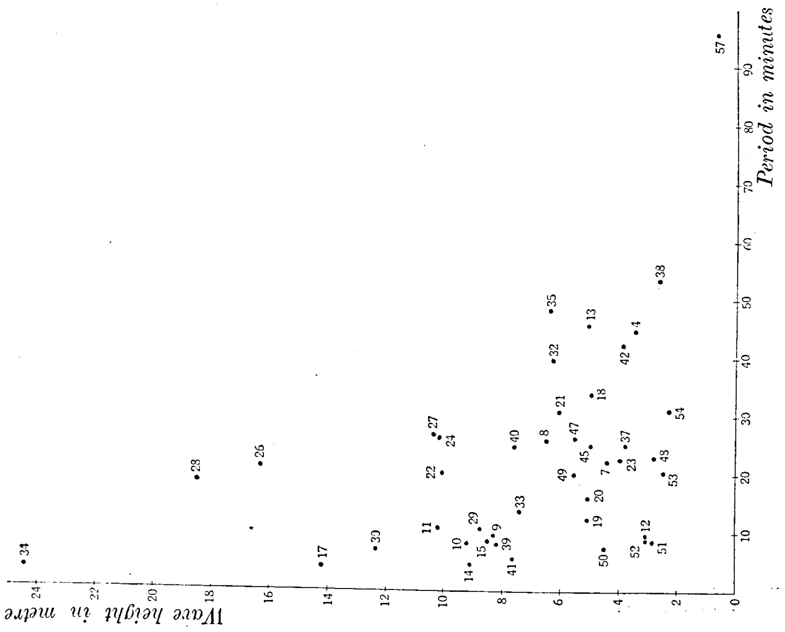

Fig. 4*a*. Wave height, given by Earthquake Research Institute.

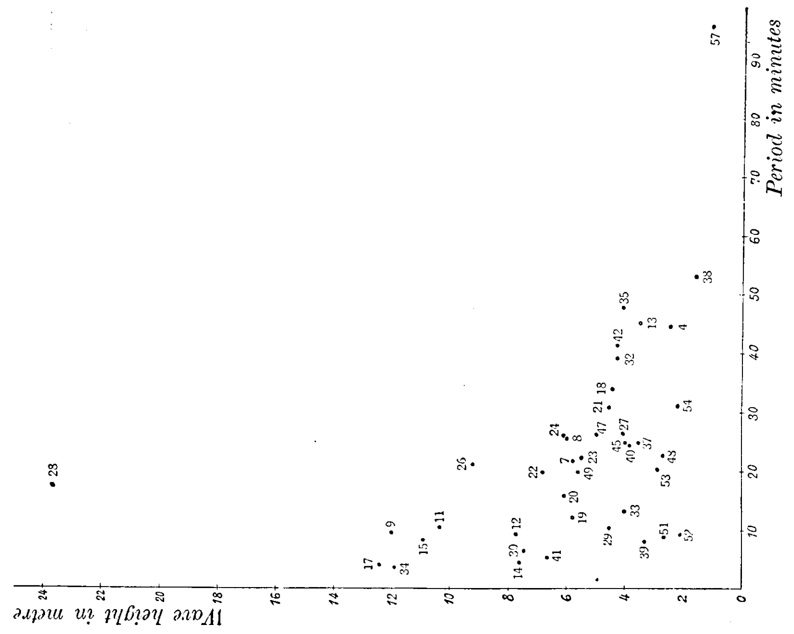

Fig. 4*b*. Wave height, given by Central Meteorological Observatory.

