CHAPTER 14

LABORATORY STUDY OF SCALE EFFECTS IN TWO-DIMENSIONAL BEACH PROCESSES

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In order to disclose the essential relationship between the beach processes and wave characteristics, two dimensional model tests are often performed for beach profile changes due to incident breaking waves normal to the beach. In applying the results of such experiments to the prototype of beaches, the scale effects of waves and sediments on the beach processes with equilibrium beach profiles should necessarily be considered.

In this paper, as an approach to solve this problem in two dimensional beach studies, the effects of wave height and sediment size on the shore line movement and equilibrium beach profiles are discussed based on the results of experiments made by the authors and other experiments with smaller and larger scales by some researchers. It has been found that the ratio of wave height to sediment diameter is a very significant factor in this problem. In addition, the changes in a character of breaking waves during the time period of wave action from the beach having an initial constant slope to that with an equilibrium profile are presented.

INTRODUCTION

In order to understand correctly the problem of beach erosions, it is necessary to disclose the complicated phenomena of beach processes mainly by the wave action. In treating beach erosion phenomena, a study should be made generally dividing sediment transport into the following two modes:

1. Sand movement normal to the shore line by the direct action of waves; and
2. sand movement along the shore by currents due to breaking waves.

The sand movement in the first mode causes the beach process of a short period of time and it is well known that the characters of incident waves influence greatly this phenomenon. On the other hand, the sand movement in the second mode governs the beach process of a relatively long period of time which depends on an alongshore distribution of the littoral transport rate. From this point of view, many researches have been made at Kyoto University. Especially much effort has been made in establishing the mechanics of the beach process not only by laboratory experiments but also by field observations, on the beach profile changes with the problem of equilibrium beach profiles for the first mode of sand movement (Hayami, Ishihara and Iwagaki, 1953; Iwagaki and Sawaragi, 1955, 1956, 1958; Iwagaki and Noda, 1961a, 1961b) and on the estimation of the littoral transport rate as an approach to disclose the beach erosion mechanism for the second mode of sand movement (Sawaragi and Murakami, 1957; Iwagaki and Sawaragi, 1960). However, the method to analyze the beach process by observing under natural circumstances at actual beaches for the purpose of disclosing the beach erosion mechanism is generally not hopeful except under certain limited conditions because it is difficult to separate clearly the effects of main factors which influence this complicated phenomenon. Therefore, model experiments are often made considering hydraulic similarity to some extent, and then various phenomena which occur at actual beaches are explained or predicted, so that a counter-measure is established. Accordingly the most importance in such experiments is the problem of the similarity between models and prototypes. The purpose of this paper is to discuss how the relative sizes of deep-water waves and sediments in addition to the deep-water wave steepness influence the two dimensional beach process due to the sand movement normal to the shore line and the equilibrium beach profile, based on the results of experiments by the authors and other researchers.

A laboratory study for equilibrium profiles of beaches by Johnson (1949) indicated that the profile of a beach is changed with the value of the deep-water wave steepness H_0/L_0, and especially it is called the "normal" beach when the steepness is small and, on the other hand, the "storm" beach characterized by the appearance of longshore bars when the steepness is large, in which the critical wave steepness in deep-water for both is 0.025 to 0.030. Iwagaki and Sawaragi (1955, 1956, 1958) made experiments of equilibrium beach profiles and the sand movement due to breaking waves by using the sands of three different sizes. Kurihara and others (1956) and Shinohara and others (1958) compared the results of experiments by the pulverized coal having small specific gravity with those by the sand. In the United States of America, many experiments were made by Scott at the University of California (1954), and Rector (1954), Watts (1954) and Saville (1957) at the Beach Erosion Board. These experiments showed that the storm beach is developed even when the deep-water wave steepnesses are 0.019 and 0.0064 according to the results by Scott and Saville respectively. Especially it should be noted that the results by Saville who made experiments with as large waves as at actual beaches are remarkably different from those with small waves. Accordingly it is presumed that such phenomena involving the sand movement have much scale effect, and this is a reason why the authors began such an investigation.

Since the scale effect on the beach process is also expected as well as on the equilibrium beach profile, the distance of shoreline movement when the beach having an initial constant slope is changed into the state of equilibrium is treated as an example, and the experiments are made in an effort to disclose the effects of the relative size of waves and sediments on the two dimensional beach process with considerations for the equilibrium beach profile. In addition, the changes in a character of breaking waves in the beach process from a uniform slope to an equilibrium state are reported.

EQUIPMENTS AND PROCEDURES FOR EXPERIMENTS

Laboratory experiments of beach processes have been made using a concrete wave tank 70 m long, 1.0 m wide and 1.5 m deep (Fig. 1a) and a steel wave tank 70 m long, 0.5 m wide and 0.6 m deep (Fig. 1b) at the Ujigawa Hy-

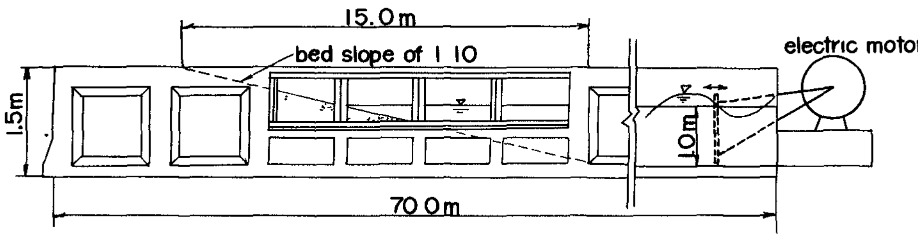

Fig. 1a. Schematic drawing of concrete wave tank.

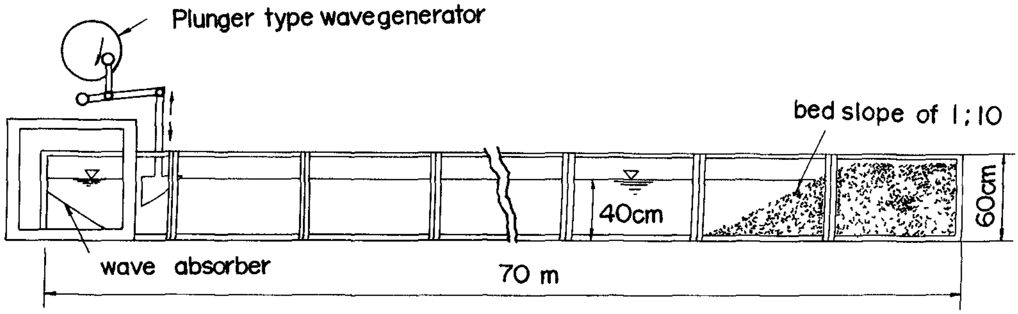

Fig. 1b. Schematic drawing of steel wave tank.

