PART II

INLET STABILITY AND CASE HISTORIES

By

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I. INTRODUCTION

Inlet Stability

Inlets which require frequent channel dredging due to gradual shoaling, exhibit migration, or shoal up during storms, are in general unstable and pose a problem to the engineer. This problem of inlet stability is a complex one, because of the rather large number of variables that go into defining stability. The reference here is to inlets on sandy coasts only, because in the absence of sand or similar sedimentary material the problem does not arise. Shell is also found in varying proportions with sand. Some of this is new, whereas in some areas it is ancient reworked material whose size distribution is close to that of the sand with which it is associated.

Long-term Effects and Closure

Two facets of the stability problem concern us. The first is a relatively long-term phenomenon, ranging from a few months to perhaps a decade or more, during which either the inlet remains stable, or deteriorates due to shoaling of the channel and a reduction in the tidal prism. The second is the phenomenon

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of inlet closure, which often occurs as a result of a single storm.

Fig. 1 illustrates an example of the long-term progression of an unstable inlet. Here, the littoral drift is predominantly in the direction of the arrow, and the tidal flow through the inlet is clearly insufficient to counter the growth of littoral spit in the direction of the drift. In Fig. 1 (a), a new inlet has been dredged across a barrier. Under the action of tidal flow and waves, a characteristic throat section (minimum flow area) has developed, as in (b). In (c), the littoral spit has extended itself and begun to constrict the throat and lengthen the channel. This has resulted in a corresponding increase in the overall resistance to flow and a reduction in the tidal prism. In (d) the situation has worsened. Jetties, channel dredging and/or sand bypassing may be required to maintain the inlet at this stage. The progression described in this sequence may occur in a few months or in a few decades, depending on the size of the inlet, bay, availability of sand, and the direction and intensity of the seasonal wave climate.

Example 1-1

Fig. 2 shows Indian Pass in 1873, and again in 1926. This pass was located south of Clearwater, Florida, connecting the Gulf of Mexico to a waterway called the Narrows. A predominant southerly littoral drift is observed to have considerably elongated the channel in the period of 54 years. A breach across the narrow barrier island is seen to have created a new inlet. The long channel had undergone considerable shoaling, and in 1929 the pass was closed by the Corps of Engineers inasmuch as it was unstable and contributed to shoaling in the Intracoastal Waterway at the Narrows.

