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SHINOHARA, Kinji
Research Institute for Applied Mechanics, Kyushu University

TSUBAKI, Toichiro
Research Institute for Applied Mechanics, Kyushu University

YOSHITAKA, Masuo
Research Institute for Applied Mechanics, Kyushu University

AGEMORI, Chiaki
Research Institute for Applied Mechanics, Kyushu University

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SAND TRANSPORT ALONG A MODEL SANDY BEACH BY WAVE ACTION

By Kinji SHINOHARA, Tōichirō TSUBAKI,
Masuo YOSHITAKA and Chiaki AGEMORI

1. Introduction In this report, an attempt has been made to clarify the mechanism by which the sandy beach profile changes due to waves and to evaluate the beach sediment moving thereby, i.e., the amount of beach drift. Beach drift is supposed to move on the beach surface by waves near the shore, especially by the breakers, or to float and transport by longshore current. Such phenomena of the beach drift moving by waves and changing shore line as this have been already given three dimensional experiment by Saville[1] and Johnson.[2] And Dr. Iwagki[3] has also conducted measurement of two dimensional equilibrium profile and the distribution of sand transport which is in normal direction to shore line, obtaining interesting result respectively. In these experiments, however, sand of 0.3 mm was used for beach sediments and the properties of the waves of deep water were so much alike. and if the result is applied to actual sandy beach, it seems to correspond to the case where the beach sediment size is comparatively large. Judging from the important part played by the sediment size upon the non-dimensional representation of tractive force of flow, the distribution of concentration of suspended load and its amount in sediment problem in rivers, the effect of beach sediments is considered to be extremely great. Accordingly, when experimental results are to be applied to actual sandy beach, it is necessary to enlarge the sediment size to a wider range and to establish similarity between the property of beach sediments and that of waves. From such viewpoint as this, the authors have tried in this experiment to investigate sand transport by wave action at the beach of small sediment size by reducing the specific gravity, using pulverized coal instead of small size of sand. If classified roughly as in the case of river sediment, the form of sediment transport may be divided into the traction near the bottom and suspension, and in view of little attention hitherto paid to it despite of its practical importance as the cause for beach drift, they also measured the amount of bed-load as well as that of suspended load.

2. Experimental Apparatus and Method The experiment was carried out in a water tank of organic glass, stiffened steel frame works, 50 cm wide, 50 cm tall and 20 m long. The wave making machine was of flutter type and its general view is seen by the Photograph 1 and 2. In this tank was made a model sandy beach, 4.5 m long in the part of slope and 1/10 in gradient, as shown in the Photograph 3. The depth of the water was made 35 cm at all cases. As to the measurement of wave property, wave length and mean wave height were evaluated at the adjacent part of the beach end by an electric point gauge, transforming it into the quantity of wave of deep water by the theory of waves with small amplitude. Height of breakers, breaking depth and the change of wave height near the plunge point were

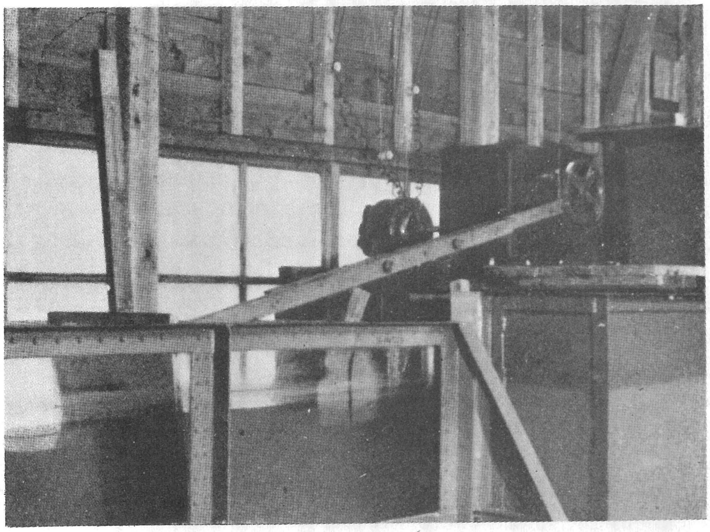

Photo.-1. Wave making apparatus (1)

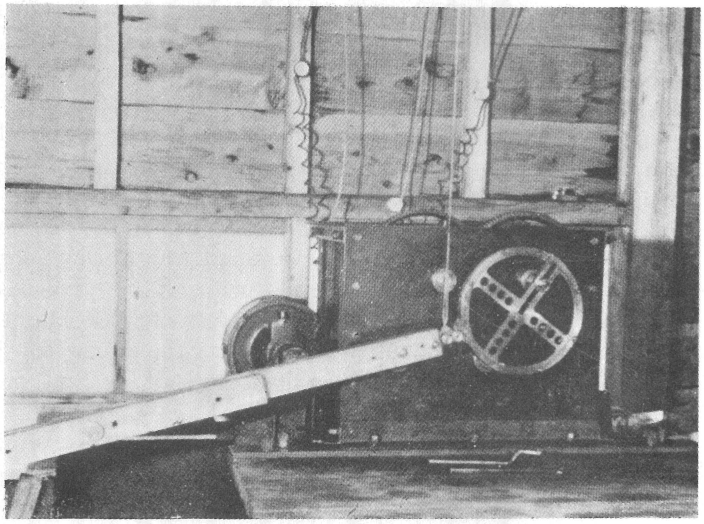

Photo.-2. Wave making apparatus (2)

determined by piecing together the results of measurement from the side as well as those from pictures and electric point gauge. The Photographs 4 and 5 show the electric point gauge used for measurement deviced by Mr. Awaya of this Institute.

With a view to catching the sand that moves near the bottom, the authors adopted the method to bury at the bottom a sand trap which is provided with a rectangular opening, about 5 cm long and 3 cm wide, nearly the same

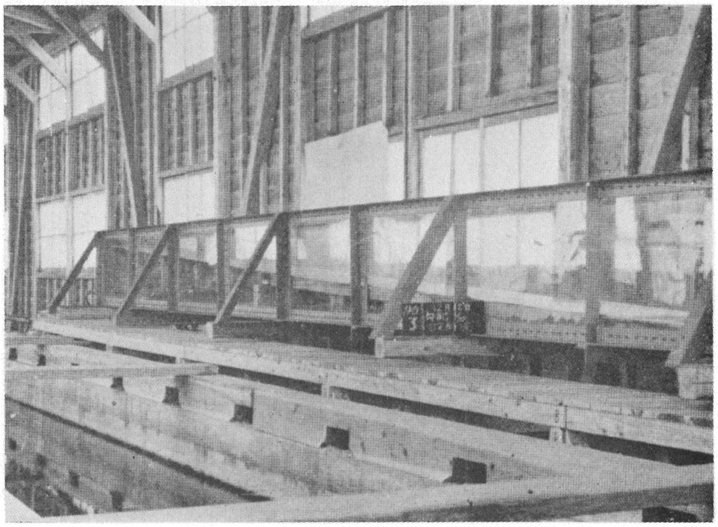

Photo.-3. Water tank

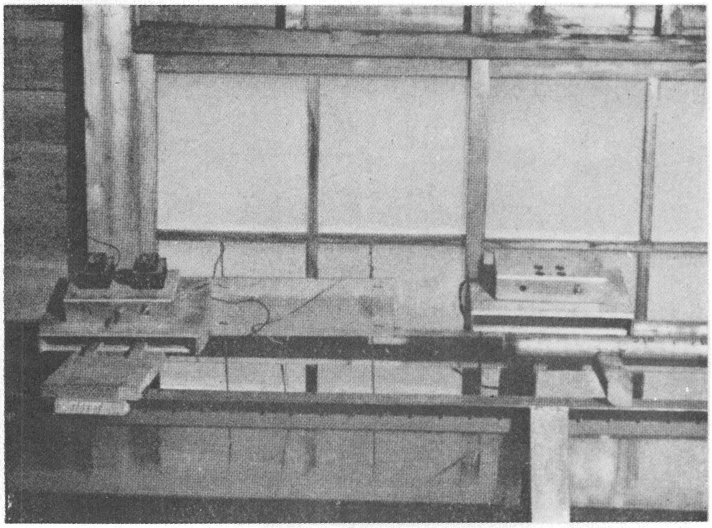

Photo.-4. Electric point gauge (1)

with the apparatus used by Dr. Iwagaki. The sand trap was allotted one per a section, and measurement was carried out while sucking out the sand that fell through the opening together with water by means of siphon, putting no distinction between uprush and backrush. In using siphon, it is desirable to make its absorption rate as small as possible, because it leads to overestimate sand amount due to the generation of downward velocity on the surface of the sand trap. However, as the pipe becomes choked if velocity

