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SHŌITIRŌ HAYAMI, TŌJIRŌ ISHIHARA
AND
YŪICHI IWAGAKI

KYOTO UNIVERSITY, KYOTO, JAPAN

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Synopsis

For some years now the writers have engaged in the field study on some important topics of beach erosions. The purport of this paper is to report briefly the main results obtained therein. Following an introduction, in Chapter 2, wave observations made along the beaches of Toyama Bay and of Ise Bay around Tsu City are described. The observed breaker heights were well explained by the effect of wave refraction. From the wave observations made along the beach of Tsu City, it was further suggested that the mean wave energy is proportional to breaker heights just at the moment of breaking. In Chapter 3 another factor which causes, besides the wave refraction, the distribution of breaker heights, that is, the effect of fetch, is discussed along the southern beaches of the east coast of Ōsaka Bay, and it was suggested that for the beach erosion of this region the effect of fetch played an important role. In Chapter 4, the grain size distributions of the beach sediments together with the beach profiles along the same beaches in Chapter 2, are discussed. From the sand ridge towards the shore the beach profile has two distinct slopes, the one corresponding to the surf zone, the other corresponding to the up-rush zone — a zone over which the breakers at the shore rush up after breaking. The grain size of the sediments increases rapidly in the surf zone towards the shore and in the up-rush zone it becomes abruptly large. It was noticed that different hydraulics must be applied to these two zones. In Chapter 5, the results of wave observations at the beach of Sano City along the

same coast in the previous chapters are described. The wave profiles were recorded simultaneously with the particle velocity associated with a wave by the wave profile recorder and current recorder. Two distinct types of breakers were found, one which is called flow type has the maximum of velocity in the fore side of a wave, and seems to develop to a bore after breaking, while the other which is called wave type has the maximum of velocity at the crest of a wave and seems to crush after breaking. These two types of breakers are compared with the results of wave observations made in a wave tank. In Chapter 6, some results of observations of the sediment transportation along the up-rush zone at the same beach are described. It was found that for the breakers of flow type the net transfer of sediments is on-shore, that is, beach sedimentation takes place, whereas for the breakers of wave type the net transfer of sediments is off-shore, that is, beach erosion takes place.

1. Introduction

Beach processes have long attracted the minds of scientists and engineers. In the classical work of D. W. Johnson[1)], the various phases of beach processes are described in clear language and its comprehensive references tell us how wide is the interest of scientists in this field. But the physical science of beach processes is only of recent origin, especially it has developed during and after the World War II. From the point of wiew of coast engineering, the most important beach processes is probably, among others, the beach erosion and sedimentation.

In treating these processes, the insurmountable difficulty lies in the complexity of factors involved. Needless to say the principal factor is the sediment itself and it obeys the law of continuity of matter, and in case the quantity of sediment carried away from one place exceeds that transfered to the same place, an erosion takes place. In this process, however, the transportation mechanism plays an important role. It consists of advection, eddy diffusion and settling, of which the advection is effected by the wave and current, the eddy diffusion is caused by the wind stress, bottom stress and irregularity of waves, and lastly the settling velocity is determined by gravity and friction, while these agents are governed by meteorological and oceanographical conditions, bottom topography and the size, shape and density of sediment particles. The continuity of sediment is also governed by the boundary conditions, that is, by the supply of sediment from outside the system concerned. The main source of supply of sediments is river and to determine the quantity of sediment discharged from a river, is another difficult problem.

Today, we are far from analysing and integrating these processes theoretically and the totality of the problems to be solved constitutes the science of beach erosion. In recent years, however, a remarkable advance has been made in this field of science and an orientation of the problems seems to be established in general outline.

Among many important researches on this subject, the following poineer works deserve to be mentioned; Prediction of Sea and Swell by H. U. Sverdrup and W. H. Munk[2,3], Extension of Wave Refraction Theory by W. H. Munk and M. A. Taylor[4], Prediction of Long-Shore Current by J. A. Putnam, W. H. Munk and M. A. Taylor[5], Mathematical Theory of Breakers and Bores by J. J. Stoker[6], Experimental Study of Breakers by F. Suquet[7] and T. Hamada[8], Theory of Sediment Transportation by M. P. O'Brien[9] and S. Hayami[10].

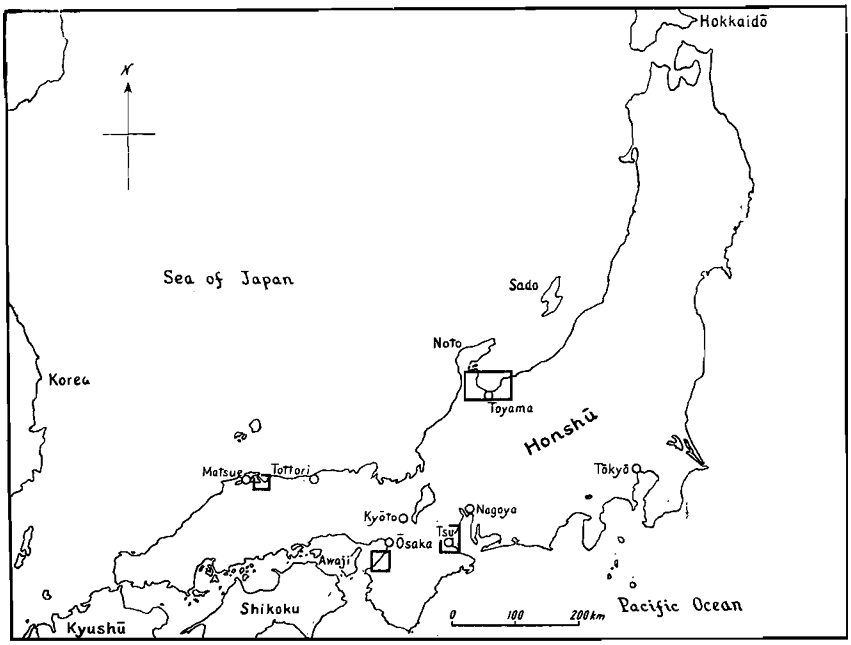

Fig. 1 Key map showing the sites of our beach survey.

As it is in every young science, the most desirable in the science of beach erosion is to get more observational materials and to devise useful theoretical tools. These several years the present writers are engaged in the field study on some important topics of beach processes along some coasts of Japan. In this paper, they wish to report briefly the main results of their observations and theoretical considerations on these results will be published in subsequent papers[11,12,13]. The observations were carried out along Yumigahama, Toyama Bay, Ise Bay, and Ōsaka Bay, the sites of which are shown in the key map Fig. 1.

2. Wave Refraction

2.1[4] The velocity of a surface wave is affected by the depth of water when the wave length becomes greater than roughly twice the depth. In this case, according to Snell's law in optics, the phenomenon of wave refraction occurs resulting in divergence and convergence of wave energy along a beach. The distribution of wave energy along a beach is well represented by a refraction diagram. The refraction diagram consists of successive wave fronts, or crests, and their orthogonals. The interval of originally equidistant two orthogonals changes in accord with the bottom topography and it is used as a sufficient measure of wave energy.

If we assume no energy loss before breaking, the mean flux of energy taken over one wave length contained between two adjacent orthogonals, must be invariant. From this condition, we get

$$E_0 V_0 S_0 = EVS \qquad \cdots\cdots\cdots(1),$$

where E mean wave energy per unit area
S distance between two adjacent orthogonals
V velocity of energy transfer

and suffix 0 indicates respective initial value. From (1) we get

$$\frac{E}{E_0} = \frac{V_0}{V}\frac{S_0}{S} \qquad \cdots\cdots\cdots(2).$$

For surface waves the ratio V_0/V is a function of relative depth h/λ_0 (h, depth of water; λ_0, initial wave length), so, along any isobath the ratio E/E_0 is proportional to the ratio S_0/S.

We cannot measure directly the mean energy E, but some thoretical relations exist between wave height H which is observable, and the mean energy E. For the oscillatory waves of small amplitude E is proportional to H^2 and for the waves of permanent type E is, according to Boussinesq, proportional to $(hH)^{\frac{3}{2}}$. For the oscillatory waves, therefore, H/H_0 is proportional to $(S_0/S)^{\frac{1}{2}}$ along an isobath, while, if we assume the waves near the breaking point to resemble the solitary waves, H/H_0 is proportional to $(S_0/S)^{\frac{1}{3}}$ at the breaking point, because H is nearly proportional to h at that point. But, at the breaking point, whether waves have really the character of solitary waves or not is a problem not yet solved. The ratios $(S_0/S)^{\frac{1}{2}}$ and $(S_0/S)^{\frac{1}{3}}$ are called the refraction factors and are usually denoted by K and K_b respectively.

We see, from the above deduction, that the wave is high at the converging places of a refraction diagram where refraction factor is large, and is low at the diverging places of small refraction factor. As the wave energy is transfered along orthogonals, the water flows from the region of divergence to the region of convergence and the beach erosion takes place at the place where the velocity gradient is most conspicuous, that is, nearly at the intermediate region, while sedimentation occurs at the converging region. This is one of the most important types of beach erosions, and there are many examples of this type. In the subsequent paragraphs two examples will be described from the writers' own observations.

2.2 Example 1.[13]

Along the southern coast of Toyama Bay which lies at the centre of Honshū, facing Sea of Japan, there are many places suffering severe erosions.

The waves in the Bay is specially large in winter due to monsoon from the continent. The submarine topography of the Bay is very complicated and is believed to have been formed on land. In some places fossil forests are found and the submarine valleys continue to present river valleys.

Many sediment carrying rivers empty into the Bay, among which the Jōganji, the Jintsū and the Shō are relatively large. Contrary to ordinary rivers, there are no shoals in and off the mouth of these rivers and along the beaches adjacent to the estuaries, erosions are marked.

Suspecting the beach erosion along this coast is mainly caused by wave refraction due to peculiar submarine topography, an extensive wave observation was planned under general supervision of T. Ishihara. The actual observations were carried out by the students of Civil Engineering, Toyama Technical Academy, under field direction of S. Saitō.

Beaches from Ichiburi to Uba fishery harbour, about 86 km, was selected as the survey region. This region was divided into 13 sections, the interval of which was 6∼8 km. To each section, one observation party consisting of 4 observers was assigned. About 100 observation points were selected along the whole sections, the mean interval of which was 0.87 km, the maximum and the mimimum being 2.7 km and 0.4 km respectively and at predetermined epochs each party made the wave observation at points in his section, moving from one point to another.

