2. *The Tunami considered as a Phenomenon of Sea Water overflowing the Land.*

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In the early morning of March 3, 1933, about half an hour after a very strong earthquake that occurred at $2^{h}\cdot 31^{m}$ a. m., the Pacific coast of Sanriku (the three provinces), consisting of the prefectures of Aomori, Iwate, and Miyagi, were visited by tunami. As these regions consist of hard Palaeozoic, Mesozoic, and volcanic rocks, the earthquake itself practically caused no direct damage, but the tunami did extensive damage by washing away a large number of houses and boats and killing a number of people.

Such tunamis that accompany seismic phenomena are believed to be a long wave,[1] resulting from extensive topographic changes occurring on the sea floor. In fact the wave lengths and periods of these tunamis are comparatively long. In the recent tunami the period was observed to be from 10 to 20 minutes. When a wave of this kind advances to fairly shallow places it is only natural that the wave height should increase and that its form should change, provided of course that the energy of the waves remain undiminished.

When a tunami propagates, the motion of the sea water, just as in the case of an ordinary long wave, is parallel to the direction of progression and is the same for every particle in a vertical line. Consequently, if we pay attention to only certain parts of the wave, it appears like water flowing with a fairly large velocity, but as its wave length is extensively long, it is nothing more than an extensive region of water flowing uniformly;[2] so that vessels out to sea are seldom feel the wave motion.

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[1] The wave velocity of long wave is given by $\sqrt{gh}$, where g is the acceleration of gravity and h is the depth of the sea.

[2] The velocity of water particles is given by $v=\sqrt{\frac{g}{h}}\,\eta$, where g is the acceleration of gravity h the sea depth, and η the wave height. For instance, let $h=100^{m}$ and $\eta=10^{m}$, then $v=3^{m/sec}$.

In considering a wave of this kind that has reached the shore, although a flow, such as mentioned above, could exist out to sea, at the shore where there is a limit to further wave motion and the reflection of wave occurs, there can be no more flow and the only motion possible is rise and fall of the water level.[3]

In the case of coasts indented with bays, as in the Sanriku, when the waves enter the bay the wave height may increase or decrease according to the depth and other characteristics of that bay, as indicated by the actual observations. But in any event, so long as the sea at the shore does not overflow the land, all that will happen is rise and fall of the sea level.

It must be said however that the wave velocity in shallow places, becomes a function of the wave height, just as we see at the sea shore, and on this account the crest of the wave travels at a relatively heigher velocity than that of the trough that proceeds it, and the wave slope gradually increases its inclination to such a extent that it breaks, in which case a flow towords the shore can be considered. But the places where the tunami does not reach so great height, these phenomena do not come into the question at all. Even in the case when only a rise and fall of the water level occur at the shore, a flow shall be produced by the overflow of the sea water upon the land.

Examinations made of districts devastated by the recent tunami, vividly brought out the fact that damage to buildings and other structures was caused by the water height and water velocity of the overflow of sea water[4] upon the land: the latter is in fact most intimately related to the damage to houses. If there are any space which is to be filled up by the water then the water moves towards it and the flow is occurred. We have noticed many facts that the houses that stood where a flow formed were destroyed or washed away, whereas even houses adjoining it but which had hillocks behind it, owing to there being no space for the water to fill up were practically undamaged. At

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3) This phenomenon is equal to such case as when we observe an ordinary seiche of a bay or lake at the shore. In this case we can notice only the water level rising and falling.

Mr. T. WATANABE, engineer of the Department of Railways, who was standing on a high hill and witnessed the tunami at Odawara in the time of the great Kwantô eathquake of 1923, likens the tunami to the water in a cup gradually tilted.

4) In Chinese, tunami is called as "hai-i" (海溢), the meaning of which is overflow of the sea water.

Ootuti, Yamada, Ryôisi, Kamaisi, Hongô (Tôni), etc., in particular, where the tunami was not so high, the phenomena just mentioned was more clearly evident than elsewhere. This is noticed also in the case of the tunami that visited the same region on June 15, 1896, and upon comparing the two tunamis the local distribution of damage is found to be very similar. In both cases, houses build in the places that have no back spaces for the water flow to, suffered least. If, as has been frequently believed, the flow had come in from quite a distance out to sea, then every house would have been damaged in the same way and to the same extent regardless of the character of the topography behind them.

The elements of the damage that tunami cause to structures are, as has already been said, water height and water velocity. When a combination of these two elements exceed a critical state, damage results. Although the maximum height of the tunami may be known from traces left on piers, walls, buildings, etc., there is nothing to enable us to know directly the velocity with which the water flowed, so that all we can do is to estimate it with some assumption.