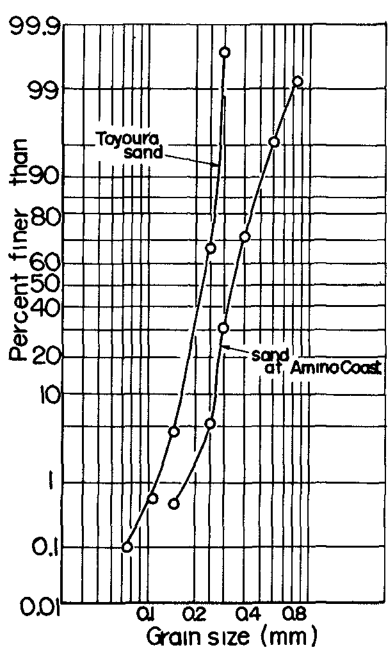

Fig. 2. Sieve analysis of sands used in the tests.

draulic Laboratory, Disaster Prevention Research Institute, Kyoto University. Some of the data were taken by dividing the beach in the concrete wave tank longitudinally into two parts and putting the sands of two different sizes to find the effect of sand sizes on beach processes.

In the concrete wave tank waves are generated by a multi-purpose flatter type generator with a 10 HP electric motor or by a pneumatic type wave generator with a 7.5 HP blower. In the steel wave tank a plunger type wave generator with a 2 HP electric motor is installed.

Incident wave heights were measured by an electric point gage or an electric resistance type wave gage with an inkwriting-oscillograph. Water depths tested were 1.0 m in the concrete wave tank and 0.4 m in the steel wave tank.

Two kinds of sands used in the experiments were the well-sorted sand at Amino Coast and the standard sand by JIS, which is called Toyoura sand, with median diameters of 0.34 mm and 0.22 mm and specific gravities of 2.62 and 2.59 respectively (Fig. 2). The initial slope of the beaches constituted by these sands was 1 on 10 every time. Table 1 shows the characters of waves and sands used, the duration times of the experiments and the data obtained.

The profiles of beaches were measured by a point gage 15 min, 30 min, 1 hr, 2 hrs, ... after the beginning of the experiment, and the measurements were continued until it appeared that the equilibrium state was reached. In the later experiments the measurements of the beach profiles in the course of beach processes were omitted because the duration time of 20 hours was considered to be almost enough to obtain the equilibrium state.

In order to investigate, furthermore, the changes in the character of breaking waves were filmed through the side glass wall of the concrete wave tank every one or two hours by a 16 mm cinecamera. A small wave tank 14 m long, 0.3 m wide and 0.4 m deep, was used to find the relationship between the beach slope and the characters of breaking waves on the fixed bed with the beach slopes of 1° to 5° and the deep-water wave steepnesses of 0.02 and 0.04. The profiles of breaking waves on the fixed slopes of beaches were photographed by a camera in the same manner as for those on the movable bed in the concrete wave tank. In this case a plunger type wave generator was used, by which the wave periods are varied from 0.5 sec to 3.5 sec and the wave heights from 1.5 cm to 4.0 cm continuously.

RESULTS OF EXPERIMENTS AND CONSIDERATIONS

PROGRESSION AND RECESSION OF SHORELINE

The beach profile having a uniform slope of 1 on 10 before testing was deformed with the lapse of time due to wave action and finally reached the equilibrium state after about 15 to 20 hours as shown in Fig. 3. During that time, the change in the beach profile near the shore line was very rapid for a few hours after the beginning of the test and then became gradual asymptotically or in some cases periodically. In this paragraph, the distance of progression or recession of the shore line until the beach having an initial uniform slope reaches the equilibrium state is treated and

Table 1

Characters of waves and sands used and data obtained.

Run No.	Wave period T (sec)	Deep-water wave height (Ho cm)	Deep-water wave steepness H_o/L_o	Median dia. d_{50} (mm)	H_o/d_{50}	Distance of shore-line mov. X_{SL} (m)	X_{SL}/L_o	Duration time (hrs)	Investi-gators
1	1.29	2.40	0.009	0.48	5.00×10^1	0	0	6	Iwagaki-Sawaragi
2	1.21	2.13	0.009	0.28	7.64 "	+0.060	$+3.0 \times 10^{-2}$	9	
3	1.29	2.41	0.009	0.93	2.59 "	+0.096	+ 3.7 "	5	"
4	3.58	20.3	0.010	0.34	5.97×10^2	+0.54	+ 2.6 "	12	Iwagaki-Noda
5	2.54	9.00	0.009	"	2.64 "	+0.43	+ 4.3 "	18	
6	2.69	11.6	0.010	"	3.40 "	+0.25	+ 2.2 "	15	"
7	3.58	19.8	0.010	"	5.81 "	+0.72	+ 3.6 "	18	"
8	2.93	20.4	0.015	"	6.00 "	+0.58	+ 4.0 "	20	"
9	2.07	9.9	0.015	"	2.90 "	+0.08	+ 1.3 "	13	"
10	2.52	14.9	0.015	"	4.38 "	+0.29	+ 2.9 "	15	"
11	3.26	24.5	0.015	"	7.20 "	-1.15	- 6.9 "	17	"
12	3.58	28.2	0.014	"	8.28 "	-0.58	- 2.9 "	18	"
13	0.96	3.34	0.023	0.48	6.95×10^1	-0.03	- 2.0 "	7	Iwagaki-Sawaragi
14	0.98	2.66	0.019	0.28	9.53 "	-0.084	- 6.0 "	6	
15	0.97	3.67	0.025	0.93	3.95 "	+0.055	+ 3.7 "	5	"
16	2.52	21.1	0.021	0.34	6.20×10^2	-1.48	-15.0 "	20	Iwagaki-Noda
17	2.19	17.6	0.023	"	5.17 "	-0.32	- 4.2 "	17	"
18	3.10	30.0	0.020	"	8.81 "	-0.57	- 3.8 "	20	"
19	2.84	25.0	0.020	"	7.34 "	-1.45	-11.4 "	20	"
20	3.00	20.2	0.020	"	5.93 "	-1.54	-14.8 "	20	"
21	3.00	29.1	0.021	0.22	1.32 "	-1.60	-11.4 "	20	"
22	2.50	19.0	0.020	"	8.64 "	-0.93	- 9.50 "	20	"
23	2.20	15.9	0.021	"	7.23 "	-0.70	- 9.3 "	20	"
24	1.86	11.3	0.021	"	5.14 "	-1.10	-20.3 "	20	"
25	1.56	8.0	0.021	"	3.64 "	-0.24	- 6.3 "	16	"
26	3.00	29.1	0.021	0.34	8.55 "	-0.35	- 2.5 "	20	"
27	2.50	19.0	0.020	"	5.59 "	-0.95	- 9.7 "	20	"
28	2.20	15.9	0.021	"	4.67 "	-0.64	- 8.5 "	20	"
29	1.86	11.3	0.021	"	3.32 "	-0.51	- 9.6 "	20	"
30	1.56	8.00	0.021	"	2.35 "	+0.08	+ 2.1 "	16	"
31	1.45	6.39	0.020	"	1.88 "	+0.21	+ 6.4 "	11	"
32	1.25	4.87	0/020	"	1.43 "	+0.02	+ 0.6 "	11	"
33	1.00	3.80	0.024	"	1.12 "	-0.12	- 0.8 "	11	"
34	0.98	6.90	0.046	0.48	1.26 "	-0.16	-10.0 "	12	"
35	2.00	23.8	0.038	0.34	6.99 "	-1.90	-30.5 "	20	Iwagaki-Noda
36	2.40	34.9	0.039	"	1.02×10^3	-1.75	-19.6 "	20	
37	2.20	30.0	0.040	"	8.81×10^2	-1.74	-23.0 "	20	"
38	2.40	35.4	0.039	0.22	1.61×10^3	-2.57	-28.6 "	20	"
39	1.90	22.0	0.039	"	1.00 "	-1.25	-22.2 "	20	"
40	1.65	17.3	0.041	"	7.86×10^2	-1.31	-30.8 "	20	"
41	1.20	9.7	0.043	"	4.41 "	-0.51	-22.6 "	15	"
42	2.40	35.4	0.039	0.34	1.04×10^3	-1.73	-19.2 "	20	"
43	1.90	22.0	0.039	"	6.50×10^2	-1.21	-21.4 "	20	"
44	1.65	17.3	0.041	"	5.10 "	-0.55	-12.9 "	20	"
45	1.20	9.7	0.043	"	2.85 "	-0.46	-20.4 "	15	"