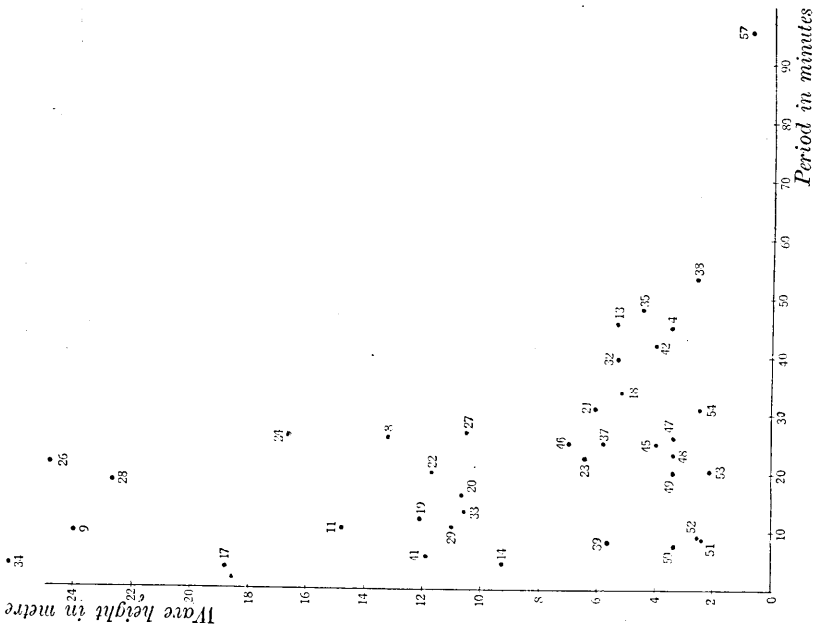

Fig. 4 *d*. Wave height, in 1896.

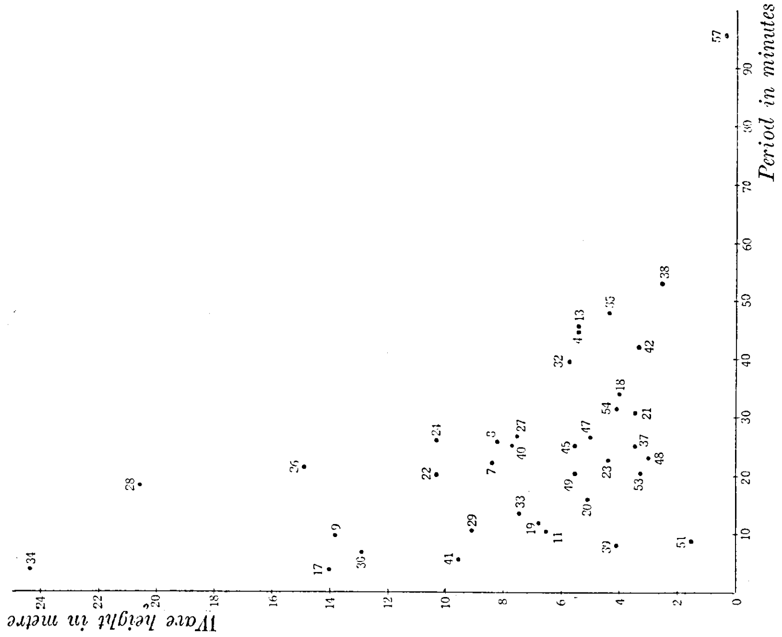

Fig. 4 *c*. Wave height, given by Public Works, Home Department.

With the purpose of obtaining a partial explanation of irregularity shown in the above figure, the directions of the mouths of bays as well as the distances from the bottoms of bays (or the places on which the heights of "Tunami" were taken), to the line of 100 metre depth, were taken into consideration.

3. Depths of the Neighbouring Sea, out of Bays.

As another factor which seems to determine the unusual frequency of damage due to "Tunami" in this region, we may quote the fact that the depth of the sea along the coast of this district is comparatively large. As to the effects of the slope of sea bed and the depth of the coast upon the height of sea-wave, it was already reported in the case of "Tunami" due to cyclone in the Japan Sea Coast, on Jan. 2, 1929.[2] To verify these results again, the distances from the stations of observation of sea-waves to the line of 100 metre depth were measured, and compared with the height of "Tunami". The result is shown in the xy-diagram, Fig. 5, *a*. The full curve in the middle part of the diagram was calculated, assuming the relation, $h=ae^{-bD}$, where h is the height of sea-wave in metre and D, the distance in kilometre. The values of $a=12.3$ and $b=0.067$ were estimated graphically, consequently, $h=12{\cdot}3e^{-0{\cdot}067D}$, was obtained. Similarly, the relation, $y=a+bx$, where $y=\log_{10}h$, and $x=\log_{10}\frac{100}{D}$, was assumed, and we had a nearly straight line, $h=0.376\left(\frac{100}{D}\right)^{1.16}$ as shown in Fig. 5, *b*.