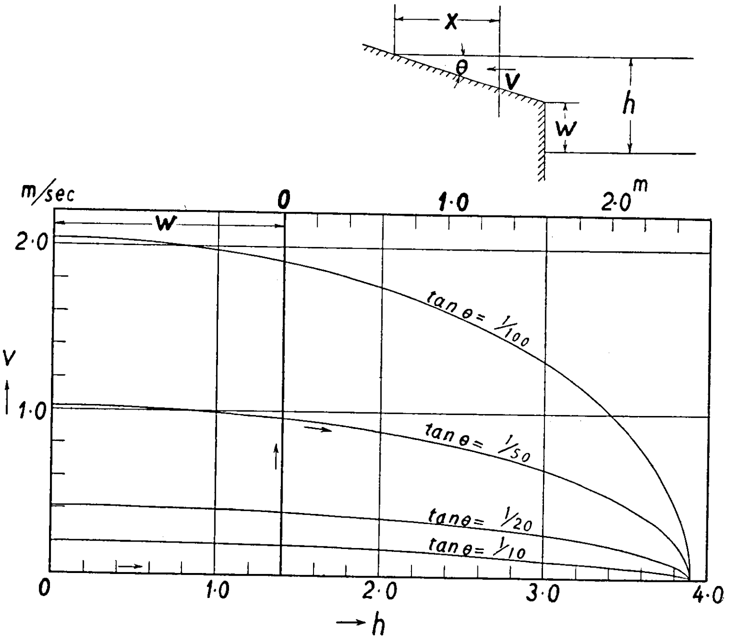

Fig. 1. Relations between the wave height and the velocity of overflowing water: h the wave height, v the velocity of overflowing water, θ the inclination angle of the land.

Let us now consider the case when the sea overflows the land simply as the result of the rise in level of the water at the shore, and try to ascertain what velocity the water would develop. For simplicity, we shall regard the problem as one-dimensional, and as shown in Fig. 1, suppose that the sea overflows the land which has the angle of slope θ, and that the condition that the sea always maintains a horizontal level is not disturbed. Then letting dt be the time in which the level rises dh, and v the velocity of the water at the distance of x from the place reached by the water, then we get the followtng relation,

$$xdh = vdt \cdot x \tan\theta,$$

whence

$$v = \cot\theta \frac{dh}{dt}.$$

The velocity of the water v is independent of x. And the smaller the angle of slope and greater the velocity with which the water rises, the greater will be the value of v.

We shall now select for illustration what we observed at Kamaisi. Although at Kamaisi the tunami advanced and receded several times, the level reached its highest point at its second onslaught, and was 3·9 m. higher than the normal sea level at that time, while its period is understood to have been 10 minutes.

Assuming now the change of sea level at the shore of Kamaisi to be of the harmonic type, we shall after substituting numerical values into the above equation, graphically express the relationship between the water velocity v and its height h with respect to various values of θ, see Fig. 1. The road on the Kamaisi waterfront stood 1·4 meters above the sea level at the time of the tunami, so that this height substracted from h gives the tunami height above the road on the waterfront. It was possible to know the maximum height attained by the tunami at this place by the large quantities of sardine fertilers adhering to the various structures in the town, which had been drying near the waterfront at the time of the tunami and were carried there by the water. The numerals in Fig. 3 denote the maximum heights of these marks left by the waters as measured from below the foundations of houses and other structures, and since we may regard that when the water height attained its maximum the water surface was in the condition of perfect horizontal level[5],

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[5] According to Mr. Nasu's determinations, the height of the water in the middle of the town of Kamaisi itself was somewhat lower than at the beach. In this paper it is presumed that the maximum height of the water was everywhere the same. See Nasu's paper in the same volume.

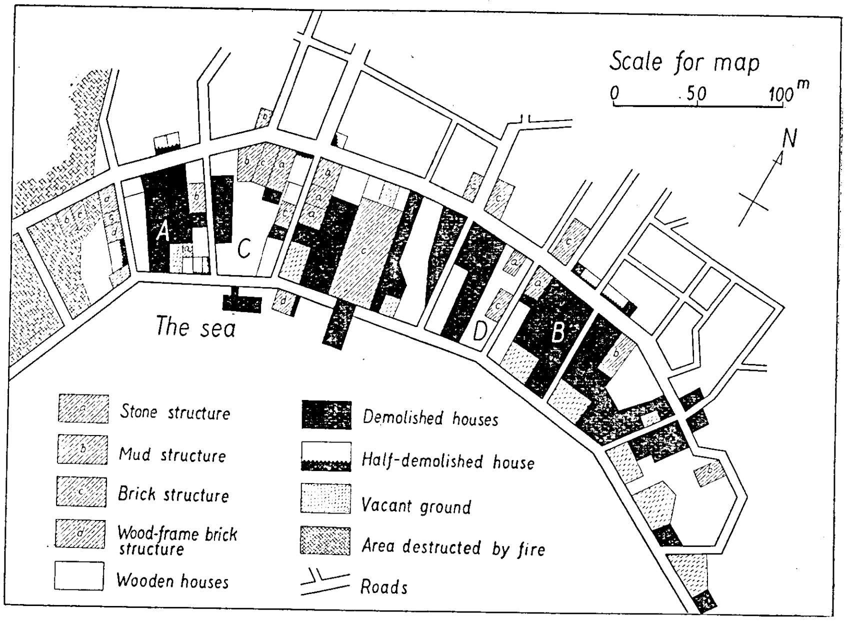

Fig. 2. Distribution of damage at Kamaisi.