the effects of the wave height and the sediment size on that distance are discussed. Although, of course, it may be dangerous to derive a general conclusion on the two dimensional beach process only from such shoreline movements, it would be significant to adopt the distance of the shoreline movement as a representative dimension of beach processes in investigating the effects of wave heights and sediment sizes.

The distance X_{SL} of shoreline progression (in this case, positive value) or recession (negative value) from the initial location is a function of the deep-water wave height H_o, the wave period T, the still water depth on the horizontal bed in a wave tank h, the initial slope of the beach i_o, the median diameter of sand d_{50}, the specific gravity of sand in water S, the duration time of wave action t and the gravity acceleration g. Since the deep-water wave length L_o is equal to $gT^2/2\pi$, the following dimensionless expression is derived by the method of dimensional analysis:

$$X_{SL}/L_o = f_1(h/L_o,\ H_o/L_o,\ H_o/d_{50},\ t/T,\ i_o,\ S), \tag{1}$$

in which the effect of fluid viscosity was neglected because it appears that the viscosity effect is much less than those of other factors by the presumption from sediment transport in alluvial channels except the attenuation of waves due to bottom friction. The effect of h/L_o is considered to be neglected as far as the zone of sand movement is limited on the beach slope and t/T can be dropped in the discussion for the equilibrium state. In addition, the specific gravity of sand in water S is also dropped if constant. Therefore, Eq. (1) is written

$$X_{SL}/L_o = f_2(H_o/L_o,\ H_o/d_{50},\ i_o). \tag{2}$$

If the fall velocity w_o is taken instead of the median diameter d_{50} and the specific gravity in water S of sand as a character of sand because of significance of the suspension phenomenon in beach processes, Eq. (2) is replaced as

$$X_{SL}/L_o = f_3(H_o/L_o,\ \sqrt{gH_o}/w_o,\ i_o). \tag{3}$$

Since, furthermore, the fall velocity of a spherical sand particle with a diameter d_{50} is expressed

$$w_o = \left\{(4/3)Sgd_{50}/C_D\right\}^{1/2}, \tag{4}$$

Eq. (3) is written as follows:

$$X_{SL}/L_o = f_4(H_o/L_o,\ H_oC_D/Sd_{50},\ i_o), \tag{5}$$

in which C_D is the drag coefficient of a sand particle. It is noted that Kurihara and others (1956) used a factor of H_o/Sd_{50} in analyzing their data of equilibrium beach profiles and beach material movements.

Figs. 4a, 4b, 4c and 4d show the relationships between X_{SL}/L_o and H_o/d_{50} with a parameter H_o/L_o obtained by the plots of data for the initial beach slope of 1 on 10 based on Eq. (2). The data include the results of experiments by Iwagaki and Sawaragi (1955, 1956) and Kurihara and others (1956) in addition to those by the authors. The similar plots of data by

Saville (1957) for a 1 on 15 initial beach slope and Rector (1954) for a 1 on 30 slope are shown in Fig. 5. The Rector's data consist of the results for four different sand sizes of 0.22, 0.47, 0.90 and 3.44 mm in median diameter and the wave heights of about 9 to 11 cm. The experimental results by Saville are for a median diameter of 0.22 mm and the wave heights of about 45 to 170 cm.

The same data as in Figs. 4a - 4d are plotted based on Eq. (5) in which H_oC_D/Sd_{50} is introduced instead of H_o/d_{50} as shown in Fig. 6.

The conclusions derived from these figures are as follows:

1. The progression and recession of a shoreline depend not only on the deep-water wave steepness but also on the ratio of the deep-water wave height to the median diameter of sand H_o/d_{50} or H_oC_D/Sd_{50}.

2. It is found that in the case of a 1 on 10 initial beach slope, the recession of a shoreline will take place whenever the values of H_o/d_{50} and H_oC_D/Sd_{50} are larger than approximately 650 and 1100 for a deep-water wave steepness H_o/L_o of 0.015, 250 and 370 for H_o/L_o of 0.02, and 60 and 40 for H_o/L_o of 0.04 respectively. In the case $H_o/L_o = 0.009$, the critical values of H_o/d_{50} and H_oC_D/Sd_{50} can not be determined from the figure because of no enough data for large values of H_o/d_{50} and H_oC_D/Sd_{50}.

