Chapter 7

THE INTERNAL VELOCITY FIELD IN BREAKING WAVES

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INTRODUCTION

As far as is known, the results presented here are the first detailed measurements of the horizontal velocity component inside breaking waves. The field study was originally undertaken in 1960 to determine the presence and strength of mid-depth return flow under shoaling waves (Miller and Zeigler, 1961, 1964). In the course of the experiment, a series of measurements was made very close to the shore. During one tidal cycle, the instruments became exposed to breakers, and continued to operate. A study of the resulting data convinced us that detailed velocity measurements could be made within the natural breaker in the field. Accordingly, a series of runs was made and velocity data collected on breakers ranging from very small to storm size. This data will be presented and discussed in detail in a later portion of this paper.

A number of laboratory studies have been made on breakers. These may be placed in three categories for our purposes. The first group includes detailed discussion of observations and sequential figures illustratin the development of breakers. An example is Mason (1951). The second group of papers gives some detail on the structure of breakers and presents, either by direct photograph or sketch of, the trajectory inside the breakers. Examples are Hamada (1951) and Morison and Crooke (1953). The third group of papers presents, in addition to most of the material referred to above, a series of vector maps of the internal velocity under various types of breakers, including both sinusoidal and solitary wave generated breakers. Papers in the third category include Iversen (1951), Larras (1952), and Ippen and Kulin (1955). The latter were of most direct interest to us within the context of the present study.

Several qualitative studies made either directly or in part on breakers in the field were found particularly useful. These include O'Brien (1949) and Hayami, Ishihara, and Iwagaki (1953). Finally the work of Inman and Nasu (1956) includes observations of both horizontal and vertical velocity

components at a fixed point near the bottom as well as the surface trace, for several breakers, taken during the course of a study of shoaling waves. These were found to be particularly useful, and served as the only available check on our data.

FIELD TECHNIQUE

To make measurements in very shallow water and in breakers, a reasonably mobile system was developed. This was necessary in order to take advantage of suitable tide, weather and bottom configurations. Details are illustrated in Figure 1. Three towers were employed consistin of 1-1/2 inch pipe driven approximately 5 feet into the sand. The overall pipe lengths were about 20 feet. Two guy wires held by mushroom anchors were used to steady each tower. The entire system was put in at low tide on a section of coast on the eastern side of Cape Cod. The tide range at this location is approximately 8 feet. The large tide range was a critical factor in the technique and served two purposes. First it allowed proper and unhurried mounting and re-mounting of velocity meters at low tide, when the entire test area was above water. Second, the rise of tide brough the breaker line in past the outer to the innermost tower on the rising tide and in the reverse order on the falling tide. In this way it was possibl to consider any tower as sampling sequentially the front, middle, or rear of the breaker, and during higher tide stages, as sampling simultaneously the breaker on the innermost tower and the near-breaking and shoaling wave at the middle and outer towers respectively.

The data consisted of the following:

1. The tide level (short term still-water level)
2. The surface time-history of the water level, (the wave trace)
3. Up to four continuous recordings of the horizontal velocity component on any one tower, depending on the sampling scheme

All the above data were recorded simultaneously on Sanborn records for visual analysis. Several of the runs were also recorded on magnetic tape as a pilot study for future work in which high speed computer facilitie will be used.