Observations were tried on 11th, 12th and 21st, Sept. 1952, but, owing to the weather conditions, only the last one was relatively successful, though the observations failed at several points. The epochs of the observation were 9, 10, 11, 12, 13, 14, 15, 16 h. At every point the breaker height, wave period, wave velocity and other wave and beach characteristics were observed. For the sake of comparison with other observarions, a base station was selected at Higashi-Iwase, nearly centre of bay head, and at every epoch wave observations were carried out. The breaker height was measured on the pole elected at the breaker point and the mean of relatively large ones among 20 successive breakers was taken. The wave period was measured by counting the number of waves per minute.

Though the actual waves were composed of one of various origins, the basic wave was swell to which the attention of observers was directed. The results of observations are shown in Fig. 2. As is seen from the observations at base station, waves became gradually large from 9 to 11h and thenceforth remained nearly constant. Corresponding to this general increase of breaker height, the wave character also changed gradually from a smooth form of swell to an irregular form caused by the superposition of wind waves of short period to the basic swell. This tendency was also observed at every other point. The fluctuation of observed periods shown in Fig. 2, though it is not so large, may probably be the result of this situation, and from which we may infer that the off-shore character of the basic swell did not change appreciably during most portion of observed epochs. The periods for the sections east of River Kurobe where they were definitely longer, seem to be an exception indicating that the waves observed there were quite different types as compared with those in other sections. In the following we shall only consider the waves in the sections west of the Kurobe.

For the sake of comparison with the theoretical expectation, several refraction diagrams were prepared. The conditions for those diagrams were as follows; periods, 7 and 10 sec; initial directions of propagation, from NNW, N and NE; intial interval of adjacent orthogonals, 500 m.

For the submarine topography we used a Japanese hydrographic chart. As the chart indicates only a general outline of the topography, espcially in the shallow region, we could not draw a diagram in detail. In Fig. 3 one example of refraction diagrams is shown. From these diagrams refraction factors were calculated along the beach and some results of which are shown in Fig. 2.

In spite of the local irregularities and perturbations of wind waves, we see from Fig. 2 that the general trend of observed breaker height coincides fairly well with the distribution of the refraction factor.

As the beach erosion occurs at the place where it is expected from the distribution of wave heights, we may infer that at least one of the basic causes of erosion along this beach is the wave refraction associated with the characteristic submarine topography of the Bay.

2.3[11] When a wave breaks at the shore all the wave energy is converted to the kinetic energy and the water rushes up the slope of the shore. We shall call the travel distance of up-rushing water up-rush distance

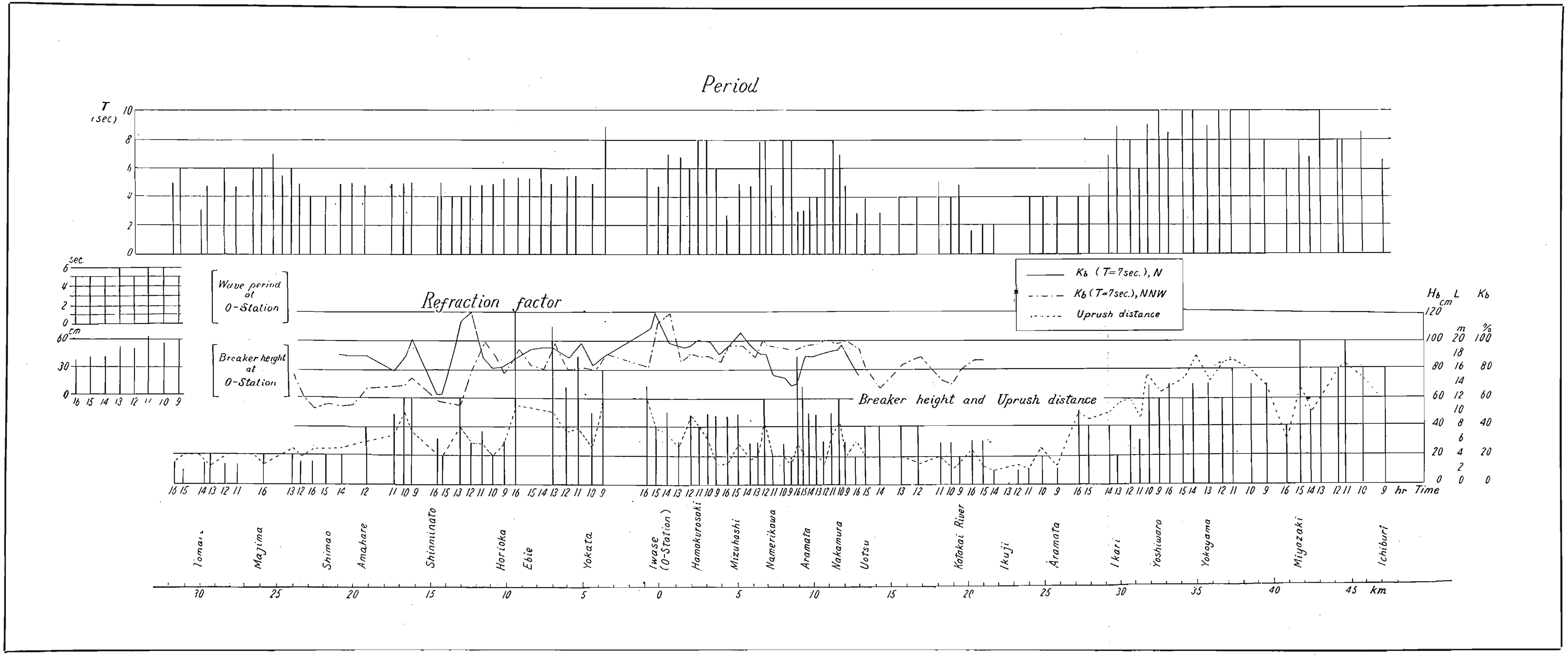

Fig. 2 Distribution of observed breaker heights, wave periods, up-rush distances and refraction factors along the beach of the southern coast of Toyama Bay.

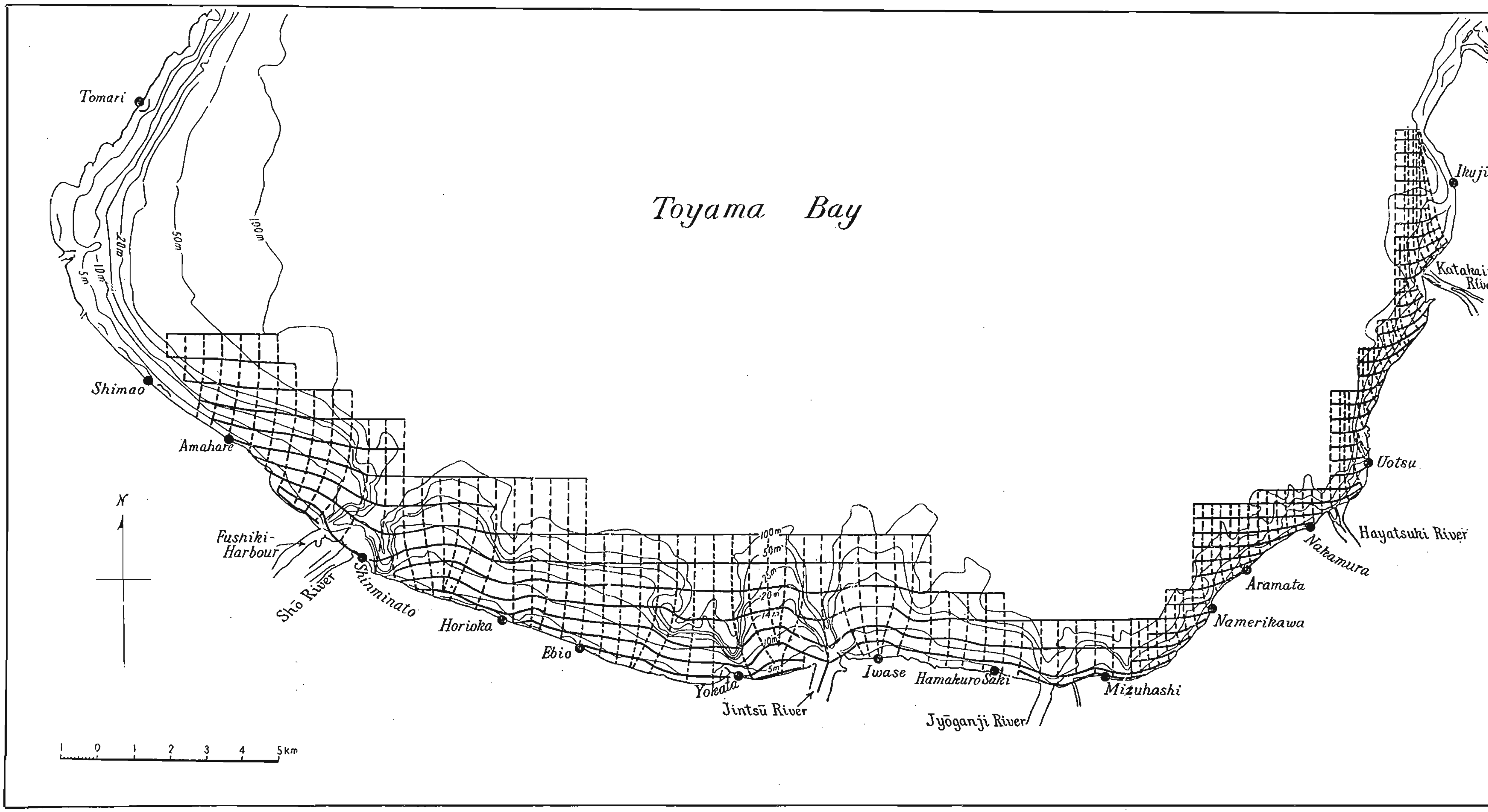

Fig. 3 Refraction diagram in Toyama Bay.

and denote it by L. The up-rush distance is frequently small for high waves because of the interaction of a breaker and return flow, but in the mean, it increases with the breaker height as is seen from Fig. 2 where observed L is compared with the breaker height.