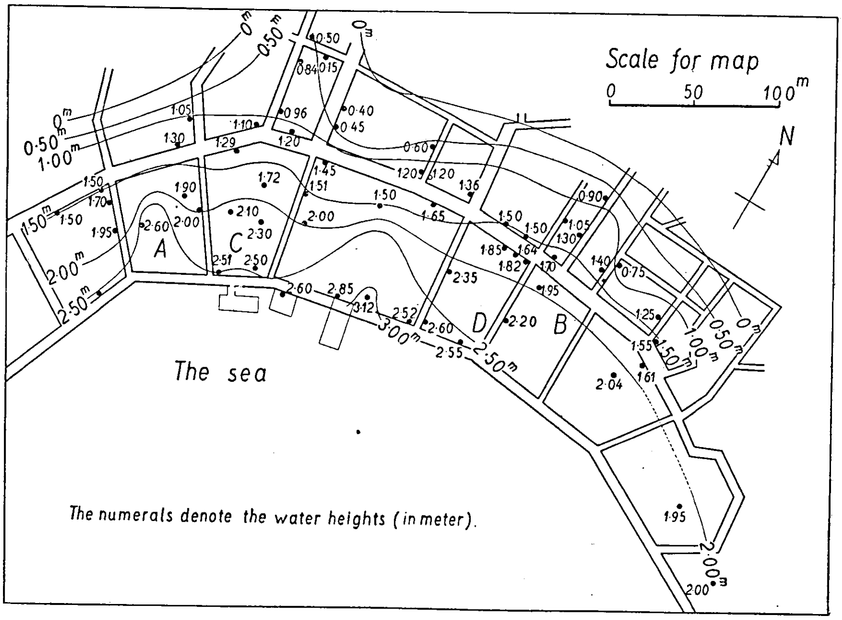

Fig. 3. Distribution of water height at Kamaisi.

we can get an idea of the topography of the district by reasoning backwards from these numerals.

According then, it follows that angle of slope near the Kamaisi waterfront is about 1/50. Then from Fig. 1, it may be deduced that the velocity of the tunami at Kamaisi was at maximum about 1 m/sec.

Fig. 2 gives the distribution of damage at Kamaisi. As will be seen from the figure, the number of houses demolished equal the number of these that were not. From this it may be concluded that the power for demolition of structures was near its critical limit, so that a structure was demolished or not according as conditions exceeded this limit or otherwise. According to Fig. 2, the stone, brick, and mud structures escaped damage. Moreover, the wooden houses that stood on the places where the ground is relatively high and accordingly the water was low, or those that received the water of low velocity, owing the presence of such a structure as stone building in the behind, escaped demolition.

In Fig. 3, parts A and B are depressed ground and the water was high compared with their vicinities, so that the houses in these places are severely damaged. At C and D, owing to the presence of stone structures behind it, the velocity of the water was curbed to a certain extent, so that they escaped demolition.

It follows from the foregoing that the wooden structures reached the critical state owing to the water having reached a height of 2 meters and were demolished with such small water velocity as of the order 1 m/sec, whereas most of the stone and brick structures were quite safe.

The above is a discussion based on the effects on structures due to the tunami, in which the process of inundation was supposed to be extremely slow, and the water level at all times maintained horizontal plane. In practice, however, when we deduce the velocity we should take into account the depth of the water and the inclination of its level, and bottom friction. And for this purpose the hydraulic formulas of Basin or Cutter are usually employed.

According to Basin

$$v=\frac{87}{1+\frac{\gamma}{\sqrt{R}}}\sqrt{RI},$$

where v is the water velocity, $R=\frac{A}{S}$ (here A is the sectional area of the water channel and S the length along the bottom in the section vertical to the flow) which, in our case, corresponds to the depth (H); I=the inclination of the water surface, and $\gamma =$ a variable coefficient for roughness of the bottom, ranging from 0·65 to 1·65. If now we neglect $\frac{\gamma}{\sqrt{R}}$, we have

$$v = 87 \times \sqrt{HI},$$

and puting $v = 1$ m/sec., $H = 2$ m., the inclination of the water surface I becomes approximately 1/15,000, and may be regarded as a perfect horizontal plane. In other words, in the case of the velocity of the tunami, until it reaches a number of meters per second, the surface may safely be regarded as level. In the onslaught of a tunami, so long as the waves are not very high, there is practically no change in the wave form; it advances without forming any breakers, and if we observe tunami at one spot there is only the phenomenon of gradual rise and fall of the surface. And even if the waves are very high, since a tunami wave is exceedingly long, there is no such breaking up of the entire waves as we see at the sea shore in the cases of ordinary sea waves; and as in the tidal bores of Whangchow[6] in China, only a front part of the wave surface break. But the places where this condition prevailed is confined where the water was very high or where the ground had very little slope, such as along rivers.

