CHAPTER 36

TIDAL INLET CURRENT--OCEAN WAVE INTERACTION

by

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Abstract

An experimental study was conducted in a three-dimensional wave basin to investigate the manner in which surface gravity waves propagating toward a tidal inlet are altered. Dimensional analysis of the pertinent variables indicates that a functional relationship exists between as many as five dimensionless terms, and the functional relationship is displayed in graphical non-dimensional form to apply to all scales. Results indicate the ebb current increases the steepness in the ocean region to such an extent that the wave begins to lose energy by the crest spilling down the front of the wave, and the wave characteristics in the inlet proper may never reach the breaking limit unless factors other than a current alone are involved.

Introduction

The non-uniform current created by tidal flow through the relatively narrow inlets connecting many bays and estuaries to the open ocean can have a significant influence on the characteristics of surface gravity waves propagating toward the inlets. For a flood flow, the waves will be lengthened and will experience a decrease in height. The ebb current is seen to compress the wave length and concentrate the energy of the wave form which is reflected in a dramatic increase in height. This has a direct bearing on the energy propagation through the inlet and into the bay or estuary, as well as implications regarding the flushing of littoral drift and sediment from the inlet.

The pattern of the build-up of the non-uniform tidal current on the flood stage from the region of essentially zero velocity offshore to its maximum value at the inlet throat is distinctly different from the decay of the ebb current as it is discharged into the ocean. The ebb flow emanates from the inlet as a jet and can be detected much further offshore

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than can the flood currents. This jet action creates a channel effect through the offshore bar and shoal region, and it is often this natural channel which will be improved and maintained for navigation. On the other hand, the flood currents form smaller flood channels to the sides of this main ebb flow channel.

Coastal inlets in a natural state are subjected to opposing forces which alternately try to close or enlarge the passage. During the flood stages, the littoral transport of sand in the surf zone tends to be swept into the tidal inlet by the wave action and strong currents created by the rising tide. On the ebb flow, the estuary experiences a flushing condition and sediment, both suspended and bed load, may be swept through the tidal inlet and passed down coast or lost to deep water. A river may also drain into the bay, augmenting the ebb flow. When a balance of these forces exists the inlets tend to be stable and remain open. Otherwise the inlets may try to migrate or close completely.

It is desirable that the inlet location and geometry remain fixed, so decisions are frequently made that corrective engineering works be undertaken to insure the stability of a tidal inlet on an erodible coast. To prevent the lateral movement of the coastal inlet, jetties are often constructed which extend seaward from the shore and become essential to the operation of a dependable inlet for navigation purposes. When both a jetty system and maintenance dredging of a navigation channel through the offshore bar are required, the characteristics of the surface gravity waves being propagated toward the inlet can be significantly altered.

An understanding of the phenomena connected with the interaction of tidal inlet currents and ocean waves is important for several reasons. The current will alternately oppose or flow with the waves as they are propagated upstream. During the ebb flow, waves which are entering the estuary will have their steepness increased and hazards to navigation are accordingly produced. In the alternate case, waves traveling with the tidal current will have their lengths increased and the energy propagation into the estuary occurs at a rate proportional to the vector sum of the group celerity and the current velocity plus an additional interaction term. The energy propagation and dispersion into the estuary will frequently affect harbor facilities and marinas and knowledge of the amount of energy amplification or reflection at a tidal entrance is desirable

Previous Studies

Considerable analytical effort has been expended in an attempt to explain the mechanism by which a current can alter a wave's characteristics, but the subject has had only a limited amount of experimental input. A two-dimensional study of the point where waves become unstable and break as they are propagated against a current was performed for deep water conditions by Yu (1). Experimental studies of hydraulic breakwaters were performed by Herbich, Ziegler, and Bowers (2) to determine the effect of wave characteristics and breakwater requirements on wave attenuation. Another two-dimensional study was made by Sarpkaya (3) to determine the conditions of stability of progressive, oscillatory waves in flowing water.

Collins (4) performed a two-dimensional study of the effects of currents on the mass transport of progressive water waves, and Hughes (5) created a Couette-type flow between two concentric cylinders in which he studied waves with lengths of the order of 2.5 cm and periods of the order of 0.1 sec. No experimental work is known to exist for a three-dimensional situation where the current can vary in the direction of wave propagation.

Historically, the classic analysis was given by Unna (6) in which he showed that when the current opposes the wave propagation and has a velocity of one-fourth the wave celerity in deep water, the waves must break however small their initial steepness. But Unna assumed without justification that the wave energy is propagated with a velocity equal to the sum of the group velocity and the local stream velocity, and that no coupling takes place between the waves and the current. On the contrary, it was shown later by Longuet-Higgins and Stewart (7) that gravity surface waves riding on non-uniform currents are modified to a much greater extent than would be predicted if there were no interchange of energy between the wave system and the current.