3. The effect of H_o/d_{50} or H_oC_D/Sd_{50} on the shoreline movement is very complicated, but it is evident that the sand size affects the beach process with the scale of waves. The variations in the values of X_{SL}/L_o become remarkable with increase in the values of H_o/d_{50} or H_oC_D/Sd_{50}.

4. In the case of a 1 on 30 initial beach slope, the variations in the values of X_{SL}/L_o with H_o/d_{50} are much more systematic than in the case of a 1 on 10 beach slope. In this case, also, there exist the critical values of H_o/d_{50} for the change from progression into recession of a shoreline, which depend on the deep-water wave steepness. It appears that the sand size hardly affects the beach process when the values of H_o/L_o and H_o/d_{50} are smaller than approximately 0.01 and 250 respectively. This tendency is also seen in Fig. 4a for the wave steepness of 0.009 and a 1 on 10 initial beach slope though the upper value of H_o/d_{50} is different.

5. Although there are no sufficient data to discuss for a 1 on 15 initial beach slope by Saville, it should be noted that they include the data for as large value of H_o/d_{50} as approximately 10^4. It is found from these data that even when the deep-water wave steepness is as small as 0.0023, the recession of a shoreline takes place if H_o/d_{50} is larger than a certain critical value, and that even if the order of magnitude of H_o/d_{50} is changed from 10^3 into 10^4 in the case $H_o/L_o = 0.035$, the absolute value of X_{SL}/L_o does not become large extremely. However, it is said that more data are needed to derive the correct conclusion.

Generally speaking, it is concluded that the effect of sand size on the beach process is remarkable at least within a certain range of H_o/d_{50} or H_oC_D/Sd_{50} including certain critical values of these factors for each value of H_o/L_o. It is presumed that this reason is because the mode of sand transport by breaking waves is changed from that of bed-load transport

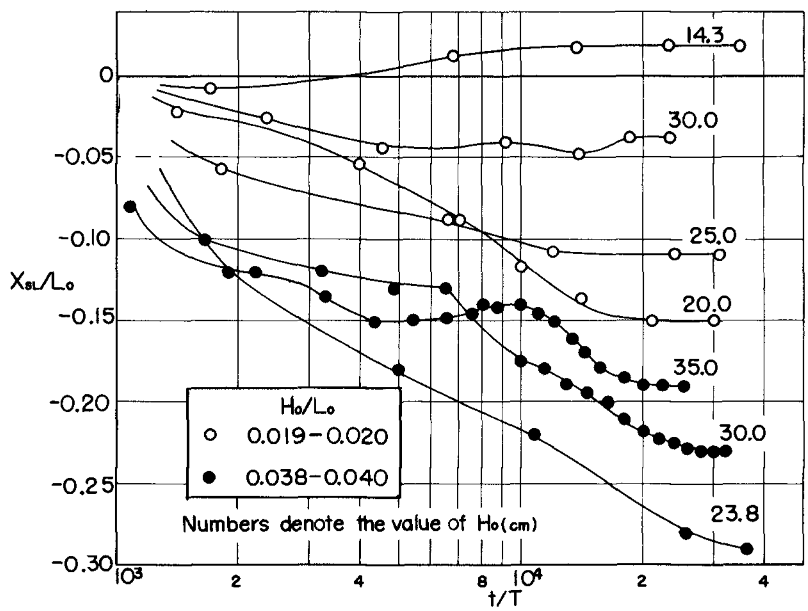

Fig. 3. Dimensionless plots of shoreline movement with time from an initial beach slope of 1 on 10.

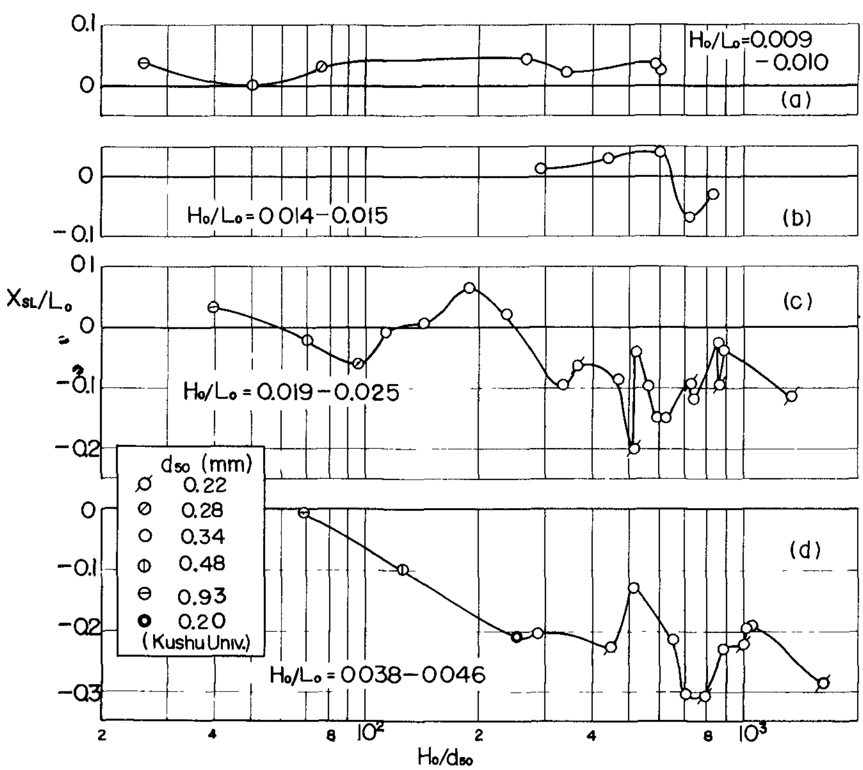

Fig. 4. Dimensionless plots of shoreline movement from an initial beach slope of 1 on 10 to the equilibrium state against the ratio of wave height to sand size.

