# CHAPTER 32

## LONGSHORE CURRENTS AND NEARSHORE TOPOGRAPHIES

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## ABSTRACT

Validity of seven analytical formula as well as linear and non-linear multiple regressive schemes was tested using field data from the Outer Banks, North Carolina. Generally, agreement proved unsatisfactory. Field experiences indicate that the longshore current is a velocity field consisting of a multitude of velocity vectors whose basic pattern varies depending upon the regimes of wave-current-topography interaction. The need to recognize topography as a responding variable as well as a process variable in the physical scheme of longshore current is emphasized.

## INTRODUCTION

One may quote today more than a dozen longshore current formulae which have been developed on the basis of simplified analytical schemes. Table 1 lists the exponents of individual variables when these formulae are reduced to a product form. Scanning down each column, it is found that these formulae contain widely vaired contributions of the component variables. For instance, note the incidence angle, $\Theta$. This important variable is taken as a sine function in some formulae, as a cosine function in others, with $\Theta$ or $2\Theta$, carrying different exponents. Thus, the question arises as to which of these formulae gives the best approximation to phenomena as observed in the field. Also, it has not been established whether the simplifying assumptions used in deriving these forumlae would give a marginal or a significant distortion of reality. These problems are dealt with in this paper on the basis of field experience.

Three different procedures of quantitative analysis are applied. The first attempts to approximate the mean alongshore components of longshore current velocities through a linear combination of individual variables; a method known as multiple linear regression. The second is a non-linear approximation using a product form of optimum powers of individual variables. By a simple mathematical manipulation this form is reduced to the case of linear regression. The third

Table 1. Exponents of key independent variables from product-form representation of twelve known formulae of longshore current velocities.

| AUTHORS | FORMULA | POWER OF COMPONENT VARIABLES | | | | | | BASIC SCHEME OF ANALYSIS |
|---|---|---|---|---|---|---|---|---|
| | | Wave Height H | Period T | Incidence $\theta$ | Celerity C | Bed Slope $\alpha$, arctn m | Friction f | |
| Putnam-Munk-Traylor (1949) | $\frac{a}{2}\left[\left(1+\frac{4C_b}{a}\sin\theta_b\right)^{\frac{1}{2}} - 1\right]$ $a = 8mQ_b \cos\theta_b / f d_b T$ | $1^*$ | $1^*$ | $\cos\theta_b{}^*$ and $(\tan\theta_b)^{\frac{1}{2}}$ | $\frac{1}{2}{}^*$ | $(\tan\alpha)^{1*}$ | Darcy Weisbach coeff $-1$ | Momentum Balance, Solitary Wave |
| ,, | $\left(\frac{4\,\mathrm{sm}\, C_b E_b \sin 2\theta_b}{f \rho d_b}\right)^{\frac{1}{3}}$ | $\frac{2}{3}$ | | $(\sin 2\theta_b)^{\frac{1}{3}}$ | $\frac{1}{3}$ | $(\tan\alpha)^{\frac{1}{3}}$ | $-\frac{1}{3}$ | Energy Balance, Solitary Wave |
| Inman-Quinn (1951) | $\left[\left(\frac{1}{4x^2}+y\right)^{\frac{1}{2}} - \frac{1}{2x}\right]^2$ $x = 108\ 3\, H_b \tan\alpha \cos\theta_b / T$ $y = C_b \sin\theta_b$ | $-2^*$ | $2^*$ | $(\cos\theta_b)^{-2*}$ | $1^*$ | $(\tan\alpha)^{-2}$ | $\backsim V^{-\frac{3}{2}}$ | Momentum Balance |
| Nagai (1954) | $\frac{1}{8} H_b C_b \left(\sqrt{1+\frac{16\sin\theta_b}{KH_b}} - 1\right) \times \tan\alpha / kd_b$ | $\frac{1}{2}{}^*$ | | $(\sin\theta_b)^{\frac{1}{2}*}$ | 1 | $(\tan\alpha)^{\frac{1}{2}*}$ | | Momentum Balance, Oscillatory Wave |
| Brebner-Kamphuis (1963) | $8H_0{}^{\frac{2}{3}} / T^{\frac{1}{3}} \left[\sin 165\,\theta_0 + 0\,1 \sin 3\,30\,\theta_0\right] \times (\sin\alpha)^{\frac{1}{3}}$ | $\frac{2}{3}$ | $-\frac{1}{3}$ | $(\sin\theta_0)^{1*}$ | | $(\sin\alpha)^{\frac{1}{3}}$ | | Energy Balance |
| ,, | $14\, H_0{}^{\frac{3}{4}} / T^{\frac{1}{2}} \left[\sin 165\,\theta_0 + 0\,1 \sin 3\,30\,\theta_0\right] \times (\sin\alpha)^{\frac{1}{2}}$ | $\frac{3}{4}$ | $-\frac{1}{2}$ | $(\sin\theta_0)^1$ | | $(\sin\alpha)^{\frac{1}{2}}$ | | Momentum Balance |
| Galvin-Eagleson (1965) | $kgT \tan\alpha \sin 2\theta_b$ | 0 | 1 | $(\sin 2\theta_b)^1$ | | $(\tan\alpha)^1$ | K=1 by lab experiment | Momentum Balance |
| Inman-Bagnold (1962) | $\frac{2}{\sqrt{3}}\left(\frac{H_b}{d_b}\right)^{\frac{1}{2}} T^{-1} \sin 2\theta_b \times (\tan\alpha)\ \mathrm{l}$ | $0^*$ | $-1$ | $(\sin 2\theta_b)^1$ | | $(\tan\alpha)^1$ | | Continuity, Regular Rip Interval = l |
| Bruun (1963) | $\frac{0\,38\, H^2_{B(1/3)} \cos\theta_b\ \mathrm{l}}{AT}$ | $H^{4*}_{B(\frac{1}{3})}$ | $-1$ | $(\cos\theta_b)^1$ | | $(\tan\alpha)^{-1}$ | | Continuity, Regular Rip Outflow, Spectral Wave |
| ,, | $C\sqrt{R\ \frac{Q_b \sin 2\theta_b}{2r\, L_b}}$ | $H^1_{B(\frac{1}{3})}$ | $-1^*$ | $(\sin 2\theta_b)^1$ | | R Hydraulic radius r Bar separation | | Continuity, Straight Single Bar |
| Sitarz (1963) | $0\,125\, g \left(\frac{R}{D}\right)^{\frac{1}{6}} H^2\, T/S$ | 2 | 1 | | | S Cross-sectional area of surf zone | | Continuity, Sediment Entrainment |
| Shadrin (1961) | $\pm\sqrt{111\frac{d}{T}\sqrt{gd}\left(1-\frac{l_1}{l_2}\right)}$ | $\frac{3}{4}{}^*$ | $-\frac{1}{2}$ | | | $l_1, l_2$ Distances between bar and shoreline | | Surface gradien Lunate bar, Rip outflow |

* Approximate, subscripts o and b for deep- and shallow-water equivalents, respectively

tests the goodness of fit between formula – derived predictions and actual field observations. The formulae tested include those by Putnam-Munk-Traylor (1949), Inman-Quinn (1951), Nagai (1954), Brebner-Kamphuis (1963), Galvin-Eagleson (1965), and Inman-Bagnold (1962).

The second half of this paper deals with realistic recognition of the role of topography in the physical scheme of longshore currents. The longshore current is recognized as a velocity field which consists of a multitude of velocity vectors. Field experiences are presented indicating that the topography is a responding variable as well as a process variable, and that depending upon the regimes of wave-current-topography interaction some meaningful patterns of velocity field could take place.

## DATA BACKGROUND

The data utilized in this paper include: (1) a series of field measurements conducted by the Coastal Studies Institute, Louisiana State University, on the Outer Banks beach, North Carolina; (2) field and laboratory data from Putnam-Munk-Traylor; and (3) field and laboratory data from scattered sources.