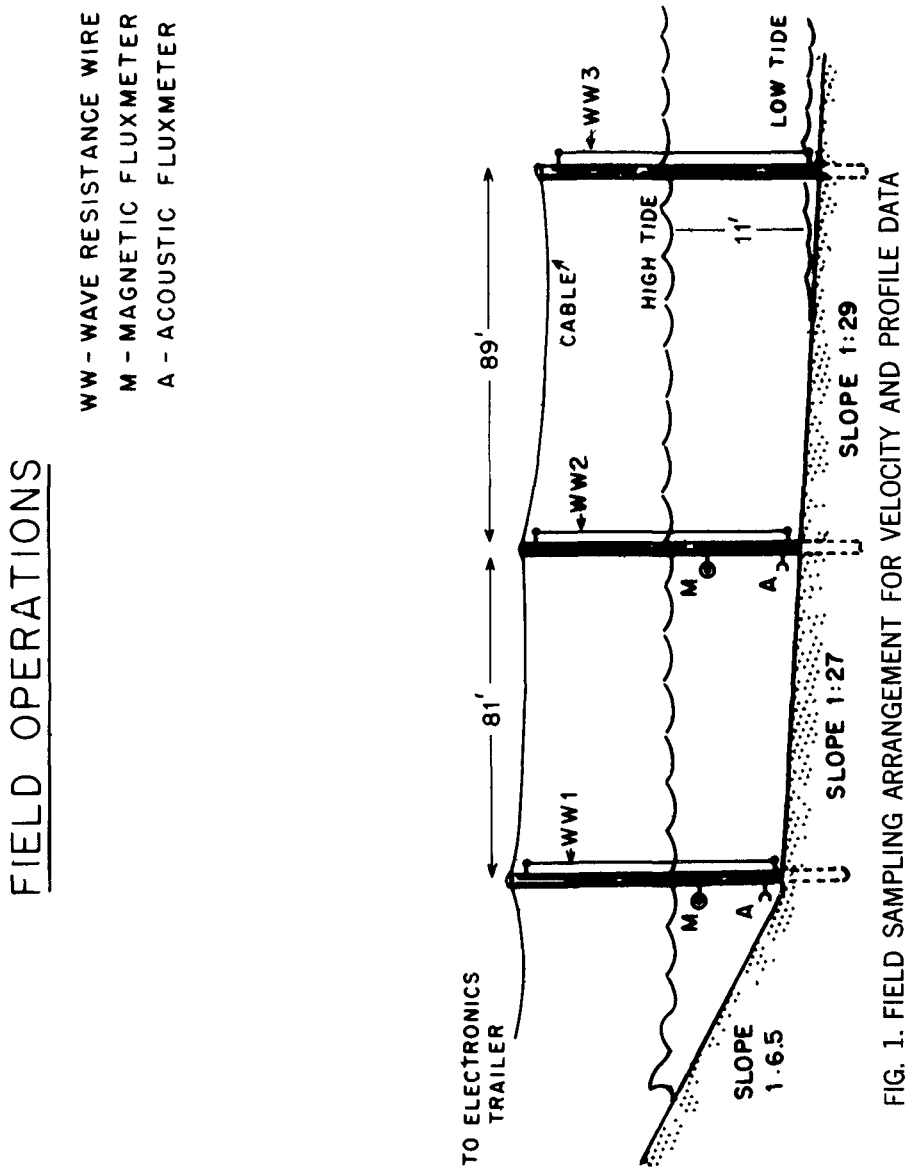

FIG. 1. FIELD SAMPLING ARRANGEMENT FOR VELOCITY AND PROFILE DATA

The velocity meters and resistance wave wires received power from a portable gasoline powered generator on the shore through cable strung from top to top of the towers as shown in Figure 1. The returning signals utilized the same cable and were carried to an enclosed trailer on the beach about 170 feet from the inner tower. The Sanborn recorder, tape recording system, and necessary electronics for the velocity meters and wave wires were all housed in the trailer. Figure 2 shows the system at early rising tide before the breakers have arrived at the inner tower. As soon as the breakers arrived at the inner tower, all systems were switched on and recording began.

Additional field activity included a detailed bathymetric survey of the area from the shore to well beyond the outer tower. Measurements were confined to those periods where local wind effect was negligible and refraction at a minimum. Thus, relatively uncomplicated, swell-generated breakers were studied.

INSTRUMENTATION

Details of the instruments used cannot be given sufficient space here, and will be described fully in a forthcoming paper.

SURFACE WAVE RECORD

Each tower was equipped with two stainless steel resistance wires .015 inch diameter with a resistance of 1.01 ohms per linear foot. One wire was suspended inside the pipe. A 1/8 inch hole drilled through the pipe served as a low pass filter so that essentially short term still-water level was recorded. The external wire served as the wave sensor. It was tightly mounted on a pair of brackets attached to the pipe (see Figure 1). The system follows that described by Farmer and Ketchum (1961). Critical factors include equality of length of internal and external resistance wires the relative distance of both from the center of the pipe cross-section and from the pipe itself, and the length of wetted to exposed wire. Excellent results were obtained with this system.