Again, such small bays were picked up which are situated in the open coast, and in this case, the distance from the station to the line of 50 metre depth was taken. The distance was compared with the sea-wave height similarly as before, assuming the relation, $h=ae^{-bD}$, which is shown in Fig. 5, *c*.

In all the above cases, the data used for the wave height, were those given by the members of the Earthquake Research Institute.

Similarly, using the data given by the Central Meteorological Observatory, and also those by the Public Works, Home Department, as well as the similar data for the sea-waves of 1896, taken from the Reports of the Imperial Earthquake Investigation Committee, above cited, xy-diagrams were drawn as shown in Fig. 5, *d*, *e*, *f* and *g*.

From these diagrams, we can see in some measure the effect of decay

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[2] S. YAMAGUTI, *Bull. Earthq. Res. Inst.*, **7** (1929), 555.

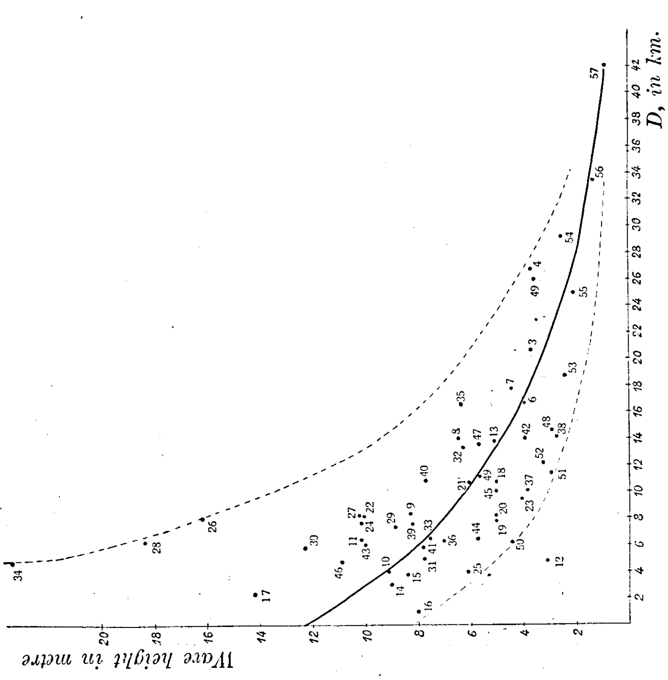

Fig. 5 *a*. ——: $h=12{\cdot}3\,e^{-0{\cdot}067D}$

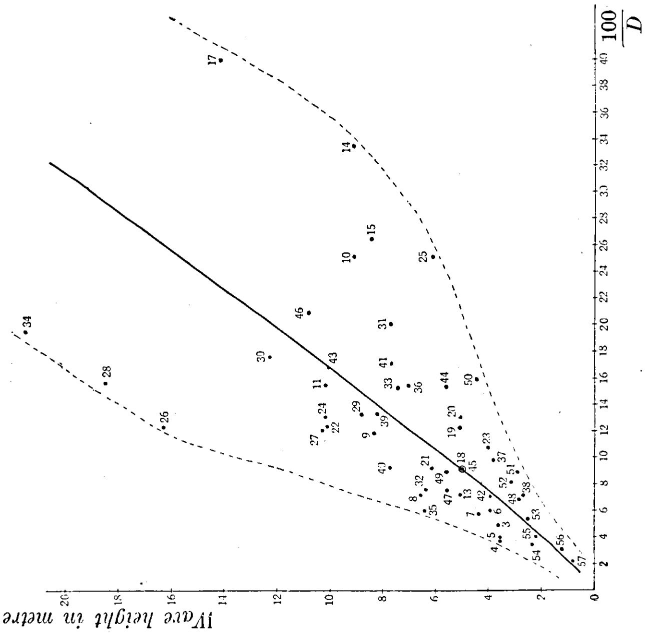

Fig. 5 *b*. ——: $h=0{\cdot}38\left(\frac{100}{D}\right)^{1{\cdot}16}$.