Johnson (8) made a theoretical development for deep-water conditions of a wave train crossing a current at an angle, in terms of the initial wave length and direction, and the magnitude of the current. He showed that refraction of the waves by the current effects a change in the wave length and stretches or compresses the wave crest. Classical shallow-water theory for the propagation of long waves in running water was modified by Burns (9) to include the effects of the vorticity present in the main stream as the result of the action of viscosity. Hunt (10) analytically considered some particular cases of the effects of a non-uniform current. For linear waves on a current varying as the one-seventh power of the depth, the velocity of propagation was found as a power series in the square root of the Froude number. For the non-linear solitary and cnoidal waves, both the profile and the velocity were found to depend on the value at the free surface of the current and its first derivative. Longuet-Higgins and Stewart (7) theoretically studied the changes in wave length and wave amplitude of surface gravity waves riding on steady non-uniform currents. They recognized an interaction term for which they coined the phrase "radiation stress". It appears this same phenomenon had been deduced previously and quite independently by Lundgren (11).

The limited experimental work has all been performed under certain specific conditions to obtain particular information about one facet of the overall subject. It appears that no experimental work of a three-dimensional nature has been performed in an effort to either verify or refute the analytical conclusions.

Experimental Apparatus

An experimental study was conducted at the U. S. Army Corps of Engineers, Waterways Experiment Station to determine quantitatively the manner in which surface gravity waves are altered by non-uniform tidal inlet currents. A wave basin of dimensions 150 ft long, 50 ft wide, and 3 ft deep, shown in Fig. 1, was used in which a relatively narrow opening was constructed to connect the ocean with a bay region. All flow was required to pass through

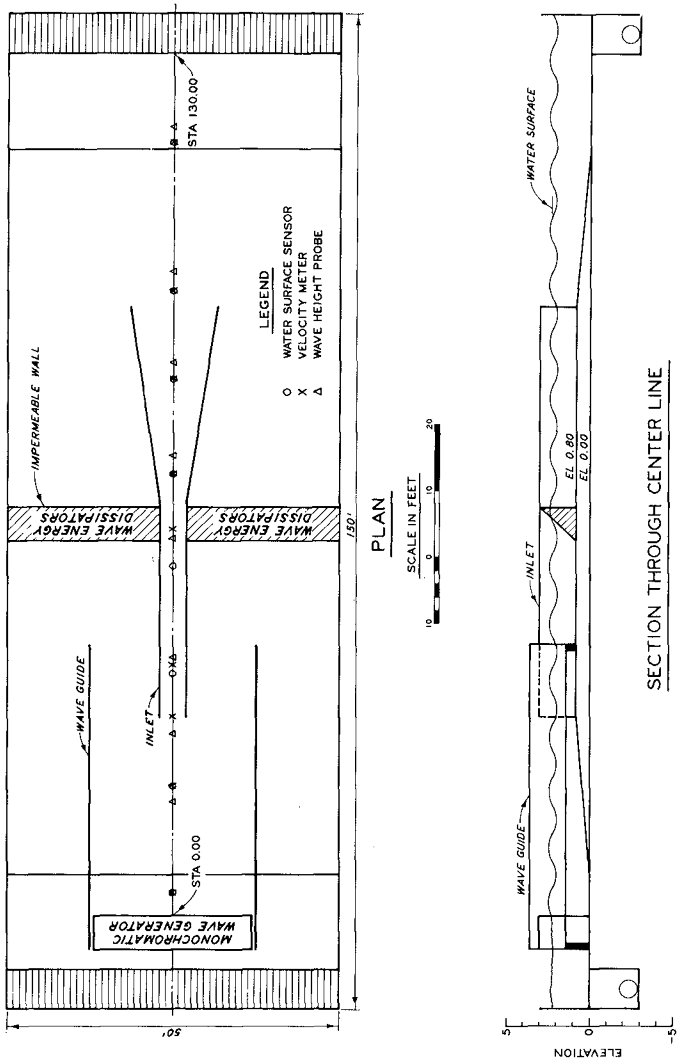

FIG. 1-THREE-DIMENSIONAL WAVE BASIN AND EXPERIMENTAL APPARATUS

this simulated tidal inlet which had dimensions 4 ft wide and 32 ft long and was situated in the center section of the basin. The bottom of the inlet was horizontal and elevated 0.8 ft above the basin floor with a slope of 0.033 ft/ft approaching the inlet from the ocean side, and the same slope at the rear of the inlet into the bay region. This caused the approaching waves to experience a shoaling effect as well as refraction due to the tidal inlet current, typical of prototype inlets.