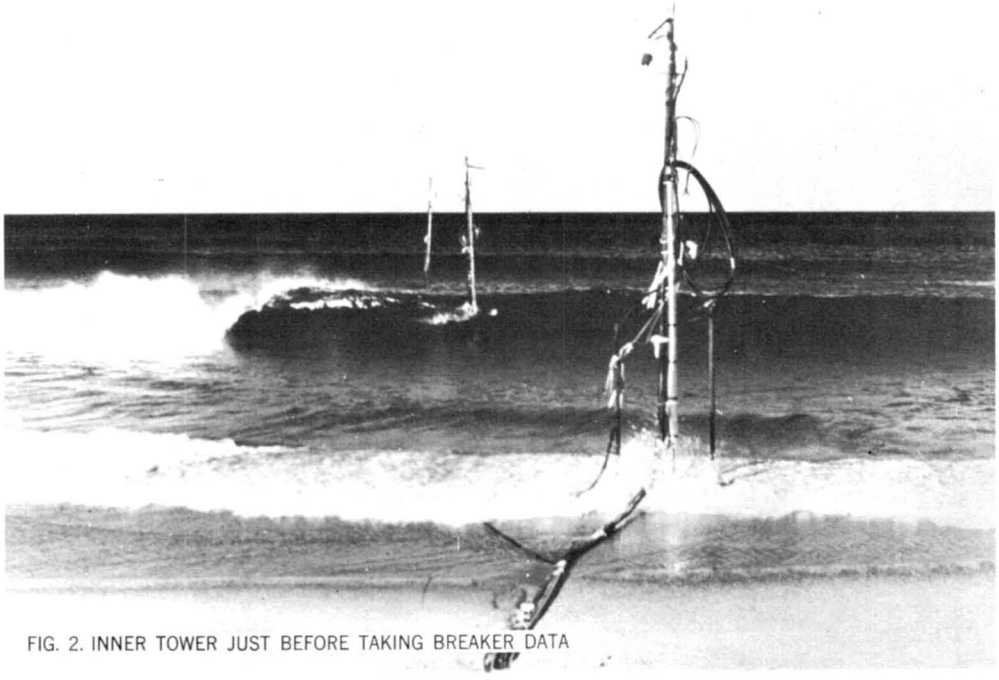

FIG. 2. INNER TOWER JUST BEFORE TAKING BREAKER DATA

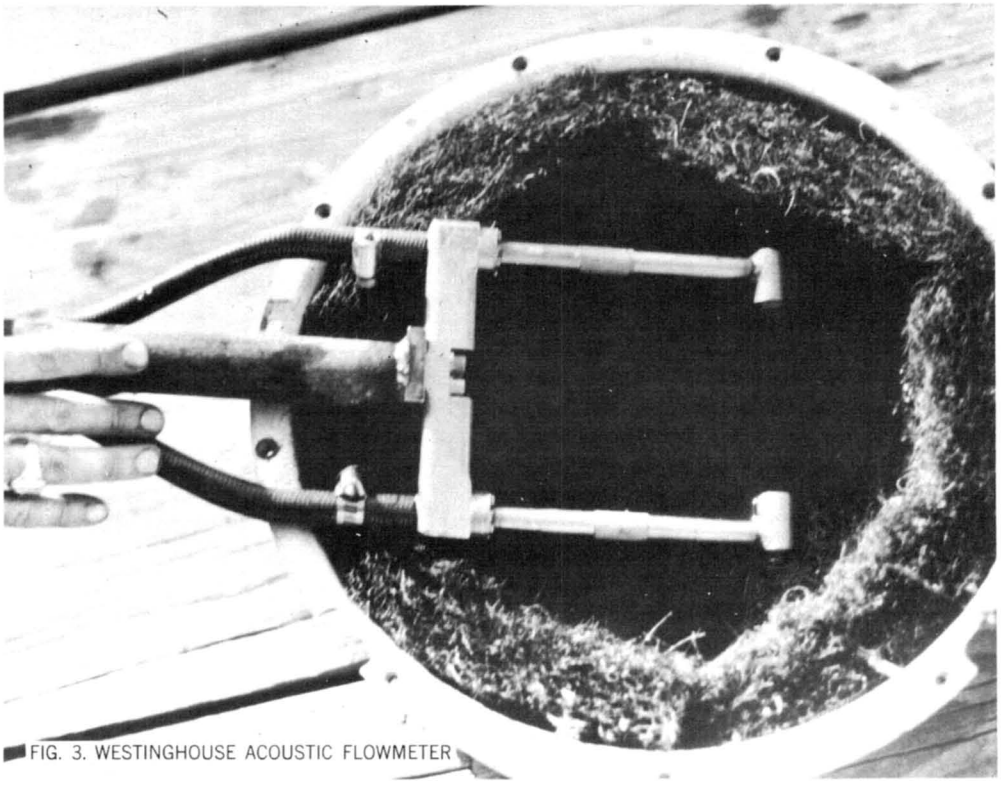

FIG. 3. WESTINGHOUSE ACOUSTIC FLOWMETER

VELOCITY METERS

Two types of meters were used in collecting the data used in this paper. Each type was independently calibrated under both linear flow and in wave tanks. The output of the two meter types was found to be quite comparable within the velocity ranges experienced under field conditi

1. Acoustic Flowmeter

The instrument is made by Westinghouse. The basic operation consi of two simultaneous acoustic signals sent in opposite directions between a pair of probes spaced 8 inches apart. The meter itself is roughly in the sh of a tuning fork with a flat base (see Figure 3). The instrument is position so that an imaginary line between the tips of the probes is parallel to the velocity component to be measured. When the fluid is in motion, the acous signal traveling in the direction of fluid flow will be out of phase with the acoustic signal traveling against the flow. The resulting phase angle is directly related to velocity and the signal identification gives the instantaneous direction of flow.

2. Magnetic Flowmeter

The basic components for this meter consist of a Foxboro Magnetic Flow Meter housed in a fiberglas sphere 8 inches in diameter. During flo from left to right, the fluid acting as a moving conductor, enters the apert ture on the left and then passes through a straight tube containing two electrodes and around which is a pair of saddle-shaped magnets. The magnets create a constant magnetic field at right angles to the moving flui The result is a change in voltage directly proportional to the velocity of the fluid through the tube. The fluid then leaves the spherical housing through the aperature at the right. For operation the tube is aligned with the velocity component which is to be measured.

DISCUSSION

Details of calibration and tests made for direction sensitivity, and c the degree to which the external shapes of the two types of meters interfe with the flow will be given in a later paper. However, as a result of thes tests and our field experience, we are, at present, using the acoustic me in preference to the magnetic type.

DATA ANALYSIS

The data was received in the form of continuous records on a 10-channel Sanborn recorder, in which the horizontal axis represents time (t) with 1 second time marks for scale. The vertical axis gave magnitude in terms of voltage output calibrated against velocity for the meters, or height for the resistance wires. An optimum record included three surface wave traces and their associated still-water levels, and four velocity traces directional in the seaward or shoreward sense as the trace crossed above and below zero.

