CHAPTER 11

THE EFFECTS OF BOTTOM CONFIGURATION ON THE DEFORMATION, BREAKING AND RUN-UP OF SOLITARY WAVES

Frederick E. Camfield

Research Associate, Department of Civil Engineering
Oregon State University, Corvallis, Oregon
(formerly of Stanford University)

and

Robert L. Street

Associate Professor, Department of Civil Engineering,
Stanford University, Stanford, California

ABSTRACT

Experiments were conducted to determine the various effects on the shoaling, breaking and run-up of solitary waves resulting from the bottom configuration. An initial set of experiments investigated the effect of the initial bottom slope on the breaking and run-up of a wave on a second, higher slope. A second set of experiments considered the effect of a continental shelf configuration on the transmissibility of waves in the shoreward direction, and the decomposition of the waves due to the shallower water depth on the continental shelf. It was found that, in order to make predictions at or near the shoreline for waves generated in deep water, it is necessary to consider the total configuration of the bottom leading to the shoreline.

INTRODUCTION

Large, long ocean waves moving shoreward are influenced by the bottom topography while still at a great distance from the shoreline. Two major changes occur in the bottom topography: a relatively steep continental slope which flattens out into the continental shelf, and a steepening of the bottom slope in the area of the shoreline. To the latter one must add the slope change created by man on structures placed at or near the shoreline. The primary objectives of the experiments described herein were, therefore, to establish bounds on the fluid volume delivery onto a shelf resulting from long wave encroachment, and to study the behavior of waves on a sloping bottom as a function of a previous incident slope.

While large ocean waves are most commonly described in terms of periodic wave trains or impulsively generated wave groups, our experience has shown that solitary wave studies provide valuable information on the complex bottom-wave interaction processes because of the ultimate simplicity of the solitary wave and its description (Camfield and Street, 1967). Accordingly, solitary waves have been used in the present study. As the solitary wave is the limiting case for finite amplitude periodic waves as length becomes large relative to other parameters, this study of the limiting case is very instructive and should provide a basis for future investigations.

THE EXPERIMENTS

FACILITIES AND EQUIPMENT

The present experiments were run in the Stanford Wind, Water-Wave Research Facility (Hsu, 1965) located in the Hydraulics Laboratory at Stanford University. The facility consists of a 115 foot long by 3 foot wide wave channel (Fig. 1). A glass-walled test section, 85 feet long, is located downstream from the wave generator, and waves from the generator travel 15 feet through the channel forebay before entering the test section. The inside width of the test section is 35½ inches.

Waves are generated by a vertical piston-type wave plate with a total available forward motion of 18 inches. The motion and position of the wave plate are controlled through a hydraulic-servo-electronic system by an externally applied voltage from an electronic function generator. For the present experiments a small, self-contained, electronic function generator was used. This generator produces a voltage signal in the form of a hyperbolic tangent function, has a continuously adjustable signal amplitude with a range of 0 to 5 volts, and also has an adjustable time base with a range from 0.5 to 10.5 seconds (Camfield and Street, 1967). The position of the wave plate is registered electronically by means of a gear-rack and potentiometer, and the control system matches the plate position with the input signal through a feedback circuit. The distance through which the wave plate moves is linearly related to the change in applied voltage. A change of 5 volts produces the full 18-inch motion of the plate. To produce a solitary wave a single, unidirectional, forwsrd motion of the wave plate is used.

The beach for the continental shelf configuration is shown schematically in Fig. 2. The beach is composed of three sections: the beach slope, the horizontal beach shelf, and the vertical reflecting barrier. Clearly, the objective of the beach slope and horizontal shelf was to simulate the continental slope and shelf. The vertical reflecting barrier was installed with the idea in mind that the barrier, by perfectly reflecting the waves, would provide a virtual doubling of the shelf length as the reflected waves ran back over still water.

The second beach configuration consists of a long, low slope, 45 feet in length, followed by a short, steep slope, varying in length from 5 to 10 feet. This allowed the simulation of waves in a shoreline region, impinging on a higher slope such as a man-made structure.

The initial beach slope for the continental shelf configuration is a single 10 foot long aluminum plate. This plate is 35 inches wide and 0.125 inch thick. It is rigidly supported on a welded frame composed of 2 inch by 2 inch aluminum angles. The beach slope plate was anchored to the wave tank bottom at the toe of the slope (see Fig. 2) and connected by hinges to the first plate in the horizontal beach shelf, this plate was also specially stiffened with 2 inch by 2 inch angles. In spite of the firm support, some minor flexing of the beach slope under the action of the waves was observed. The flexing had no apparent effect on the results.

The remaining beach sections were constructed from series of aluminum plates interconnected to form long, flat surfaces. The individual aluminum plates are 30 inches long by 35 inches wide and are made of 0.125 inch thick plate. Stiffening members were added to the underside of each plate. The interconnection of the individual plates is accomplished with 0.188 inch thick by 4 inch wide aluminum plates placed under the joint and connected to the plate on either side by eight machine screws. The plate assembly is suspended from above by steel rods; there are two 0.5 inch rods attached to each plate at a distance of 1.5 inches from the walls of the wave tank.