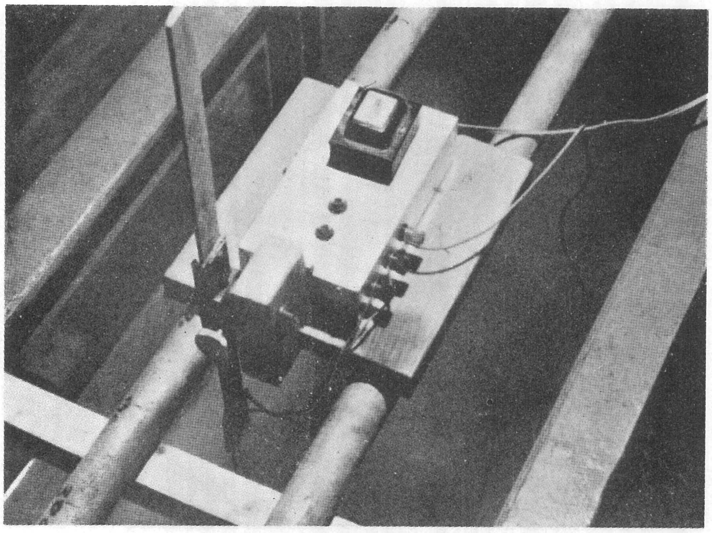

Photo.-5. Electric point gauge (2)

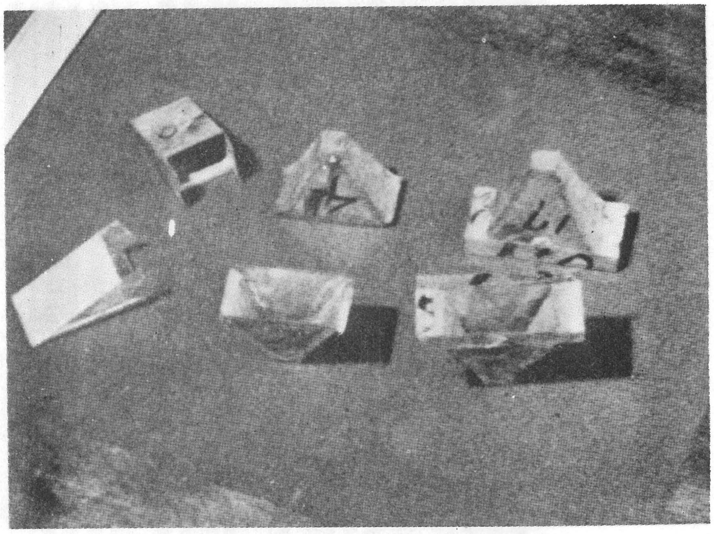

Photo.-6 Sand traps catching for bottom transport

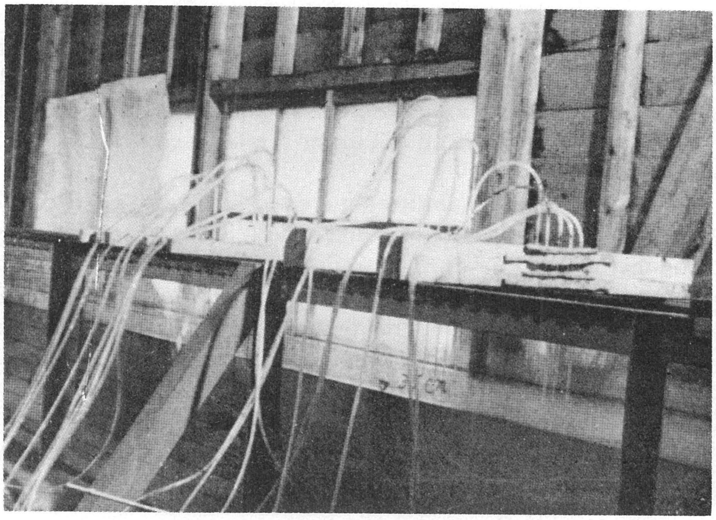

Photo.- 7. Sampling suspended load

is too small, the standard for this experiment was placed at the condition where the velocity at the sand trap is almost equivalent to the settling velocity of sand and pulverized coal respectively. By the way, in order to prevent sand from falling into the hole sideways, flanges were installed at the sides; 2 mm one for sand, 1 cm one for pulverized coal.

As it is impossible to sample sand with siphon on the land-side from the shore-line and as amount of transport also changes considerably according to the distance from the shore-line, measurement was made by burying a sand trap of 2 cm long and 3 cm wide for a given time and taking it up by hand. These sand-traps are shown in the Photograph 6. The distribution of sediment concentration in depth direction of each section was examined, sampling suspended load with siphon by arranging glass tubes of 2 mm inside diameter 4～10 per a section in zig-zag lines, covering the entire range in which sand moves from the beach-line. The Photograph 7 shows the condition of sampling suspended load.

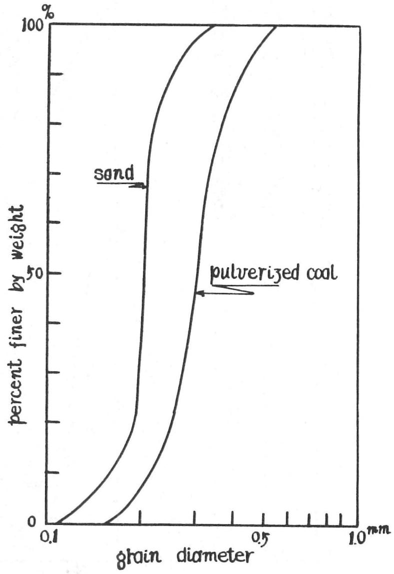

Fig.- 1. Grading curve for beach sediments

The beach sediments used for experiment are sand and pulverized coal with such grading curves as shown in Fig. 1, whose mean diameters are respectively 0.2 mm and 0.3 mm and almost uniform. Specific gravity of sand was 2.66 and that of pulverized coal 1.29. The settling velocity of sand and pulverized coal which was evaluated by dividing both according to diameter and was averaged by adding weight to grading distribution were respectively 2.19 cm/s (water temperature 15° C) and 1.14 cm/s (water temperature 25° C).

The property of wave submitted to experiment was 0.59 ~ 1.65 sec. in period, 1.99 ~ 5.68 cm in wave height and 0.00922 ~ 0.0685 in initial steepness.

As to the method and order of experiment, suspended load was measured after four hours from the beginning, when the beach was assumed to have nearly reached to its equilibrium condition, then beach profile was measured after 5 ~ 7 hours both at the sides and the central section and after that, measurement of the amount of sand transport on the bottom was done by means of sand traps.

The result of experiment obtained by the above-mentioned method looks like the attached table, a part of which will become Fig. 2, when illustrated.

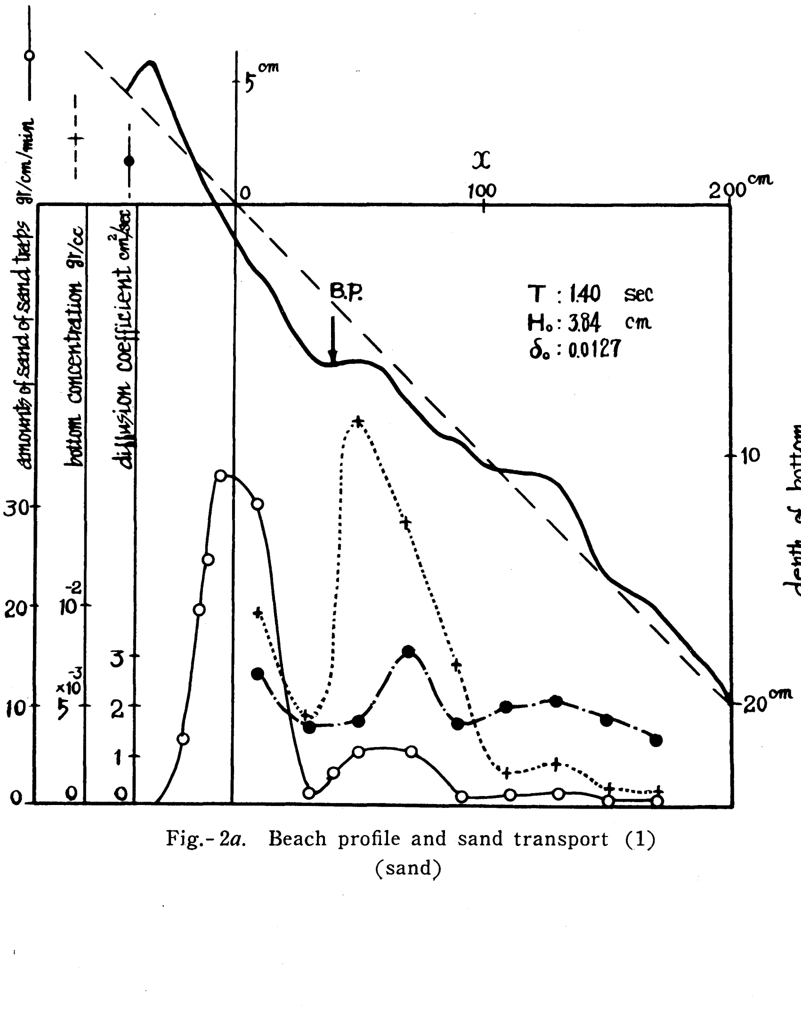

Fig.-2*a*. Beach profile and sand transport (1)
(sand)