The velocity field maps were constructed in the following way:

1. Approximately 200 breaker traces were selected from the many thousands recorded. These were chosen on the basis of clarity of pen trace, and were intended to represent as wide a spectrum of breaker sizes as was available. The actual breaker heights varied from two feet to about 12 feet.

2. Using a magnifying glass and templates, the breaker traces were then digitized and each separate breaker plotted on a dimensionless graph. The absicissa consists of zero at the center of the graph and units of t/T_B increasing both to the left and to the right of zero; t is time and T_B is defined as the breaker period and is equivalent to the period of the following breaker T_f, plus the period of the preceding breaker T_p, divided by two, following the method of Inman and Nasu (1956). The ordinate consists of units of Z/B_d where Z is the observed water height above the bottom and B_d is the height of the breaker crest above the bottom. The crest is placed at zero on the horizontal reading and $Z/B_d = 1$ on the vertical. By comparing the breaker profiles plotted on the dimensionless graph described above, it was noted that the breaker forms fell into three major categories. These are referred to as "symmetric", "asymmetric", and "very asymmetric", in the

remainder of the paper, and serve as a useful classification. It seemed possible to spend a good deal of time in considering the classification of breaker shapes and in erecting subdivisions within the three major classes. However, we felt that much more data on a wide variety of bottom configurations and wave conditions would be needed before useful results could be expected.

3. The individual breaker traces for each class were then averaged, resulting in a single trace. The single breaker profile for each class was then transferred to large graph paper with ordinate z/B_d and absicissa t/T_B as before.

4. Corresponding to a given breaker trace, velocity data in the form of both magnitude and direction was available from one to four points on the vertical. Since the tower is fixed as the breaker passes, velocity data was thus available in continuous form from the front to the back of the breaker under scrutiny. Thus our data is on an Eulerian coordinate system with fixed x and varying time. Due to the changing tide level, the relative vertical position on a line from surface to bottom of the velocity input for a given meter changed accordingly. By utilizing this fact, and by choosing a sufficiently wide array of absolute breaker sizes, fairly close control on the vertical scale was achieved. This, together with the continuous recording on the horizontal scale, gave us a closely spaced grid of velocity points from front to back and top to bottom of the breaker. The locations of the velocity values were finally plotted on a single graph (referred to in Step 3 above), for each of the three breaker classes.

5. The velocity value was entered in the form of $u/u_{max.}$ where u is the observed velocity and $u_{max.}$ is the maximum velocity for the individual breaker. In addition, a plus or minus sign is entered to indicate either seaward or shoreward direction, (plus represents shoreward, and minus represents seaward).

6. Finally, the velocity entries were contoured in feet per second intervals and the velocity field-breaker shape map was completed.

RESULTS

DISCUSSION

In the work described in this paper, we focus attention on that region in which the shoaling wave begins to deform to a marked degree, becomes unstable, and finally breaks. Before presenting our results, some discussion on relevant literature and related areas of investigation seems appropriate.

A considerable number of papers have been devoted to investigation of the various properties of Stokes' finite amplitude (non-linear) waves, and of Cnoidal waves including solitary waves. Summaries are given in Stokes (1957), Laitone (1961) and Ippen et al. (1963). An example is Biesel (1951) whose solutions include a wave shoaling over a sloping bottom and finally breaking. Recently, interest has been shown in the properties of long waves and surges as they break on a beach, for example, Freeman and Le Mehaute (1964). A non-linear model has been developed by Meyer and his colleagues in which the entire sequency of shoaling, breaker formation and collapse, and subsequent uprush and backwash is described. (See Ho and Meyer, 1962; Meyer and Taylor, 1963; and Ho, Meyer, and Shen, 1963)

Papers specifically devoted to breaking wave criteria in addition to those referred to in the introduction include Michell (1893) and a summary by Reid and Bretschneider (1953). For the solitary wave in particular, a summary is given by Ippen and Kulin (1955).

The concensus of opinion seems to be at the present time that in the very shoal region, but not including the breaker, Stokes' finite amplitude theory holds reasonably well to an inner limit of $d/L \cong 0.10$, Cnoidal wave theory in general, in the region $0.10 \geq d/L \geq 0.02$ and solitary wave theory in particular in the region $d/L < 0.02$. (See Ippen et al, 1963; Keulegan, 1950; Morison and Crooke, 1963; and Inman and Nasu, 1956.) It would appear, therefore, that information on the internal velocity field in near-breaking waves and breakers, would be of considerable interest in the theoretical investigations of the shallow water and breaking properties of waves, and indeed, may serve as an additional boundary condition for a successful theory of the complete phenomenon.

The general problem of sediment transport is also directly related. For example, a sandy coastline is almost always under direct attack by breakers. Under certain conditions, the net result is transportation of sediment from the sea through the breaker, with ultimate deposition on the shore. Under other conditions, the sediment is ultimately transported seaward through the breaker. The phenomenon of erosion and deposition on coastlines are under active investigation both in the laboratory and in the field. However, the internal structure of the natural breaker, itself a basic aspect of this whole area of investigation, is not well understood.