The vertical reflecting barrier is composed of two plates identical to those used in the sections above. The barrier is attached by hinges to the final plate in the shelf. When the slope and shelf were in proper position the reflecting barrier was blocked firmly in place with 2 inch by 4 inch wood studs to which the barrier was clamped after the assembly was plumbed to vertical. This barrier was also used to study wave run-up on a vertical wall, and was later adjusted to a 45° slope for studies of wave run-up.

Wave heights were recorded by means of capacitance-type wave height gages (Camfield and Street, 1967; Colonell, 1966). The output from the gages was recorded by means of a Sanborn recording oscillograph system, series 950, equipped with carrier preamplifiers. The gages were suspended on long steel tubes from 2 inch by 6 inch aluminum channels mounted atop the wave tank. The gage calibrations were linear and were obtained by raising and lowering the gage (and mounting tube) in still water. Motion pictures were taken of the breaking and run-up detail, using a 16 mm Bolex movie camera with a 10 mm wide-angle lens and Tri-X film.

THE SOLITARY WAVE

The solitary wave has a form lying entirely above the still water line and consisting of a single swell that propagates without change of form and at a constant celerity in water of uniform depth (Ippen, 1966, Camfield and Street, 1967). Figure 3 shows a solitary wave of height H, in water of depth D, and traveling with celerity c in the positive x-direction. On the basis of considerable analysis and many experiments, it has been determined that the following equations quite adequately describe the wave on a horizontal bottom. The surface profile η is given by

$$\eta = H \operatorname{sech}^2 \left[\left(\frac{3H}{4D^3} \right)^{\frac{1}{2}} (x - ct) \right] \qquad (1)$$

where t is time. The celerity c is

$$c = [g(H + D)]^{\frac{1}{2}} \tag{2}$$

where g is the acceleration due to gravity.

From Equation (1), the volume above the still water line in the wave is

$$V = \int_{-\infty}^{\infty} \eta \, dx = \left[\frac{16}{3} D^3 H \right]^{\frac{1}{2}} \tag{3}$$

per unit of crest length. It follows that

$$\frac{H}{D} = \frac{3}{16} \left(\frac{V}{D^2} \right)^2 \tag{4}$$

Hence, V/D^2 is a useful measure of the volume in a given wave and simultaneously is directly related to the relative wave height H/D. As we are concerned here with the volume delivery over a beach slope and onto a shelf, the ratio V/D^2 is taken as the primary non-dimensional parameter of the study.

HYDRAULIC JUMPS AND BORES

If a solitary wave moves up a plane beach into ever shallower water, the wave will eventually break. If the beach slope is small (say less than 8°, cf., Camfield and Street, 1967), the breaking wave will propagate shoreward and maintain a relatively steep, turbulent face. Such a progressing wave with a steep front is called a bore (Stoker, 1957). This bore is the direct analog of the hydraulic jump, i.e., the bore is a moving hydraulic jump. In the shelf experiments, it was observed that the appearance and behavior of the experimental solitary waves after passage over the slope onto the shelf was not unlike that of hydraulic jumps.

Consider a moving hydraulic jump. View this jump with respect to a set of coordinates fixed in the face of the jump and traveling at the speed C_S of the jump. The classical results of stationary jump analysis (Henderson, 1966) are easily adapted to the moving system. Figure 4 shows the two common types of hydraulic jump expected for the Froude number range of the present experiments and the notation to be employed here.

If the depth in front of the jump is $y_1 = D_S$ and that behind the jump is y_2, application of the momentum and continuity principles in the moving coordinates yields the sequent depth relationship

$$\frac{y_2}{y_1} = \frac{1}{2} \left[(1 + 8F_1^2)^{\frac{1}{2}} - 1 \right] \tag{5}$$

where the Froude number F_1 is given by

$$F_1 = \frac{C_S}{(gD_S)^{\frac{1}{2}}} \tag{6}$$

Recall that C_S is the speed of the jump over the fixed bottom of the shelf, while $D_S = y_1$ is the still water depth ahead of the moving jump.

The rationale behind the existence of the undular and broken jumps has been examined by Benjamin and Lighthill (1954). Their comments on the work of Favre (1935) and Lemoine (1948) are summarized below.

The classical jump analysis shows that, across the jump, the rate of energy loss $\dot{e}$ per unit of jump crest length per unit time is

$$\dot{e} = \frac{1}{4} g \frac{(y_2 - y_1)^3}{y_2 y_1} \rho q \tag{7}$$

where ρ is the fluid density and q is the flow rate. The point of basic interest here is that the energy loss need not necessarily be dissipated into heat and lost; part (even most in some cases) may be radiated downstream behind the jump through the trailing wave train of the undular jump.

Thus Favre found that, for $F_1 < 1.21$, none of the waves of the jump exhibited any breaking. Lemoine concluded that under these circumstances the required loss of energy may occur not by friction, but by radiation through the trailing wave train. Favre found further that the trailing waves form behind the bore one by one after it is first created. The number of waves present at any instant may then be regarded as an indicator of the period of existence of the bore. This is in accord with Lemoine's view that the trailing wave group carries the energy away as it is liberated at the bore.