As the zone covered by an up-rush distance — the up-rush zone* — is an important stage of sediment transportation, the study of distance L will be useful to the beach erosion. In 8 th~10 th, Nov. 1949 the writers with their colleagues made, first in Japan, wave observations similar to those mentioned above along the beach of Yumigahama, a large

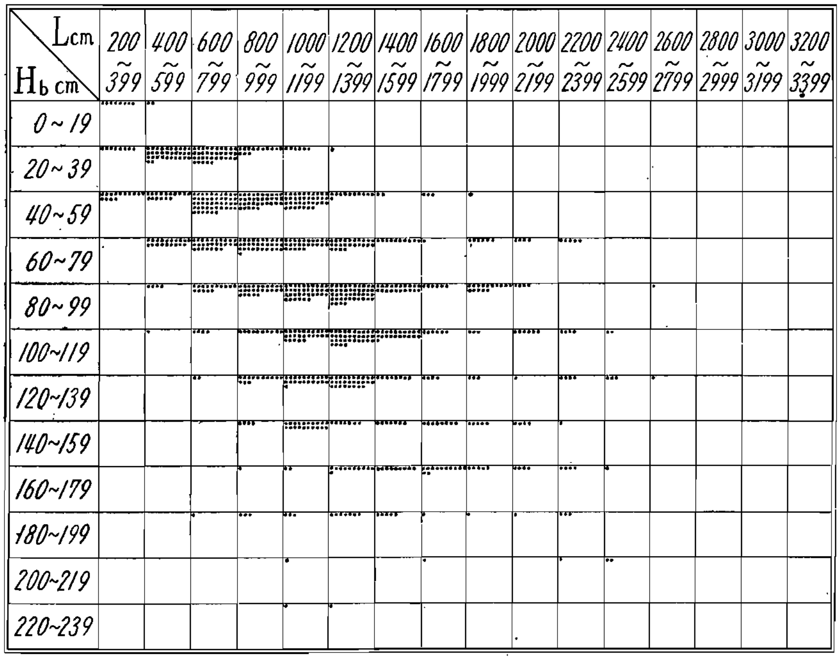

Fig. 4 Relation between wave height and up-rush distance.

tombolo developed in the north western coast of Honshū facing Sea of Japan (Fig. 1). In Fig. 4 the values L for about 1000 waves then observed are plotted against breaker height H, the number of observations being represented by the number of dots. The beach slope was about 10°, varing from 8°~12°. The scattering of points in the figure is large, but the correlation between H and L cannot be denied.

* The term up-rush zone here defined is a part of the shore in the terminology of D. W. Johnson[1], but, as it moves continuously along the shore, owing to the tide, the entire zone covered by the up-rush zone practically coincides with the shore.

2.4 Example II[14]

Beaches around Tsu City named Akogiga-Ura and Nie-Zaki are famous summer resorts. They situate nearly at the head of Ise Bay (Fig. 1). In former times the beach developed well, but in recent years, especially after the great Nankai earthquake in 1946, it gradually retreated and at some places the sea dyke is attacked directly by waves. As the ground level of large portion of the city lies below the sea level, it became an urgent problem to take some measures for beach protection.

The sediment of the beach is mainly supplied from the Kumozu, a heavy sediment carrying river which pours into the Bay at some distance south of the above beaches. The retreat of the beach in general may be explained by several causes such as an extensive ground subsidence associated with the great earthquake, the decrease of sediment supply from the Kumozu.

The erosion, however, is not uniform along the beach and to account for its special distribution, some other causes leading to this effect must be searched for. Our attentions naturally turn to the action of waves.

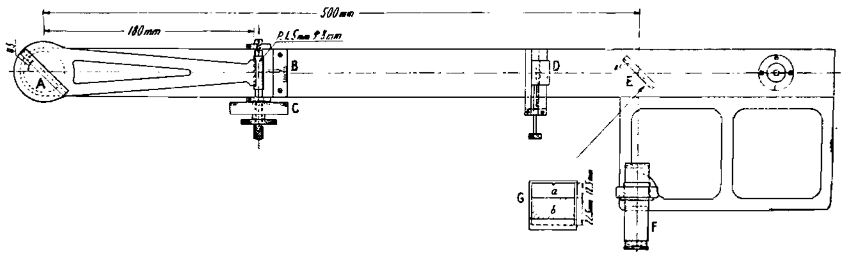

Fig. 5 Diagram of a range-finder modified of a sextant for wave survey.

Ise Bay opens to the Pacific Ocean and great summer swells generated in the zone of typhoon proceed directly to this beach through the bay mouth.

In order to investigate the effect of refraction of the swell upon the beach, a wave survey was undertaken by S. Hayami and his assistant I. Imai. The observations were carried out on 21st, 22nd, and 23rd, Oct. 1950. Along the beaches of Nie-Zaki and Akogiga-Ura wooden piles, 34 in all, were piled at the interval of 500 m (Fig. 6, below) and the wave observations were made at every pile.

To make simultaneous wave observations at many places along a long beach by small number of observers is not an easy task. For this purpose a special instrument was devised. Its general construction is shown in Fig. 5. It is a simple range finder modified of a sextant. The length of base line is 50 cm, at both ends of which two plane parallel mirrors A and E(G) are fixed vertically. The upper half of the mirror E(G) is transparent, while the lower half is silver plated. The mirror A is all silver plated and is mounted on an arm. The arm is fixed to the base plate and rotates around the vertical axes through the centre of mass of the mirror A. The length of arm is about 18 cm and by screw and dial C it rotates around the centre. The pitch of the screw is 1.5 mm and one revolution of the dial corresponds to 30′. By the scale on the dial we can measure the angle of rotation up to the fraction of 1 minute. The reading of degree is made by an indicator attached to the arm (B). In the field of telescope F the direct image of an object through E and the reflected image from A and E are seen. By rotating the mirror A so as to make these two images coincide, and reading the scale on the dial, we can easily obtain the distance of the object. The scale on the dial is also seen in the field of telescope by a convex lens D placed between the dial and the mirror E. The instrument is usually held by hand as a sextant or mounted on a cine-tripod. The instrument was calibrated experimentally and the calibration curve thus obtained was used in the practice.

The breaker height is measured as follows; we first determine the breaker distance by the sharp crest line and next by rotating the dial, make the crest line coincide with the trough line just at the moment of breaking. Then, reading the angle of view of the breaker height and multiplying it with the breaker distance we get the breaker height. Within the breaker distance of 20 or 30 m, we can get practically the breaker height up to a few cm. This instrument was used for our observations. We measured 10 breaker heights successively and took their mean. The wave period was determined by counting the number of waves for 1 minute.

The time spent for observations at one place was less than 5 minutes. To make observations as fast as possible we used a motor car for moving from one place to another. The observations were carried out 3 days, but, in view of the constancy of wave conditions, only those of the middle day, 22nd, Oct. 1950, will be described here. On the day, the weather was calm and the sea surface was smooth. The swells of small amplitude broke near the shore line and it was very easy and accurate to determine the breaker height. The observations were made at 22 stations from pile No. 1 to No. 22, and epochs of observations were $8^h 50^m$ at No. 1, $12^h 35^m$ at No. 13, $13^h 53^m$ at No. 14 and $15^h 43^m$ at No. 22.

The results of observations are shown in Fig. 6 (below). As is seen from the figure the wave periods were almost constant, in other words, the wave conditions were practically steady during the observations. The breaker heights were very low at piles No. 18 to No. 22, then increased rapidly towards No. 15, while they indicated secondary minima at No. 9 and No. 5. The beach erosion is marked at the places pile No. 14 to No. 18, No. 9 to No. 11, No. 8 to No. 9 and No. 5 to No. 6, and the facts are well explained by the observed distributions of breaker heights.

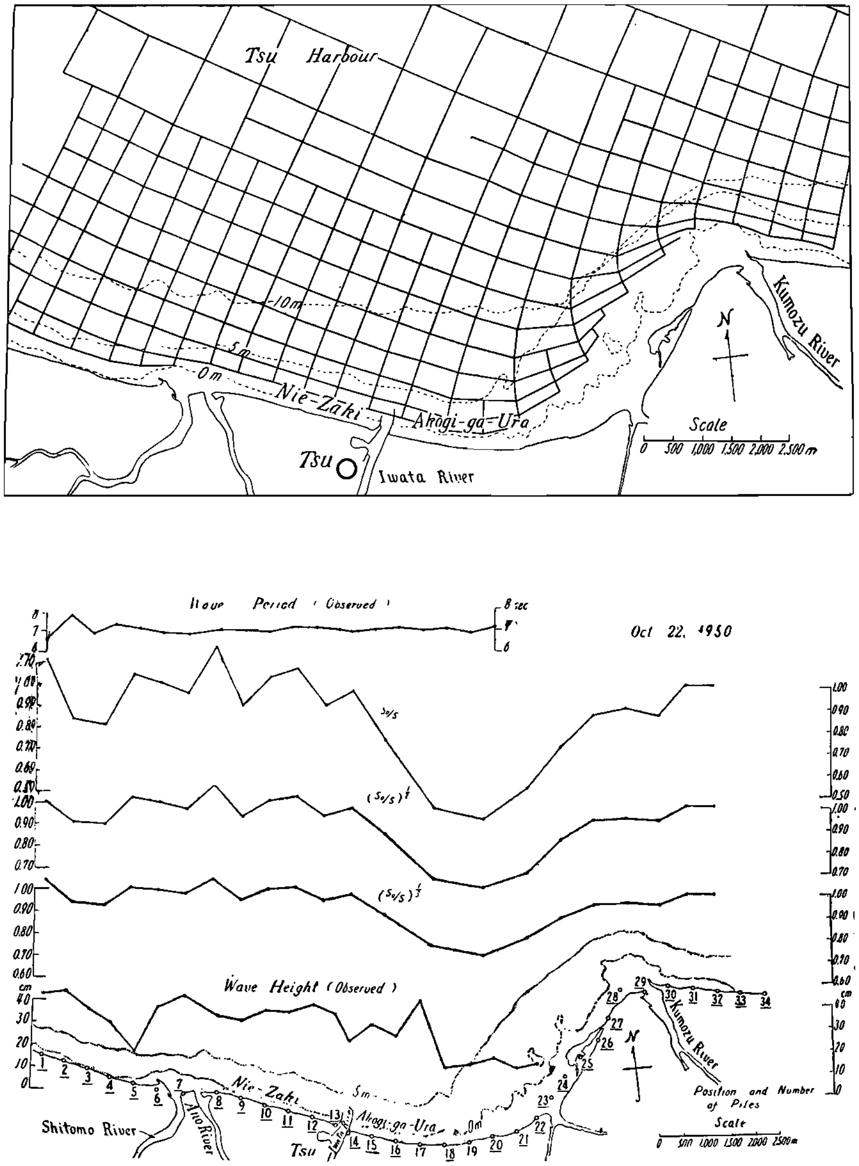

Fig. 6 Above. Refraction diagram in Tsu Harbour.
Below. Distribution of observed breaker heights, wave periods and refraction factors along the beaches of Nie-Zaki and Akogiga-Ura, Tsu City.