RESULTS OF THIS STUDY: THE NEAR-BREAKING WAVE:

The near-breaking wave average profile and internal horizontal velocity field map was constructed according to the method described in the previous section. It is shown in Figure 4. The profile is quite asymmetric with a well defined break in slope on the shoreward side just above still-water level. Maximum velocity is in the shoreward direction throughout the crest and extending well into the body of the breaker. Comparison with the analogous theoretical profiles and velocity fields can be made by inspection of Figure 5 for the finite amplitude Stokes' wave and Figure 6 for the Cnoidal wave. These calculations were facilitated by using tables from Masch and Wiegel (1961), and Skjelbreia (1959). In profile, the near-breaking Cnoidal wave most nearly resembles the natural wave, although the asymmetry is not present in the theoretical wave. The internal velocity field of the Cnoidal wave, although much more regular in appearance, again more nearly resembles the natural wave, in the consideration of shoreward velocity in a "chimney" under the crest, flanked both in front and behind by regions of seaward motion. Considerable differences are apparent however, in that asymmetry of the velocity field does not appear in the Cnoidal wave, nor the well-defined increase in shoreward velocity toward the bottom under the crest. Also of note is the presence of significant seaward motion on the back slope of the wave, well above still-water level.

RESULTS OF THIS STUDY: THE BREAKERS:

Theory is presently not available for calculation of internal velocity fields under breakers. Therefore, the results of the field observations will be presented and discussed for each class in turn.

Class I, "Symmetric" Breaker (Figure 7)

Transition from the profile and velocity field of the near-breaking wave to the symmetric breaker does not appear to be easily made in this case. It is apparent that in further work care must be