An essential contribution to this concept by Benjamin and Lighthill (1954) was the extension of the analysis of Lemoine to finite amplitude waves. They show that the behavior of a supercritical stream (or, as in the present case, a disturbance moving over still water at a speed such that $F_1 > 1$) is describable as follows: for a bore with no frictional effects at all the only form of disturbance that can arise is the solitary wave; for a bore in which the classical value of energy is dissipated in friction at the bore, no trailing wave train can arise; the undular jump or bore with trailing wave train exists when the frictional losses lie between these extremes. Thus, the formation of a train of waves behind the bore front requires some frictional dissipation, but not too much.

EXPERIMENTAL RESULTS

THE CONTINENTAL SHELF PROBLEM

The experimental configuration is shown schematically in Fig. 2. The independent variables of the study were:

D_T = the "deep water" depth at the toe of the beach slope

D_S = the water depth on the horizontal beach shelf

α = the angle of inclination of the beach slope

H = the solitary wave height

Accordingly, the test parameters were:

H/D_T = relative deepwater wave height

D_T/D_S = water depth ratio

α

For the present tests, water depth ratios of $D_T/D_S = 2.0$, 3.0, 6.6, 9.2 and 12.1 and beach slopes of $\alpha = 4$, 6, and 8 degrees were used. The range of the volume parameter was $0.10 \leq V/D_T^2 \leq 1.25$. This corresponds to a range of relative, deepwater wave heights of $0.002 \leq H/D_T \leq 0.30$. Under the given conditions and with the present facility and equipment, the lower limit on H/D_T was imposed by the resolution of the wave gages and the limited ability of the wave plate to generate pure solitary waves of extremely small heights, while the upper limit on H/D_T was imposed by the limited motion of the plate (18 inches maximum).

Wave volume data were obtained from capacitance wave height gages located at stations 17, 28.15 feet to the right of the toe; 18, 30.85 feet to the right of the toe; and 19, 33.20 feet to the right of the toe (Fig. 2). The area beneath the oscillograph wave height trace was planimetered, and the wave volume on the shelf was obtained from the product of this area and the wave celerity C_S (Street, Burges, and Whitford, 1968).

The volume of the initial, solitary wave in deep water (depth D_T) was determined directly from the displacement of the wave generating plate through use of the following argument. First, the leakage between the wave plate and the channel walls is assumed to be negligible. Then, if the sole effect of the single, unidirectional forward motion of the wave plate is to produce a solitary wave form, given by Eq. (1), lying entirely above the still water line, it can be assumed that all the water displaced by the motion of the plate has gone into the region above the still water line. That this should be the case is intuitively obvious. In addition, we have made the necessary experimental observations to verify the assumptions for waves with a proper time base.

Shelf wave height data were taken at station 17. This has been designated H_{17}. The adjoining station 18 was used in a few cases, but on the average the data from the two stations appear to be essentially the same.

The results are defined using the parameters:

K_T = the fraction of the initial wave volume that reaches station 17; V_S/V, where V_S is the wave volume on the shelf.

$1 + \frac{H_{17}}{D_S}$ = the relative total water depth beneath the crest of the leading wave or bore on the horizontal beach shelf.

C_S = celerity of the leading wave or bore front on the shelf.

These results will be interpreted in terms of their relationships to the volume V of the incident solitary wave, the ratio of water depths and the beach slope angle α. Data have been plotted for K_T and $1 + (H_{17}/D_S)$ versus V/D_T^2 for the various ratios of D_T/D_S. These results are summarized in Figs. 5 and 6.

The significance of the various parameters is now summarized. First, the relationships between K_T and V/D_T^2 depicted in Fig. 5 describe the fraction of fluid volume delivered onto a shelf by the encroachment of a long wave. Fig. 6 gives the equivalent results in terms of the relative total water depth, $1 + (H_{17}/D_S)$, at the bore front, the crest of the leading wave of a system or the crest of a single wave on the shelf. Recall that the incident wave height $H/D_T = (3/16)(V/D_T^2)$.

Fig. 7 depicts the relationship between the actual sequent depth ratio of a wave system, $(D_S + H_{17})/D_S$, and the sequent depth ratio, y_2/y_1, of an equivalent hydraulic jump, i.e., a jump with Froude number F_1.

The summary plots (Figs. 5 and 6) show the deepwater to shallow water depth ratio D_T/D_S as a parameter. It is clear that a change in D_T/D_S has a pronounced effect on the shelf wave heights and on the fraction of volume transmitted. The linear relationships proposed in Fig. 5 were chosen because no consistent results could be obtained with curves of a more sophisticated nature. For $D_T/D_S = 12.1$ data were available only for $\alpha = 8^\circ$. The linear fit to these data was not consistent with that for other D_T/D_S values. Because of the absence of other data for $D_T/D_S > 12.1$ (not possible in the present facility) or other α, the 12.1 data for K_T are not included on Fig. 5.