In order to confirm whether the observed distribution of the breaker heights is caused by the wave refraction or not, a refraction diagram was prepared. As the swells of observed periods, about 7 sec, cannot be generated in the Bay, they must come from open sea. Assuming they have proceeded straight towards the beach from the bay mouth, we have constracted a refraction diagram of the following conditions; the wave priod, 7 sec; the initial depth, 30 m; initial distance of adjacent orthogonals, 400 m. As for the bottom topography, Japanese hydrographic chart No. 95 (Tsu Habour, dated 1927) and No. 1051 (Ise Bay, dated 1947) were used. As an appreciable time has elapsed since these charts were made, some changes of bottom topography may be expected, especially on the beach. The refraction diagram in the vicinity of the beach is shown in Fig. 6 (above). Taking the interval of adjacent orthogonals at the depth of 1 m as the value of S, we have calculated various refraction factors such as (S_0/S), $(S_0/S)^{\frac{1}{2}}$. $(S_0/S)^{\frac{1}{3}}$ along the beach. They are

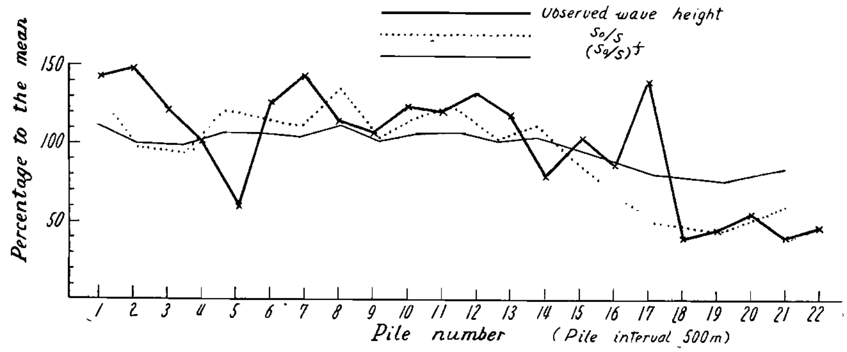

Fig. 7 Distribution of ratio of observed breaker heights, (S_0/S) and $(S_0/S)^{\frac{1}{3}}$ to their respective mean along the beaches of Nie-Zaki and Akogiga-Ura.

shown in Fig. 6 (below). The general trends of distributions of these factors are similar to one another and in spite of somewhat ambiguous topography of the beach, all of them seem to represent remarkably well the observed trends of breaker heights.

From the quantitative point of view, however, they do not represent the observed distribution equally well. Though the refraction factor $(S_0/S)^{\frac{1}{2}}$ or $(S_0/S)^{\frac{1}{3}}$ is usually used, it is very interesting that the range of variation of the observed breaker height is conspicuously large as compared with the variation of these factors, while the factor (S_0/S) seems to fit best with the observations. This is clearly seen when we take the ratio to the mean for respective quantities. The results are compared in Fig. 7. From Fig. 7 it may be inferred that the factor (S_0/S) really represents the observed variation of breaker height quantitatively as well as qualitatively. This result suggests that at least in our case the mean wave energy is proportional to the breaker height just at the moment of breaking—an important fact which deserves a further research.

3. Effect of Fetch[12]

3.1 There is another factor which produces, similar to a wave refraction, a non-uniform distribution of breaker heights along a beach. It is the effect of fetch. When wind blows for suitable duration over a limited sea surface such as an enclosed sea, a steady state prevails and the wave characteristics, such as period and height, are soley determined by the wind velocity and fetch. In such a case the breaker height differs from one place to another along a beach according to the distribution of fetch.

As the wind blows usually at some angle with a shore line, the wave front and, consequently, breaker line also make some angle with the shore line and causes a current parallel to the shore line in the surf zone—a long-shore current. If we assume the wind velocity and breaker angle to be constant, the intensity of a long-shore current will be determined mainly by the fetch. When the intensity of the long-shore current is enough to carry the bed sediments and has a distribution in accord with the fetch, the beach erosion or sedimentation must occur.

Of late years, the writers made an extensive study of beach erosions along the southern beaches of east coast of Ōsaka Bay, from Kishiwada to Kaigake (Fig. 8). These beaches also suffer a beach erosion, though its intensity varies widely from place to place. The cause or causes of the erosion is not yet clear. The landblock of this region slowly rises and falls in a geological sense and in quite recent years a tendency of subsidence is noticed which may be one of the basic causes of the erosion. But, considering many evidences, especially those of sediment transportations along the beach, the writers believe the above mentioned effect of fetch combined with the wave refraction is, among others, the main direct cause of the beach erosion.

The prevailing wind over the Bay is northerly in summer and westerly in winter, the latter is more intense and longer in duration. The wave front makes an angle (about 30°) with the shore line for both of these winds. A long-shore current originated of these wind waves flows northward in winter and southward in summer, the net flow directing towards north.

Along the beach there are many jetties and groins and sediment accumlates in winter south of and in summer north of them, though southern accumulation is more marked except along the southern part of the beach, south of Ozaki, where the northern accumulation is intense. Many small rivers pour into the Bay along the beaches in consideration. The quantity of sediments carried by them is negligible, except during occasional floods.

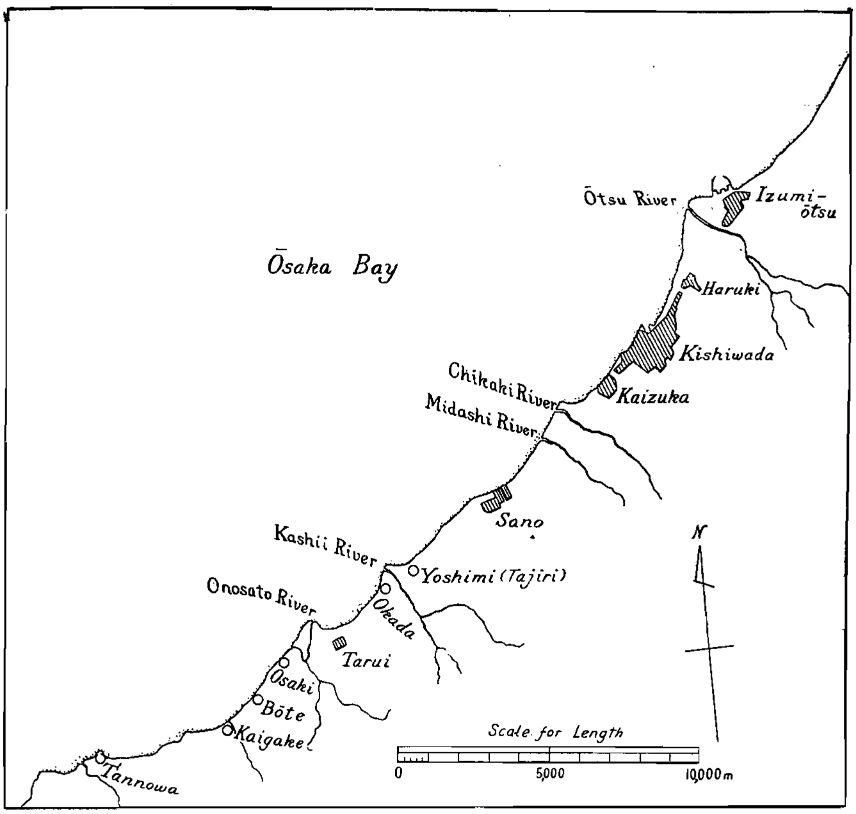

Fig. 8 Map of the east coast of Ōsaka Bay.

In general, the development of the beach along this coast is very poor. It develops gradually towards north and in the north of Kishiwada a well developed beach is first seen, while in the southern coast the beach occasionally lacks and in the south of Bōte the waves attack directly the cliff and a severe coast erosion is taking place.

3.2 In 2.1 we have derived the relations,

for solitary waves $\frac{H_b}{H_0} \propto \left(\frac{S_0}{S_b}\right)^{\frac{1}{3}}$ .... (3),

for oscillatory waves $\frac{H_b}{H_0} \propto \left(\frac{S_0}{S_b}\right)^{\frac{1}{2}}$ .... (4),

or

$$H_b \propto H_0\left(\frac{S_0}{S_b}\right)^{\frac{1}{3}} \qquad \text{.................. (3)}',$$

$$H_b \propto H_0\left(\frac{S_0}{S_b}\right)^{\frac{1}{2}} \qquad \text{.................. (4)}'.$$

In those relations, (S_0/S_b) is obtained from the refraction diagrams for the beach and H_0 is derived from the fetch graph by H. U. Sverdrup and W. H. Munk.[2] To calculate H_0 from the fetch graph is, however, somewhat troublesome, so we have prepared a diagram based on a fetch graph which gives directly from wind velocity and fetch the off-shore wave height H_0, wave period T and initial wave length λ_0, as shown in Fig. 9.