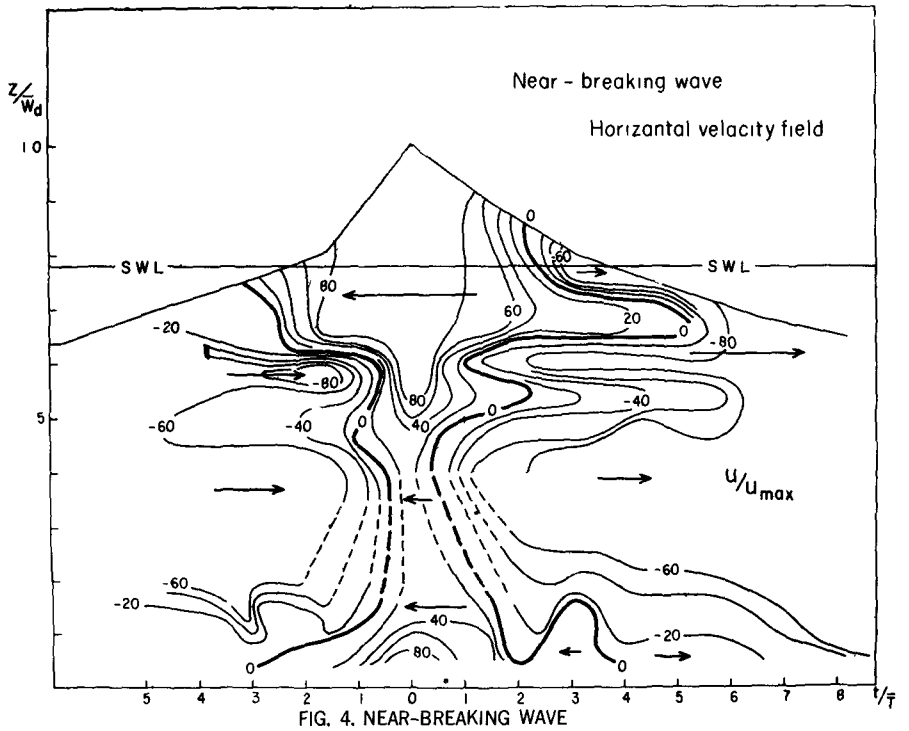

FIG. 4. NEAR-BREAKING WAVE

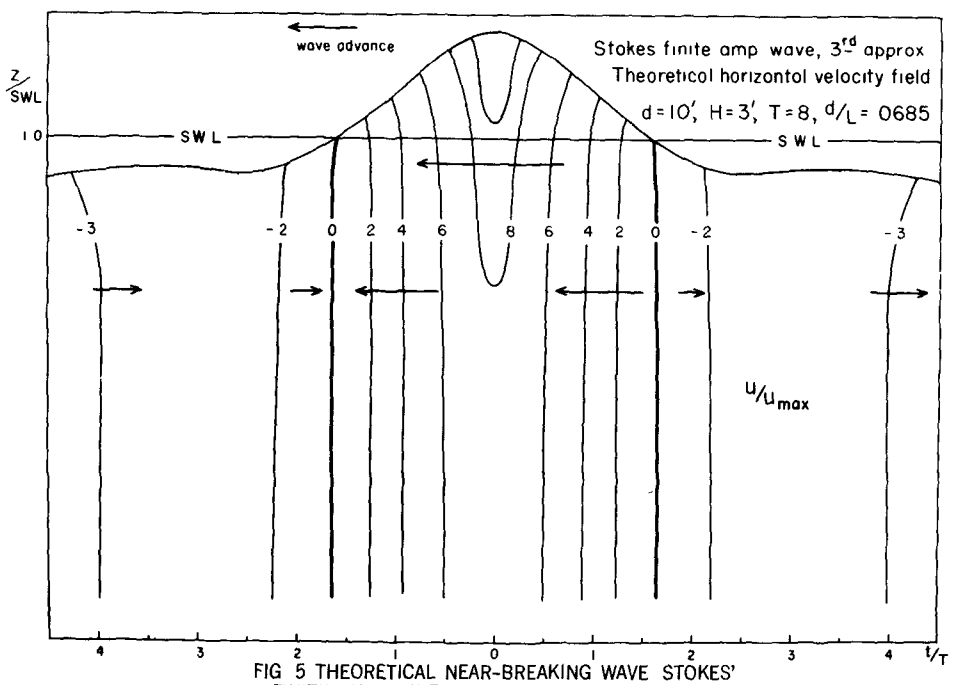

FIG 5 THEORETICAL NEAR-BREAKING WAVE STOKES' FINITE AMPLITUDE WAVE, THIRD APPROXIMATION

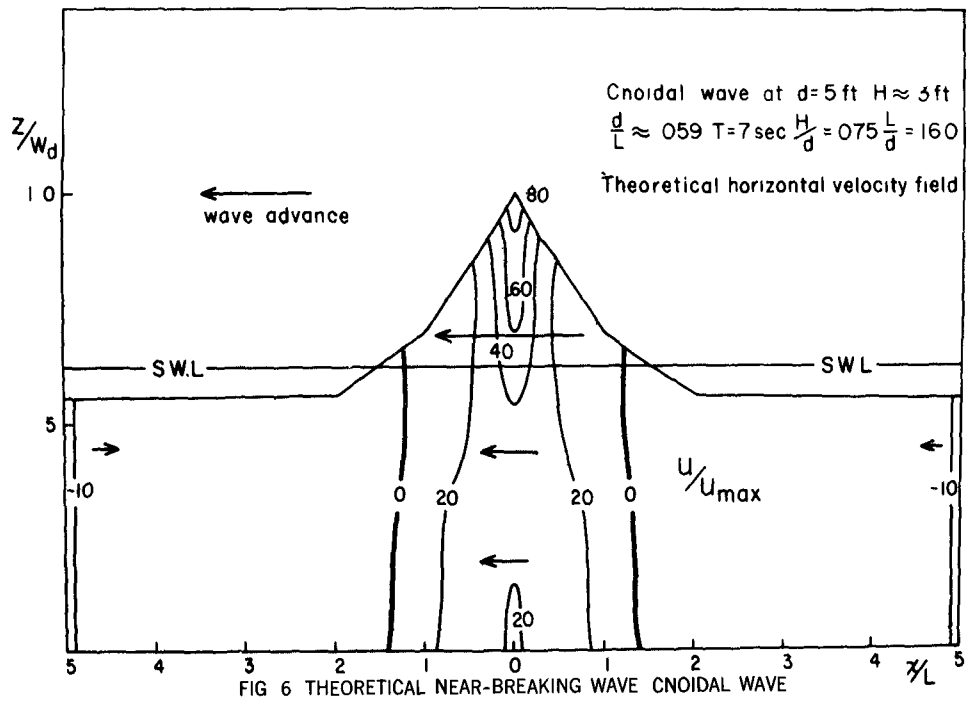

FIG 6 THEORETICAL NEAR-BREAKING WAVE CNOIDAL WAVE

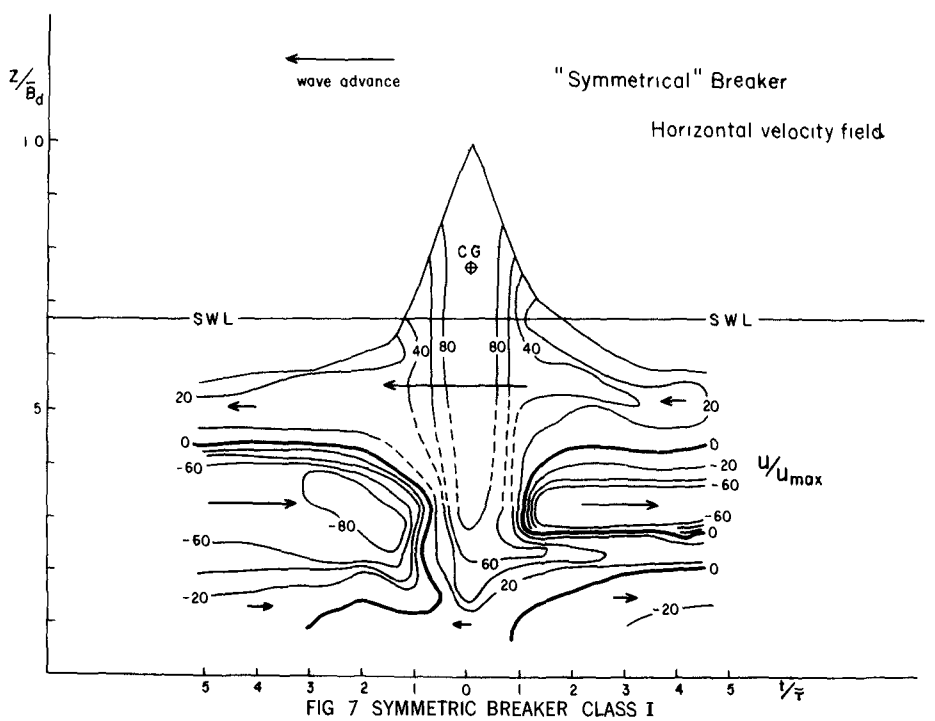

FIG 7 SYMMETRIC BREAKER CLASS I

taken to identify each near-breaking wave with its breaker in order to avoid ambiguity. Fortunately, this is not difficult with the system we are now using.

Particularly notable in this breaker class are the following features:

1. The close approach to symmetry in the average breaker profile, which closely resembles the theoretical profile for a Cnoidal wave in very shallow water, see Figure 6.

2. The lack of symmetry in the velocity field of the lower portion of the breaker.

3. The absence of seaward movement in the upper half of the breaker.

4. The persistence of the "chimney" of shoreward movement from crest to bottom.

Class II, "Asymmetric" Breaker (Figure 8)

This class of breakers as well as Class III appears to complete the transistion from the near-breaking wave (Figure 4) in both profile and velocity field, the difference being a matter of degree. In comparison with the near-breaking wave profile, the profile of the "Asymmetric" breaker is more peaked and the asymmetry greater. With respect to the internal velocity field, the following is noted:

1. The distribution of magnitudes and direction is less complicated than in the Class I "Symmetric" Breaker (Figure 7).

2. The seaward motion on the high back slope of the near-breaking wave (Figure 4) has now become an isolated pocket, but remains in about the same location.