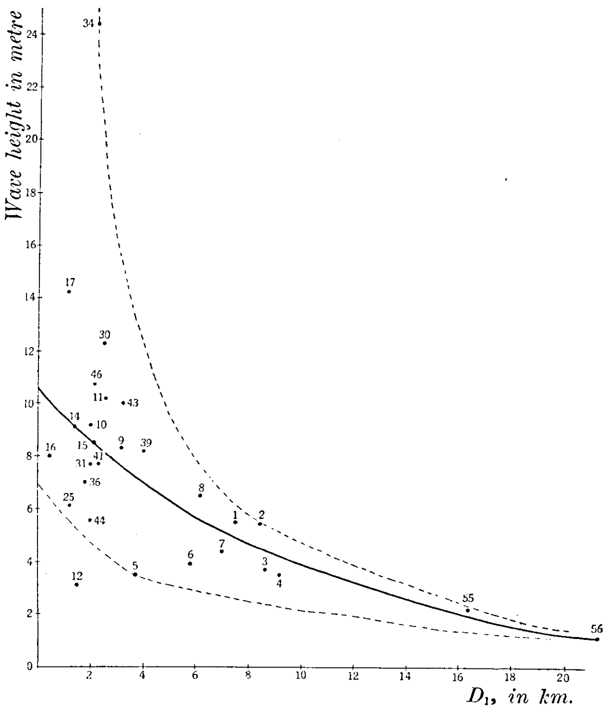

Fig. 5 *c*. Open coast only. ——: $h=10{\cdot}5e^{-0{\cdot}10D_1}$
D_1: The distance from the station to the line of 50 metre depth.