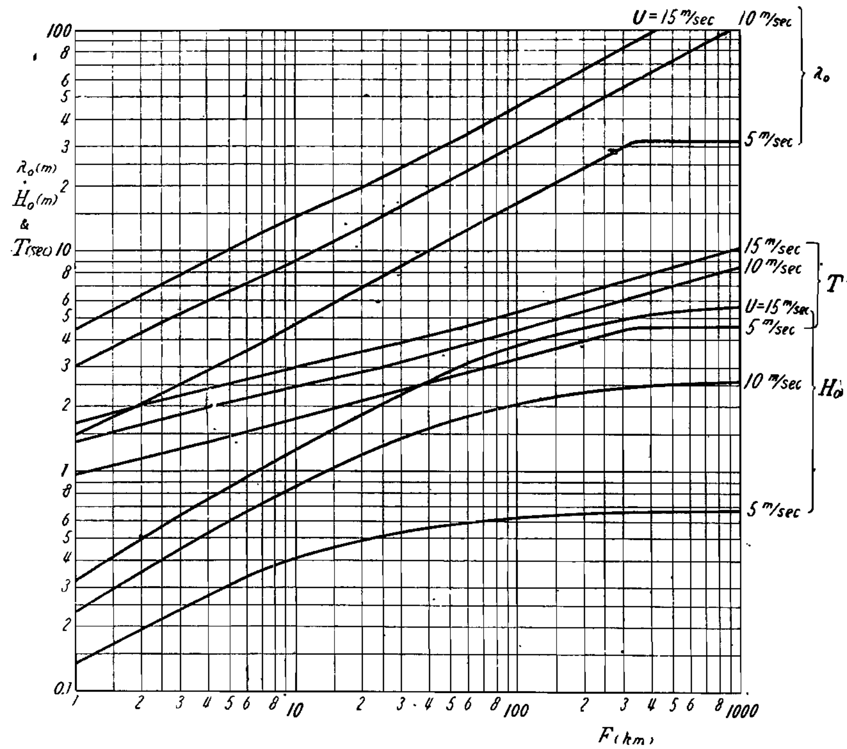

Fig. 9 Relations between H_0, λ_0, T, wind velocity U and fetch F.

From the map of the Bay we have measured the fetch at various places along the beach for westerly and northerly winds and from Fig. 9 estimated the corresponding values of H_0 for the wind velocity 15 m/sec. As the mean value of the fetch is about 35 km for both wind directions, the wave period becomes about 4 sec for the wind velocity 15 m/sec. So, we have prepared the refraction diagrams for the waves—period, 4 sec; initial direction of propagation, towards S and E—and calculated the respective value of (S_0/S_b). Then we could easily get the distributions of $H_0(S_0/S_b)^{\frac{1}{2}}$ and $H_0(S_0/S_b)^{\frac{1}{3}}$ along the beach which are shown in Fig. 10.

In Fig. 10, the general trend is due to the effect of fetch and the local fluctuations are the effects of wave refraction. The most remarkable local fluctuation is from Ozaki to Okada which is due to the effect of wave refraction by the shoals in the mouth of the Onosato. We can infer from Fig. 10 that the breaker height and, consequently, the long-shore current gradually increases northward for the westerly wind up to Kishiwada, and then decreases which will result in beach erosion from Kaigake to Kishiwada and sedimentation in the north of the latter, while, conversely, for the northerly wind the intensity of long-shore current will increase southward up to Kaigake resulting in an erosion from Haruki to Kaigake. The net effect is the beach erosion between Kaigake and Kishiwada and beach sedimentation in the north of Kishiwada.

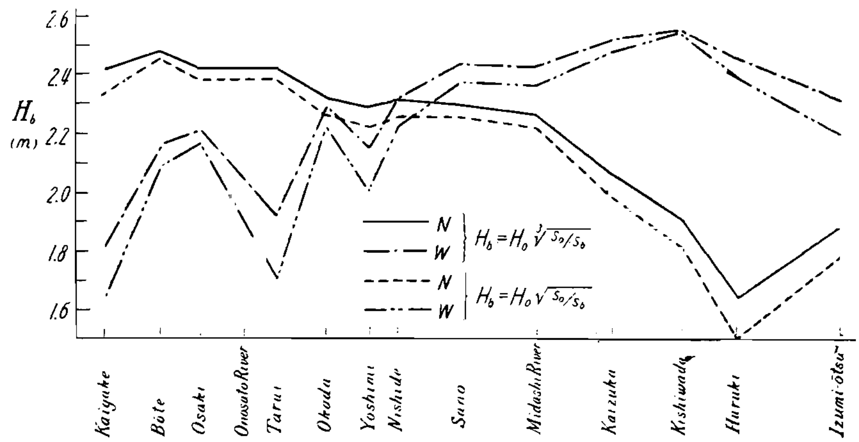

Fig. 10 Distribution of theoretical breaker heights for northerly and westerly winds along the southern beach of the east coast of Ōsaka Bay.

The beach from Tarui to Okada and that from Yoshimi to Nishide where the gradient of the long-shore current is specially large, are expected to suffer a severe erosion, and actually a severe erosion is really taking place there.

4. Beach Sediments and Beach Profiles[12]

4.1 As in the case of bed sediments of a river, the character of beach sediments such as the grain size distribution reflects the hydraulic conditions of the beach. In the beach study, therefore, it is customary to begin with an investigation of the beach sediment. We have collected beach sediments at 26 stations along the beach considered in the preceding chapter and made shieve analysis for each sediment by the usual processes. Sediments were collected at an interval of 10 m to the depth of 3 or 4 m below the mean sea level. Some examples of the results of mechanical analysis together with the beach profiles at respective stations are shown in Fig. 11.

The beach profile at each station, as is seen from Fig. 11, shows an off-shore sand ridge clearly at the depth of about 2 m. As this sand

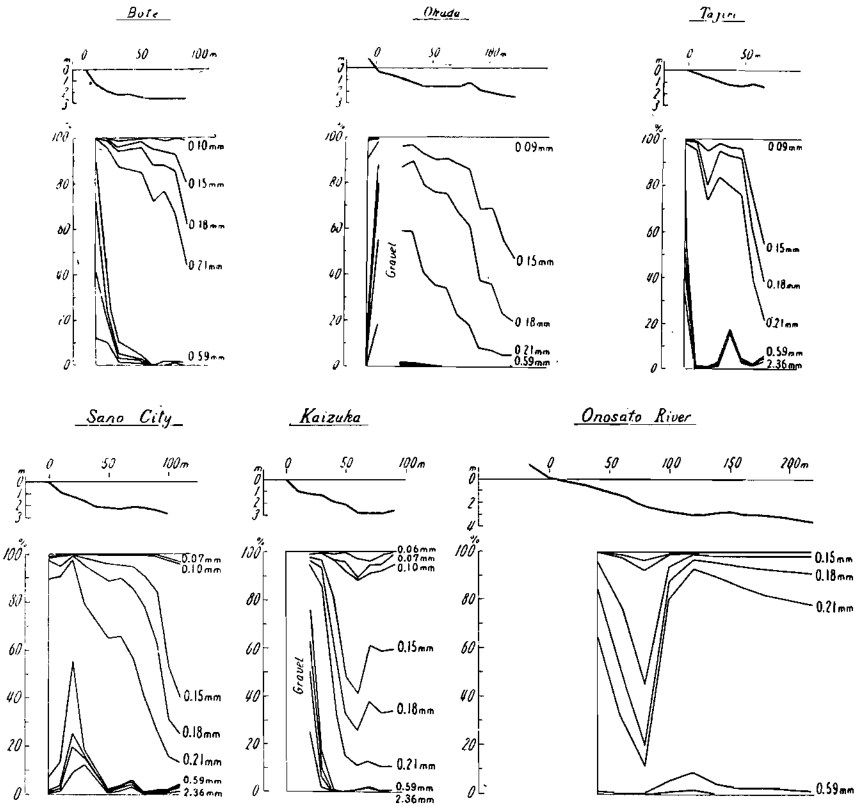

Fig. 11 Beach profiles and grain size distributions of beach sediments in the sections through some places along the same beach with Fig. 10.

ridge is believed to have been formed by the actions of breakers, the on-shore region from the ridge will be considered as the surf zone. Assuming the fetch graph and breaker index by H. U. Sverdrup and W. H. Munk,[2,3] we get, for the breaker depth of 2 m, the wind velocity 8 m/sec, the wave period 3 sec, wave steepness 0.082 and wave height about 1.2 m, where the breaker height is assumed to be nearly equal to the deep sea wave height for the large steepness under consideration.

The beach profiles show an abrupt change of slope at the depth of about 1 m and the on-shore beach slope from this point is about 10/100 (6°), whereas the off-shore slope from the point is about 2/100 (1°). As the tidal range of the beach is 2~3 m, the depth of about 1 m below the mean sea level corresponds to the low water level and the beach of large slope corresponds to the up-rush zone of shore breakers mentioned in 2.3, while the beach of small slope is always under water and its slope angle of about 1° is the value commonly observed for this part of the beach.

The up-rush zone and surf zone have thus distinctly different slope angles which indicate that the hydraulic conditions of these zones are quite different from each other. These two zones constitute the principal part of the beach from the point of view of beach erosion.

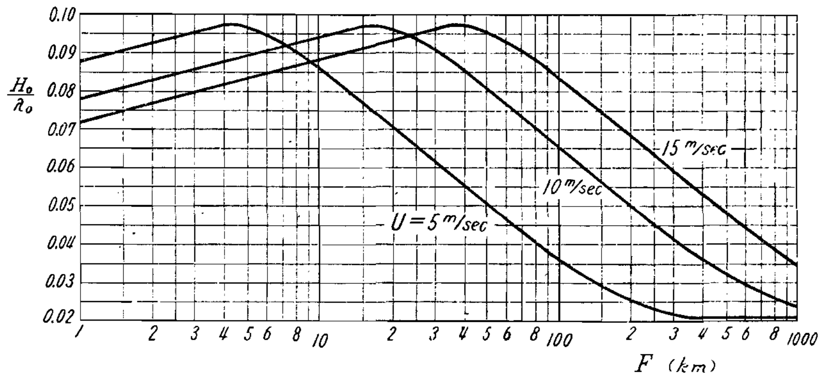

Fig. 12 Relation between wave steepness, fetch and wave velocity.

As we see in Fig. 11, the grain size of beach sediment rapidly increases in the surf zone from sand ridge towards the shore and in the up-rush zone the increase of grain size becomes abruptly large. While in the surf zone the main constituent of a sediment is from fine sand to medium sand, it is in the up-rush zone usually gravel or coarse sand. To the difference of beach slope corresponds the difference of grain size, but their functional interrelation is not yet explored.

The generation of the sand ridge gives a beach a special character. The long-shore current caused by the breakers flows in the surf zone and from the hydraulic point of view the surf zone behaves somewhat as a river. The sorting of beach sediments in the surf zone will be explained similarly with that of the bed sediments of a river. The sediment carried by a river is divided into two categories, one is suspension, the other is bed load. The grain size distribution of bed sediments is mainly determined by the bed load, whereas the suspension is carried away from the river system giving little effect upon the bed sediment.[10]

Now we shall estimate the intensity of long-shore currents along the beach. Assuming the depth of a sand ridge, about 2 m, to be the breaker depth and using the fetch graph and breaker index we get wind velocity 8 m/sec and the breaker height about 1 m for the fetch corresponding to both northerly and westerly winds. Then assuming the breaker angle with the shore line to be 30°, the beach slope 2/100, we get by the method of J. A. Putnam and others, the velocity of long-shore current about 1 m/sec for the breaker height above obtained. The grain size distribution of the beach sediments will be explained approximately by the current velocity of this order.