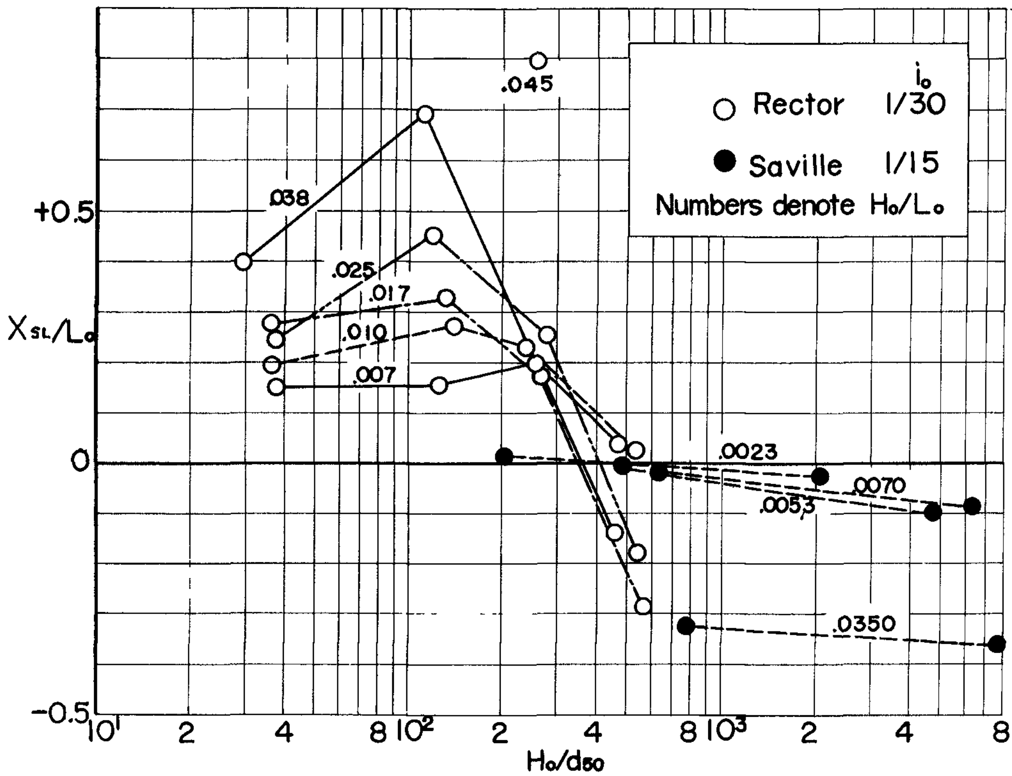

Fig. 5. Dimensionless plots of shoreline movement from initial beach slopes of 1 on 15 and 1 on 30 to the equilibrium state.

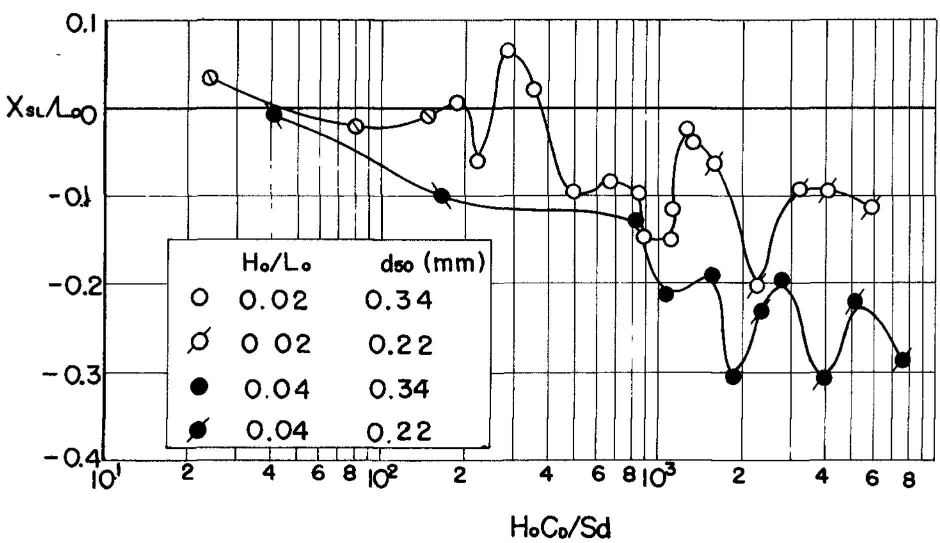

Fig. 6. Dimensionless plots of shoreline movement from an initial beach slope of 1 on 10 to the equilibrium state against H_OCD/Sd_{50}.

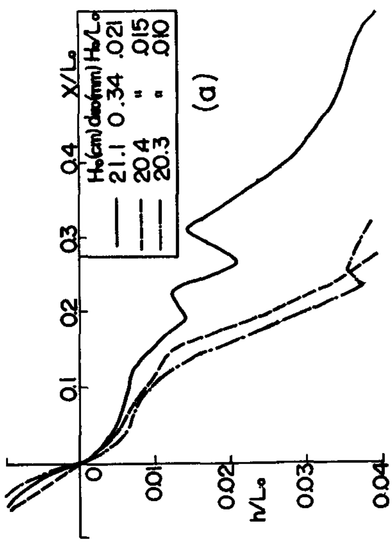

Fig. 8a

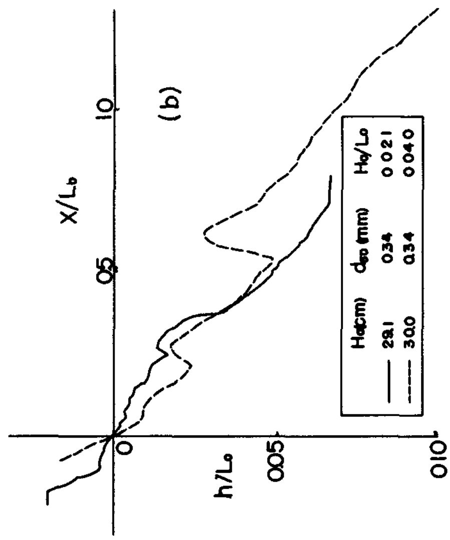

Fig. 8b
Dimensionless plots of equilibrium beach profiles for approximately same wave height and sand size, and different wave steepnesses.