As little as 40 percent of the initial wave volume appeared on the horizontal beach shelf in some cases. However, a significant or coherent reflected wave moving to the left away from the beach slope was never observed. It is thought that the reflected volume moved away as a low solitary wave.

It is noted that the wave system on the shelf continued to evolve as it propagated. In particular, it was observed that wave crests continued to appear after the initial deformation on the beach slope, that after the wave system reflected from the vertical barrier the waves in the system began to appear to take on equal heights, and finally that the deformation to an undular bore occurred in many cases without breaking. If these observations are coupled with those above that establish that the wave system on the shelf moves like a moving hydraulic jump, then it is clear that the precise situation described by Benjamin and Lighthill (1954) and Lemoine (1948) has been observed. Thus, the wave system is continually radiating energy downstream (or to the rear). Finally, a check of the data confirms the Favre (1935) result that the transition of a supercritical stream can take place for $F_1 < 1.25$ without any breaking.

THE TWO-SLOPE PROBLEM

When a submerged, symmetrical hump was placed on a horizontal channel bottom, and solitary waves were generated in the channel, waves of a proper height were observed to break downstream from the hump. This breaking occurred in relatively the same location for a fairly wide range of wave heights. From this the following conclusions were drawn·

(1) Waves which reach a critical ratio of wave height to water depth, H/D , will not necessarily immediately break, as the breaking process depends upon particle motion within the wave and is time dependent.

(2) Waves which reach some critical state, as yet not well defined, will always break, even if the wave has passed into a region where the ratio H/D no longer exceeds a critical value.

From these conclusions it is possible to say that the breaking process is not dependent on the bottom configuration immediately below the wave, but instead is dependent on the slope which the wave has passed over preceding its arrival at the breaking position. Also, it may be concluded that the bottom slope affects the shape of the wave, and that sufficient loss of wave symmetry precipitates breaking.

The above leads to a question concerning the validity of previous results for wave breaking and run-up on a slope, where the generated waves passed over a horizontal bottom before impinging on the slope. The bottom slope in the region of a shoreline would not normally be expected to be horizontal. This created the necessity for investigating waves passing over initial low slopes before running up on a second, higher slope.

Extensive experiments have been conducted (Camfield and Street, 1967) for solitary waves shoaling for long distancea over low slopes. From these an empirical solution was obtained for the limiting height of waves on low slopes. The ratio H_B/D_B , where H_B ia the wave height at breaking and D_B is the still water depth at that point, was found to be represented by the expression

$$H_B/D_B = 0.75 + 25\ S - 112\ S^2 + 3870\ S^3 \tag{8}$$

This expression was found for $0.000 \leq S \leq 0.045$.

Experiments were then performed for waves traveling long distances over low slopes and then onto higher slopes. If the initial low slope is S_1 , the second alope S_2 , the water depth at the intersection of the two alopes D_O and the wave height at that point H_O , the maximum value of the ratio H_o/D_o is given by Eq. (8) as

$$(H_o/D_o)_{max} = 0.75 + 25\ S_1 - 112\ S_1^2 + 3870\ S_1^3 \tag{9}$$

Values of H_B/D_B were recorded for waves which broke on the second slope. Fig. 8 shows a summary of results for $0.01 < S_1 < 0.03$ and $S_2 = 4^o$. The solid lines terminate at the point where the waves break at the toe of the second slope and $H_B/D_B = H_o/D_o$. It can be seen that H_B/D_B increases with increasing S_1 for given values of H_o/D_o. Limited experiments were run for $S_2 = 8^\circ$ and $S_2 = 12^\circ$ and the same trend was seen to exist. However, the number of data points was insufficient to plot due to the experimental errors inherent in obtaining this type of data.

In addition to measuring H_B/D_B, values were obtained for the vertical rise of water, R, on the second slope. Fig. 9 shows a summary of data for $0.01 < S_1 < 0.03$ and $S_2 = 4^\circ$ and 8°. Again, limited data obtained for $S_2 = 12^\circ$ showed the same general trend, but data on this slope is insufficient to include in the plots. It is readily noted that the run-up factor R/H_o increases for fixed values of H_o/D_o and S_2 as the initial slope S_1 increases. It is also evident that R/H_o increases as H_o/D_o decreases and S_2 increases.

Additional experiments were carried out with the initial slope set at values of $S_2 = 45^\circ$ and 90°. This allowed a comparison with previous results on wave run-up obtained for waves impinging on 45° and 90° slopes after passing over a horizontal bottom (Camfield and Street, 1967). Results for a 45° slope are shown in Fig. 10 in comparison with the empirical line of Hall and Watts (1953). Results for $S_2 = 45^\circ$ show that the run-up was increased by the non-zero initial slope. For a second slope of 90° (Fig. 11) results of considerably more interest were obtained. Previously, for waves passing over a horizontal bottom and onto a vertical wall, the equation

$$R/H_o = 2.0 + H_o/D_o \tag{10}$$

was obtained. For waves passing over a slope of $S = 0.01$ and when H_o/D_o was small, values of R/H_o were still somewhat within the range of the above equation as the waves remained fairly symmetrical. However, as H_o/D_o increased, the waves became very steep fronted and came into contact with the vertical wall with explosive impact. Visual observations of waves having high values of H_o/D_o indicated values of $R/H_o \approx 5.0$ with spray reaching approximately twice this height. As the higher portion of the run-up became a thin film, it was difficult to accurately measure the exact height of run-up. Therefore the values shown in Fig. 11 are somewhat conservative.