4.2 While the surf zone behaves as if a river, the up-rush zone is very peculiar with respect to the flow conditions, and the hydraulics of the up-rush zone is complicated. To calculate the velocity of up-rush and return flows in the up-rush zone, the method of J. A. Putnam and others seem to be inadequate. For this purpose the character of breakers at the zone must be taken into consideration which is probably one of the main problems of beach erosion. The special value of its slope is the expression of this process.

It has long been known that the up-rush zone has a well defined smooth surface and its slope seems to have connection with the intensity of prevailing wind.[16] In recent years, several evidences were found which suggested the slope of the up-rush zone had a close relation with wave steepness.

J. W. Johnson[15] made some model experiments on the equilibrium beach slope in his wave tank. According to him the near shore slope of a beach decreases with the increase of wave steepness and beyond a certain value of the steepness, roughly 0.03～0.05, a sand ridge is formed at some distance from the shore. He expressed the observed profile of the model beach for respective wave steepness with the non-dimensional parameters h/λ_0 and x/λ_0, where h is the depth, x is the off-shore distance from the shore line, λ_0 is the initial wave length; and obtained a sufficient result.

The initial steepness of a wave is given by H_0/λ_0 which is easily calculated from the diagram shown in Fig. 9 for various wind velocities. But, in order to estimate it directly from the fetch and wind velocity, we have prepared a new diagram which is shown in Fig. 12. It will be worth to notice that the wave steepness along the beach under consideration (mean value of the fetch, about 35 km) increases very rapidly with the wind velocity. We have calculated the values of wave steepness at some places along the beach for the wind velocities 5 m/sec, 10 m/sec, 15 m/sec and compared the actual beach profiles with the experiments of J. W. Johnson, showing some of which in Figs. 13 and 14.

From Fig. 13 we see that, for the wind velocity 5 m/sec, the actual beach profile roughly agrees with the experiments. In this case as λ_0 is equal to about 9 m, the main portion of the beach in the figure corresponds to the up-rush zone. On the other hand, for the wind velocity 15 m/sec, the agreement is not good, especially the actual up-rush zone is too steep as compared with the experiment. These evidences suggest that the up-rush zone of the beach is roughly in the state of equilibrium

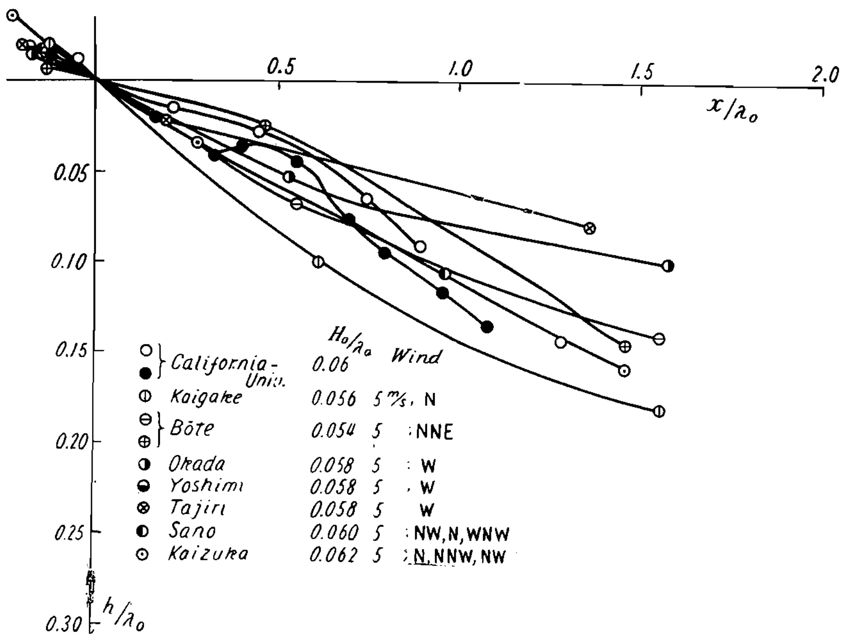

Fig. 13 Beach profiles represented in non-dimensional parameters (h/λ_0) and (x/λ_0) through some places along the same beach with Fig. 10. Wave velocity 5m/sec.

for the wind velocity 5 m/sec which is the most frequent wind over this region. Therefore when a strong wind blows over this region, the beach sediments will be carried off-shore so as to decrease the slope of the up-rush zone and, if at the same time this sediment is carried away by a strong long-shore current associated with it, the retreat of the shore line will not be recovered.

The physical processes that constitute the relation between the wave steepness and beach slope treated above, will be touched again in the next chapter.

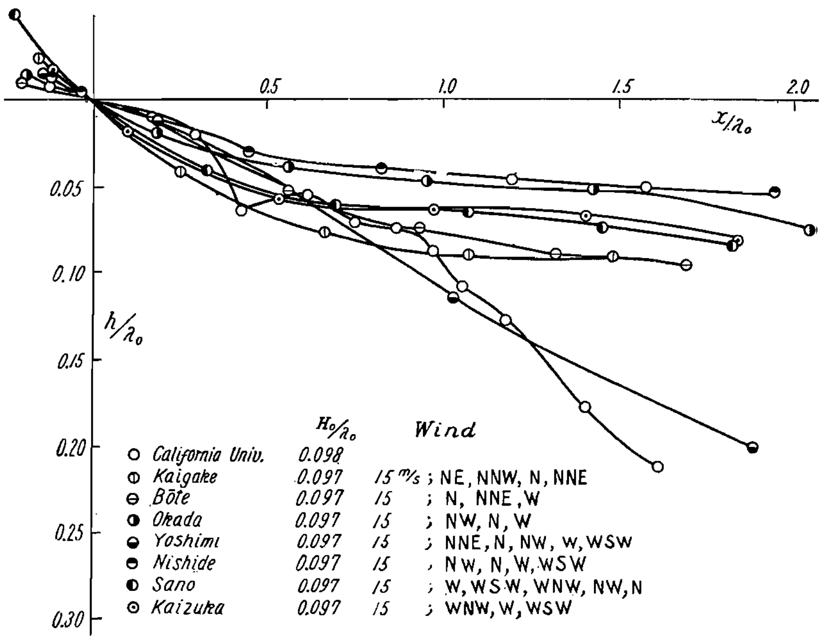

Fig. 14 Same with Fig. 13. Wind velocity 15m/sec.

5. Breakers Over A Sloping Beach[17]

5.1 Many workers, especially in recent years F. Suquet, T. Hamada and others, made an extensive wave observations along sloping beaches in their wave tanks, but as the water of a wave tank is limited, the results of its observation cannot be directly applied to the actual beach. For the sake of comparison, wave observations along the actual beach is very desirable. In the last summer the writers carried them out along the beach of Sano City which lies nearly at the centre of the beach considered in the preceding chapter (Fig. 8). The details of the beach is shown in Fig. 15. The length of beach is about 170 m, at both ends of which jetties are constructed.

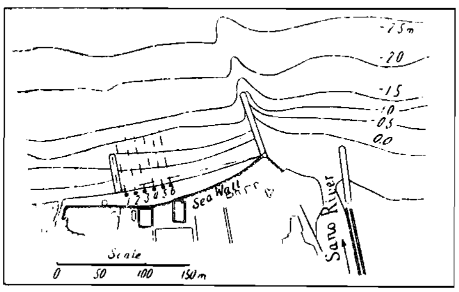

Fig. 15 Beach of Sano City where wave and sediment observations were carried out.

To determine the shape of the beach, six wooden piles were placed at constant intervals along the beach as shown in Fig. 15, and the beach profile was determined through every pile-spot showing the results of which in Fig. 16. The profiles of the beach show two distinct slopes, one corresponds to the up-rush zone has a slope of 6°, while the surf zone has an angle of about 1°. The inclined plane of the up-rush zone well develops and the waves of small amplitude break over the zone. These conditions were adequate for a study of breakers over a sloping beach.

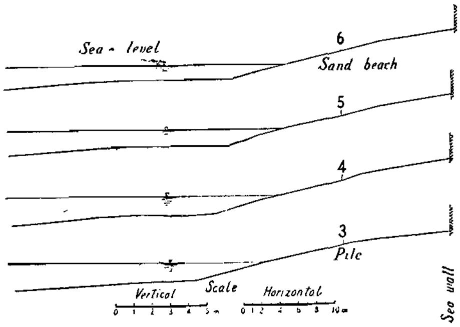

Fig. 16 Profiles of the beach shown in Fig. 15.

The writers measured wave profiles and particle velocities near the breaking point with automatic recording instruments. The wave profile recorder used was of the usual type of resistance. The main arrangement of the instruments is shown in Fig. 17 I. The under water portions of the instrument (B) consists of two nickel plated copper wires, which are insulated at their lower ends. The electric current flows through sea water from one wire to the other, and the resistance of water is directly proportional to surface level of the water. As nickel plated copper wire is liable to be attacked electro-chemically it is recommended for long observations to use platinum wires. The terminals of

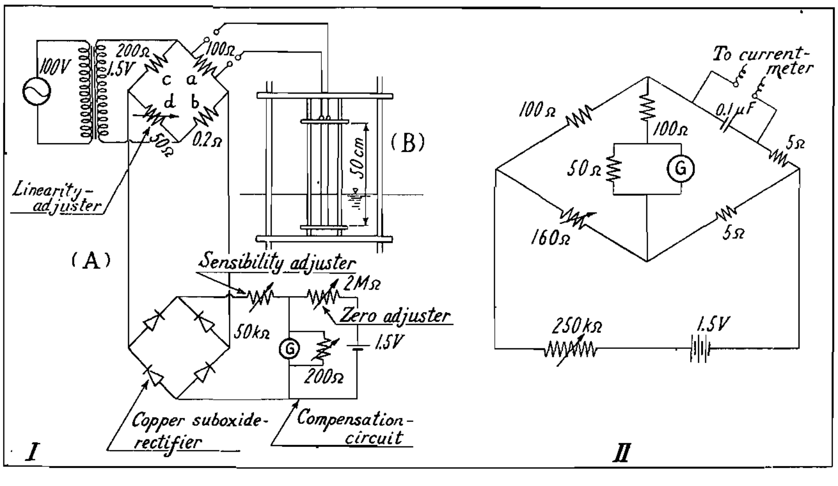

Fig. 17 I. Diagramatic sketch of the wave profile recorder (A) and wave meter (B).
II. Diagramatic sketch of the current recorder.

the wave meter were connected in parallel with one side of a bridge shown in Fig. 17 I(A).