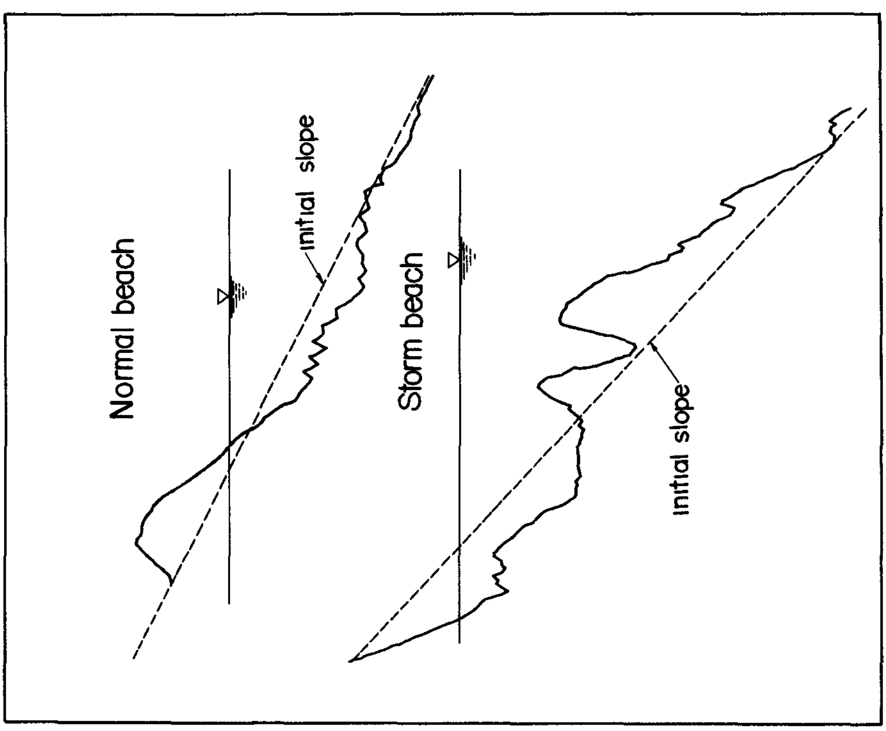

Fig. 7. Profiles of the normal beach and the storm beach.

for small values of H_0/d_{50} or H_0C_D/Sd_{50} into that of suspended-load transport for large values of H_0/d_{50} or H_0C_D/Sd_{50}.

EQUILIBRIUM BEACH PROFILES

A laboratory study by Johnson (1949) indicated that equilibrium beach profiles are classified those of the "normal" or "ordinary" beach, where there are no longshore bars, and of the "storm" beach, which is characterized by the development of longshore bars, as shown in Fig. 7. Rector (1954) made an effort to express the dimensionless equilibrium beach profile using the deep-water wave length L_0 as a function of H_0/L_0 and d_{50}/L_0. Watts (1954) made experiments to investigate the effect of varing wave periods on equilibrium beach profiles with an initial beach slope of 1 on 20. However, all of these experiments were of very small scales including the tests in Japan, compared with actual beaches. The results of the large scale experiments made by Saville (1957) showed the fact that even when the deep-water wave steepness is very small, storm beaches having longshore bars appear in the equilibrium state, which are not seen in the common experiments of small scale. From this reason, the scale effect on the equilibrium beach profile is considered by dividing the experimental results into three following cases:

Case when wave heights and sand sizes are same and wave steepnesses are different - Figs. 8a and 8b show the dimensionless plots of the equilibrium beach profiles, which are expressed by the ratios of a distance from the shoreline X and the water depth h to the wave length L_0, for the wave heights of approximately 21 cm and 30 cm, a sand size of 0.34 mm in median diameter and the different wave steepnesses. It is found from these figures that the wave steepness affects the equilibrium beach profile remarkably when H_0/d_{50} is constant. Furthermore, it should be noted that the beach profiles in the case $H_0/L_0 = 0.021$ are of the storm beach though this value of the wave steepness is smaller than the critical value 0.025 - 0.03 determined by Johnson.

Case when wave steepnesses and sediment sizes are same and wave heights are different - Fig. 9 shows comparisons of the equilibrium beach profiles for approximately constant wave steepnesses 0.021 - 0.024, a sand size of 0.34 mm in median diameter and various wave height. It is disclosed from the figure that the equilibrium beach profile depends not only on the wave steepness and sediment size but also on the wave heights. In the cases $H_0 = 21.1$ cm and 29.1 cm, the storm beaches were formed, and in the case $H_0 = 3.8$ cm the normal beach was developed though the wave steepness were almost same, and also the sediment size was constant. In the case $H_0 = 11.3$ cm it is undecided whether or not. Such differences in the equilibrium beach profile were already indicated by Saville (1957).

Case when wave steepnesses and wave heights are same and sand sizes are different - The equilibrium beach profiles are shown in Figs. 10a, 10b and 10c for two different sand sizes (d_{50} = 0.34 mm and 0.22 mm), same wave heights of 29.1 cm, 15.9 cm and 11.3 cm and same wave steepness of 0.021. As shown in Fig. 10a, the longshore bars of approximately same scale are formed and the profiles are very similar except in the vicinity of the beach-face in spite of different sand sizes in the case of a large wave height of 29.0 cm. With decrease in the wave height as shown in Fig. 10b, longshore

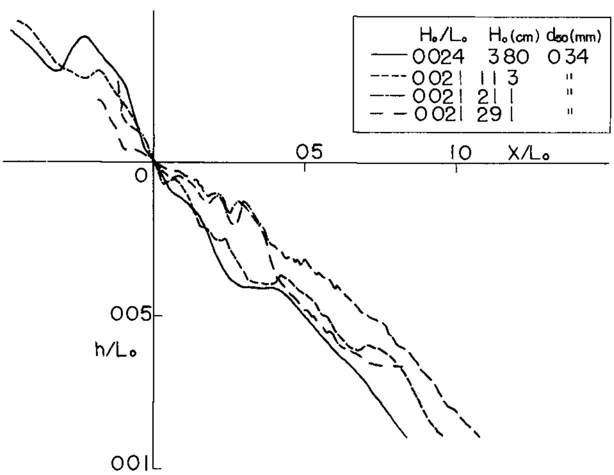

Fig. 9. Dimensionless plots of equilibrium beach profiles for approximately same wave steepness and sand size, and different wave heights.

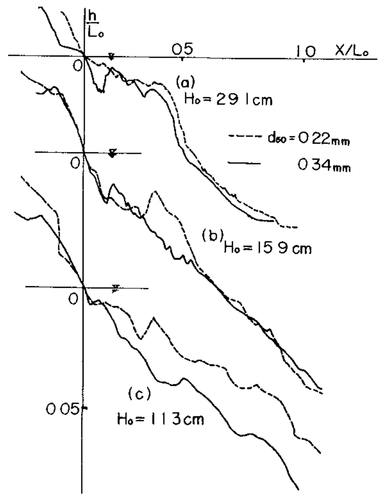

Fig. 10. Dimensionless plots (equilibrium beach profiles fo: same wave heights and constan' wave steepness of 0.021, and (ferent sand sizes.