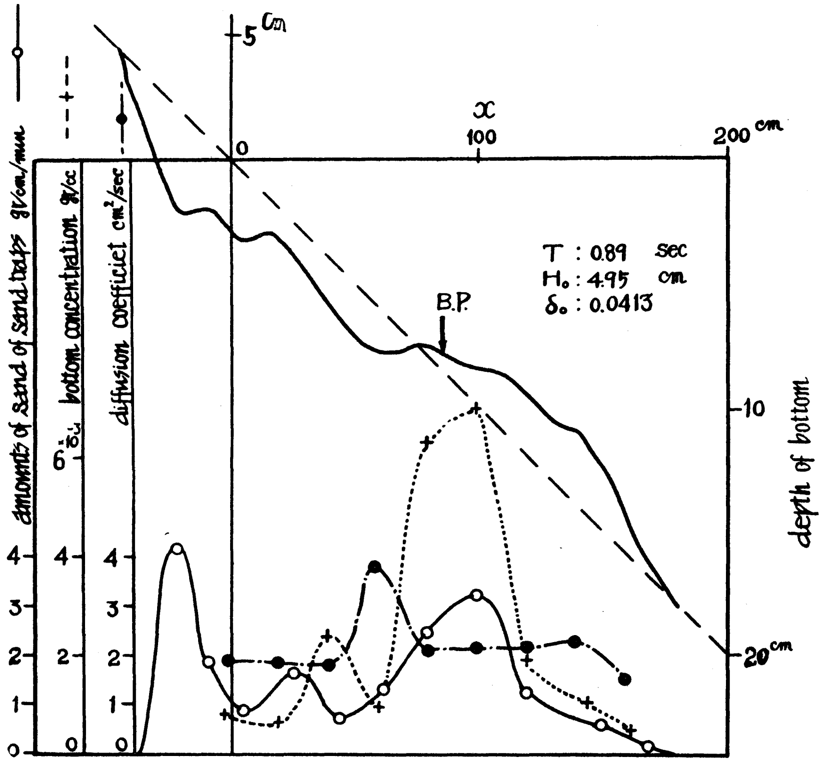

Fig.- 2*b*. Beach profile and sand transport (2)
(sand)

The original points in the figure are the shore line on the slope 1/10, and what is called "the amount of sand trap sand" represents the amount of sand that moves back and forth near the bottom. Explanations concerning to bottom concentration and diffusion coefficient will be given in later chapters.

3. Beach Profiles

When a given wave of deep water is sent to beach of a slope 1/10, it is gradually changed, approaching to a equilibrium condition corresponding with the characteristics of wave of deep water and the properties of beach sediment. Letting the depth from still water surface to the bottom be h to express this profile (Fig.-3), h is considered to be the function of (1) the property of waves, (2) the property of beach sediment, (3) the distance x from shore line which is made origin. As the properties of waves, wave height H_0, period T, gravitational acceleration g or wave length L_0 are considered, and as the properties of sediment, specific gravity of beach sediment in the water s and granular diameter D are considered. Accordingly, taking axis x to the open sea makingshore line origin, the beach profile reaching

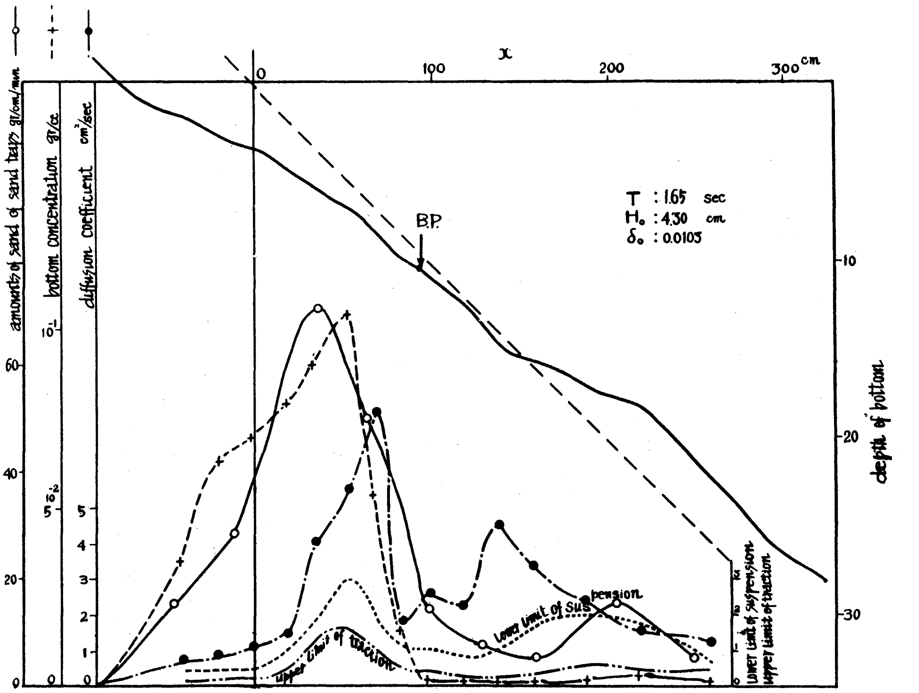

Fig.- 2c. Beach profile and sand tronsport (3)
(pulverized coal)

to a equilibrium condition is considered to be expressed by the following functional form:

$$h/T^2 g = f(x/T^2 g,\ H_0/T^2 g,\ H_0/sD,\ s) \qquad (1)$$

Letting wave length of the waves of deep water be L_0, then $L_0 = gT^2/2\pi$, and, therefore, the equation (1) becomes

$$h/L_0 = f(x/L_0,\ \delta_0,\ H_0/sD,\ s) \qquad (2)$$

where $\delta_0 = H_0/L_0$ is initial steepness which is considered to be the parameter govering the property of breakers. Since height of breakers and depth of breaking are considered to be expressed as function of δ_0 according to the

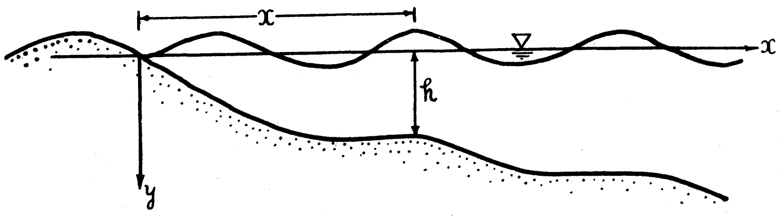

Fig.- 3.

past studies, it is most important as the parameter providing for beach profile. It is also possible to consider H_0/sD as follows, i.e., non-dimensional expression of the tractive force of stream flow is u_*^2/sgD putting u_* for friction velocity. As for the velocity corresponding to u_* in case of waves,

(i) assuming δ_0 as small and having the property of long wave at plunge point, we get

$$u_* \sim \sqrt{gH_b} = \sqrt{gH_0} f_1(\delta_0) \qquad H_b: \text{ height of breakers}$$

(ii) and assuming it as having the property of surface wave, we get

$$u_* \sim \frac{H_b}{T} \infty \frac{H_0}{T} f_1(\delta_0) \sim \frac{H_0}{\sqrt{L_0/g}} f_1(\delta_0) = \sqrt{gH_0}\, \delta_0^{1/2} f_1(\delta_0)$$