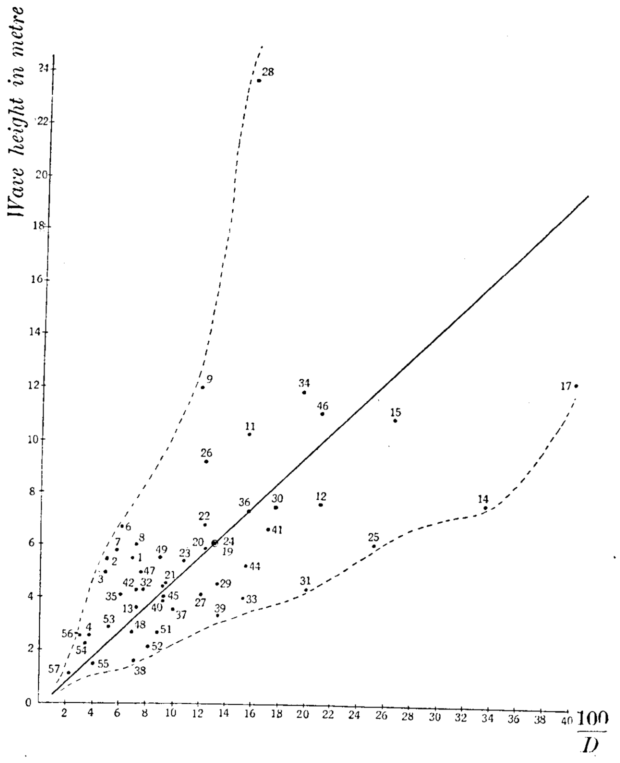

Fig. 5 *d*. ——: $h=0{\cdot}43\left(\frac{100}{D}\right)^{1{\cdot}14}$

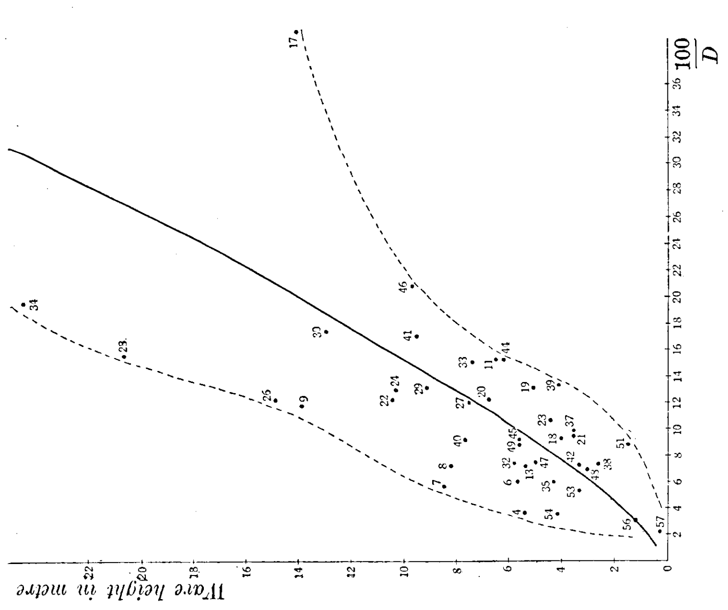

Fig. 5 e. ——: $h=0{\cdot}31\left(\frac{100}{D}\right)^{1{\cdot}27}$

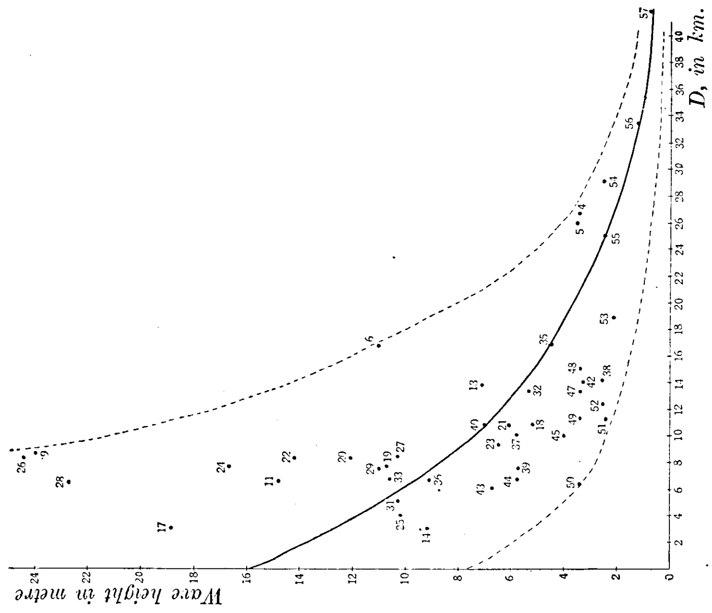

Fig. 5f. Wave height in 1896.
——: $h=15{\cdot}9e^{-0{\cdot}075\,D}$

of the wave energy, due to the friction of the relatively shallow sea bottom near the coast in travelling a distance before reaching the shore.

Also it is seen that, in a small bay, or in an open coast, situated near the mouth, i.e., near the nodal line of the oscillation of a large bay, the sea-wave does not develop so much high inspite of deep sea in the vicinity, as for example, in the cases of Anesaki and Titose.

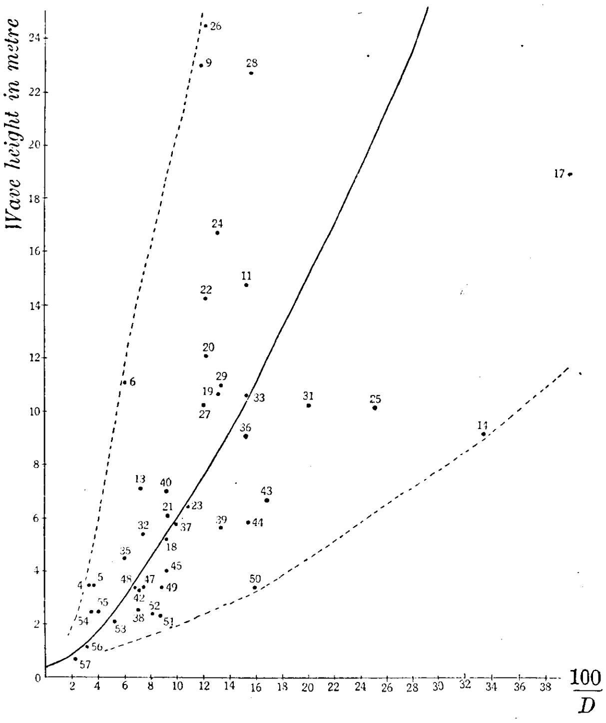

Fig. 5*g*. Wave height in 1896.
—— : $h=0{\cdot}30\left(\frac{100}{D}\right)^{1{\cdot}32}$