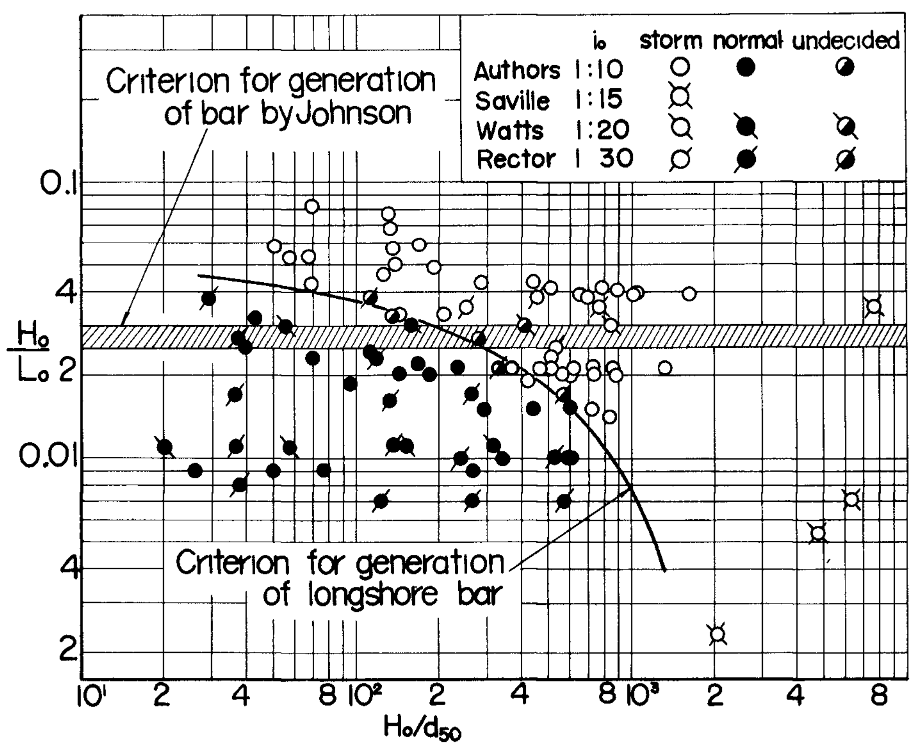

Fig. 11. Criterion for generation of longshore bars.

bars in the coarser sand (d_{50} = 0.34 mm) are reduced, thus the profiles are different in the inshore zone. Further decrease in the wave height produces the completely different profiles for the difference of sand size as shown in Fig. 10c. A longshore bar is still formed in the finer sand, and on the other hand, in the coarser sand it almost disappears. These facts can also be found in the results of experiments four different sand sizes and same waves by Watts (1954).

CRITERION FOR GENERATION OF LONGSHORE BARS

In the foregoing section, it has been found that the equilibrium beach profile depends not only on the deep-water wave steepness but also on the wave height and the sand size. From this fact it is presumed that a limitation between the storm beach and the normal beach, which is a criterion for generation of longshore bars, can also be expressed by the deep-water wave steepness H_0/L_0 and the ratio H_0/d_{50} or H_0C_D/Sd_{50}. Fig. 11 shows the log-log plots of experimental data by the authors and other investigators with the ordinate of H_0/L_0 and the abscissa of H_0/d_{50}, in which the data are distinguished between the normal beach and the storm beach, and plotted for each initial beach slope. In the figure the boundaries between the normal beach and the storm beach have been drawn, the one is by Johnson and the other is that proposed by the authors under the assumption that the initial beach slopes are independent of equilibrium beach profiles, especially the generation of longshore bars.

It is evident from this figure that when the value of H_0/d_{50} is smaller than a certain value, the critical value of H_0/L_0 proposed by Johnson is approximately valid; however, with increase in the value of H_0/d_{50} the critical wave steepness becomes small rapidly. This fact indicates that at the beach being constituted by fine sand and where large waves attack, the storm beach is formed and longshore bars appear even when the deep-water wave steepness is considerably small. It is very significant that the limitation between the storm beach and the normal beach is expressed by H_0/d_{50} and H_0/L_0.

CHANGES IN CHARACTERISTICS OF BREAKING WAVES DURING BEACH PROCESSES

It is well known that there are generally two types of breaking waves, which are called spilling breakers and plunging breakers. Laboratory studies by Iversen (1952) and Hayami (1955, 1958) indicated that the limitation between both types of breakers can be expressed by the deep-water wave steepness and the beach slope (Fig. 12). The critical wave steepness theory is based on the idea that the types of breakers are much related with the beach process; that is, beach erosion will occur with spilling breakers and beach accretion will take place with plunging breakers.

Since, however, the experimental results shown in Fig. 12 are for the fixed beds of uniform slopes, the question arises whether the same results can be applied to the beach of a movable bed or not. In Fig. 12, furthermore, the limitation is not clear when the bed slope is very small. For example, according to this figure plunging breakers appear whenever the deep-water wave steepness is 0.02, and thus beach accretion is to take place in this case. However, it is seen in Fig. 4c that beach erosion occurs even when H_0/L_0 is approximately 0.02. It is very difficult, therefore, to

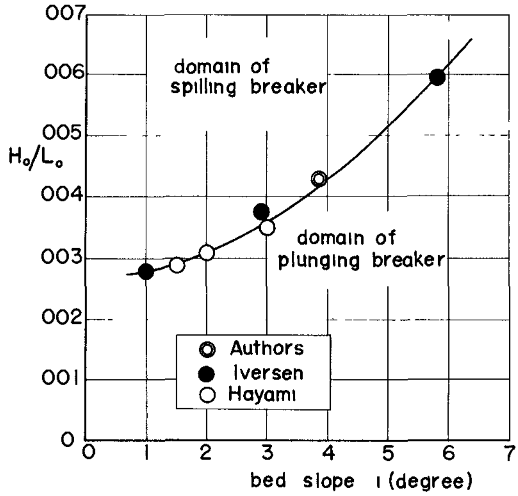

Fig. 12. Limitation between spilling breakers and plunging breakers.