The wave generator was placed perpendicular to the inlet throat and data measurements were taken at 8 selected points along the inlet axis from the ocean into the bay. In the absence of a current, the wave characteristics were recorded by direct print oscillograph at these selected locations. A steady non-uniform flood current was then created by circulating flow from the bay region and discharging into the ocean with a reversible variable-speed pump. The intake and discharge manifolds were carefully adjusted so that negligible disturbance occurred in the still water region. For this steady-state flow condition, velocity measurements were taken at the predetermined locations and the wave characteristics were again recorded. Then the flow would be changed, steady-state conditions achieved and measurements once more recorded. Ultimately the data obtained consisted of current and wave measurements recorded at 8 locations for no flow condition, 4 flood conditions, and 4 ebb conditions for each wave generator setting.

Results and Conclusions

Some authors, for example Barber (12) and Barber and Ursell (13), have argued that waves crossing a tidal stream on the open ocean experience a change in the apparent wave period. Wilson (14) has expressed the belief that when waves are being propagated onto a non-uniform current, they suffer a Doppler shift in frequency, causing a decrease in period in a following current and vice versa.

The water surface time histories of the fluctuating wave motion recorded by wave gage no. 2, located in the ocean region near the entrance to the inlet, were analysed by spectral means to determine if, under steady-state flow and monochromatic waves, a shift in the generated frequency would occur. This gage was chosen because it experienced the effect of both ebb and flood currents. The results of the spectral analysis are shown in Fig. 2, and it appears the peak of the energy spectrum occurs at the same period under all flow conditions. Further study reveals the period remains constant with space as well as time for steady-state flow conditions. There does appear to be a flow of energy to other frequencies, as reflected by the shift of the curves for the accumulated percent of the total energy in the wave form occurring at periods greater than a specified period. The ebb flow shift is particularly dramatic, indicating for a given percentage of the total energy, the ebb condition occurs at a slightly higher period. This appears to be in line with the hypothesis of Wilson (14), although in the absence of local accelerations the flow of energy to other periods was not enough to cause a shift in the peak of the energy spectrum.

Changes in the Inlet:

Dimensional analysis of the pertinent variables indicates that for the

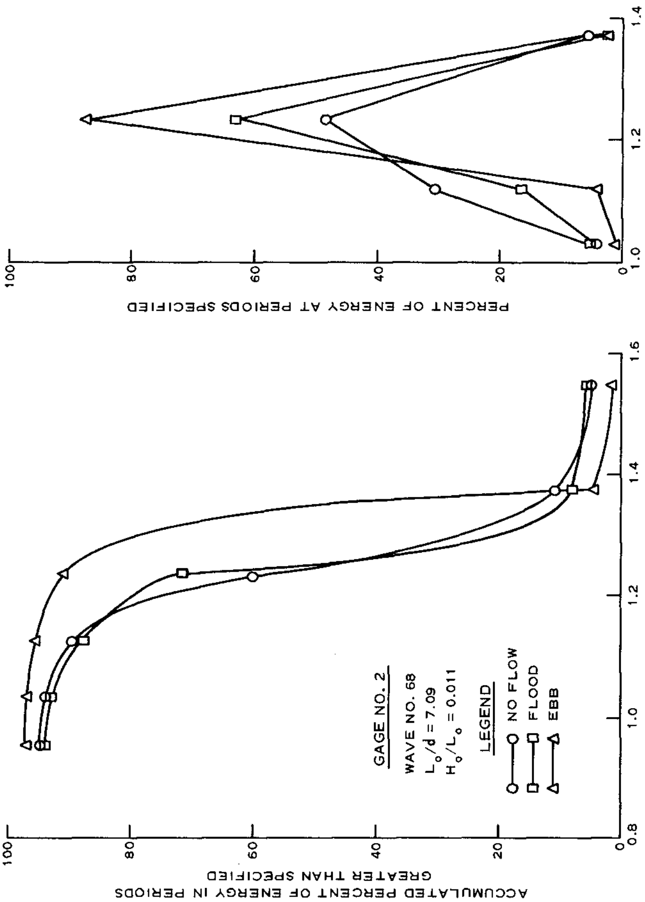

FIG. 2-ENERGY SPECTRUM RECORDED AT GAGE NO. 2. (Curves are for percentages of total energy, and do not reflect the actual magnitude of the wave form.)