The field data on the Outer Banks beach (Figure 1) were obtained by measuring the current velocities four times within each tidal cycle, simultaneously with other related variables such as winds, waves, tides, air and water temperatures, beach profiles and sediment characteristics. Since the coordinated coverage of all these variables required the use of a stable platform, the field activities were maintained close to a fishing pier (Figure 2). The current velocity was measured by timing the movement of a dye patch over a fixed distance of 70 feet in either direction from this pier. The wave data were supplied by the step-resistance gage of the Coastal Engineering Research Center, which was maintained alongside the pier at a position approximately 5 meters (15 feet) deep. The field operation was continued for approximately 6 months between December, 1963 and May, 1964.

## QUANTITATIVE TESTS OF SIMPLIFIED SCHEMES

### MULTIPLE LINEAR REGRESSIVE SCHEME

The analytical technique of a multiple linear regressive scheme has been excellently described by Harrison and Krumbein (1964). The basic equation is written:

$$Y = b_o + b_1 X_1 + b_2 X_2 + \ . \ . \ . + b_k X_k,$$

in which Y is the dependent variable, $b_o$, $b_1$, . . . the partial regression coefficients, and $X_1$, $X_2$, . . . the independent variables. In the present case, the

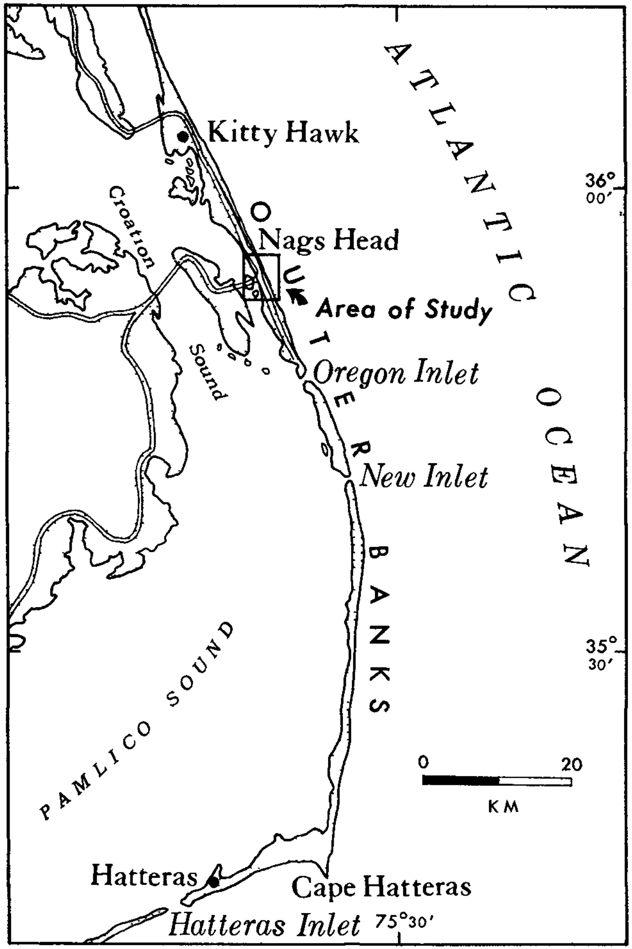



Fig. 1. Location of study area; Nags Head, the Outer Banks, North Carolina.

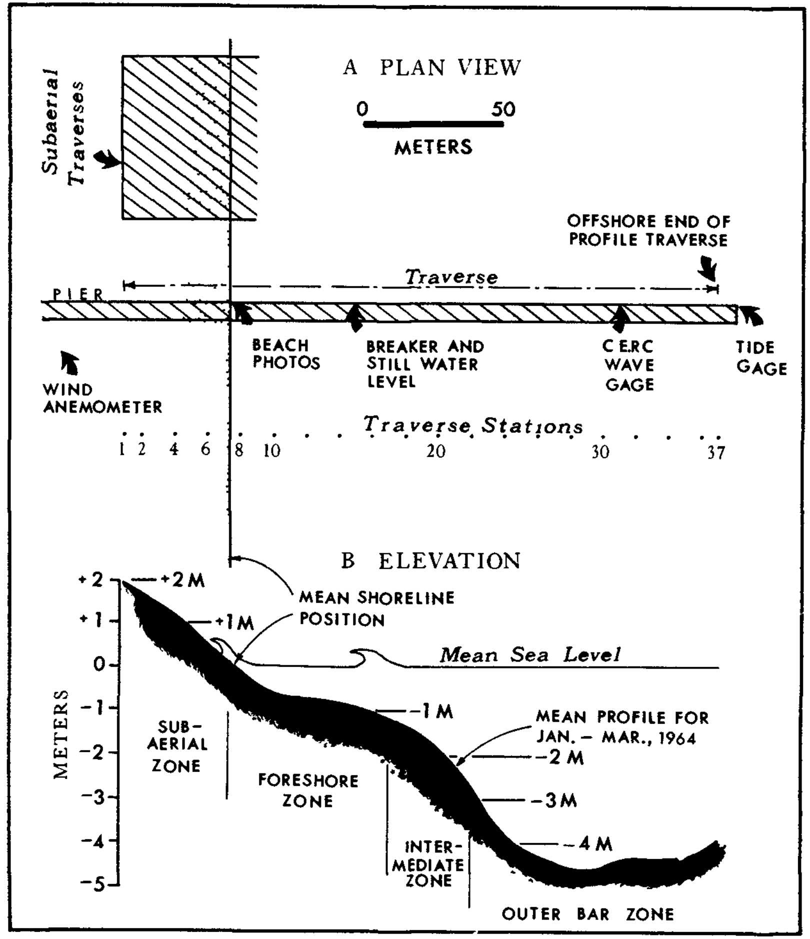



Fig. 2. Field instrumentation and beach profile at study site.

dependent variable is the mean alongshore component of the longshore current velocities. The independent variables are chosen as follows: two measures of wave height (H, wave height measured by the CERC wave gage, and $H_b$, breaker height visually observed over the inner bar), the wave period (T), the angle of incidence ($\Theta$ or $\sin 2\Theta$, the angle between the wave crest and the shoreline), the mean slope of the surf-zone bed (M), and the alongshore component of wind velocities (W). The signs are positive for V, $\Theta$ and W arriving from the north, and negative for these arriving from the south.

In the numerical computation, a special IBM program was designed, so that all the possible combinations of different numbers of independent variables could be dealt with. The relative contribution of each independent variable to observed mean longshore current velocities was evaluated by noting the reduction in $R^2$ between two regressions including and excluding this particular variable. In statistical terminology, $R^2$ is a measure of the fraction of the total variance of the dependent variable which is accounted for by the regression. The square root of this measure, R, is the multiple correlation coefficient. The results of the multiple linear regression analysis are shown in Table 2.

The analysis shows that a considerably high level of explained variation (up to 72 per cent in $R^2$) could be attained by use of multiple linear regression. The most important single variable affecting the mean longshore current velocity turns out to be the angle of wave incidence, $\Theta$ or $\sin 2\Theta$, which alone accounts for approximately 68 per cent out of the maximum $R^2$ level of 72 per cent. This is followed by the wind velocity (accounting for the mere fraction of 3.1 per cent in $R^2$), the wave height (1.3 per cent in $R^2$), the bed slope (0.7 per cent in $R^2$), and the wave period (0.0 per cent in $R^2$) in the order named. It appears, therefore, that so far as the Outer Banks data are concerned, the mean longshore current velocities can be explained to a reasonably high degree through a simple linear regression containing the angle of incidence as the sole independent variable, as follows:

$$V = -0.264 + 2.958 \sin 2\Theta,$$

$\Theta$ in degrees, and
V in ft./sec.

Similar results were obtained by using the field and laboratory data of Putnam-Munk-Traylor (1949) (Table 3). The levels of explanation, $R^2$, using these data were 89.1 and 65.3 per cent for the laboratory and field observations, respectively. In both of these sets of data, the most important single variable was also the angle of incidence, which accounted for 81.6 per cent of the total $R^2$ of 89.1 per cent and 47.9 per cent out of the total $R^2$ of 65.3 per cent, respectively.