Fig. 1 (e) illustrates the case of storm closure. In this situation,

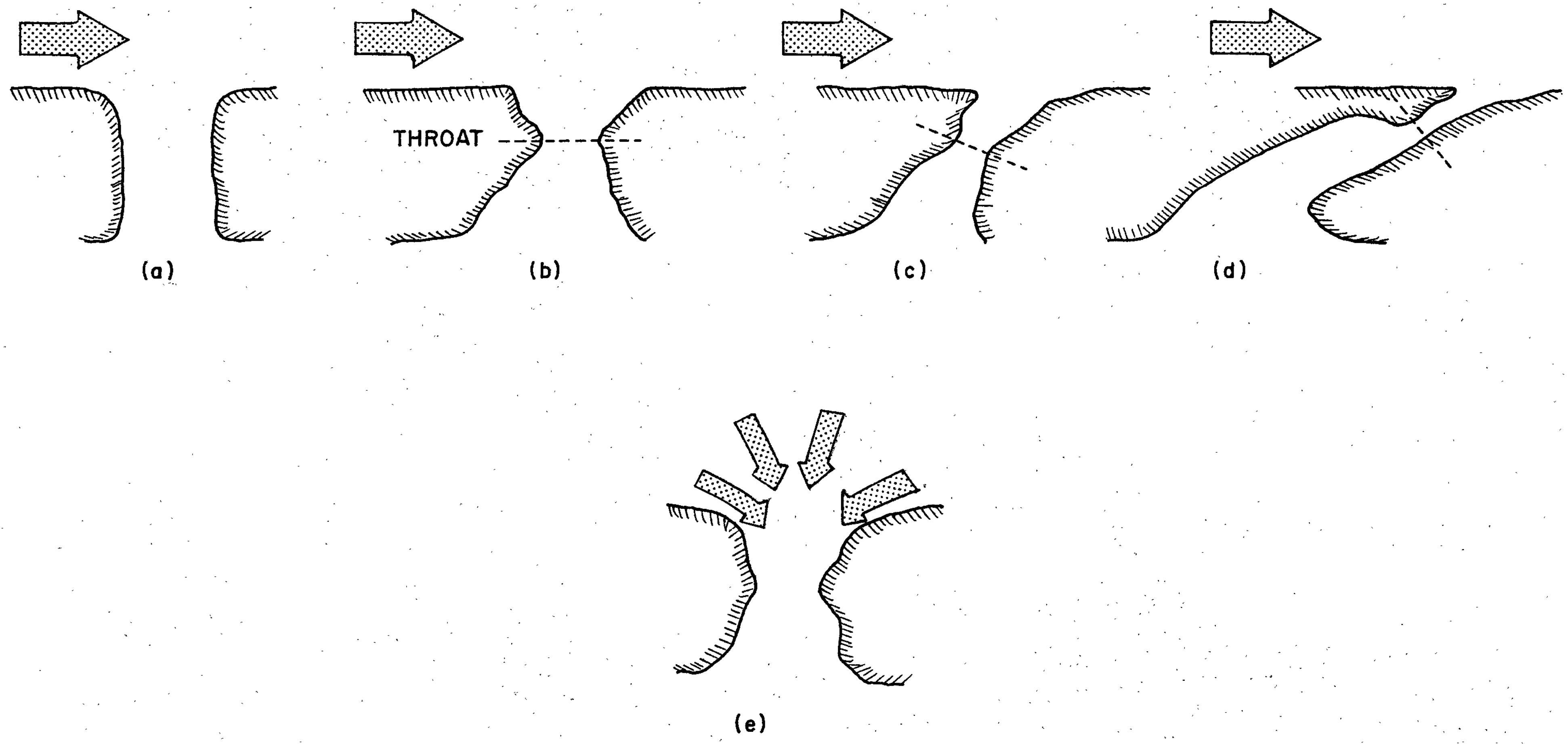

Fig. 1. (a), (b), (c), (d) - Long-term Instability of a Newly Cut Inlet.
(e) - Sand Movement During Storm Closure.