Alternate current of the commercial cycle about 60 c was applied to the bridge through the tranformer. The voltage applied to the bridge was 1∼1.5 volts. The alternate current flowing out of the bridge was rectified by 4 copper suboxide rectifiers, and the rectified current was controlled by a volume control of 50 kΩ. To this rectified circuit another circuit containing 1.5 volts dry cell and 2 MΩ vari-ohm was connected which nearly compensated the rectified current, and thus only small fructuations of the current caused by wave motions deflected the mirror of galvanometer of the oscillograph.

We used three wave meters and their simultaneous records were taken on the oscillograph. The periods of galvanometers were about one second and used under the critical damping of 200 Ω. As the galvanometers have proper periods and their deflections are forced by wave actions, a certain phase lag will appear in the wave records.

The phase lag δ° is given by

$$\delta = \tan^{-1}\frac{2hu}{u^2-1}\,. \qquad u = \frac{T_p}{T_n} \qquad \cdots\cdots\cdots\cdots(5),$$

where T_p and T_n are the period of the external force and of the galvanometer respectively, and h is the damping factor of the galvanometer.

In the case of our observations

$$h = 1\,, \qquad u = \frac{2}{1}\sim\frac{3}{1},$$

so putting $u = 2.5$, we get

$$\delta \simeq 43^\circ \qquad \cdots\cdots\cdots\cdots(6).$$

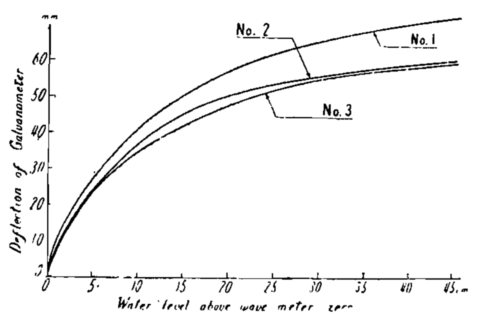

Fig. 18 Effective sensibitity curves of three wave meters used.

The effective sensibility was determined in the field for each wave meter, the results of which are shown in Fig. 18.

As the sensibility curves were not linear, it was a very tedeous work to reconstruct actual wave profiles. If we exchange the resistance of c with that of d in Fig. 17 I, the linearity would have been much more improved. The field arrangement of the instruments is shown in Figs. 20 and 21.

The current meter used for the measurement of particle velocities associated with a wave was usual one of the propeller type of about 5 cm in diameter. The propeller contacts twice during one revolution. One contact is made to be longer than the other, so that we can know the direction and velocity of flow by counting the number of contacts. The contacts of a current meter were recorded by the oscillograph. Its connection diagram is shown in Fig. 17 II. We used 3 current meters and their speeds were calibrated in the laboratory, the results of which are shown in Fig. 19. For the current meter No. 3 the calibration curve was different with the direction of the flow.

5.2 Some examples of the recorded wave profiles, which are adjusted for phase lag together with the simultaneous velocity changes are shown in Fig. 22. For the observations on 22nd (started 18^h28^m), shown in Fig. 22, three wave meters were set at an interval of 50 cm towards the sea and the middle of them recorded the waves just at the breaking, the shore-side one after the breaking and sea-side one before the breaking, while for the observation on 23rd (started 16^h37^m), in the same

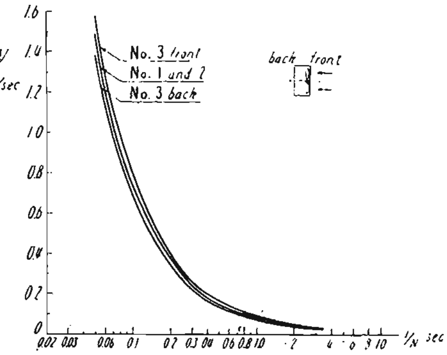

Fig. 19 Calibration curves of three current meters used.

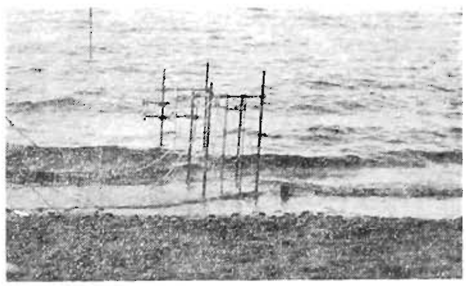

Fig. 20 Field arrangement of wave and current meters.

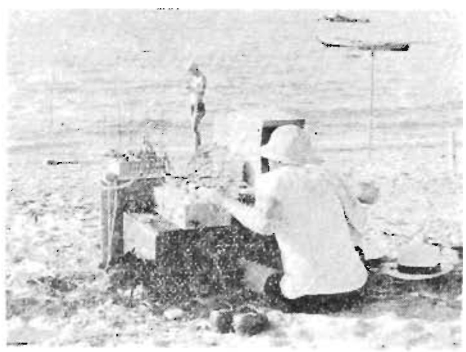

Fig. 21 Field arrangement of wave profile and current recorders.

figure, three wave meters were put at intervals of 50 cm and 1 m towards the sea and the conditions for waves for respective wave meter were the same with the above. The weather was very fine on both days. The current meters were fixed to the frame of the wave meters somewhat lower than the lowest level. Their positions are shown in the following table.

Time	Position (cm below mean level)	
	sea side current meter	central current meter
VIII 22, 18^h28^m	21.5	11.5
VIII 23. 16^h37^m	18.0	8.0

We notice in Fig. 22, two distinctly different types of breakers. We think this is very important and interesting finding. In the record of wave profiles on 22 nd, the maximum velocity nearly coincides with the crest of a wave, whereas in the record of wave profiles on 23 rd the velocity usually attains the maximum before the crest, that is, in the fore-side of a wave. We shall call the latter type as flow type, and the former as wave type. A breaker of flow type seems to develop to a bore, while a breaker of wave type seems to crush mainly at the breaking point.

The wave steepness seems to have some connections with the causes of these two types of breakers, but their inter-relations seem to be complicated. In order to search for the physical processes leading to these two types of breakers, the writers are now making an extensive wave observations in their wave tank under various conditions. As everyone who begins with a wave tank observation will immediately notice,[7,8] there are two types of breakers. An example of them is shown in the photograph (Fig. 23) taken in our wave tank.

The wave profiles in Fig. 23 was taken by a specially designed wave profile recorder. It consists of a light source of line filaments arranged in a straight line and cylindrical lens of about 1 m in length. The light source is focussed on the water surface where some quantities of aluminium powder are scattered, and the waves generated by a wave generator is photographed from a side in the direction $5^\circ \sim 10^\circ$ above the water level. In one type of breakers shown in Fig. 23, the foreside of a breaker is disturbed conspicuously, while in the other, an appreciable portion of a wave crest falls at the front of the wave and it does not contribute to the forward motion. Whether these types of breakers over the sloping beach in a wave tank agrees with the two types found in Fig. 22 or not, the writers cannot say yet definitely.

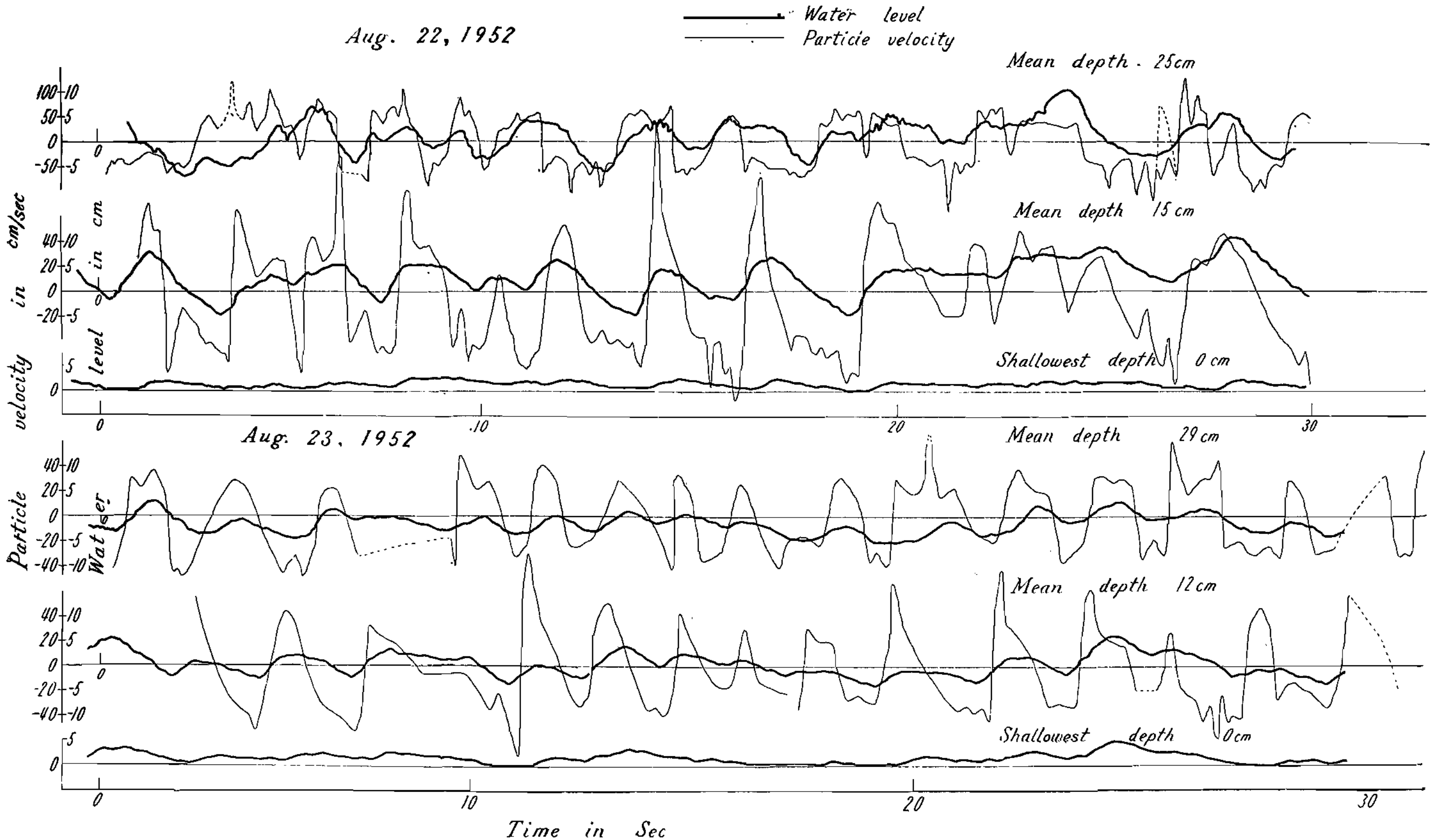

Fig. 22 Observed changes of sea level and particle velocity due to wave motions at the beach shown in Fig. 15.