in any cases, the tractive force in case of waves will be expressed by

$$\frac{gH_0}{sgD} f_1(\delta_0) = \frac{H_0}{sD} f_1(\delta_0)$$

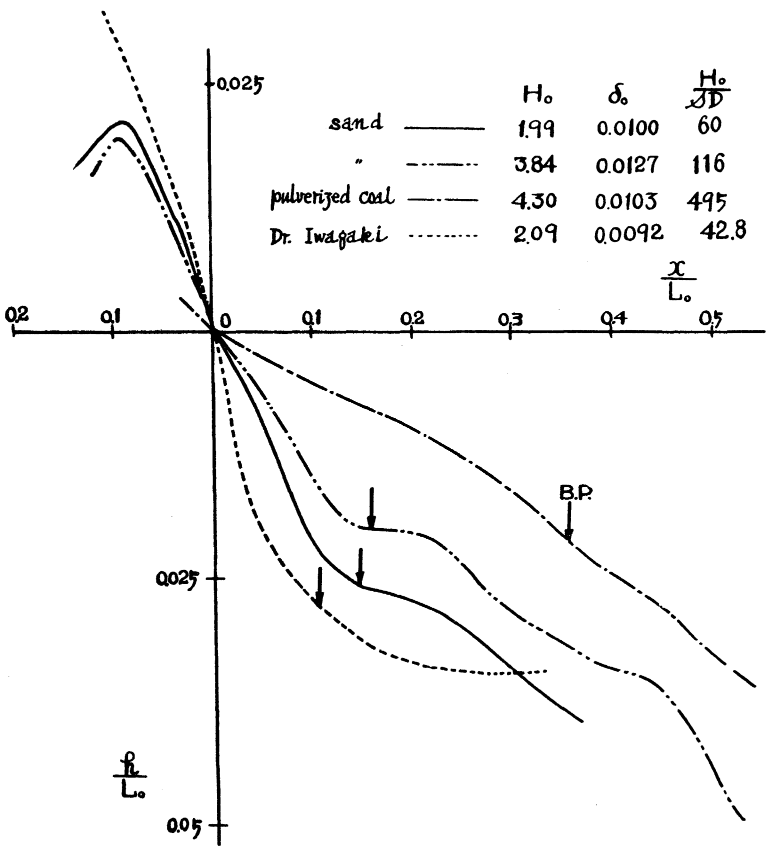

Fig.- 4*a*. Equilibrium beach profile (1) where H_0/sD becomes parameter indicating the magnitude of tractive force in case of waves.

When beach profile of an actual shore where waves suffer such local effect as refraction and others is compared to an experimental one, it is desirable to express beach profile non-dimensionally with the property of breakers as Dr. Iwagaki has pointed out. In this case, it will suffice to represent beach profile with H_b instead of H_0 in the equation (1).

The experiment on equilibrium beach profiles has been made in full details by Dr. Iwagaki, but the sand used being 0.3 mm in mean diameter and H_0 within the range of $2.05 \sim 5.88$ cm, the value of H_0/sD in the equation (2) becomes $42.7 \sim 122.5$ assuming $s = 1.6$, and if applied to actual beaches, it corresponds to the case of beaches with the sediment of large granular diameter. As it is difficult in the experiement of sand to maintain similarity between the shore where beach is composed of fine sand and the experiment, pulverized coal was used to remove this difficulty, with success to enlarge the range of H_0/sD for the same δ_0 five times.

According to the authors' experiments, it was $H_0/sD = 59.9 \sim 170.8$ when sand was used and $H_0/sD = 350 \sim 640$ when pulverized coal was used.

With respect to the change of beach profile, the difference of equilibrium beach profile due to the change of initial steepness δ_0, the effect of H_0/sD and the relation δ_0 with the slope of foreshore were examined.

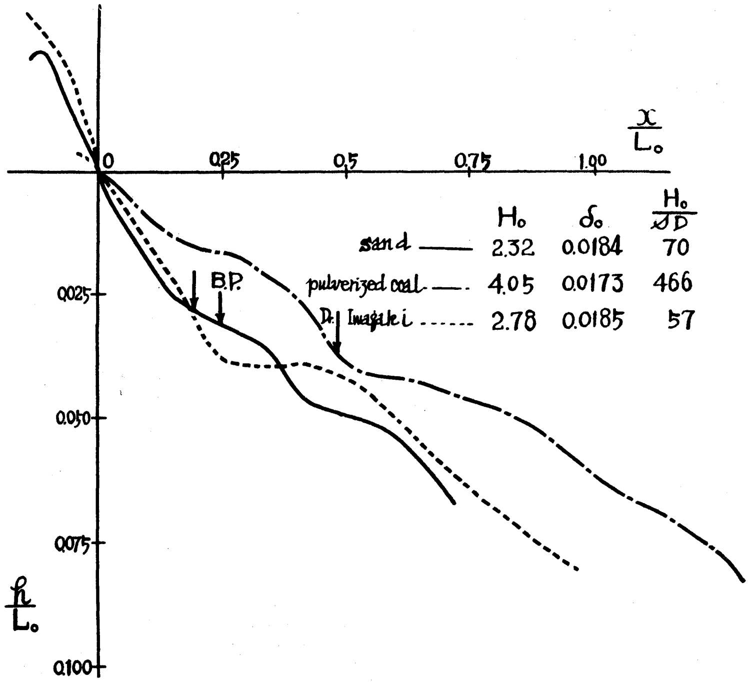

Fig.- 4b. Equilibrium beach profile (2)

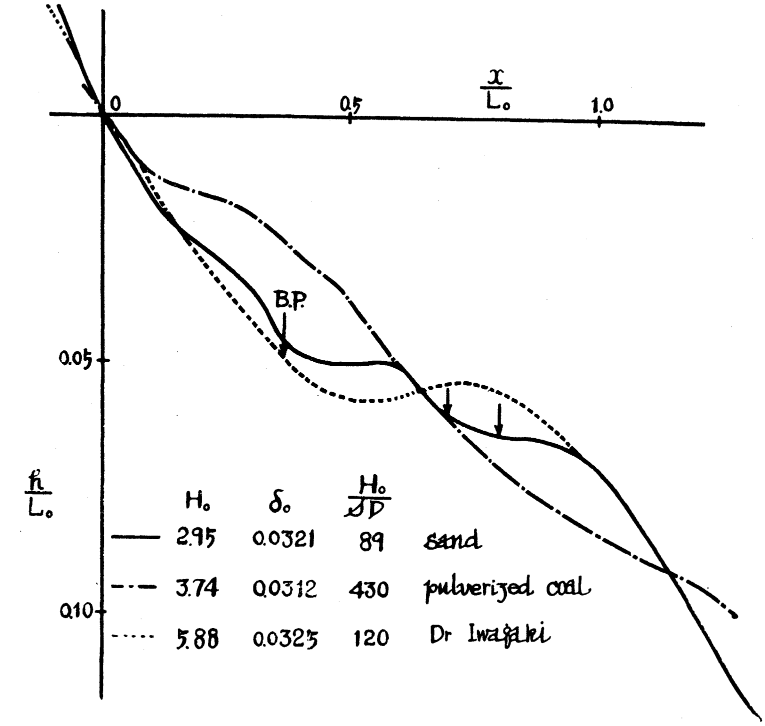

Fig.- 4*c*. Equilibrium beach profile (3)

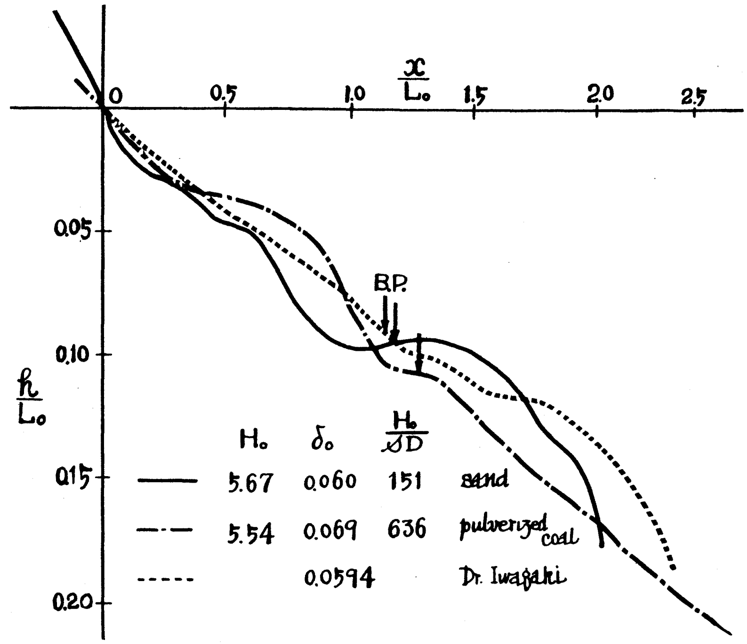

Fig.- 4*d*. Equilibrium beach profile (4)

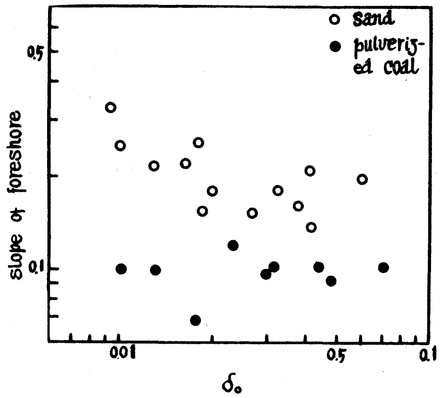

Fig.- 5. Relation of the slope of foreshore I with δ_0

Fig.–4 shows beach profile expressed non-dimensionally when steepness is approximately 0.01, 0.18, 0.03 and 0.06, where the result of Dr. Iwagaki's experiment is also shown in broken lines for comparison. In Fig.–5 is given the relation of slope of foreshore I with δ_0. These figures reveal that the slopes of foreshore and surf zone are considerably different according to beach sediment. That is to say, while both the results of Dr. Iwagaki's experiment and of the authors' experiment using sand for beach sediment correspond very well due to nearly the same H_0/sD, the slope in the case of pulverized coal whose H_0/sD is as large as about $4\sim6$ times of sand is pretty small compared to sand. This seems to reveal that beach profile is subject not only to the steepness but to the effect of H_0/sD. Since s is nearly constant at an actual shore, it is considered to be due to this that the smaller the size of beach sediment is, the slower beach slope becomes.