inlet proper, a functional relationship exists of the form

$$\phi(L_o, L, H_o, H, d, U, C_o) = 0 \quad \text{.............................} \quad (1)$$

which can be rearranged to produce

$$\frac{L}{L_o} = f'\left(\frac{L_o}{d}, \frac{H_o}{L_o}, \frac{U}{C_o}\right) \quad \text{.................................} \quad (2)$$

and

$$\frac{H}{H_o} = f''\left(\frac{L_o}{d}, \frac{H_o}{L_o}, \frac{U}{C_o}\right) \quad \text{...............................} \quad (3)$$

The determination of such functional relationships is frequently very difficult if not completely impossible by analytical means, so recourse is often taken to hydraulic model studies. The strength of dimensional analysis lies in its ability to provide insight into the manner in which certain variables are related, and thus initiates the planning of the research program.

The functional relationships of Eqs. 2 and 3 were substantiated by random plots of the change in wave length and wave height as a function of the current parameter. The relationship can be displayed as a series of charts for different values of H_o/L_o, each chart containing a family of curves for different values of L_o/d, where the subscript zero always refers to still water conditions in the inlet where the water depth is d.

Because the data obtained from the model was for random values of L_o/d and H_o/L_o, the technique of fairing the experimental data was applied so that the results could be displayed in a more systematic form. Figs. 3 and 4 show the manner in which the wave height and wave length changed as the flow in the inlet increased, at a constant value of H_o/L_o. For the range of data obtained, the change in wave length appeared as a straight line; however, the analytical studies indicate that the curves will eventually approach an asymptotic value similar to the change in wave height. For ebb currents flowing through the inlet, the change in wave height and wave length are shown in Figs. 5 and 6. It was noted in the experimentation that in the inlet, the waves increased in height and decreased in length for the ebb flow until a certain condition was reached, at which time the wave records showed a decrease in height with increased ebb current. The steepness of the waves at this condition was determined, and it was found that most of the waves were not even approaching the limiting steepness for breaking waves in still water. It was observed that the ebb flow emanating as a turbulent free jet into the ocean region was causing the waves to increase in steepness and lose energy by the crest spilling down the front of the wave as it continued to propagate onto the current. Consequently, when the wave reached the inlet, it had decreased in height because of energy losses in the ocean region, and not because of breaking in the inlet. Hence, the approximate limits for stable waves shown in Figs. 5 and 6 do not really reflect a cause-and-effect relationship in the inlet, but are a reflection of events which occurred in the ocean.

Changes in the Ocean:

Photographic documentation of the ebb and flood conditions occurring

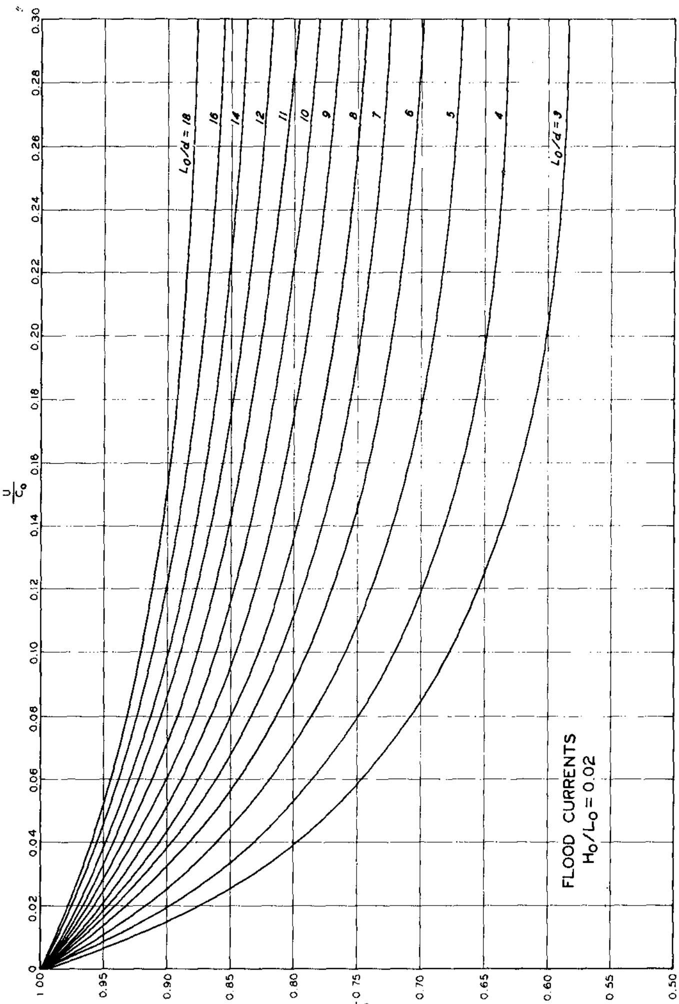

FIG. 3-CHANGE IN WAVE HEIGHT IN THE INLET PROPER UNDER CHANGING FLOOD CURRENT CONDITIONS FOR A CONSTANT VALUE OF H_o/L_o

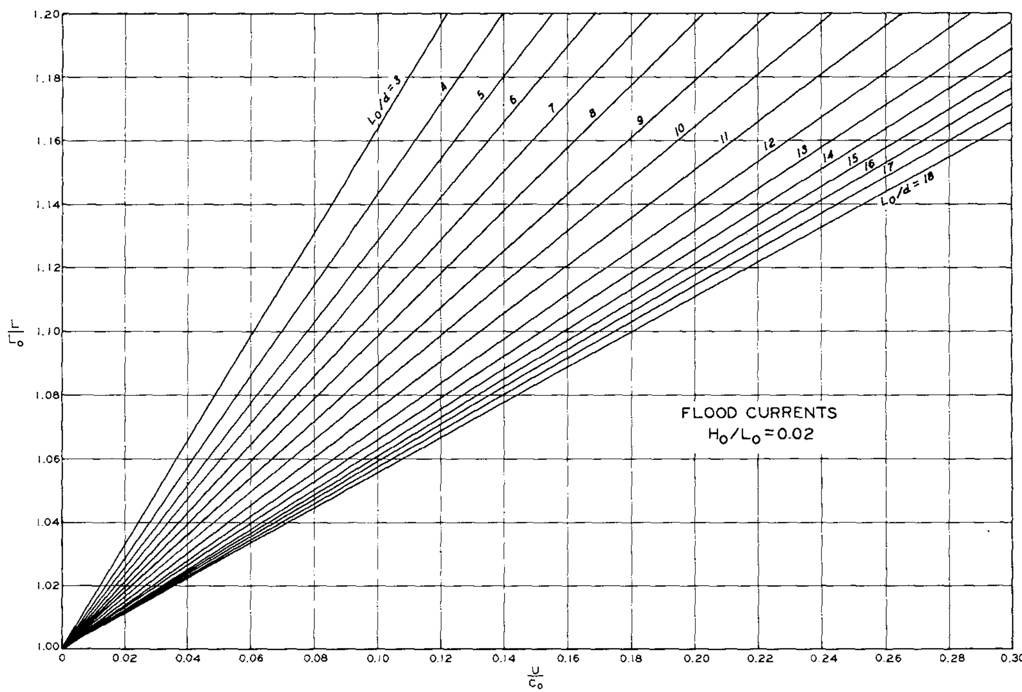

FIG. 4-CHANGE IN WAVE LENGTH IN THE INLET PROPER UNDER CHANGING FLOOD CURRENT CONDITIONS FOR A CONSTANT VALUE OF H_o/L_o

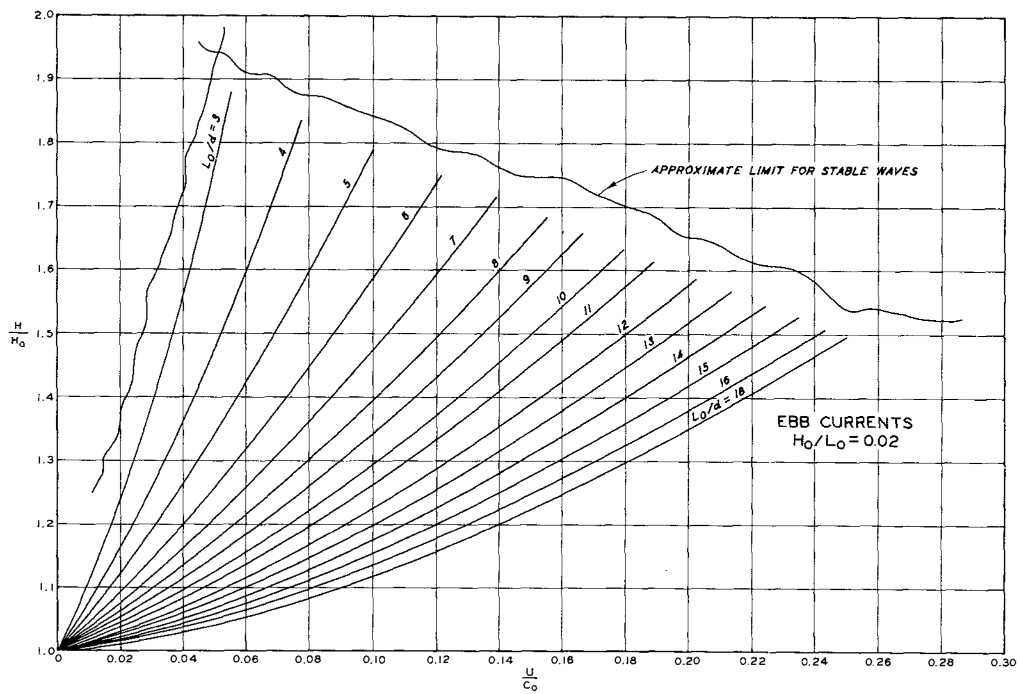

FIG. 5-CHANGE IN WAVE HEIGHT IN THE INLET PROPER UNDER CHANGING EBB CURRENT CONDITIONS FOR A CONSTANT VALUE OF H_o/L_o

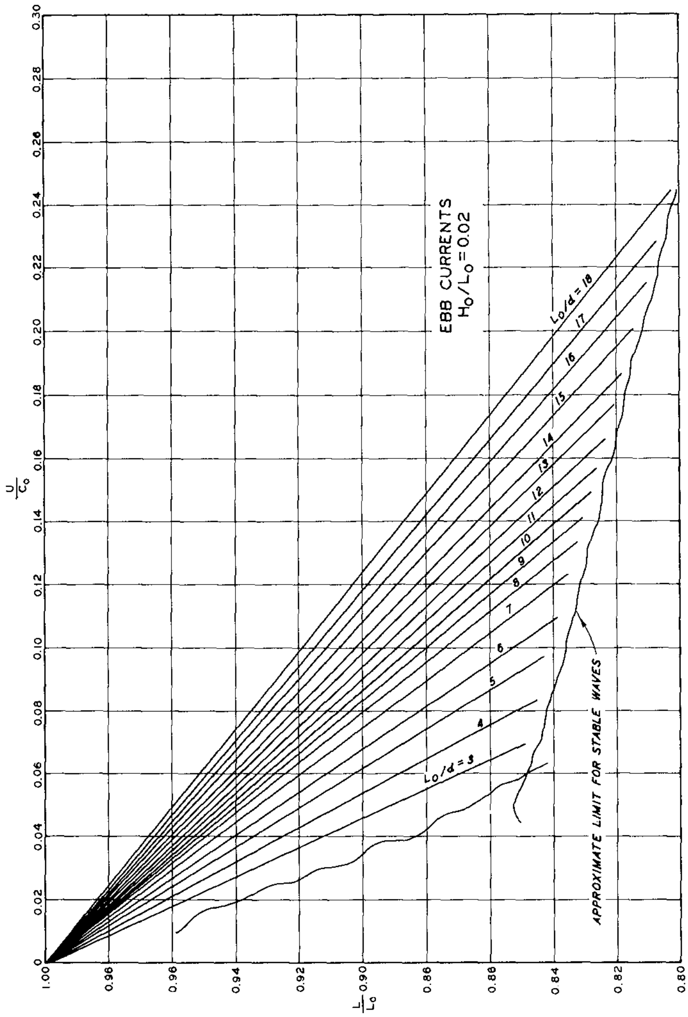

FIG. 6-CHANGE IN WAVE LENGTH IN THE INLET PROPER UNDER CHANGING EBB CURRENT CONDITIONS FOR A CONSTANT VALUE OF H_o/L_o

in the ocean near the entrance to the inlet indicated the flood pattern to be relatively insignificant when compared with the flow pattern of the ebb current. Fig. 7 is a typical dye and confetti pattern photograph of the ebb flow emanating from the inlet and dispersing as essentially a turbulent free jet. For the simplified two-dimensional free jet turbulent flow, French (15) has shown that the ratio (distance from exit)/(inlet width) is a pertinent dimensionless quantity for completely describing the manner in which the flow field changes. Accordingly, it is deduced that in addition to the four previously defined dimensionless parameters necessary for displaying the experimental data obtained in the inlet, to adequately describe the functional relationship existing between variables in the ocean region, Eqs. 2 and 3 must be re-written as

$$\frac{L}{L_o} = f'''\left(\frac{L_o}{d}, \frac{H_o}{L_o}, \frac{U}{C_o}, \frac{x}{W}\right) \qquad (4)$$

and

$$\frac{H}{H_o} = f''''\left(\frac{L_o}{d}, \frac{H_o}{L_o}, \frac{U}{C_o}, \frac{x}{W}\right) \qquad (5)$$

where x is the distance from the entrance of the inlet to the point of interest and W is the width of the inlet. The conclusions by French (15) from momentum considerations include the face that the depth of flow in the inlet is apparently mot pertiment for describing the flow patterns coming from the inlet.