It can be noted that the trend of data on the higher slopes is the opposite of the trend on the lower slopes, i.e., the run-up increases with increasing H_o/D_o and decreases with increasing S_2. This can be explained by noting that the waves broke where the second slope had a low value. As waves having lower values of H_o/D_o and/or traveling over higher values of S_2 tended to break relatively closer to the shoreline, less energy was dissipated and the run-up increased where the second slope was small. On the other hand, as the second slope reaches a high value the wave does not break but the effect of gravity becomes more predominant.

Attention is called to the one point on Fig. 11 for a wave which broke on the initial slope before reaching the vertical wall. When a wave breaks there is a rapid decrease in wave height (Camfield and Street, 1967), much more rapid in fact than the decrease in energy. Therefore, for waves which break in front of the wall, the value of R/H_o can be expected to be higher than the value of R/H_o for a nonbreaking wave with the same value of H_o/D_o, where H_o/D_o is measured at a point the equivalent of one-half of the effective wave length in front of the vertical wall in each case.

Limited observations were made for a case where the first slope was set at $S = 0.03$ and 0.045 , the second slope was set at 1/5, and the wave was allowed to break on the first slope, forming a bore. It was found that the bore would reflect from the second slope. This reflected bore was superimposed on the increased water level caused by the incident bore and the resulting water level was higher than the incident bore.

CONCLUSIONS

By use of solitary waves propagated over a stepped slope it has been shown that long waves can deliver a significant portion of their initial volume to an arbitrary point on a shelf beyond the slope. In addition, the wave system, formed on the shelf by shoaling of a solitary wave, was shown to behave essentially as a moving hydraulic jump or bore when the ratio of water depths before and after the slope is, at least, greater than or equal to 2.0.

The restricted travel distance of the present wave generator plate limited the range of these exploratory tests. It is believed that it would be instructive, for example, to run tests for $D_T/D_B < 2.0$ and > 12.1 to ascertain if the indicated trends persist in these domains. In addition, it would be instructive to use larger values of α or a longer beach slope (hence, greater D_T/D_B) to see if the solitary wave could be forced to break on the beach slope. This did not occur herein. Accordingly as the wave size (volume) increased, K_T increased. It is believed that K_T will reach a maximum value when either the initial wave exceeds its limit height in deep water or when it breaks on the beach slope. Thus, one of the original questions posed at the start of this investigation, to wit: "Is there an optimum combination of parameters for the maximum volume delivery to a shelf?" remains unanswered, while on the other hand much has been gained in terms of our understanding of wave behavior on a stepped slope.

The results for a low initial slope followed by a second higher slope show that the initial slope has a significant effect on both the breaking height and the run-up of the waves. It is therefore necessary to consider the bottom slope at some distance from the shoreline when analyzing waves approaching the shoreline, and when predicting the breaking and run-up of the waves on the shoreline or on structures near the shoreline. The present experiments showed qualitative trends which could be used to predict the effects of various slope combinations. However, it is suggested that further data should be obtained for any quantitative analysis for design purposes.

ACKNOWLEDGEMENT

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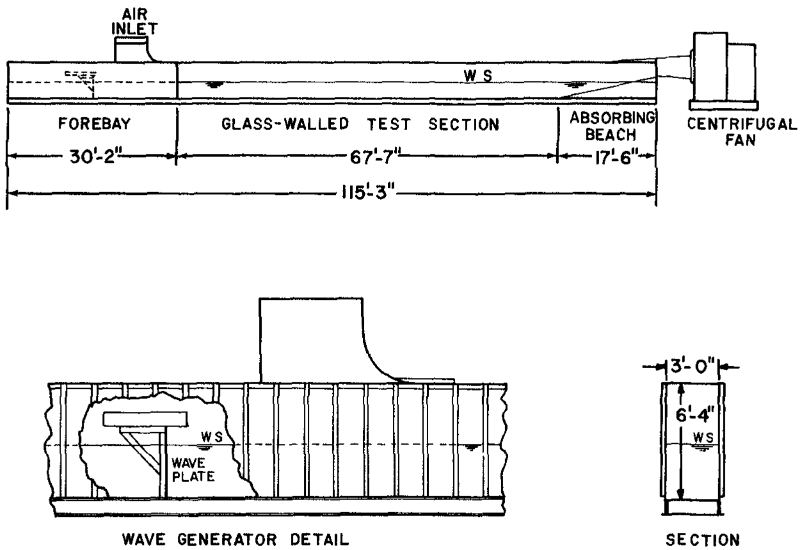

Fig. 1. The Research Facility.