4. Direction of the Mouth of Bay.

Let θ be the azimuth angle of the outward normal drawn to the mouth of bay, measured from the north, and φ, the azimuth of the line directed to the epicentre in the ocean from the middle point of the mouth of bay.

The value of $\theta-\varphi$ was calculated for each bay, of which the positive and the negative values correspond respectively to the southward and the northward directions relative to the epicentral direction.

The deviation of the wave height above mentioned, from the theoretical value, $h=12{\cdot}3e^{-0{\cdot}067D}$, was taken and plotted as ordinate, the value of $\theta-\varphi$ being taken as abscissa as shown in Fig. 6, *a*, *b*. Similarly, the deviation from the theoretical value, $h=0{\cdot}376\left(\frac{100}{D}\right)^{1{\cdot}16}$, has given nearly the same result. It seems to show a maximum height of sea-wave at about $\theta-\varphi=30°$. This seems to be explained, if the centre of wave generation be at a point about 100 km. more south than the epicentre of earthquake estimated by the Central Meteorological Observatory.

The general tendency of decrease of the height of sea-wave with

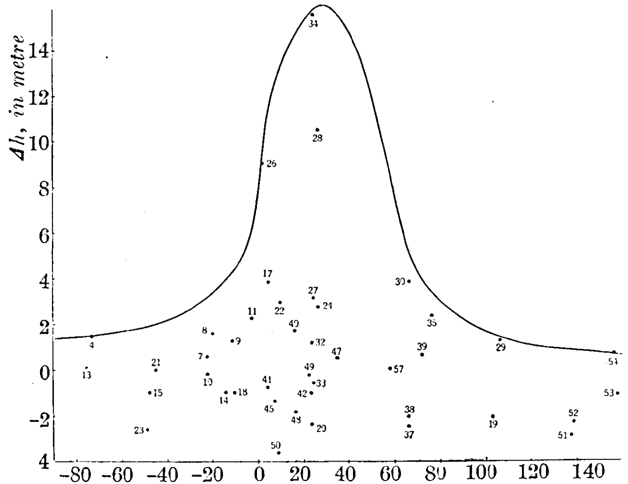

Fig. 6 *a*. Δh and $(\theta-\varphi)$ curve, including all bays.

the increase of the absolute value of $\theta-\varphi$, may be noted.

In the exceptional stations such as Ogati and Onagawa both in 1933 and 1896, as shown in Fig. 3, the heights of sea-waves are rather small compared with the values to be expected from their mean depths of bays. This fact may be explained partially by the effects of the values of D and $\theta-\varphi$, (Fig. 5 and 6), and, moreover, by the fact that numerous islands are arranged in front of these bays, and these obstacles may absorb the energy of waves before reaching the shore.

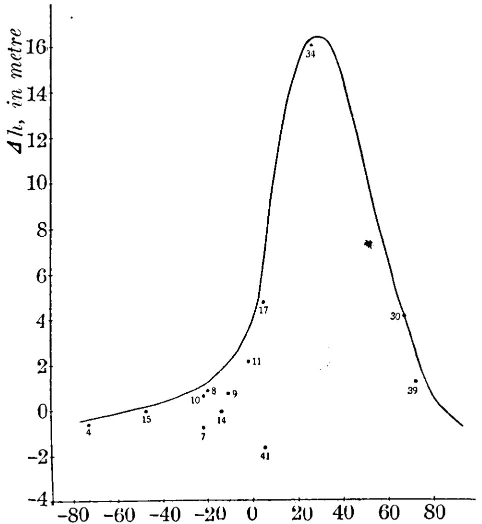

Fig. 6 *b*. Δh and $(\theta-\varphi)$ curve for the bays in the open coast only.