When the experimental data obtained from sensors located in the ocean region of the facility are displayed in dimensionless form, the relationships implied by Eqs. 4 and 5 are apparent. It was observed during the data collection phase of the study that a given current would alter some waves in a particular manner but would have little or no effect on other waves. To project a feel of advancing with distance from the inlet into the ocean, the data were displayed with the ratio x/W as the abscissa with the wave length and wave height alterations as the ordinate. The faired experimental data then generated curves of constant values of L_o/d for constant values of H_o/L_o and constant values of the current parameter U/C_o. The effect of a given current on selected waves noted in the experimentation can be seen reflected in the data curves of Figs. 8, 9, and 10, which show the manner in which the wave height is altered in the ocean for given incipient conditions.

The physical picture of the waves losing energy by spilling at the wave crest can be seen in Figs. 11, 12, and 13. These are photographs of three different waves being propagated onto the same magnitude of ebb current. The refraction of the wave train by the strong velocity gradients and vorticity in the horizontal plane is an area for further investigation.

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FIG. 7-EBB CURRENT EMANATING FROM THE INLET AND DIFFUSING AS A TURBULENT FREE JET IN THE OCEAN

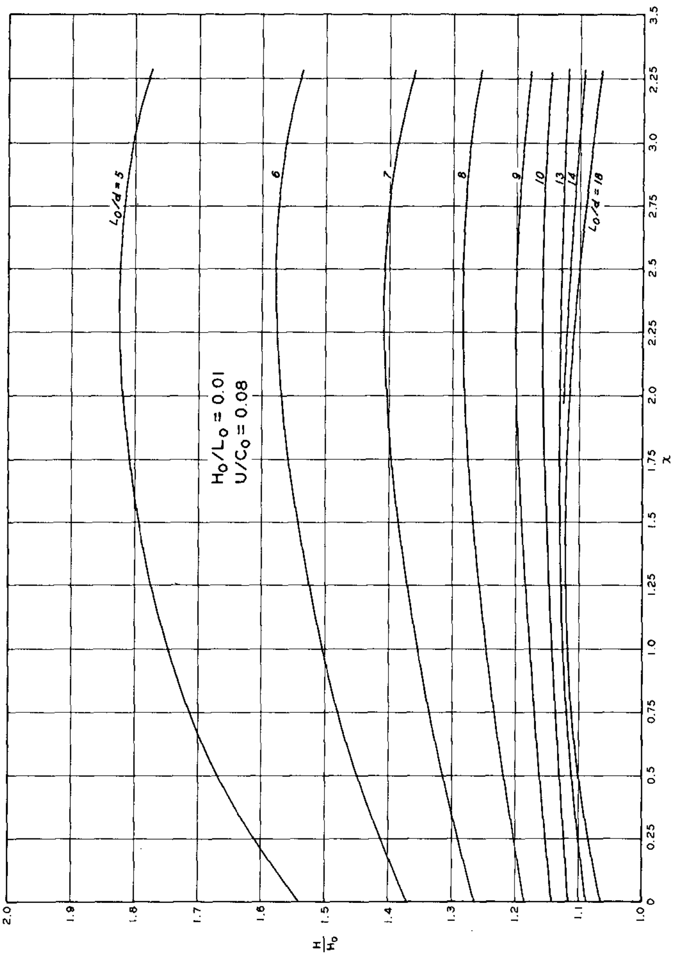

FIG. 8-CHANGES IN WAVE HEIGHT IN THE OCEAN UNDER CHANGING EBB CURRENT CONDITIONS FOR CONSTANT VALUES OF H_o/L_o and U/C_o