Since as just mentioned, the damage from a tunami depends on the height attained by the water and its velocity, in order to avoid its effects, high ground needless to say is the safest place for residence, and it would be dangerous to build on ground with very small slope.

It is a great pity that in the Sanriku region, owing to the particular topgraphy, most of the large towns stand where the ground is low and the slope gentle. Since in the event of a future tunami, all the phenomena above mentioned are likely to be repeated, the facts observed and here discussed should be borne in mind if a repetition of the disasters is to be averted.

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2. 津浪を海水の陸上溢流としての考察

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地震現象に伴ふ大規模の津浪は，海底の廣範圍に亙る地形的變動に依つて發生する一種の長波であると考へられ，實際には其の波長及び週期は比較的大である．斯様な長波は之を局部的に見る

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[6] 錢塘江.

ときは海水の運動は相當大なる速度を有する水流であるが，波長が大なることのために廣範圍の水が一樣に運動するに過ぎず，沖に於ける船舶は何等波動の存在を關知しない場合が多い．

斯樣な波動が海岸に到達した場合を考ふるに，沖に於ては上述の如き水流が存在しても波動に對する境界たる海岸に於ては水流は生じ得ず海水面の上下運動のみが主要なる現象となる．尤も淺所に於ては，平常我々が磯波に於て見る如く，波動の傳播速度は波高の函數となり，波の高部が前方の低部より比較的速かに進行する結果，波面の傾斜を次第に增加し爲めに破浪を生じ之がため幾分岸に向ふ水流を生ずる場合も皆無とは云へぬが，津浪の比較的高からざる所に於ては斯樣な現象は問題とならない．

海岸に於て單に水面の上昇が起る場合其の結果として陸上に海水の橫溢を生ずるときは此處に水流を生ずる．今回の津浪襲來の跡を見るに建築物被害は海水橫溢に依る水丈と其の際に生じた水速とに依り最も適切に說明し得られる．然も後者が家屋破壞に密接の關係を有するのである．水流を生ぜしめるためには後方に水が流入し得る空間の存在することが必要條件であつて，斯樣な條件を具へた場所にあつた家屋が破壞流失し，之と相隣した場所に於ても其の背後に丘等を控へ水の流動する餘地無き所に於ては家屋は殆ど損傷から免れて居り，一見奇異の觀を與へる現象は隨所に見ることが出來るのである．この事實は 1896 年 6 月 15 日の同地方の津浪被害の調査結果に照しても明かであつて，然も之と今回の場合とを比較對照するに，被害の局部的分布は極めて類似して居り，等しく背後の地形の影響を受けて居ることが知られる．若し假に屢々言傳へられる如く遙かに海中より水流が押寄せて來たものとすれば，其の背後の地形如何に關らず同程度の災害を與へねばならない筈である．

津浪の建物に與へる災害の要素としては建物を浸す水丈と水速とを舉げることが出來る．卽ち水位と水速と結合したものが或る極限を越すときは家屋は損傷する．津浪當時の水面の最高の位置は岩壁，建築物に殘された痕跡より知ることが出來るが，之に反し當時の水速を直接に示すものは何物も殘つて居ない．從つて水速の推定は或る假定に基く以外に道が無い．

海面が單に上昇する結果として，一樣な傾斜面を有する陸上に海水が橫溢する場合の水流の速度は計算に依り土地傾斜角の余切並に海水面の上昇速度に比例する事が知られるが吾々は之を釜石町の場合に當嵌めて最大水速 1 m/sec を得た．釜石町の海岸附近の浸水は約 2 m であつたが木造建築物の破壞せるものと，之を免れたるものと其の數相半し，木造建築物に對する水の破壞力がほぼ其の限界附近にあつたと見做すことが出來る．從つて釜石町の場合より推定して木造建築物は約 2 m の浸水に依つて破壞の極限に達し，1 m/sec 程度の水速に依つても全壞せしめられることが知られる．

津浪の被害は浸水の高さと水速に依るものであるから，此の災害より免れんと欲するならば，第 1 に高所を選んで住居するは勿論であるが，土地傾斜の緩かなる場所は同じく危險である．將來の津浪も恐らく同樣のことを繰返すであらうから何等か適切な方法を講じて再び災害が繰返されない樣に注意したいものである．