These results are conflicting with those previously reported by Harrison and Krumbein (1964), who used data obtained on the Virginia beach, approximately

Table 2. Strongest combination of multiple linear regression using the Outer Banks data. $R^2$ represents overall level of explanation. For contribution of individual variables, note reduction in $R^2$ between regressions including and excluding a particular variable.

| PARTIAL REGRESSION COEFFICIENTS FOR | | | | | | | | $R^2$ |
|---|---|---|---|---|---|---|---|---|
| $b_o$ | $\theta$ | Sin $2\theta$ | T | H | $H_b$ | M | W | % |
| -1.64 | .06 | - | -.01 | .21 | - | 17 | 04 | 71 57 |
| -1.69 | .06 | - | | .21 | - | 17 | 04 | 71 56 |
| -0.90 | .06 | - | | .17 | - | | 05 | 70.62 |
| -0.34 | .07 | - | | | - | | 06 | 69.22 |
| -0.27 | .09 | - | | | - | | | 65.75 |
| -1.39 | .06 | - | -.01 | - | .20 | .14 | .05 | 71.01 |
| -1.44 | .06 | - | | - | 21 | .14 | .05 | 71.00 |
| -0.83 | .06 | - | | - | .18 | | .05 | 70.33 |
| -1 57 | - | 2.22 | -.01 | .20 | - | .17 | .04 | 72.20 |
| -1.60 | - | 2.23 | | .20 | - | .16 | 04 | 72.19 |
| -0.83 | - | 2.25 | | .16 | - | | .04 | 71.29 |
| -0.32 | - | 2.34 | | .16 | - | | .05 | 70.12 |
| -0.26 | - | 2.96 | | | - | | | 67.80 |
| -1.30 | - | 2.19 | -.01 | | .18 | .14 | .04 | 71.60 |
| -1.34 | - | 2.20 | | | .18 | .13 | .04 | 71.59 |
| -0.74 | - | 2.22 | | | .16 | | .05 | 70.95 |

UNIT: $\theta$ in degrees, T in seconds, H & $H_b$ in feet, and W in m.p.h.

Table 3. Strongest combination of multiple linear regression using Putnam-Munk-Traylor data. $R^2$ levels from the Outer Banks data are listed for comparison.

| | INDEPENDENT VARIABLES CONSIDERED | | | | | | | $R^2$ % BY DATA SOURCE | |
|---|---|---|---|---|---|---|---|---|---|
| | $\theta$ | Sin $2\theta$ | T | H | $H_b$ | M | W | PUTNAM ET AL | OUTER BANKS |
| FIELD DATA | X | | X | | X | X | | 65.29 | 69.85 |
| | X | | | | X | X | | 64.49 | 69.81 |
| | X | | | | | X | | 58.18 | 66.32 |
| | X | | | | | | | 47.94 | 67.80 |
| LAB. DATA | X | | X | | X | X | | 89.06 | 69.85 |
| | X | | X | | | X | | 89.04 | 66 54 |
| | X | | X | | | | | 87 00 | 65 81 |
| | X | | | | | | | 81.61 | 67.80 |

X: Variable included in regression

70 miles north of our study area. The angle of wave incidence, which proved to be the most influential variable both in the Outer Banks and the Putnam-Munk-Traylor data, ranked as the fifth most important variable in their analysis. The most important variable turned out in their analysis to be the wave period, which proved to be insignificant in our analysis.

The discrepancies just described may probably indicate the very limitations inherent to the multiple linear regressive scheme. This scheme only provides a linearized description of a certain physical scheme through a particular set of sample data available for analysis. Consequently, depending upon the particular samples analyzed as well as the non-linearity characteristics of the original physical scheme, a considerable distortion of reality might result. In the present case, the sample characteristics may relate to the regional and seasonal regimes of the beach-ocean-atmosphere interaction system. While both the Outer Banks data and the Putnam-Munk-Traylor data was obtained during single seasons, the former during January to March and the latter during February to April, those of Harrison-Krumbein were taken from scattered periods between February and July.

MULTIPLE NON-LINEAR REGRESSIVE SCHEME

Review of various published formulae suggests that the relationship between the mean longshore current velocity and the independent variables might be approximated by a non-linear relationship, such as a product form of independent power variables, namely

$$Y = e^{b_o} X_1^{b_1} X_2^{b_2} \ . \ . \ . \ X_k^{b_k} .$$

By taking the logarithm on both sides, one obtains

$$\log Y = b_o + b_1 \log X_1 + b_2 \log X_2 + \ . \ . \ . \ + b_k \log X_k .$$

By regarding the logarithms of individual variables as the elementary variables the problem reduces to that of a multiple linear regressive scheme. The results of analysis are summarized in Table 4.

In the Outer Banks data, the multiple correlation level based on this non-linear scheme is found to be appreciably low, i. e. 51 per cent. Also unlike the results of linear regression, the most important variable affecting the mean longshore current velocity proves to be the wave height, accounting for approximately 22 per cent out of the total 25 per cent in $R^2$. The angle of incidence is the least important of all the independent variables. The F-tests show that any combination of variables excluding either the breaker height or the shallow-water wave height

Table 4. Strongest combination of product-form non-linear regression, using the Outer Banks data.

| PARTIAL REGRESSION COEFFICIENTS FOR | | | | | | | | $R^2$ |
|---|---|---|---|---|---|---|---|---|
| $b_o$ | $\Theta$ | Sin $2\Theta$ | T | H | $H_b$ | M | W | % |
| .34 | .08 | - | -.15 | .32 | - | -.12 | .03 | 23.86 |
| .40 | .08 | - | -.16 | .33 | - | -.12 | | 23.75 |
| .66 | | - | -.21 | .34 | - | -.09 | | 23.14 |
| .52 | | - | -.20 | .35 | - | | | 22.71 |
| .12 | | - | | .40 | - | | | 20.44 |
| .40 | .05 | - | -.14 | | .32 | -.11 | .06 | 25.68 |
| .56 | | - | -.17 | | .33 | -.09 | .06 | 25.45 |
| .71 | | - | -.19 | | 33 | -.09 | | 24.84 |
| .58 | | - | -.19 | | .34 | | | 24.46 |
| .22 | | - | | | 38 | | | 22.49 |
| .62 | - | .07 | -.16 | .33 | - | -.12 | .03 | 23.64 |
| .67 | - | .07 | -.17 | .33 | - | -.11 | | 23.53 |
| .66 | - | | -.21 | .34 | - | -.09 | | 23.14 |
| .52 | - | | -.20 | .35 | - | | | 22.71 |
| .12 | - | | | .40 | - | | | 20.44 |
| .57 | - | .03 | -.15 | - | .32 | -.10 | .06 | 25.53 |
| .56 | - | | -.17 | - | .33 | -.09 | .06 | 25.45 |
| .63 | - | | -.16 | - | .34 | | .06 | 25.00 |
| .38 | - | | -.19 | - | .34 | | | 24.46 |
| .22 | - | | | - | .38 | | | 22.49 |

UNIT: $\Theta$ in degrees, T in seconds, H & $H_b$ in feet, and W in m. p. h.

Table 5. Strongest combination of product-form non-linear regression, using Putnam-Munk-Traylor data.

| | INDEPENDENT VARIABLES CONSIDERED | | | | | | | $R^2$ % BY DATA SOURCE | |
|---|---|---|---|---|---|---|---|---|---|
| | $\Theta$ | Sin $2\Theta$ | T | H | $H_b$ | M | W | PUTNAM ET AL | OUTER BANKS |
| FIELD DATA | X | | X | | X | X | | 64.81 | 25 02 |
| | X | | | | X | X | | 64.62 | 23.71 |
| | X | | | | | X | | 59.13 | 7.27 |
| | X | | | | | | | 44.59 | 4.76 |
| LAB. DATA | X | | X | | X | X | | 67.70 | 25.02 |
| | X | | X | | X | X | | 67.64 | 24.53 |
| | X | | | | X | | | 67.00 | 23.19 |
| | | | | | X | | | 42.81 | 22.49 |

X Variable included in regression.

(measured by the CERC gage) was statistically insignificant at the 1 per cent level of probability.