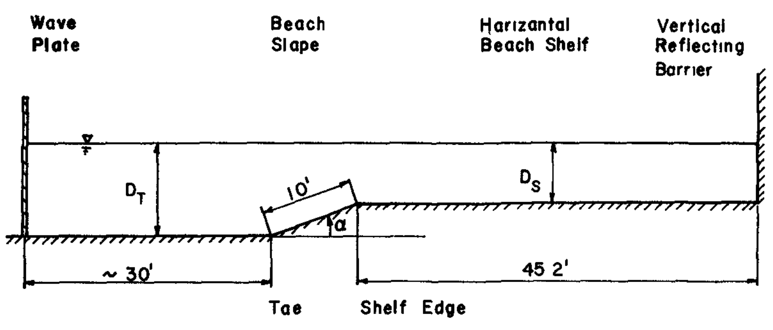

Fig. 2. The Continental Shelf Configuration.

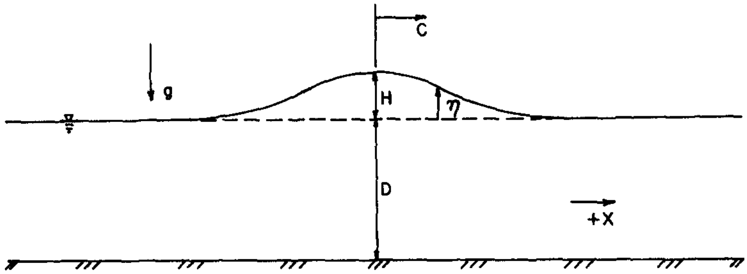

Fig. 3. Schematic of a Solitary Wave.

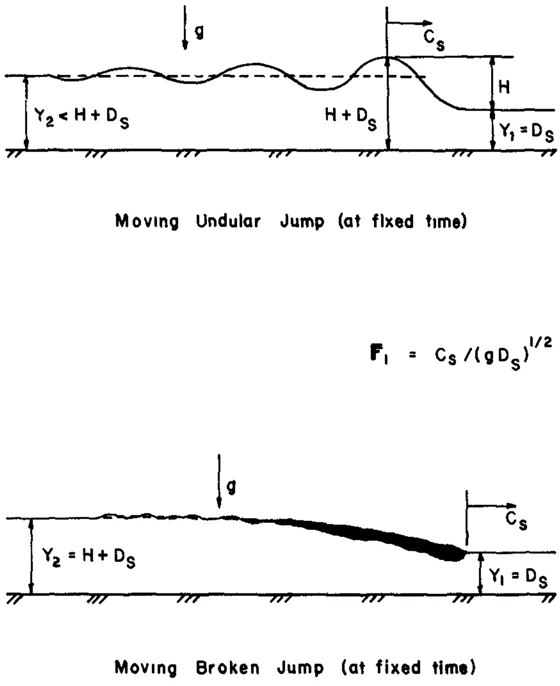

Fig. 4. Schematic of Hydraulic Jumps.

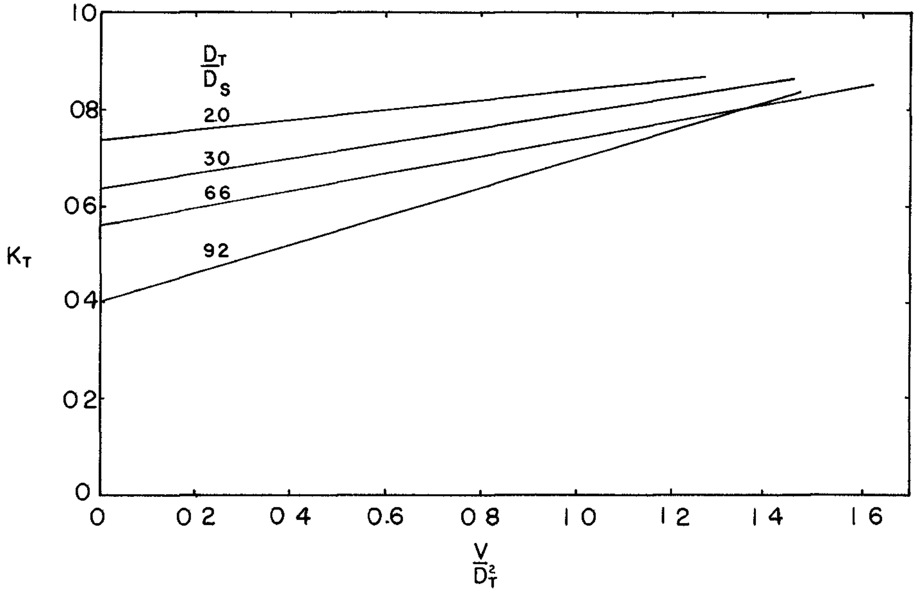

Fig. 5. K_T versus V/D_T^2 .