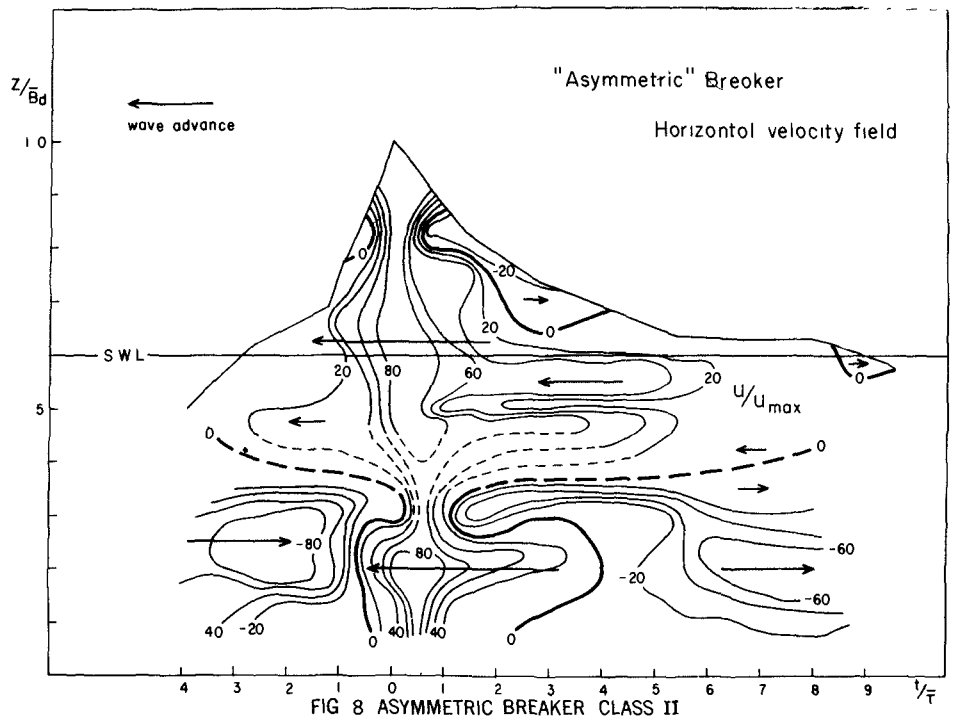

FIG 8 ASYMMETRIC BREAKER CLASS II

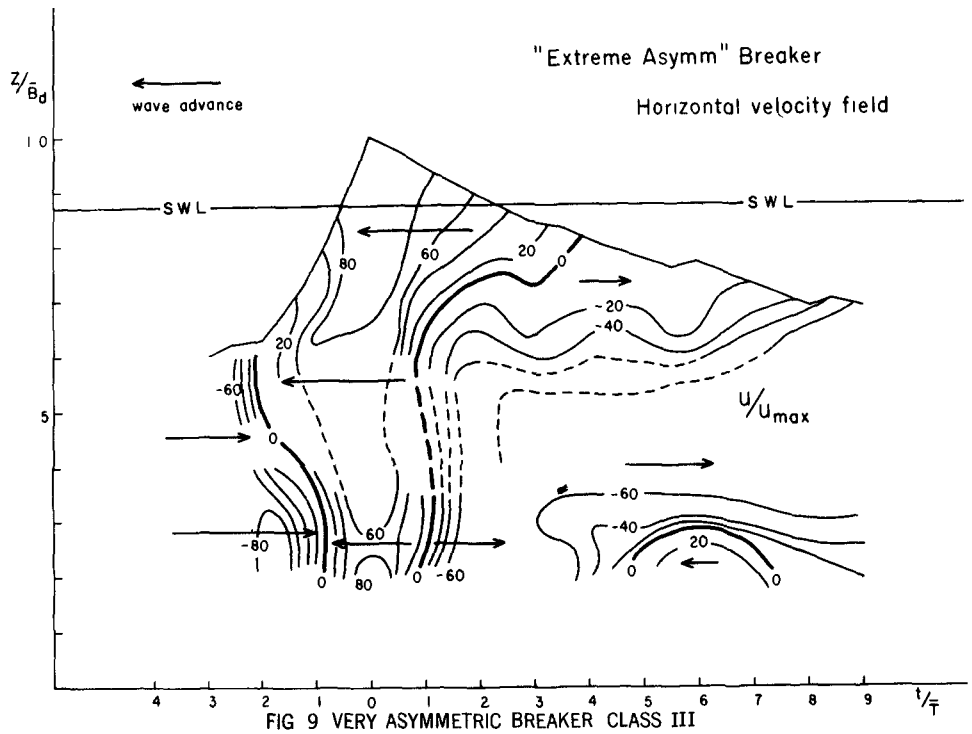

FIG 9 VERY ASYMMETRIC BREAKER CLASS III

3. The "chimney" of shoreward movement from crest to bottom still persists, but the margins are quite indented and distorted.

4. The regions of near-bottom seaward movement are enlarged and the magnitudes increased in comparison with both the "Symmetric" breaker and the near-breaking wave.

5. An anomolous region of seaward movement or at least of zero motion, appears on the front slope of the breaker just below the crest.

Class III, "Extreme Asymmetry" Breaker (Figure 9)

This breaker class is the least complicated of the three categories. Transition from the near-breaking wave (Figure 4) may be easily visualized with asymmetry of profile more strongly developed than in the "Asymmetric" breaker, and with a corresponding lowering of the profile and reduction of the crest. The internal velocity structure appears to present a smoothing and coalescing of velocity regions in the transition from the near-breaking wave field and in contrast to the "Asymmetric" and "Symmetric" breakers.

The following features seem of particular interest:

1. The persistence of the "chimney" of shoreward movement crest to bottom, in this case, with relatively straight margins.

2. The correspondence of the sharp break in slope in the forward face with the reversal in fluid direction.

3. The presence of an isolated subsidiary pocket of shoreward movement near the bottom at the back end of the breaker.

CONCLUSIONS: FURTHER INVESTIGATION

Further measurements under a variety of bottom topographies are needed before we attempt anything more than tentative conclusions. At the present time it is felt that particular effort is needed to establish both uniqueness and generality of our results. However, the data thus far suggests the following:

1. The three breaker classes appear to be well established. In comparison to classification now in general use, our "Symmetric" breaker is possibly analogous to the plunging type, the "Very Asymmetric" breaker is similar to the spilling type and the "Asymmetric" breaker somewhat intermediate between plunging and spilling. However, the three classes given here were developed directly from the field data breaker profiles by the method described in an earlier portion of this paper, and no effort was made to use visual classification of breakers as they occurred in the field.

It is of interest to note that all three classes were measured from the same tower, with single bottom slope! This seems to suggest that, in nature, in addition to the importance of bottom and of foreshore slopes, breaker shapes are affected by interaction of approaching waves and wave trains, and also by the timing and magnitude of the backwash, forming a complex system. This is in contrast to laboratory studies, where for a given simple wave form, the bottom slope is the dominant factor in breaker shape.

2. The results very strongly suggest that different breaker shapes have different internal velocity fields. This corraborates the qualitative field conclusions of Hayami, Ishihara, and Iwagaki (1953), as well as the laboratory studies referred to earlier. It would seem that observation of the direction and magnitude of sediment transit through the three contrasting velocity fields would be of considerable interest in the erosion-deposition phenomenon on coasts. This aspect is now in progress at the University of Chicago sediment transport laboratory by R. L. Miller. The

laboratory work of Eagleson and his colleagues is of particular interest here. See, for example, Ippen and Eagleson (1955), and Eagleson and Dean (1959).

3. The velocity fields under breakers appear to be less complicated than we had thought. It is possible that the initiation of instability and the subsequent development of the breaker may be characterized by one or several vortex systems, as suggested by the velocity field patterns. However, it is necessary to measure simultaneously both vertical and horizontal components before pursuing this aspect. We are engaged in these measurements at the present time.

4. The breakers studied were of the type that break directly on the shore and include within the sequence, the runup and backwash from the foreshore. We feel that the internal velocity fields under two quite different conditions deserves similar investigation:

a. breakers over bars and shoals, where the foreshore effect is absent

b. breakers in open water where both foreshore and bottom effects are removed.

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