A similar analysis using the laboratory and field data of Putnam-Munk-Traylor indicates a comparable level of correlation, approximately 81 per cent and 82 per cent, respectively (Table 5). Interestingly, the importance of wave height is noted only in the laboratory data (43 per cent in $R^2$). The angle of incidence, which was insignificant in the non-linear regression based on the Outer Banks data, proves to be important in both sets of the Putnam-Munk-Traylor data, accounting for 24 per cent and 45 per cent in $R^2$, respectively.

Consequently, it is stated that the non-linear regression of a product form does not necessarily improve the level of correlation. Comparing between the linear and non-linear regressive schemes and also between the data from the different sources analyzed here, a considerable confusion arises as to the relative contribution of individual variables. Apparently, further study is needed before the multiple regressive schemes become an effective means of prediction.

## TEST OF FORMULAE

General - All the known formulae (Table 1) have been derived from simplified physical schemes in which the bottom topography is replaced by an inclined plane. The approach by Inman and Bagnold (1962), Shadrin (1961) and Bruun (1963) has further assumed the presence of a longshore bar or multiple bars with or without regular gaps along the bar crests. Theoretical derivation of physical relationships assumes that a steady state of equilibrium is established in terms of either momentum exchange, energy conservation, mass continuity or surface gradient. The mathematical expressions of the known analytical formulae are summarized in Table 1.

Putnam-Munk-Traylor formulae (1949), revised by Inman-Quinn (1951) - Putnam-Munk-Traylor were the first to introduce a simplified physical scheme amenable for theoretical analysis. Using the extensive field observations on the California coasts, Inman and Quinn later demonstrated that the friction coefficient, K, contained in the original Putnam-Munk-Traylor formulae could be revised in accordance with the relationship:

$$K \propto V^{-1.5}$$

Computation using the Outer Banks data indicates that the prediction based on the revised momentum formula exceeds the observed current velocities by the factor of 2.67 (Figure 3). The friction coefficients computed from the original Putnam-Munk-Traylor formula (Figure 4) further indicate that the friction coefficient may not be as definite a function of the current velocities as suggested by Inman and Quinn. An adequate explanation of this difference between the results of Inman

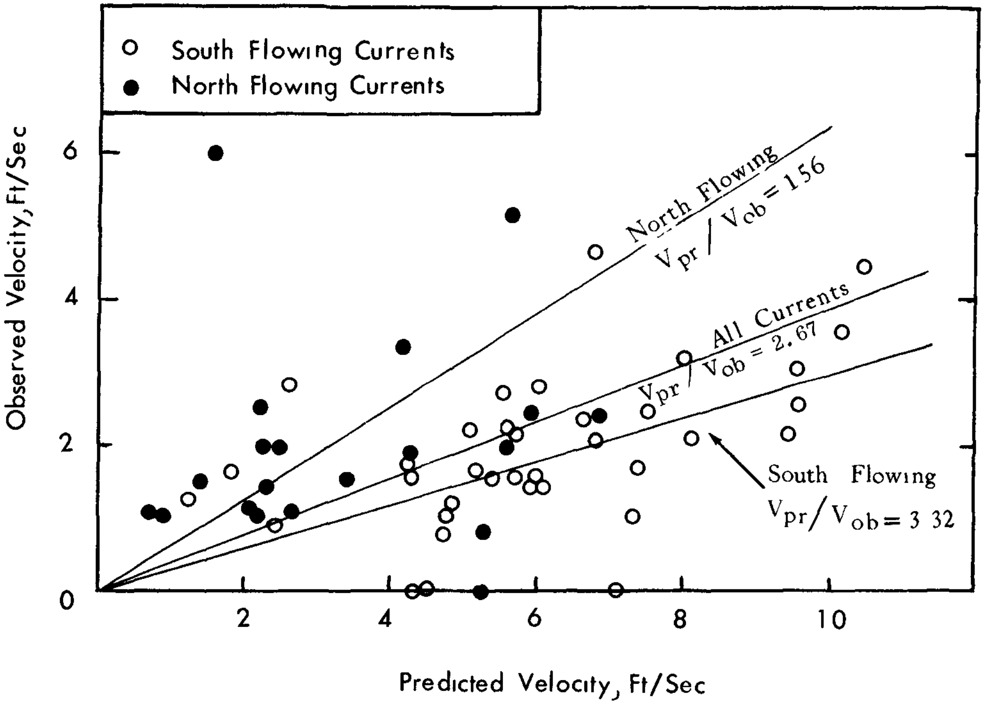



Fig. 3. Prediction using Inman-Quinn-revised Putnam-Munk-Traylor momentum formula versus field observations from Outer Banks, N.C.

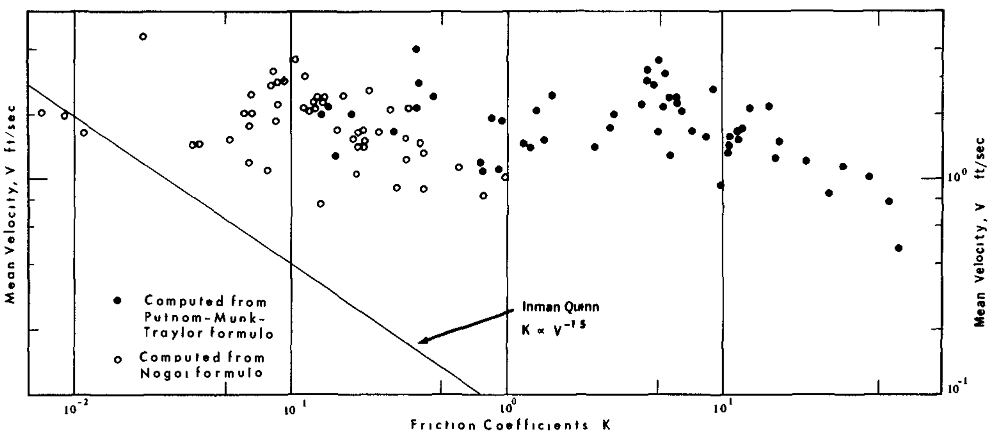



Fig. 4. Friction coefficients computed from Putnam-Munk-Traylor formula and Nagai formula versus current velocities.

and Quinn and the present authors is not immediately possible. However, it may be that the K value is influenced not only by the bed roughness but also by the effects of other energy dissipative sources - namely the internal turbulence in the surf zone, and the sediment movement and the topographic changes which take up a considerable portion of wave energy contributed here.

Nagai formula (1954) - Referring to the study of Housely and Taylor (1957), Shadrin (1961) questioned the application of the solitary wave theory to approximate breaker characteristics, such as was used in the derivation of the Putnam-Munk-Traylor formulae. This problem can be checked through a formula proposed by Nagai (1954), whose derivation used the Airy's first-order approximation along with the same physical scheme as proposed by Putnam-Munk-Traylor (Table 1).

Figure 4 includes the friction coefficients computed from this formula using the Outer Banks data. The scatter of the plots suggests that the application of the oscillatory wave theory does not substantially improve the goodness of fit with observation.

Brebner-Kamphuis formula (1963) - The energy and momentum formula proposed by these investigators contain the deep-water equivalents of wave characteristics on the consideration that these are the fundamental variables available through wave forcasting techniques.

The prediction using the energy and momentum formulae exceeds the observed velocities by the factor of 1.76 and 2.73, respectively (Figure 5). The disagreement is too obvious to be accounted for by the fact that our observed velocities tended to be small due to the proximity of a fishing pier.

Galvin-Eagleson formula (1965) - Figure 6 shows the South flowing and the North flowing currents separately. With both of these currents combined, the prediction exceeds the field observation by the factor of 2.42.