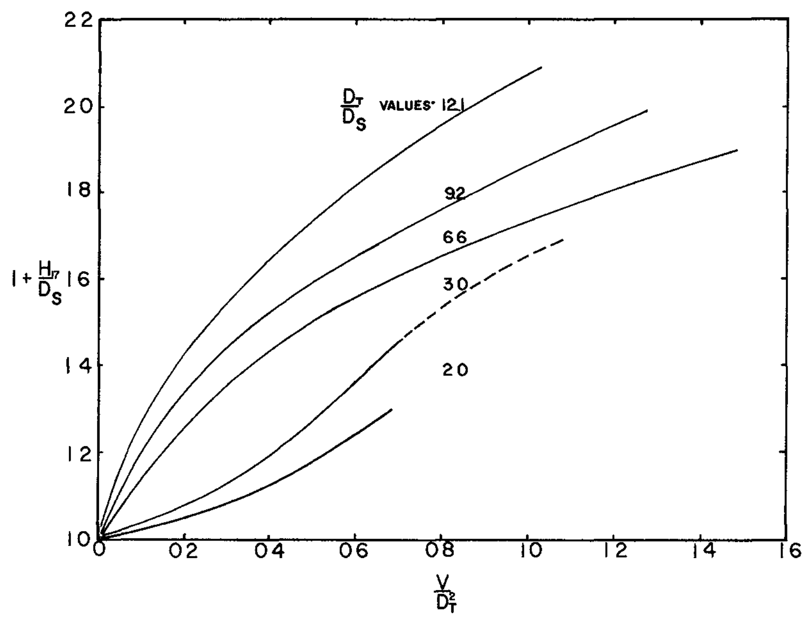

Fig. 6. $1 + (H_{17}/D_S)$ versus V/D_T^2 .

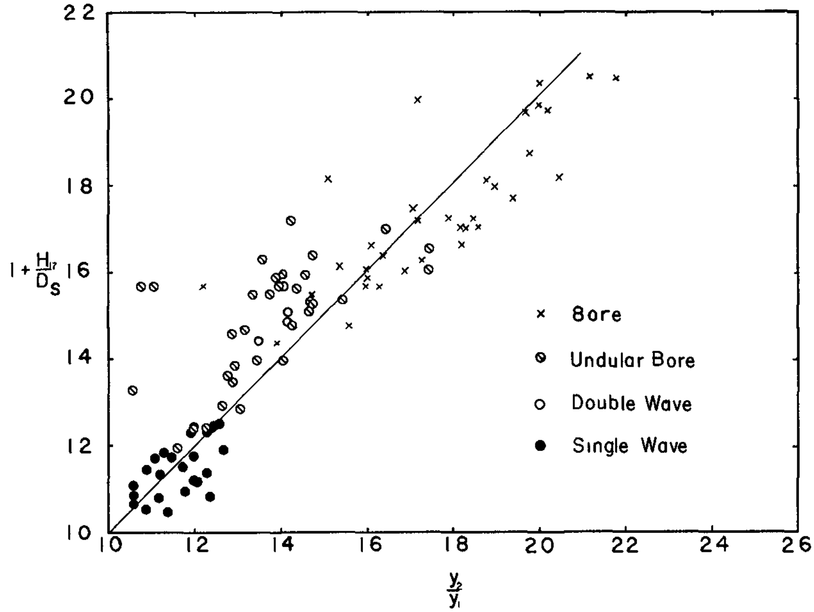

Fig. 7. $1 + (H_{17}/D_S)$ versus y_2/y_1 .