In the experiment with sand as beach sediment, there the boundary becomes apparent between the part where beach profile has changed from its initial slope 1/10 and the part that suffered no change. The end point of the change of this beach profile is also considered to indicate the limit of sand transport. Dr. Seiichi Sato[4] who assumed the transport limit of sand to be equivalent to the boundary condition in which shearing stress by waves can move sand has proposed following equation for transport limit depth h_c putting H for wave height of that point, L for wave length, and u_m for mean value of semicycle period of water particle velocity at the bottom,

$$\sqrt{\frac{D}{2.5}}u_m = \frac{\pi H}{2T\sinh\frac{2\pi h_c}{L}} \tag{3}$$

where, u_m is expressed in m/sec and D in mm. As for the definition of transport limit of sand, the points based on practical view are that sand transport grows less conspicuous or it entirely goes out, but the equation (3) corresponds to the former definition and the end point of the change of beach profile in the authors' experiment to the latter.

Letting velocity of water particle in x direction be u

$$u = \frac{\pi H}{T}\cdot\frac{\cosh\frac{2\pi}{L}(h+y)}{\sinh\frac{2\pi h}{L}}\sin\left(\frac{2\pi x}{L} - \frac{2\pi t}{T}\right)$$

accordingly, maximum velocity at the bottom is

$$u_{max} = \frac{\pi H}{T} \cdot \frac{1}{\sinh\dfrac{2\pi h}{L}}$$

When we consider the maximum fluid resistance due to maximum value of velocity of water particle u_{max}, $u_{max}/\sqrt{sgD} = \chi$ is expected to take a given value χ_c at the end point of the change of beach profile. Substituting, therefore, the value of wave of deep water for H and L, h_c/L_0 will be given by the following equation as the function of $H_0/T\sqrt{sgD} = \sqrt{H_0/sD}\sqrt{\delta_0/2\pi}$.

$$\left.\begin{aligned} &\frac{u_{max}}{\sqrt{sgD}} = \chi_c = \frac{\pi H_0}{T\sqrt{sgD}}\left[\tanh\frac{2\pi h_c}{L}\left(1+\frac{4\pi h_c/L}{\sinh\dfrac{4\pi h_c}{L}}\right)\right]^{-\frac{1}{2}} \frac{1}{\sinh\dfrac{2\pi h_c}{L}} \\ &\frac{\dfrac{2\pi h_c}{L_0}}{\dfrac{2\pi h_c}{L}} = \tanh\frac{2\pi h_c}{L} \end{aligned}\right\} \quad (4)$$

According to the experiment of critical tractive force at rivers, the ratio of critical friction velocity u_{*c} to $\sqrt{sgD}$ is 0.18～0.28, though it varies according to sediment size. Again adopting the velocity at the place detached one grain from the bottom, assuming it as representative velocity with respect to the sand transport at the bottom, it is considered to be $u_b/u_{*c} = 8.5$ and therefore, the value of $u_b/\sqrt{sgD}$ will be 1.53～2.38. In case of waves, using maximum value u_{max} of velocity of water particle at the bottom as u_b, the result is to be $\chi_c = u_{max}/\sqrt{sgD} = 1.53$～$2.38$. Now evaluating the relation of h_c/L_0 with $H_0/T\sqrt{sgD}$ assuming $\chi_c = 1.85$, it will be like Fig.-6, presenting a close resemblance with actual measurement. Putting again $s = 1.66$, $\chi = 4.04$ in the equation (4), we can get the equation (3). The fact that the value of this χ is more than twice as large as the value of χ_c which represents the authors' end point of the change of beach profile leads to a presumption that Dr. Sato's standard of transport limit indicates such depth where sand transport practically ceases to be conspicuous.

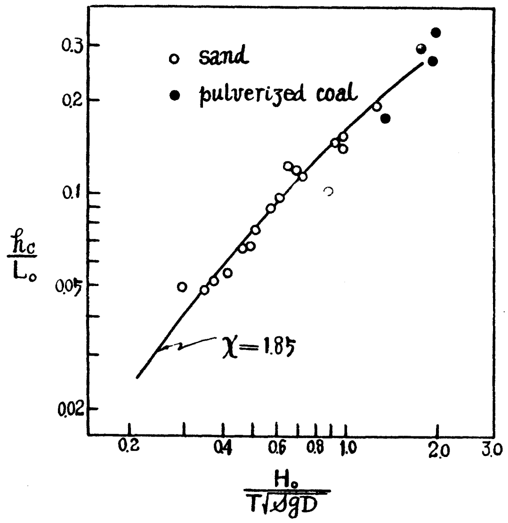

Fig.-6. Relation between $\frac{h_c}{L_0}$ and $\frac{H_0}{T\sqrt{sgD}}$

Examining the difference in beach sediment of sand and pulverized coal in the next place, while in the former, the larger δ_0 grows, the more distinct longshore bar is shaped, in the latter, there is no growth of longshore bar, only assuming the linear shape of nearly 1/10 gradient. The longshore bar is considered to be formed by the sand that had been carried from surf zone to the part of waves of deep sea due to the back rush from plunge point and deposited from plunge point to transport limit point owing to the existence of transport limit of beach sediment. Accordingly, for the growth of bar, the distance of plunge point and transport limit is considered to be one of the important factors. In case of pulverized coal, the reason why it fails to form longshore bar may be ascribed to the fact that the preceding distance is long because of its large H_0/sD and transport of beach sediment is observed all over the beach in most cases, being devoid of the function to hold beach sediments which are carried toward deep sea.

4. Sand Transport along the Bottom

As in the case of sediment of rivers, sediment transport by waves will be studied, dividing it into traction and suspension. There is the transition region between the bed load layer along the bottom and the suspended load layer above it, and it will be theoretically difficult to separate the sediment transport of the bed load layer and that of the transition region. The amount of sediment in suspension layer can be evaluated pretty accurately by absorbing sediment along with water through siphon and measuring concentration distribution, but it is empirically very difficult to measure sand transport in the bed load layer and transition region. In order to measure the amount of these sand transport, there seems to be, for the present, no better method than to represent it with sand that fell into the sand trap buried in the bottom, but this method makes it difficult to prevent mixing of suspended load. On the other hand, by absorbing the sand that fell into sand trap along with water the amount of sand will depend upon the rate of absorption. There is thus considerable difficulty in the experiment due to sand trap, especially in the case of pulverized coal, measurement error is great at the section where the amount of transport is large, for the thickness of bed load layer and transition region amounted to a few centimeters, making it also hard to give it theoretical significance. The authors will tentatively assume here for simplicity that the sand that entered into sand trap represents the amount of the sand transported along the bottom.

Beach sediment forming beach seems to be transported by various reasons such as the current after plunge resulting from velocity of water particle of a wave or mass transport, disturbance due to impact, backrush and others, but amounts of transport and their distribution are extremely complicated. In this study, therefore, it has been made an object to examine its property through experiment, shelving any attempt to clarify theoretically sand transport along the bottom for future study.

Now the amount of sand transport (in absolute volume) that passes back and forth across unit width in unit time will be assumed here as $q(L^3/LT)$. Since the parameters related to q are H_0, T and g will respect to waves of deep sea and s, D to beach sediment, following equation is conceivable for q:

$$q/\sqrt{gH_0^3}=f(\delta_0,\ H_0/sD,\ x/L_0,\ s)$$

On the other hand, in the case of rivers which are in equilibrium condition with respect to sediment, when tractive force is considerably larger than its critical value, the amount of sand transported along the river bed will be expressed as follows:

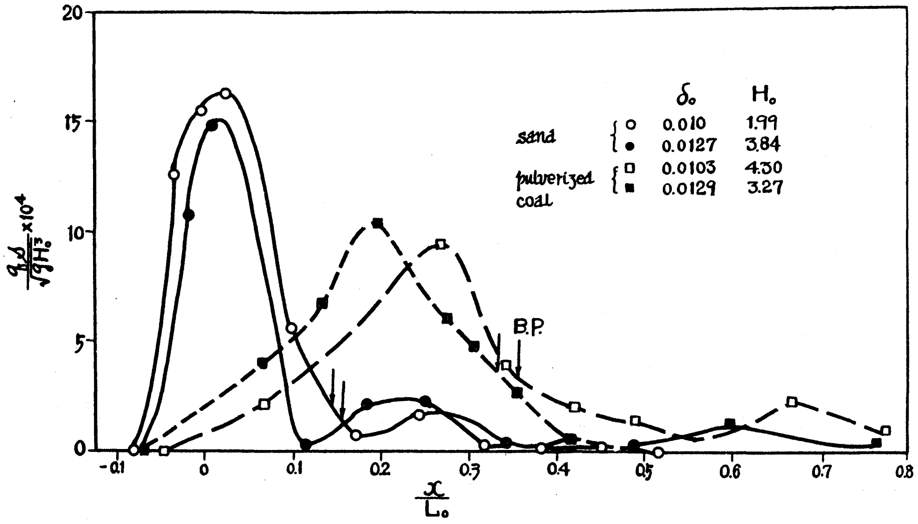

Fig.- 7a. Relation between bottom sand transport (ϕ) and x/L_0 (1)

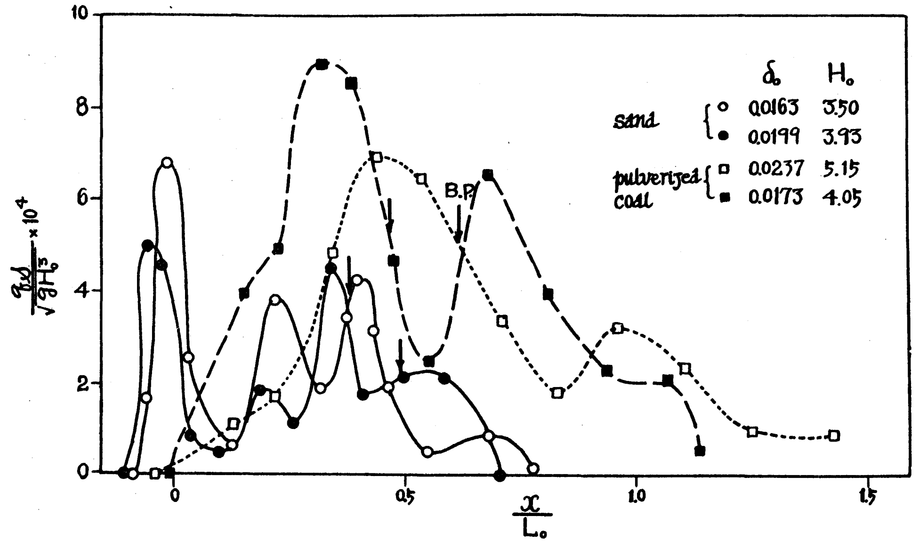

Fig.- 7b. Relation between bottom sand transport (ϕ) and x/L_0 (2)

$$q/\sqrt{sgD^3} \propto \left(\frac{u_*^2}{sgD}\right)^{3/2} \left(\frac{u_*^2}{sgD}\right)^m$$

where the value of index m is $m=1$ according to C. B. Brown,[5] and when it is only bed load, it is said to become $m=0$. The above equation may be transformed as $qsg/u_*^3 = (u_*^2/sgD)^m$.

In the case of sand transport by waves, it presents extremely unbalanced condition unlike the case of river sediment, and it seems to have sand transport mechanism different river sediment, being subject to such great influence as disturbance from impact beside the shearing stress due to current.

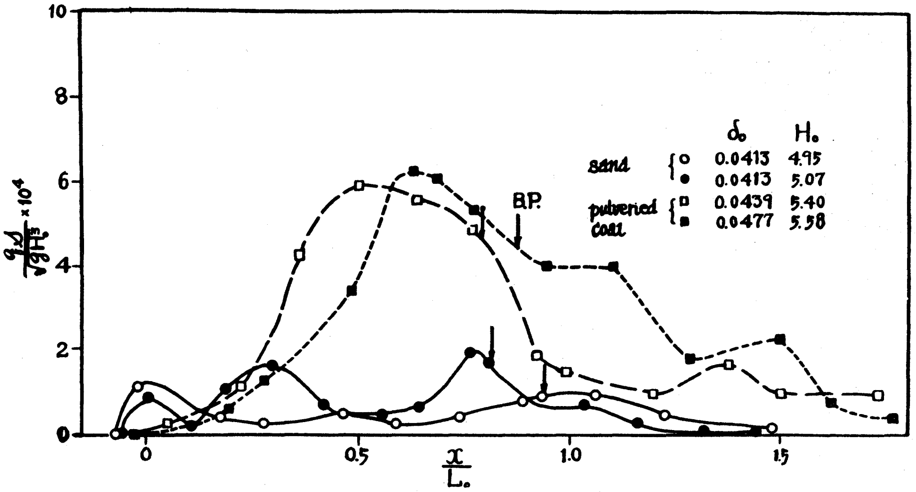

Fig.- 7c. Relation between bottom sand transport (ϕ) and x/L_0 (3)

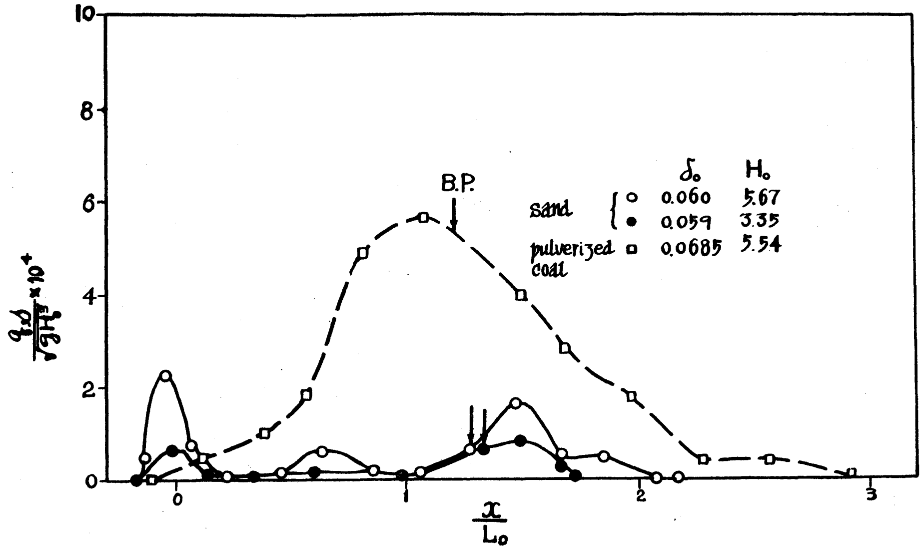

Fig.- 7d. Relation between bottom sand transport (ϕ) and x/L_0 (4)

Assuming tentatively, however, that an analogical inference is to be admitted, the amount of sand transport may be expressed by the following equation considering what corresponds to u_* as $\sqrt{gH_0}f(\delta_0, x/L_0)$,

$$\Phi = \frac{qs}{\sqrt{gH_0^3}} = f(\delta_0, H_0/sD, x/L_0, s) \tag{5}$$

Fig.-7 shows the relation of Φ with x/L_0 by various steepness, from which it is proved that, when the beach sediment is composed of sand, sand transport is concentrated to the shore line in the case of a wave or small δ_0, whereas, with the increase of steepness, transport along the shore line is reduced, sand transport at the step of surf zone as well as at the long-shore bar becomes conspicuous, and longshore drift predominates over all others. On the other hand, in the case of pulverized coal, no matter how large δ_0 is, sediment transport is seen to grow maximum at foam line just after plunge point, considerably affected by disturbance resulting from impact. It is also worth attention that sediment transport at foreshore is so extremely small that shoreline drift is negligible and that transport at the part of waves of deep sea is pretty large compared to the case of sand. As the reason for these, in the former, exhaustion of wave energy in the course of its ascent along mild slope is accounted for, while in the latter, considering from the well-known theory of sediment transport that sediment load rapidly increases with the increase of tractive force in the neighborhood of the critical tractive force, it is presumed to be possibly due to the largeness of $H_0/T\sqrt{sgD}$ or H_0/sD which represents tractive force from waves in the case of pulverized coal compared to that of sand.

Fig.-8 gives the relation between non dimensional expression of the total amount of transport Q of beach sediment and δ_0. In the case of pulverized coal, since the transport at the part of waves of deep sea becomes distinguished with the increase of δ_0 as mentioned above, the value of $Qs/\sqrt{gH_0^3L_0}$ increases with δ_0, giving quite opposite result from the case of sand. What are accountable for this in the two experiments are the difference in equilibrium beach profile due to the disparity of H_0/sD for a given wave of deep sea by 5 times, that in the degree of effect suffered by the disturbance resulting from impact and that of sediment transport at the part of wave of deep sea. Some more reasons may be considered beside this, for instance, the facts that the shape of pulverized coal is flatter than that of sand and that specific

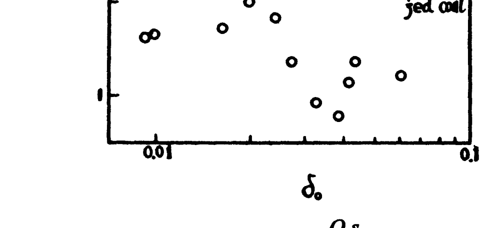

Fig.-8. Relation between $\frac{Qs}{\sqrt{gH_0^3L_0}}$ and δ_0

gravity s in the water exerts its influence directly, because sand transport by waves is periodic accelerated motion and suffers impact from the breaker. These problems, however, should be submitted to future study.