Inman-Bagnold formula (1962) - The basic scheme of derivation assumes that the mass of water released by the breaker is preserved within the surf zone until it is channeled out through the rip outflow at a downstream position. Thus, the formula contains two unknowns. the fraction of the total wave mass which is contributed to the current, denoted by $s$, and the interval between adjacent rips, denoted by $l$ (Table 1). Using the Outer Banks data, the terms excluding these unknowns are computed and plotted against observed velocities in Figure 7. The plots suggest the relationship:

$$s \cdot l \doteqdot 30 \text{ ( unit in feet )}$$

Assuming that the s value ranges between 2 and 10 per cent (Galvin-Eagleson, 1965; Brebner-Kamphuis, 1963, Inman-Bagnold, 1962), the rip interval, l, should

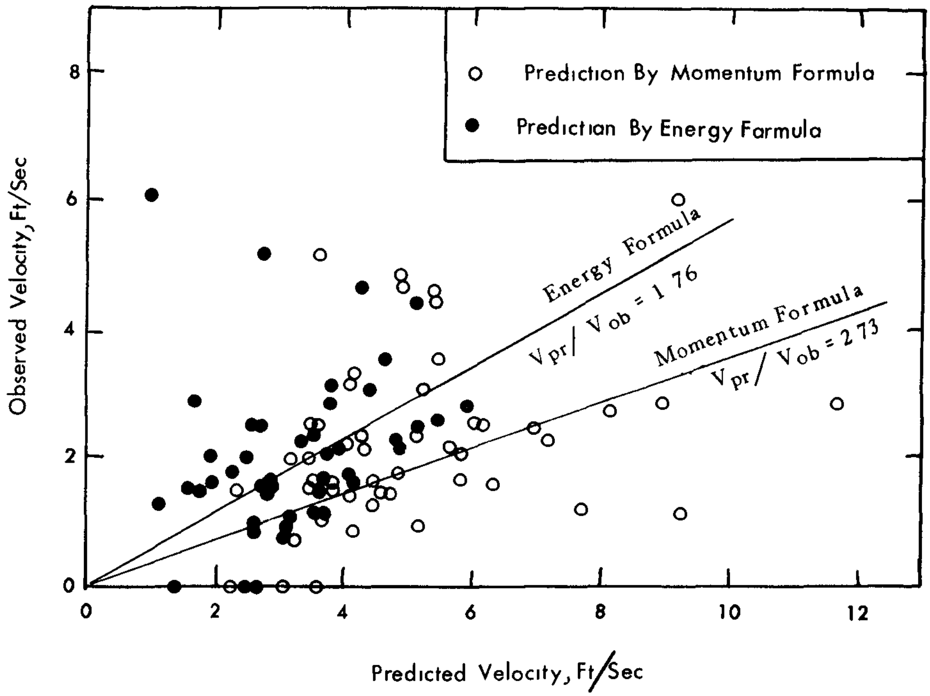



Fig. 5. Prediction using Brebner-Kamphuis formulae versus field observations from Outer Banks, North Carolina.

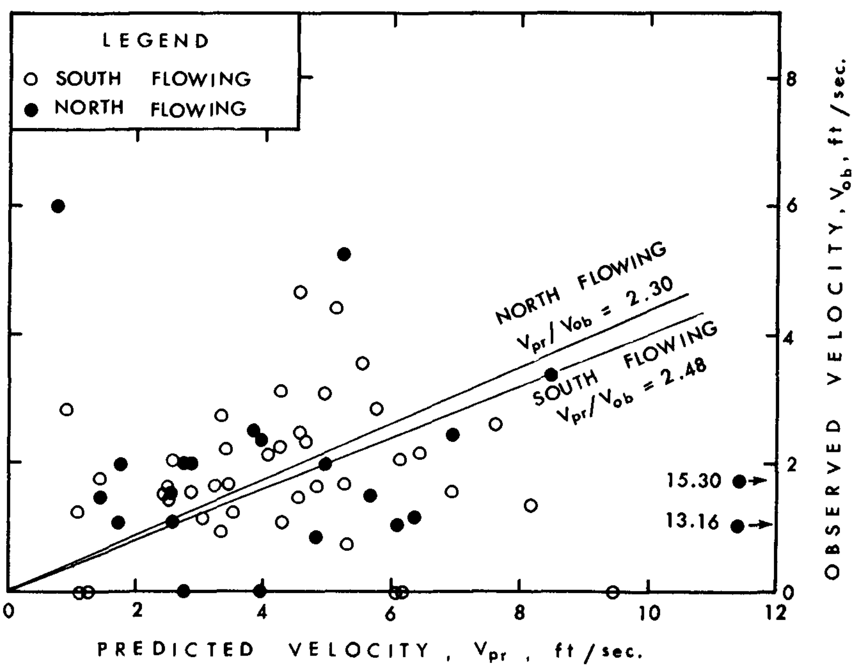



Fig. 6. Prediction using Galvin-Eagleson formula versus field observations from the Outer Banks, N.C.

fall between 1050 ft. to 210 ft. - the order roughly comparable to the case of the Outer Banks beach as well as that previously reported by Shepard (1950).

## VARIABILITY OF LONGSHORE CURRENTS

### GENERAL

It must be mentioned that the tests thus far described utilized selected data, excluding anomalies such as the currents opposed to the direction of wave approach, the non-zero current velocities with perpendicular wave incidences, the zero current velocities with oblique incidences, and the wind directions opposed to the current directions.

In all, these anomalies occurred in 35 per cent of the field observations, implying that the formulae based on simplified schemes failed to explain a considerable portion of the actual phenomenon. Even with the selected data, the disagreement between the predicted and the observed velocities was appreciable. It may be that while the formulae are designed to give the mean velocity in the surf zone, no known method of observation is capable of yielding an unbiased mean, or that the simplified analytical schemes fail to account for the actual physical mechanism of the longshore current phenomenon.

From the hydraulics point of view, the longshore current is a case of an unsteady flow confined in a time-variant boundary. The current field contains velocity vectors which are variable both in time and space, and the bottom topography is changing constantly. Generally speaking, the temporal variability may be attributed to the stochastic nature of the input waves, and the spatial variability to the interplay between waves, currents and the topography. It is likely that this latter effect is a reciprocal process, in which a change of each variable is fed back to the behaviors of other associated variables. Consequently, although the simplified analytical schemes assume the topography to be a fixed boundary and the waves and the currents to be steady in time, the actual phenomena must be comprehended in view of the dynamic regimes of interaction between these variables.

### TEMPORAL VARIABILITY

Owing to the difficulty of field measurement, quantitative data pertaining to the temporal variability are particularly scarce. The indication of the temporal variability of longshore currents has been reported by Shepard and Inman (1950) on the Scripps beach, La Jolla, California. Pulsation of the rip outflow observed on this beach, with the average recurrent period of 1.7 minutes, has been reported to coincide with that of the surf beat activities. According to observations on the Niigata beach, Japan (Fujiki, 1957), the rip pulsation was apparently associated with the angle of wave incidence; the pulsation gave way to a continuous diagonal outflow as the obliquity of wave incidence increased.

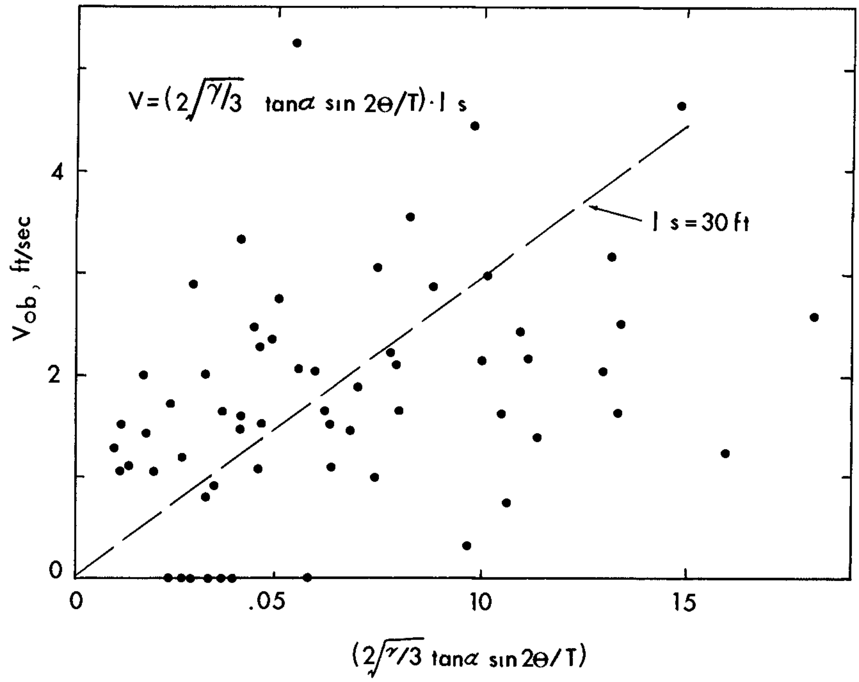



Fig. 7. Inman-Bagnold formula tested by checking the magnitude of mass contribution to currents by waves, s, and rip separation, l.