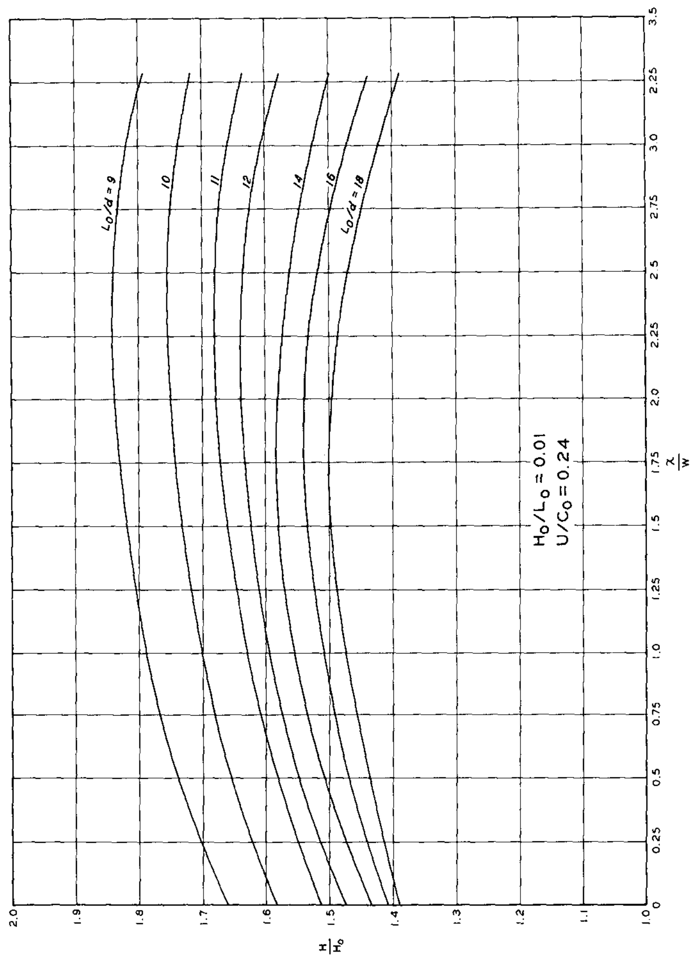

FIG. 9-CHANGES IN WAVE HEIGHT IN THE OCEAN UNDER CHANGING EBB CURRENT CONDITIONS FOR CONSTANT VALUES OF H_o/L_o and U/C_o

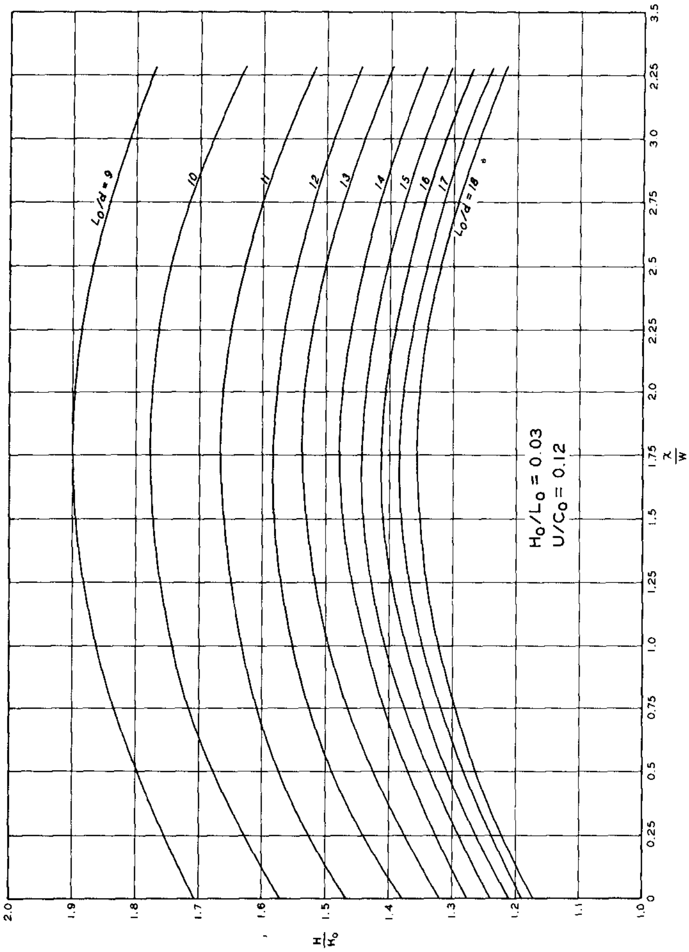

FIG. 10-CHANGES IN WAVE HEIGHT IN THE OCEAN UNDER CHANGING EBB CURRENT CONDITIONS FOR CONSTANT VALUES OF H_o/L_o and U/C_o

FIG. 11-WAVE TRAIN PROPAGATING ONTO AN EBB CURRENT. $U/C_o = 0.097$, $L_o/d = 5.37$, $H_o/L_o = 0.021$

FIG. 12-WAVE TRAIN PROPAGATING ONTO AN EBB CURRENT. $U/C_o = 0.101$, $L_o/d = 4.58$, $H_o/L_o = 0.028$

FIG. 13-WAVE TRAIN PROPAGATING ONTO AN EBB CURRENT. $U/C_o = 0.115$, $L_o/d = 3.24$, $H_o/L_o = 0.057$

partial fulfillment of graduate degree requirements and may subsequently be used as part of the Ph. D. dissertation material at Texas A&M University.

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