By the way, when sand is adopted for sediment, the value of $Qs/\sqrt{gH_0{}^3L_0}$ has decreased with the increase of δ_0, provided that δ_0 is more than 0.02. According to Saville's three-dimensional experiment of drifts, the maximum mount of drift was produced at $0.02\sim0.025$ of δ_0, but in the authors' experiment, whether maximum value is produced or not has not been clarified because of scattered measurement values.

5. Suspended load transport The sand that is suspended by waves is expected to play an important role to longshore drift as it keeps on drifting along the current as it is, but is seems that suspended load of this sort has been seldom taken up for study up to date. In this experiment, the authors conducted measurement at the area between the shore line and the end point of transport limit of sand, though they were unable to measure suspended load because of small depth at the part of foreshore to the land side from shoreline.

Fig.-9 shows the relation between the concentration in the depth direction of each section C and the distance from the bottom y. In the case of sand, linear relation is held between $\log C$ and y, while in the case of pulverized coal, the phenomenon is extremely complicated, showing thin layer that is moved by waves in a condition close to saturation over the layer of settled sediments. The top of this layer will be tentatively called upper limit of traction. The concentration forms, as seen in Fig.-9c, the distribution of two straight lines of different slope. If the upper straight line is looked upon as suspension zone, the lower one is considered to be showing transition zone. Calling the intersecting point of these two straight lines as lower limit of suspension, the concentration of this point will be assumed

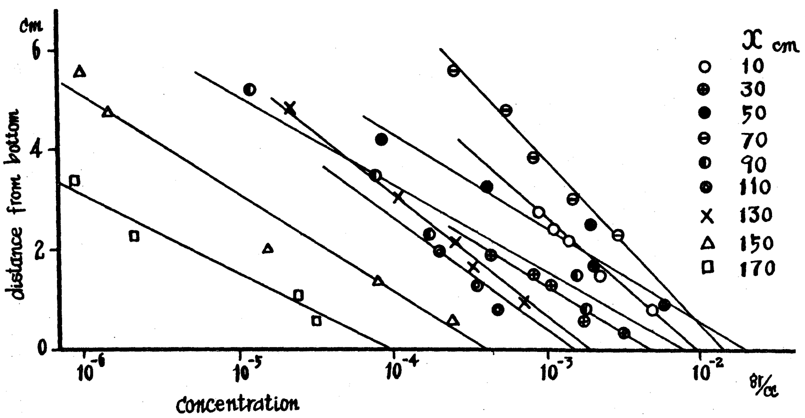

Fig.-9a. Concentration distribution of suspended load (1)
(sand)

as C_0. In Fig.-2*c* are given upper limit of traction and lower limit of suspension.

Since there exists linear relation between logarithm of concentration and depth with every case of sediment, as mentioned above, the concentration distribution may be expressed as follows:

$$C/C_0 = e^{-\alpha y}$$

The distribution of suspended load by waves is considered to be determined by diffusion equation of unsteady and non-equilibrium state. Since the validity of the above eqnation has been empirically acknowledged,

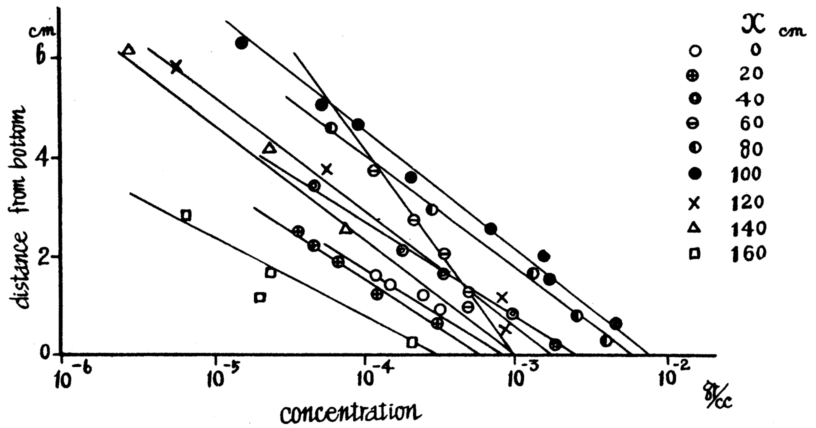

Fig.- 9*b*. Concentration distribution of suspended load (2) (sand)

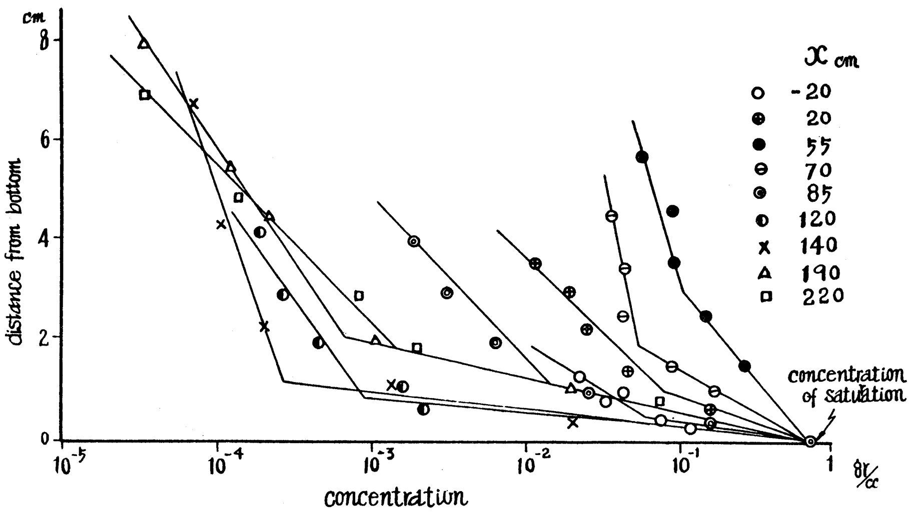

Fig.- 9*c*. Concentration distribution of suspended load (3) (pulverized coal) however, considering concentration distribution as steady and equilibrium state in average and putting v_s for settling velocity and ε for diffusion coefficient, concentration distribution is assumed to be in accordance with following equation,

$$C/C_0 = e^{-\alpha y}, \quad \alpha = v_s/\varepsilon \tag{6}$$

where, ε is explained as apparent diffusion coefficient in which is included the effect of the state of current or the effect of non-equilibrium state beside diffusion coefficient of turbulence. From concentration distribution of Fig.-9 is evaluated $y=0$ or concentration of lower limit of suspension C_0 and from the slope of straight line, the value of α or ε/v_s is obtained. v_s being known, the value of ε is also obtainable. In Fig.-2 is given the change of C_0 and ε in x direction, which proves that ε slowly increases with the decrease of depth, more increasing before breaking. This is considered to be due to the current as if it were drawn up at the crest of breakers. This is pretty distinctly observed when sediment is composed of pulverized coal. Moreover, after breaking, it grows at a point which is considered to be foam line, especially it is conspicuous in the case of pulverized coal, forming almost uniform distribution in the direction of depth due to an intense disturbance. While at surf zone, in the case of pulverized coal, it gradually decreases, in the case of sand, it seems to decreases for once, suddenly increasing again when δ_0 is small.

Though the authors failed to conduct measurement at the shore line, it is possibly estimated that a large ε will be obtained there independently of the value δ_0 owing to uprush and backrush advancing in piles to the steep slope of approximately 1/5.

The bottom concentration C_0 is expected to be larger where disturbance is stronger, and as transport along the bottom is subject to two kinds of actions of tractive force and disturbance, there is observed considerable correlation between the two.

Neglecting upward movement of still water surface by waves with longshore drift as object, when sediment is sand, suspended load S_b contained in the area between the shore line and plunge point as well as the totai amount of suspended load S between the shore line and offshore side will be as follows from equation (6):

$$S_b = \int_0^{l_b} \frac{C_0 \varepsilon}{v_s} \left(1 - e^{-\frac{v_s h}{\varepsilon}}\right) dx$$

$$S = \int_0^{l_e} \frac{C_0 \varepsilon}{v_s} \left(1 - e^{-\frac{v_s h}{\varepsilon}}\right) dx$$

where it is provided that l_b, l_e are the distance between the shore line and the plunge point or the end point of transport limit.