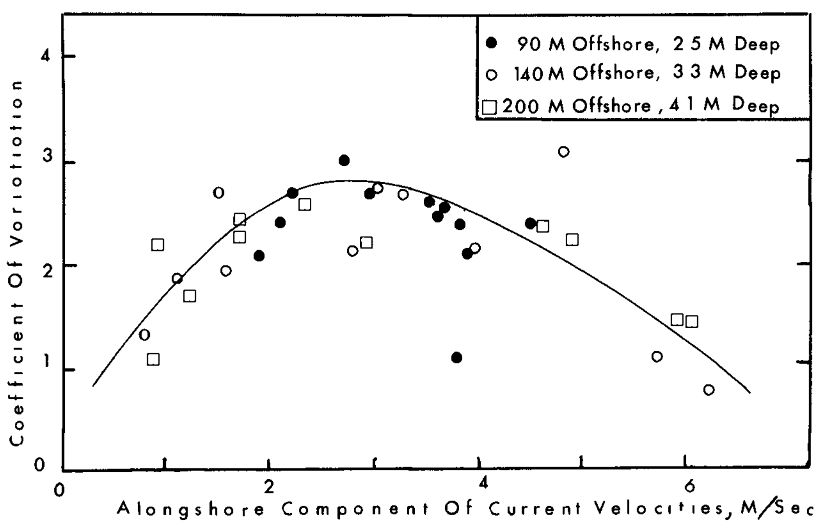



Fig. 8. Coefficient of variation versus mean of 10-minute average velocities. Data from Niigata, Japan (1958, a).

The data on the Niigata beach, Japan, obtained with a self-contained automatic recorder (ONO-Meter), probably represent the largest source of information regarding this subject (Niigata, 1958,a,b). According to these observations, the temporal variability beyond the order of 10-minute period appears to be relatively low. The standard deviation of the 10-minute average velocities remained below 0.3 ft/sec throughout the entire runs of data. This is particularly meaningful when one considers that during the period of current measurements breakers as high as 15 ft were observed. The data by Inman and Quinn (1951), taken during swell activities and probably containing the effects of both temporal and spatial variabilities, have resulted in standard deviation of 0.5 ft/sec. In the Niigata data, the coefficient of variation of the 10-minute average velocities was merely 0.3 for the velocities near 1.0 ft/sec (.3m/sec), decreasing gradually to as low as 0 1 for both lower and higher velocities (Figure 8). According to Inman and Quinn, the coefficient of variation remained not lower than 1.0 for all the velocities observed. Indications are that the proportion of the scatter in current velocities which is attributable to the temporal variability is smaller than to the areal variability. Interestingly, current reversal was reported to occur twice as frequently near the offshore bar as inshore of this position. In general, the temporal variability appears to be more pronounced near the offshore bar than inside the surf zone.

## SPATIAL VARIABILITY

The spatial variability of longshore currents perpendicular to the shoreline has been recognized in laboratory models (Galvin-Eagleson, 1964; Shimano, et al, 1957) as well as in the field (Ajbulatov, et al, 1966). Variability in the alongshore direction has received much attention in recent years (Inman-Bagnold, 1962). This type of variability includes the processes of gradual acceleration, deceleration, stagnation, and reversal, and has even been recognized in a laboratory model with straight contours (Galvin-Eagleson, 1964; Brebner-Kamphuis, 1963). Variability with depth is probably the least known feature but highly important in view of its implications on sediment transport. Actual observation has been made mostly beyond the longshore bar (Shepard-Inman, 1950, Sonu, 1961).

Certain systematic combinations of these variability features seem to emerge depending upon the interplay among the associated variables. The regularly spaced rip currents (McKenzie, 1958; Shepard, 1950) represent one of such examples. Accordingly, the longshore current velocity field may be classified into four distinctive categories in the light of the regimes of this interplay - the hypothetical regime, the natural equilibrium regime, the transitional regime, and the forced equilibrium regime.

## HYPOTHETICAL REGIME

The topography is a fixed bed, and the dynamic interaction exists only between currents and waves. Although the case represented by this regime may seldom arise under natural conditions, except when the beach is very steep and

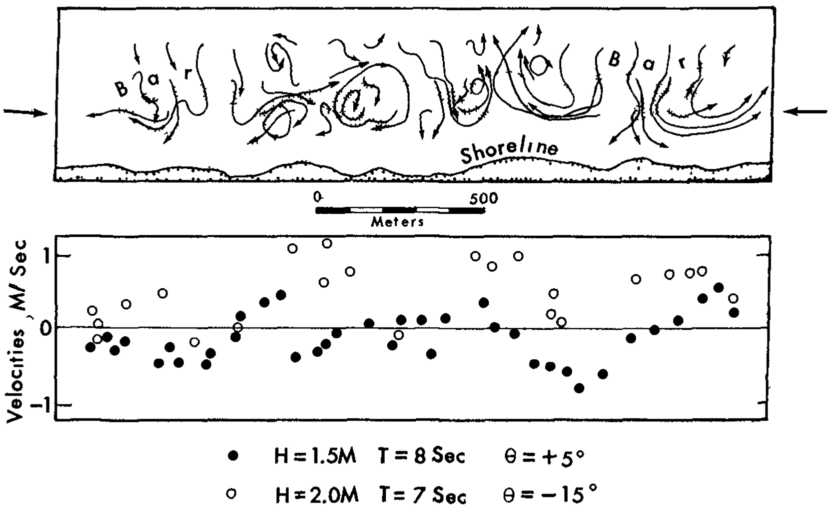



Fig. 9. Longshore current velocity field associated with sand waves. Upper diagram for H=1.5m, T=8 sec. and $\theta$=+5$^{o}$ (from right of normal to the shore). Lower diagram shows mean alongshore velocity components at 200 m from the shore, as indicated by thick arrows in the upper diagram. (Adapted from Inokuchi, 1960).

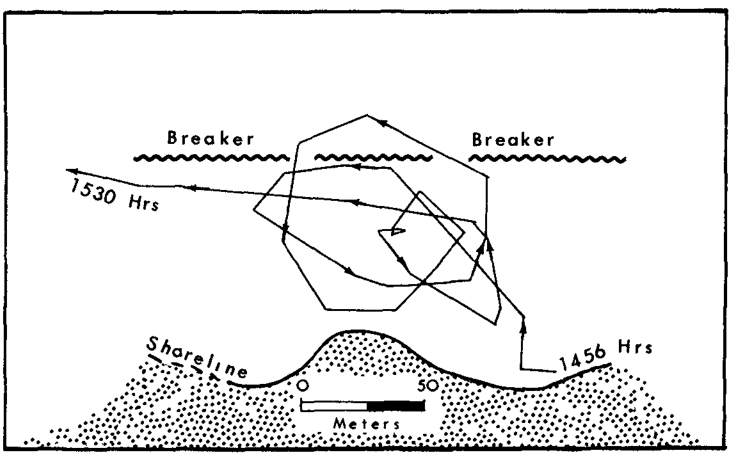



Fig. 10. Currents stagnate over the shoal, describing circulating paths. Data from Niigata, Japan (1958,b).

the wave action very weak, the hydraulic mechanism revealed in this simplified case appears to render information of basic interest.

Laboratory experiments using a fixed slope (Galvin-Eagleson, 1965) and a sandbed (Shimano et al, 1957) have demonstrated the presence of a velocity distribution across the surf zone, with the maximum velocity occuring at positions approximately 10 to 40 per cent of the surf-zone width from the shoreline. It has also been reported (Galvin-Eagleson, 1965) that "the width of the longshore current expands in the direction of flow downstream of the obstacle." This observation is consistent with a prediction resulting from the continuity approach (Inman-Bagnold, 1962) that the distance between the bar crest and the shoreline must increase in the direction downstream from the point of a rip current.