In conclusion, I wish to express my best thanks to Prof. T. Terada under whose supervision the entire work has been carried out and who has given me many useful suggestions throughout the course of my investigation.

4. 昭和8年3月3日の三陸津浪

地震研究所　山口生知

昭和8年3月3日三陸の沿岸を襲ふて，大なる被害を與へた津浪は其の高さ 20 米以上に達したものもあつたと觀測されてゐる．而して浪源は中央氣象臺の報告によれば，東經 144·°6 北緯 39·°2，又東京帝國大學地震研究所の觀測によれば東經 144·°0，北緯 38°·2 の震源附近に在るものと看做されてゐる．

此の地方は古へより特に屢々津浪の被害を蒙つてゐるが，それには何かそういふ理由がありはしないか．之を說明し得べき1つの手掛りを求めようとして先づ第1に此の沿岸の灣の副振動の週期について統計的に諸性質を調べて見た．

約10個の灣の週期に就いては，既に本多博士，寺田博士及び其他の方々に依つて計算されてあるから更に此の沿岸にて著しい灣は勿論のこと，外洋に面した小灣をも含めて合計 45 個の灣の週期を計算した．

次に港灣の形，若しくは近海の深さ，或は近海底の傾斜等が津浪の高さに及ぼす影響に就いても調べて見た．

其の結果は下の通りである．

(1) 此の地方には 7·5 分前後及び其の3倍の 22·5 分前後の2種類の週期を持つ港灣が，著しく多く羅列してゐることを知つた．之が此地方の特徵であつて昔より屢々津浪の被害を蒙る1因をなしてゐるのではないかと疑はしめられる．卽ち之等の灣が沖合の震源附近より進んで來た津浪の個有週期と，恐らく共鳴して其の浪の高さを增したものと想像される．

(2) 灣の長さと平均の深さとを，座標軸として畫いた圖(第3圖)に於て津浪の高さが 10 米以上もあつた灣は之を區別すべき境界線を引くことが出來る．而もこの曲線は一定の週期を表はす曲線と，或る角度を以つて交るように見える． 又浪の高さが 5 米以下であつた灣についても同樣に他の境界線が引かれる．

而して昭和8年の津浪の場合（第3圖 a, b）と，明治29年の場合（第3圖 c）と2つの場合殆んど同樣の結果を與へたと云ふ事實は何か或る意味の存することを示すものと思はれる．

(3) 灣の深さが津浪の高さを支配することは勿論であるが，この外に灣の週期と云ふものも津浪の高さを支配する大切なる1因子であることを忘れてはならない．卽ち廣田灣及び山田灣の場合がその1例であつて，之等の灣は他の灣と較べて可なり深いのであるが，週期が大なるために津浪の高さは豫期される程高くならなかつたのである．

一般に灣の週期が長くなる程津浪の高さは低くなるような傾向をもつてゐる．

(4) 綾里灣及び集灣の如き V 字形の灣は特に，津浪の高さが高かつたと云ふので，他のすべての灣について，灣口の幅，b 及び灣の面積，A を計算して津浪の高さと，A/b との間の關係を求めて見たが，統計的には何等目立つた相關々係を見出すことが出來なかつた．

(5) 此の地方が度々津浪の被害を蒙る今1つの理由として，此の沿岸の海の深さが比較的深いと云ふことを擧げることが出來よう．

このために津浪の觀測された場所より 100 米水深までの距離を測つてその距離と，津浪の高さと

の關係を調べて見た．その結果は第5圖に示される通り距離の大となるにつれて，津浪の高さが減ずる様な傾向が窺はれる．即ち津浪が沖より海岸に達する迄に，近海の比較的淺い底の摩擦によつて幾分その勢力が減衰するように思はれる．

(6) 震源への方向に對する灣口の向きが，津浪の高さに及ぼす影響は餘り著しくないが或る程度までは之を認めることが出來る（第6圖）．而して此の調査によつて浪源が中央氣象臺の報告による震源よりも 100 粁程南方に在るべき事を示してゐるのは面白いことゝ思ふ．