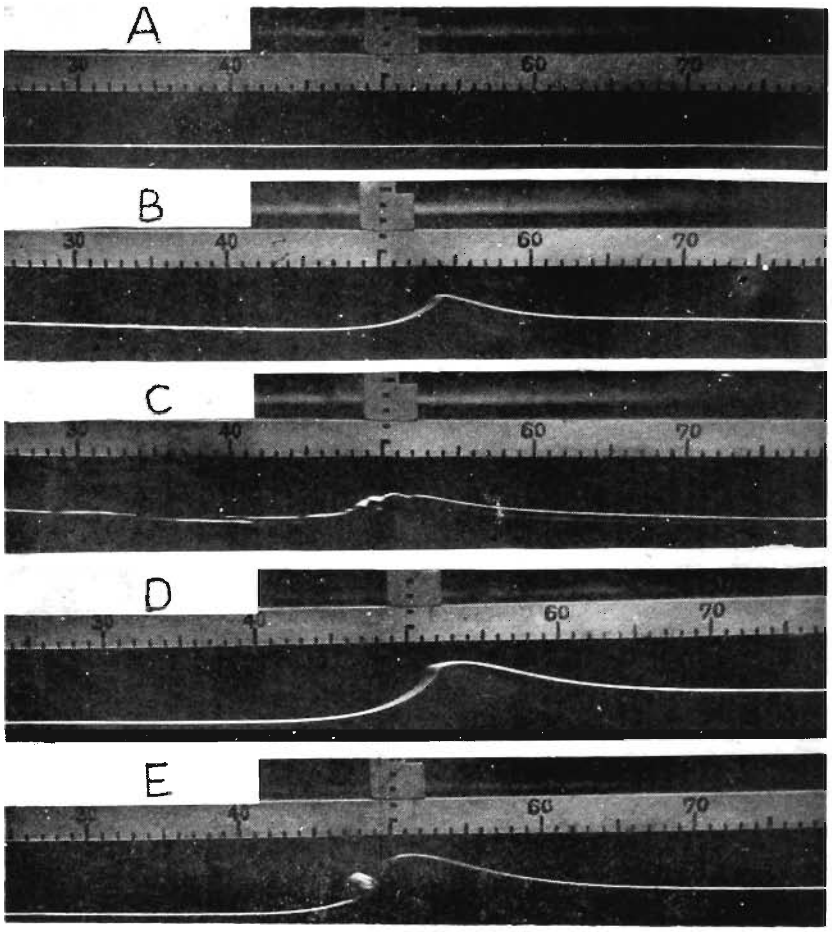

Fig. 23 Two types of breakers over a sloping beach observed in our wave tank. (Photo. by Haruo Higuchi)
A. Still water profile. Scale unit 1 cm.
B, C. Wave period 0.7 sec, depth of breaking 3.4 cm, beach slope 2°.
D, E. Wave period 1 sec, depth of breaking 4.6 cm, beach slope 2°.

6. Sediment Transportation Along An Up-rush Zone

6.1 Some observations of the sediment transportation along the up-rush zone were carried out parallel with the wave observations mentioned in the preceding chapter. For this purpose a simple sediment collector was devised: To an iron rod of diameter about 1.5 cm, length 1.5 m, four sand collectors were fixed perpendicular to one another. A sand collector is a brass tube of about 10 cm in length, diameter about 2.5 cm, at the back end of which a cotton bag is fixed so as to receive the captured sediment.

Two sets of sediment collectors were arranged on the up-rush zone, the collectors touching slightly the surface of the zone. They are shown diagramatically in Fig. 24 and their field arrangements are shown in Fig. 25. The sediment collectors were left usually for 10 minutes.

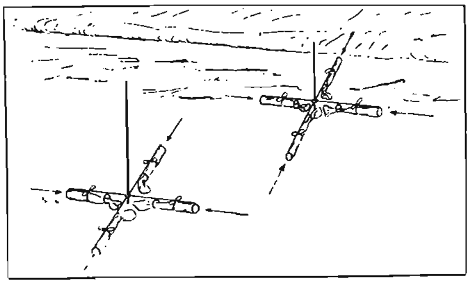

Fig. 24 Diagramatic sketch of sediment collectors.

The sediments collected in the bag were taken off, with the bag as a whole, from the collectors and were analysed mechanically in the laboratory. Observations of sediment transportations were not, however, carried out simultaneously with the wave observations, regrettable to say. But, for the sake of comparison with the wave observations shown in Fig. 22, the observations of sediment transportations

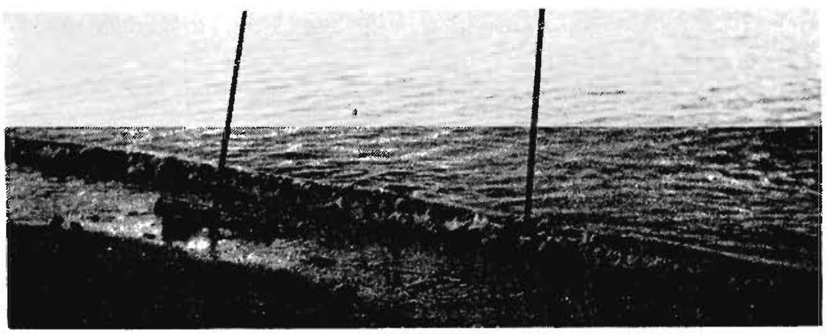

Fig. 25 Field arrangement of sediment collectors.

nearest to the epochs of wave observations are shown in Fig. 26.

We see from Fig. 26 that the net transfer of sediments in the example on 22nd ($17^h\ 35^m \sim 45^m$) is off-shore, while the net transfer of sediments in the example on 23rd ($18^h\ 26^m \sim 36^m$) is on-shore. From these observations of sediment transportations it may be reasonably inferred that the breakers of flow type cause the beach sedimentation and the breakers of wave type bring the beach erosion.

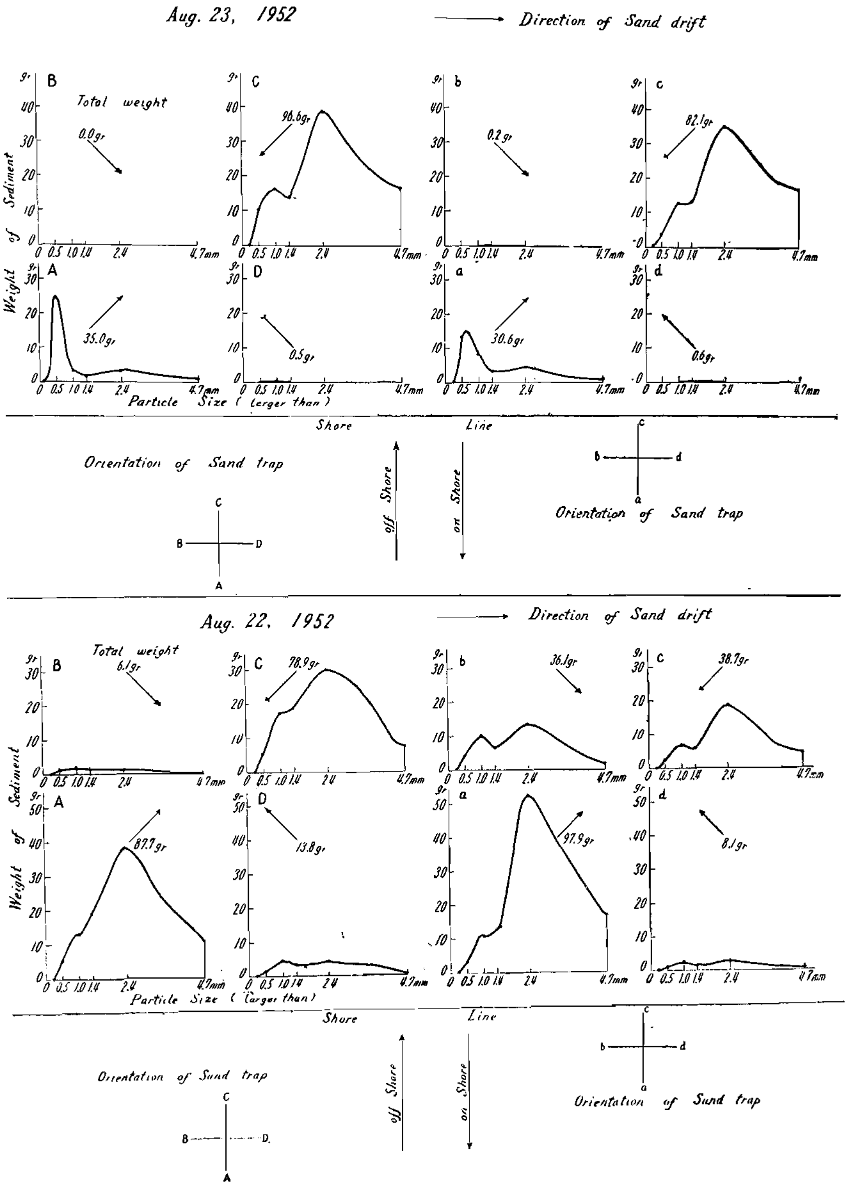

Fig. 26 Observed sediment transportations along the up-rush zone of the beach shown in Fig. 15.

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