## NATURAL EQUILIBRIUM REGIME

The natural equilibrium regime represents the case in which the interaction between waves, currents, and the topography has reached a state of dynamic equilibrium. Unlike in the hypothetical regime, the topography participates in this interaction as a responding variable as well as a process variable. Of particular interest is the fact that, when acted upon by longshore currents over a sustained period of time, the nearshore bed develops a series of sand waves having elongated ridges and troughs directed at angles to the shoreline (Sonu and Russell, 1966). These sand waves are subsequently reworked by waves and transformed into an alternate sequence of lunate bars and intermediate shoals, with a shoal-to-shoal separation of several hundred to several thousand feet alongshore. The longshore current velocity field corresponding to this type of rhythmic topography (Hom-ma and Sonu, 1962) takes on a typical pattern of natural equilibrium regime. Figure 9 shows the laboratory reproduction of such a velocity field modeled after the Niigata beach, Japan (Inokuchi, 1960). Although the current pattern is a group of circulating cells associated with the shoals and lunate bars, the alongshore velocity components plotted along the shoreline give only alternate sequences of converging and diverging currents Figure 10 represents the actual field observation of circulating water movements in the vicinity of a shoal, on the Niigata beach, Japan. The alongshore velocity components are generally greater in front of the embayment than near the apex or the shoal, the latter being associated frequently with stagnation or even reversal of current directions. Figure 11 shows the breaker distribution over the rhythmic topography, taken from the Niigata beach. The breaker type is diversified into the spilling type over the shoal and the plunging type over the bar.

Figure 12 shows the longshore current velocity field actually observed by the present investigators on the Outer Banks beach. Waves with a significant height of 2.5 feet and a period of 7.8 seconds arrived at 30° to the shore, and there was no wind. The waves broke by spilling over the shoal, releasing a considerable amount of water mass directed onshore. This free mass of water was further joined by the backwash from the subaerial beach and gradually displaced downstream by the alongshore component of oblique wave drags. Reaching the

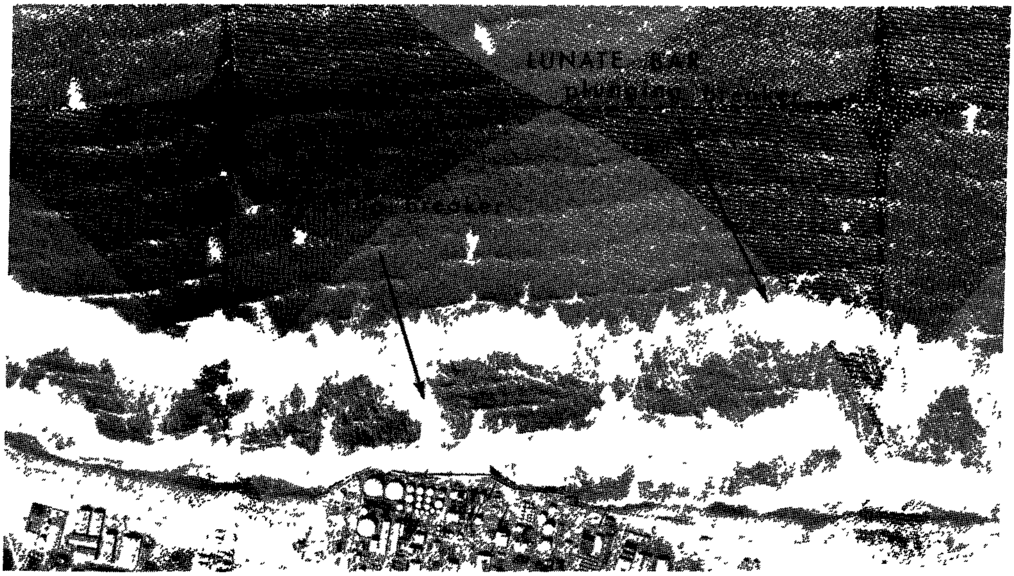



Fig. 11. Breakers over lunate bars and shoals, characterizied by plunging and spilling types, respectively. Photo showing the Niigata beach, Japan, taken by Kokusai Aerial, Inc., Tokyo, October 12, 1955.

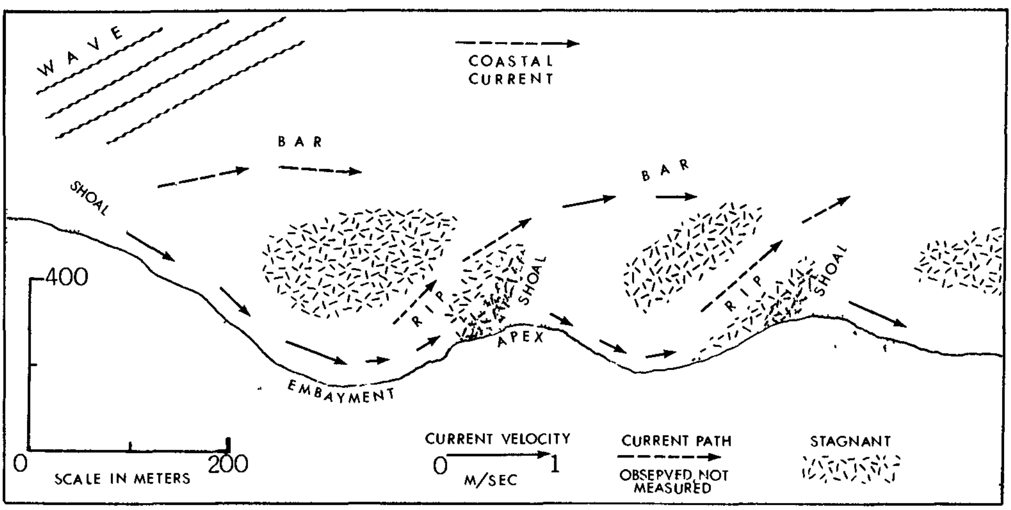



Fig. 12. Longshore current velocity field observed on the Outer Banks, North Carolina, October 24, 1965.

enter of the embayment, the water movement became stagnant, due apparently to ie shoreline curvature which resulted in a decrease in the alongshore component wave drag. The continuous influx of water caused a hydrostatic potential to uild up at this position, which was eventually released toward offshore as the iass outflow of a rip current. This phenomenon is predominantly a process of iass transfer On the other hand, the waves broke over the bar crest by plunging, ut much of their energy was absorbed into secondary waves which were regenerted above the trough. Consequently, no appreciable amount of onshore mass iovement occurred beyond the trough, the water released by the breaker undergoing a gradual displacement downstream along a relatively constricted path over ie bar crest. Surprisingly, the dye patch entering this zone created a clear deiarcation with the water offshore and was never diffused into the area between ie bar and the shoreline. This phenomenon is predominantly a process of momenim transfer. Thus, it appeared that the current field just described consisted of oth the continuity and the momentum processes operating simultaneously. Evans 1939) has reported a similar case from the Lake Michigan shore.