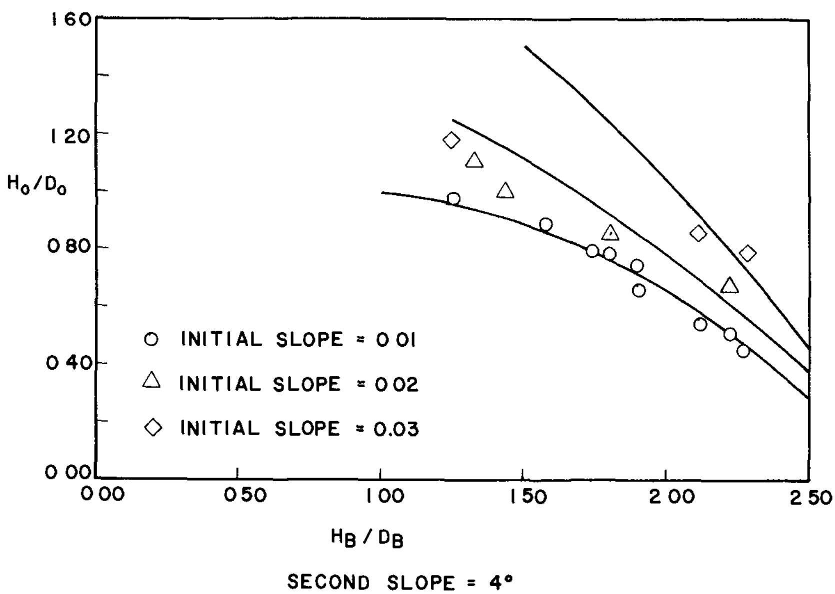

Fig. 8. Breaking Characteristics on Broken Slopes

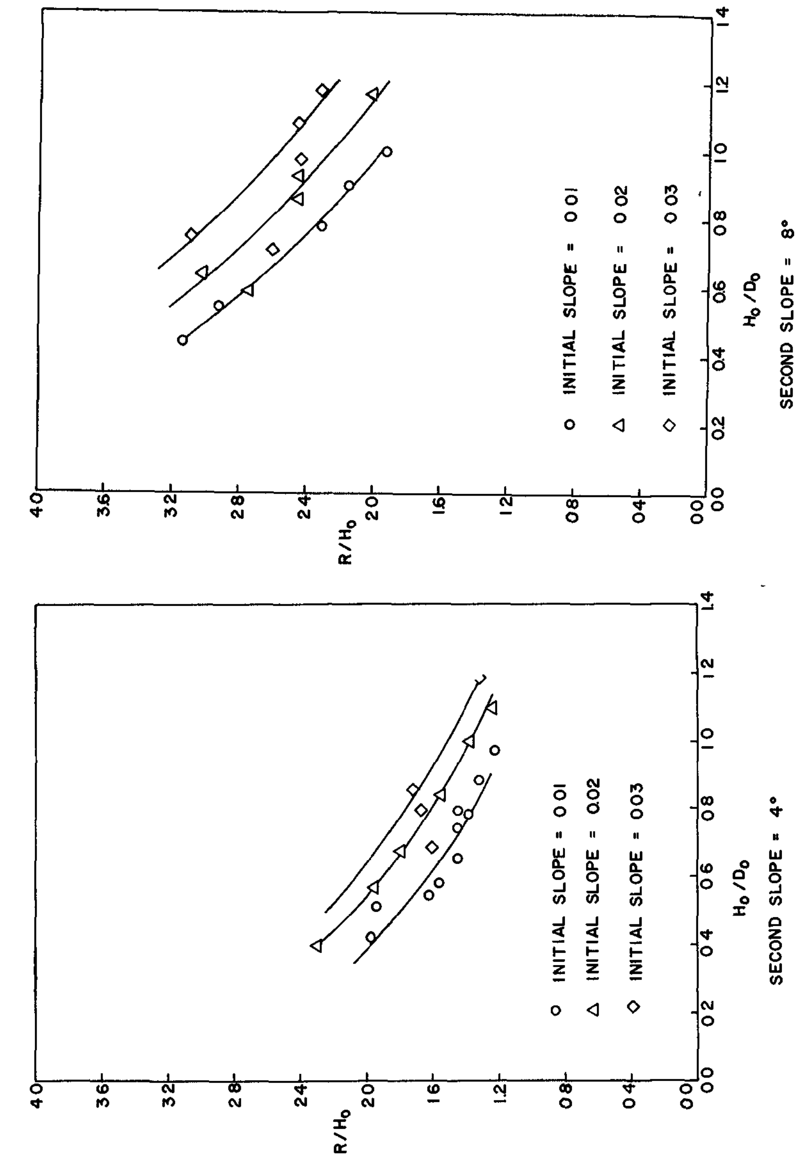

Fig. 9. Wave Run-up on Broken Slopes

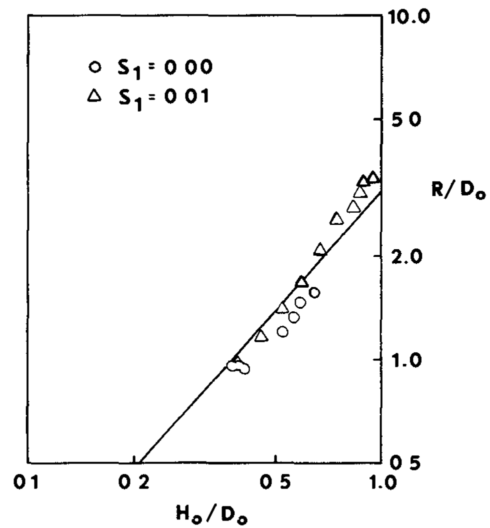

Fig. 10. Wave Run-up on a 45-Degree Slope.

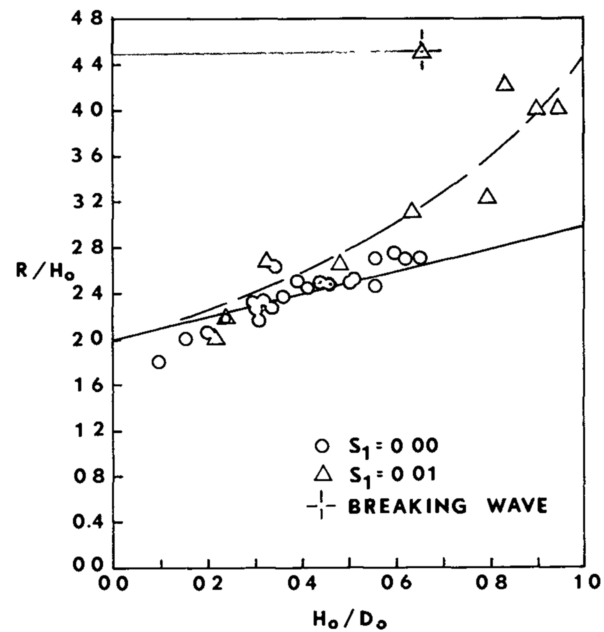

Fig. 11. Wave Run-up on a Vertical Wall.