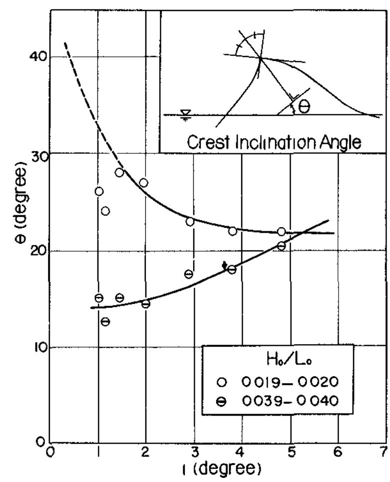

Fig. 13. Relationships between crest inclination angle of breakers and bed slope for fixed bed.

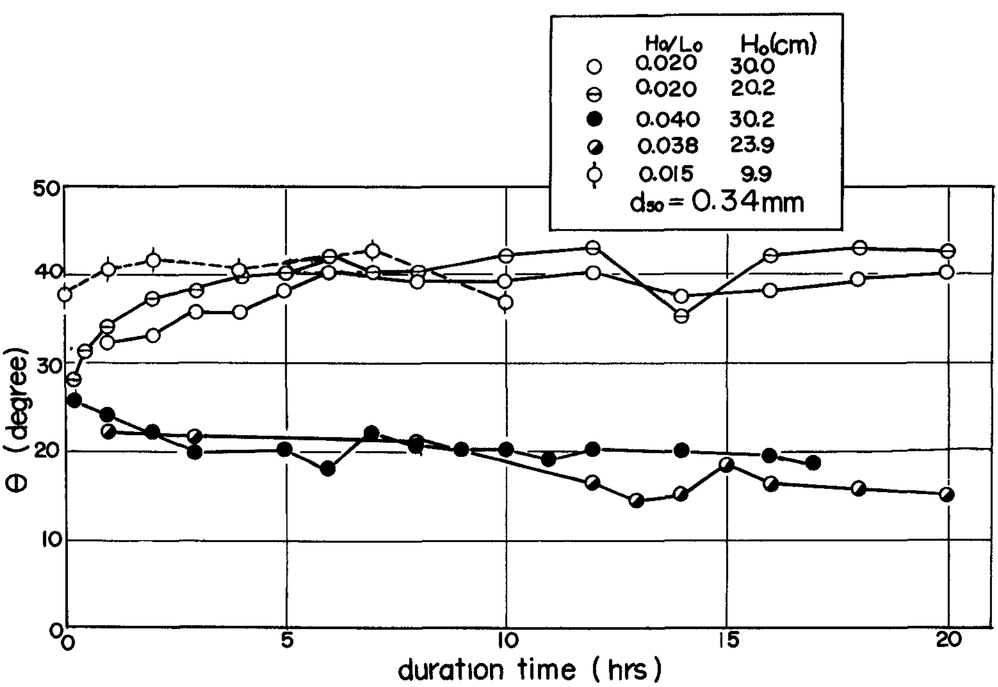

Fig. 14. Progressive changes in crest inclination angle of breakers with time for various wave steepnesses.

connect directly the critical wave steepness theory with the characters of breaking waves on the movable bed. From this reason, an effort is made in investigating the relationship between profiles of breakers and beach processes in this section.

As a quantitative expression for the profile of a breaking wave, the angle θ is treated, which is an angle between a bisector of the crest angle of a breaking wave and a perpendicular line as shown in Fig. 13. This crest inclination angle θ is very convenient to discuss asymmetricity of a breaking wave; that is, $\theta = 0^o$ if waves at breaking are symmetric completely, and $\theta = 45^o$ if they are extremely asymmetric. It is considered that the crest inclination angle becomes close to 45^o in plunging breakers and to 0^o in spilling breakers.

First, in order to disclose the relationships between the crest inclination angle θ and the bed slope i, an experiment was made by using a small wave tank with a fixed tilting beach slope. Fig. 13 shows the relationship in the cases $H_o/L_o = 0.02$ and 0.04. From this figure the followings are made clear:

1. The angle θ is changed with the slope i even if the deep-water wave steepness H_o/L_o is constant.

2. An arrow in Fig. 13 corresponds to the critical beach slope for the wave steepness of 0.04 decided by Iversen and Hayami. Therefore, the regions where the beach slopes are smaller and larger than the critical belong to those of spilling breakers and plunging breakers respectively.

3. In the case $H_o/L_o = 0.02$, the angle θ increases with decrease in the slope i. However, the experimental results show the opposite tendency when the slope is smaller than 1.5^o. It is considered that this opposite tendency may be caused by the capillary effect because of small waves. It was observed that breaking waves in this case were of the plunging type independently of the slope.

Next, the progressive changes in the crest inclination angle θ with time during beach processes are shown in Fig. 14. It is found from this figure that tha angle θ seems to reach a constant value for each wave steepness finally independently of an initial angle corresponding to an initial beach slope of 1 on 10. The duration time for the angle θ to become constant is much shorter than that for the beach to reach the equilibrium state.

In the case $H_o/L_o = 0.04$, as shown in Fig. 14, the angle θ, which was approximately 27^o on the initial beach slope of 1 on 10 ($i = 5^o43'$) after beginning of the experiment, became 19^o- 20^o at the equilibrium state. This final crest inclination angle agrees fairly with that at the beach slope $i = 4^o$- 4.5^o in Fig. 13 which corresponds approximately to the critical wave steepness theory of Iversen and Hayami. In the case $H_o/L_o = 0.02$, the final crest inclination angle was approximately 40^o as shown in Fig. 14, but the beach slope i corresponding to $\theta = 40^o$ can not be obtained precisely from Fig. 13 and it is impossible to compare that value with that by the critical wave steepness theory because there are no data for the beach slope less than 1^o in Fig. 12.

CONCLUSIONS

It is concluded from the results of laboratory tests on the two dimensional beach process that:

1. Two dimensional beach processes are influenced not only by the deep-water wave steepness but also by the scale of waves and the sand sizes.

2. The influence of sand sizes on the beach process is not remarkable when the deep-water wave steepness is smaller than approximately 0.01 and, in addition, the ratio of the wave height to the sand size is smaller than a certain value for each wave steepness.

3. Equilibrium beach profiles are also influenced not only by the deep-water wave steepness but by the wave height and the sand size.

4. The limitation between the normal beach and the storm beach, which is a criterion for generation of longshore bars, can be expressed by the deep-water wave steepness and the ratio of the wave height and the sand size.

5. The crest inclination angle of breaking waves approaches a certain value for each deep-water wave steepness with the formation of the equilibrium beach profile independently of an initial beach slope. This value of the angle agrees fairly with that of breaking waves on the fixed bed of the critical beach slope based on the limitation between spilling breakers and plunging breakers when the deep-water wave steepness is 0.04.

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