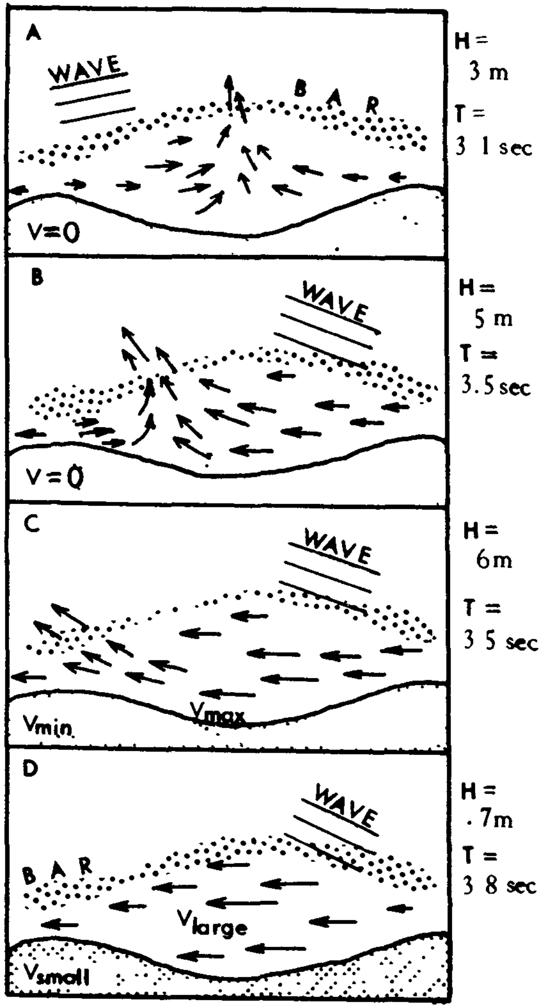
The longshore current velocity field associated with the natural equilibrium egime may be a more general occurrence than is usually believed. The rhythmic topography associated with this regime have been reported from various soures of the world, including the Azov and Caspian Sea coasts (Shadrin, 1961); Egorov, 1951; Kashechkin-Uglev), the French Mediterranean coast (Riviere et al, 961), the Italian coast (King-Williams, 1949), the Danish North Sea coast (Bruun, 954), the Japanese coast (hom-ma-Sonu, 1962, Mogi, 1960), the Gulf coast of Mexico (Psuty, 1966), the Lake Michigan beach (Evans, 1939), the Virginia beach Harrison-Wagner, 1964), and the Outer Banks beach (Sonu-Russell, 1966).

TRANSITIONAL REGIME

This regime represents the case in which the wave-current-topography nteraction is undergoing transition caused by changes in the wave field. However, systematic description of the current field seems possible as long as the topography remains relatively stable. An example is shown in Figure 13 (Shadrin, .961). The current velocities are generally greater near the embayment than iear the shoal, and the rip position is associated with the angle of wave incidence. Similar results have been reported by Riviere et al (1961) on the French Mediterranean coast, Hom-ma and Sonu (1962) on the Pacific coast of Japan, and the engineers of Niigata, Japan (Figure 14).

As the obliquity of wave incidence increases, the circulating cells become elongated parallel to the shoreline and take on the patterns such as observed on the Outer Banks. As already described, the rip pulsation gives way to a more continuous outflow, issuing diagonally toward offshore and being displaced gradually downstream with the migration of the sand-wave system.

Under natural conditions, the interaction between waves, currents, and the topography is believed to be a transition from one quasi-equilibrium to another.



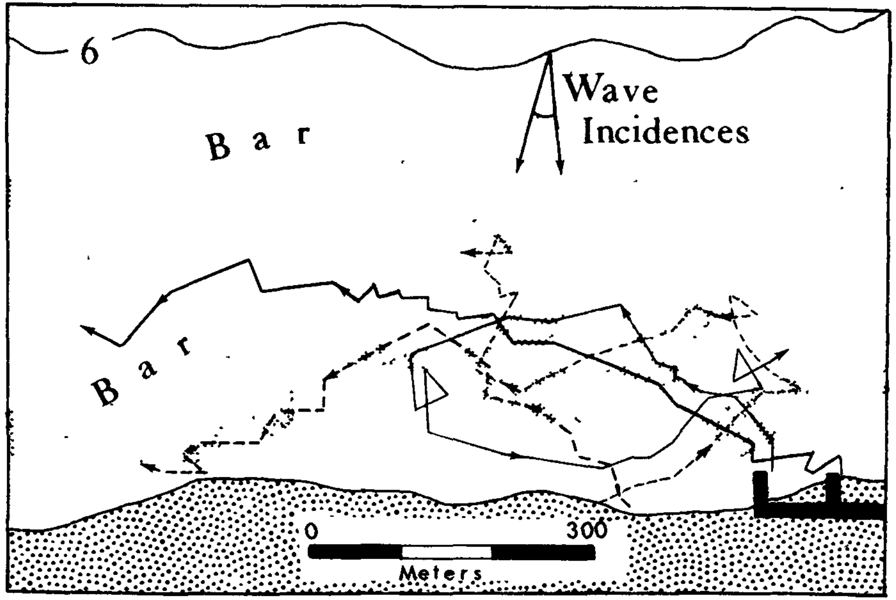




Fig. 14. Four typical patterns of current paths observed over the same area, Niigata, Japan (1958b). Note relative quiescence in the zone between bar and shoreline, and tendency of local circulation or stagnation over shoal.

Fig. 13. Change in longshore current velocity field with shifting wave conditions. Note deceleration, stagnation and reversal near apex. (Reproduced from Shadrin, 1961).

Consequently, the transitional regime may represent the most frequently encountered case in the field.

FORCED EQUILIBRIUM REGIME

Man-made structures or fixed topographic features may impose a certain constraint on the variables associated with the equilibrium regime. This seems to be best typified by the case reported from the Scripps beach, California, where topographic diversification in the vicinity of the submarine canyons forces incident waves to refract into a limited number of convergence - divergence patterns (Shepard-Inman, 1950). As a result, an extremely steep gradation of the alongshore breaker-height distribution develops on this beach – namely on the order of 1:2 or even 1:3 per less than half a mile of shoreline length - which will be rarely encountered on ordinary beaches having relatively smooth contours on the offshore bed. Since the long-period wave responds most sensitively to a forced refraction, the nearshore water circulation, reported by Shepard and Inman (1950), is most pronounced during the activity of long-period waves The constraint on the wave refraction will also give rise to an areal fixation of the current pattern as well as of the relief patterns close to the shore. Munk and Traylor (1947) have reported that a rip current is frequently observed at the head of a submarine canyon. This appears to be one of the significant distinctions from the natural equilibrium regime, in which the rip position is considerably varied as the sand waves migrate in the direction of the predominant longshore currents. The basic hydraulic mechanism governing the forced equilibrium regime thus is likely to be similar to that of the natural equilibrium regime, consisting mainly of the processes of momentum transfer over the bar crest and mass transfer along the shoreline.

## SUMMARY AND CONCLUSIONS

The results of the analyses are summarized as follows:

1. Approximation of the mean longshore current velocities using the multiple regressive scheme of both linear and non-linear types seems to be substantially influenced by the seasonal and regional characteristics of the sample populations analyzed.

2. Of all the independent variables associated with the mean alongshore component of longshore current velocities, the angle of wave incidence distinguishes itself as the most influential variable in both the linear and the non-linear product-form regressions.

3. The analytical schemes based on simplified conditions result in either an undefinable scatter (Putnam-Munk-Traylor, 1949, Inman-Quinn, 1951, Nagai, 1954), or systematic deviations (Brebner-Kamphuis, 1963, Galvin-Eagleson, 1965) from field observations. It may be that the mechanism of the phenomenon has not been truthfully accounted for in these schemes, or that the observations failed to produce an unbiased mean of the multiple-velocity current field. Namely, the

friction coefficient in the Putnam-Munk-Traylor formula may require further refinement by taking into consideration the dynamic processes of energy dissipation in the surf zone environment.

4. The temporal variability of the current velocities appears to be small as compared with the spatial variability. The temporal variability of both the current speeds and directions appears to be more pronounced over the offshore bar than inshore of this position.

5. The spatial variability of longshore currents – including the processes of acceleration, decelaration, stagnation, reversal, and occasionally, bifurcation – arises from the fact that the current field is composed of a multitude of velocity vectors whose distribution is mainly influenced by the regimes of the wave-current-topography interaction in the surf zone. Thus, the longshore current may be classified into four major types of velocity field in accordance with these interaction regimes - the hypothetical regime, the natural equilibrium regime, the transitional regime and the forced equilibrium regime.

6. The current field of the natural equilibrium regime appears to be generated by the momentum transfer from plunging breakers over the bar and the mass transfer from spilling breakers over the shoal as well as from swash activities on the subaerial slope. The seaward mass discharge by rip currents takes care of the hydrostatic potential resulting from the latter.

7. Under natural conditions, the nearshore topography participates in the longshore current mechanism as a dynamic variable, not only redistributing the breaker influx into different positions along the shore but also itself undergoing displacements and transformation due to the waves and the currents thus affected.

## ACKNOWLEDGEMENTS

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