In the above equation, diffusion coefficient ε can be transformed non-dimensional at $\varepsilon/\sqrt{gH_0^3}$ making δ_0 as parameter, and assuming C_0 as absolute

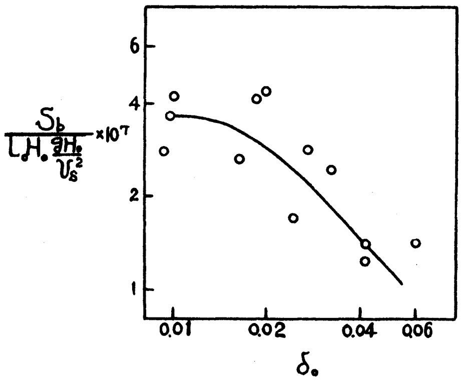

Fig.-10*a*. Relation between S_b and δ_0

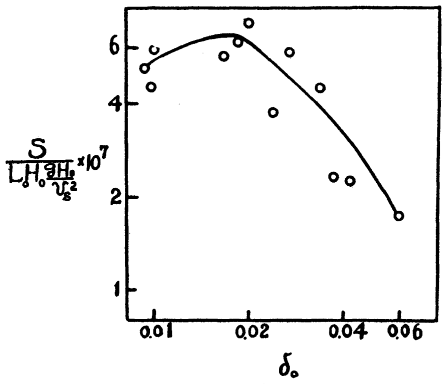

Fig.-10*b*. Relation between S and δ_0

volume of sediment in the unit volume, C_0 receives the effect of $\sqrt{gH_0}/v_s$ and δ_0. Especially $\sqrt{gH_0}/v_s$ expresses the rate of the strength of disturbance due to waves and the settling velocity and is considered to play a most important role to C_0. Referring to Kalinske's[6] theory concerning to bottom concentration of suspended load in rivers, C_0 is considered to be in proportion with $(\sqrt{gH_0}/v_s)^m$ $(m>1)$ to equivalent δ_0. Hence non-dimensional forms of S, S_b may be put as

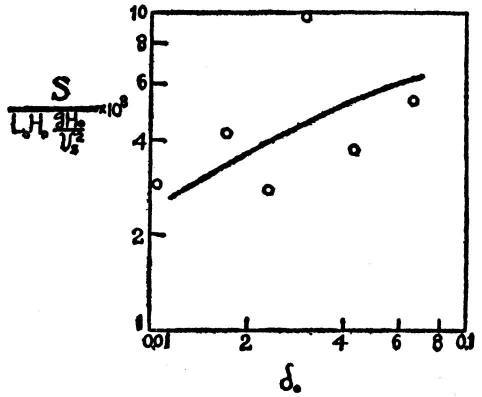

Fig.-11. Relation between S and δ_0

$$S \text{ or } S_b = L_0 H_0 \frac{gH_0}{v_s^2} f(\delta_0, \sqrt{gH_0}/v_s) \qquad (7)$$

In Fig.-10 is shown the result of test in the case of sand and in Fig.-11, that is the case of pulverized coal. The case of pulverized coal is about ten times of the case of sand. The latter is noticeable where it presents a tendency closely resembled to the relation in the case of non-dimensional expression of bed load in Fig.-8 and where maximum value is turned up with respect to the total amounts of suspended load similar to Saville's[1] experiment on beach drift.

As mentioned above, the clue to suspended load by waves is considered to depend on the clarification of characteristics of diffusion coefficient ε and bottom concentration C_0, but it is the authors' wish to wait for future experiments for the study of quantitative property of the both.

6. Summary The most difficult problems in the application of the results of experiment on the change of profile of a model sandy beach by waves and sand transport to actual beaches will be the establishment of the similarity due to difference in the size of beach sediment. In this study, as the important factor representing the characteristics of beach sediment besides the steepness of wave, the authors considered the ratio of hydraulic force of wave upon sand to frictional force or weight of sand, H_0/sD and conducted tests on the profile of sandy beach and sand transport, using pulverized coal besides sand in order to bring this value close to sandy beach of smaller sediment size. As the value of H_0/sD in the case of pulverized coal is $4 \sim 6$ times larger than that in the case of sand, it has been testified from the experiments about the profile of sandy beach that, expressing the relation of the distance and depth from shore line in non-dimensional form, H_0/sD grows large for the same initial steepness while beach slope of surf zone becomes slow, thereby approaching to the profile of actual sandy beach of small sediment size. And as to the sediment transport along the bottom, in the case of pulverized coal, it has been proved that transport near foam line is predominant, independently of initial steepness, that its distribution is considerably different from the case of sand and that the relation of non-dimensional expression of the total bed load with δ_0 (initial steepness) is extremely at variance with the case of sand. Furthermore, in the measurement of concentration distribution, what interested the authors in dealing with pulverized coal was that transition condition from traction to suspension zone has been distinctly apparent as well as the fact that concentration distribution in suspension zone can be expressed by a simple exponential form. Besides, the shapes of grains of pulverized coal which are somewhat flat seemed to affect more or less the mechanism of sand transport.

The fact that there was striking difference in the change of profile of sandy beach according to sediment size is considered to be probably caused by disparity in H_0/sD mainly, even if partially admitting the effect of the shape of sediment.

As mentioned above, the problem of sand transport by waves is difficult not only in giving theoretical treatment, being related with the current by breakers or the disturbance from impact, but also in depending only upon experiment, because more than two factors such as initial steepness or H_0/sD are involved in it. In order to get to a general conclusion, therefore, it is necessary to clarify the mechanism of sand transport as well as to conduct many experiments and observations at actual sandy beach.

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Appendix

Beach Sediments	δ_0	H_0 cm	H_b cm	L_0 cm	$\frac{H_0}{sD}$	I	$\frac{h_c}{L_0}$	$\frac{H_0}{T\sqrt{sgD}}$	$\frac{Q_S}{L_0\sqrt{gH_0^3}}$	$\frac{S_b}{L_0H_0}\frac{gH_0}{\nu_s^2}$	$\frac{S}{L_0H_0}\frac{gH_0}{\nu_s^2}$
Sand	0.0092	2.84	4.20	308	84.6	0.318	0.0487	0.356	1.54	0.279	0.516
	0.0097	3.07	4.50	316	92.2	0.256	0.0522	0.378	1.57	0.368	0.459
	0.0100	1.99	3.85	200	59.8	0.240	0.050	0.301	2.77	0.423	0.593
	0.0127	3.84	5.64	302	114.5	0.218	0.0678	0.483	2.11	0.120	—
	0.0163	3.50	4.25	215	104.4	0 225	0.0766	0.522	1.64	0.266	0.566
	0.0179	2.11	3.71	118	63.4	0.264	0.0550	0.421	2.24	0.341	—
	0.0184	2.32	3.70	126	68.9	0.159	0.0675	0.498	4.78	0.412	0.630
	0.0199	3.93	5.66	197	118.4	0.181	0.0966	0.616	1.99	0.437	0.733
	0.0241	2.96	3.53	123	88.4	0.290	0.0895	0.583	1.75	0.171	0.383
	0.0268	4.10	5.40	153	122.5	0.155	0.1175	0.720	1.29	0.288	0.582
	0.0321	2.95	3.52	92	87.8	0.182	0.125	0.664	0.925	0.245	0.443
	0.0378	2.85	3.29	75.5	85.0	0.167	0.119	0.714	0.831	0.0711	0.239
	0.0413	5.07	5.10	123	153.8	0.140	0.142	0.988	1.09	0.123	0.229
	0.0413	4.95	6.00	120	148.8	0.212	0.150	0.976	1.24	0.140	0.289
	0.0588	3.35	3.80	57.0	100.0	0.115	0.149	0.976	0.501	0.142	0.178
	0.0600	5.67	5.98	94.5	171.6	0.200	0.190	1.29	1.13	0.205	0.457
Pulverized coal	0.0103	4.30	7.8	418	495	0.100		0.892	2.45	2.83	2.89
	0.0129	3.27	4.2	254	376	0.100		0.875	2.55	—	—
	0.0173	4.05	5.3	234	466	0.070		1.128	4.96	4.09	4.16
	0.0237	5.15	6.3	217	592	0.122		1.494	4.61	2.72	2.81
	0.0305	3.12	3.2	102	359	0.100		1.336	4.92	—	—
	0.0312	3.74	4.2	120	430	0.105		1.472	5.28	9.71	9.80
	0.0371	4.44	4.5	120	510	—		1.738	3.72	—	—
	0.0407	4.80	5.3	120	552	—		1.847	5.38	—	—
	0.0439	5.40	6.0	123	621	0.105		2.078	4.94	3.67	3.69
	0.0477	5.58	5.8	117	641	0.095		2.197	6.41	—	—
	0.0618	3.40	3.0	55.0	391	—		1.973	8.62	—	—
	0.0685	5.54	5.6	80.8	636	0.105		2.598	6.46	5.13	5.30