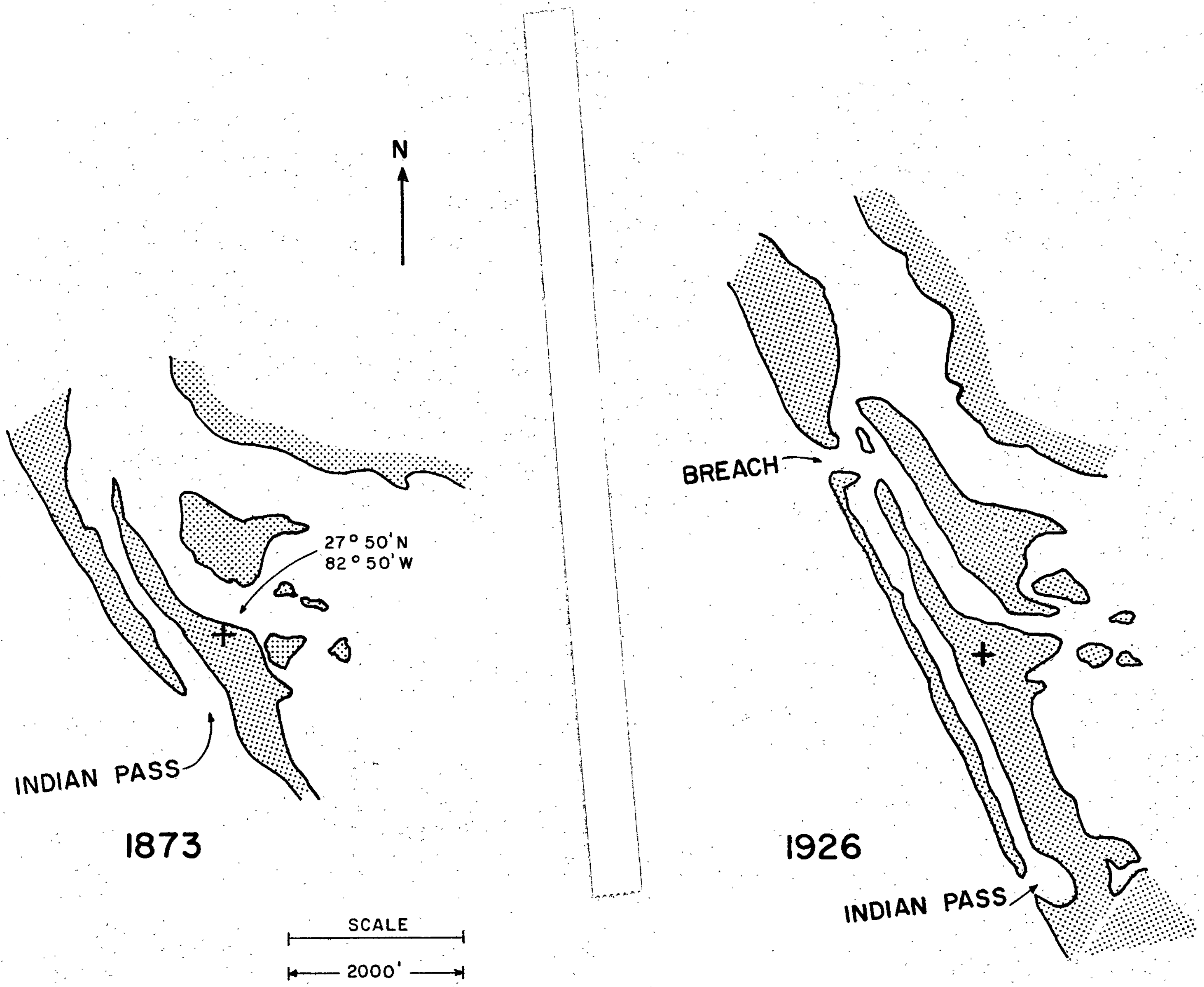

Fig. 2. Unstable Progression of Indian Pass, Florida.

sand is pushed toward the entrance from all directions, not just alongshore. Since this often occurs in a matter of hours, it is clearly a short-term phenomenon in relation to what was described earlier. Furthermore, a unique set of conditions are required to bring about closure, i.e., the flood phase of flow through the inlet under a low range of tide, high onshore wind, storm waves of high energy but low steepness which will carry sand ashore, sufficient storm duration, insignificant fresh water outflow through the inlet, shallow depths at the entrance and others. Because no thorough field or laboratory investigations involving so many parameters have been carried out, we do not, at the present time, have engineering criteria for stable inlet design against storm closure.

It should be noted that the phenomena associated with long-term stability and short-term stability, or closure, clearly overlap to some extent, and that the distinction is, to an extent, a matter of convenience only. Clearly, the onshore-offshore sediment motion as well as the frequency of storm occurance have a role in characterizing long-term stability. It is however reasonable to use such time-average parameters as the annual mean wave power, rate of littoral drift, tidal characteristics and prism in defining long-term stability. On the other hand, any criterion on closure must involve the intensity and duration of the storm.

Long-term stability criteria have been proposed by O'Brien (1931), Escoffier (1940), Bruun (1966), O'Brien (1971), O'Brien and Dean (1972), Johnson (1973), Mehta (1975) and others. All these criteria assume that sufficient sand is available to alter the inlet flow cross-section in response to the hydraulic conditions. This situation ideally exists only in the case of unimproved inlets on sandy coasts (Fig. 3 (a)). When jetties are successfully constructed to cut off the natural flow of littoral drift, the sand will bypass the inlet around the tip of the jetties, through deeper depths, as shown in Fig. 3 (b). The length of the inlet is effectively increased and waves no longer penetrate as before. The throat section will respond to these changes, its area will probably increase and its position will shift, possibly seaward. The inlet is stabilized. If the jetties are ineffective, sand will enter the inlet, in which case the stability criterion may be assumed to be applicable. In Fig. 3 (c) we note that in those cases where the littoral drift is significant in both directions, even though the inlet may not migrate as in Fig. 1, it will be constricted if the sand enters from both sides as shown.

Example 1-2

Consider Sebastian Inlet on the Atlantic Coast of Florida, (Mehta and Adams, 1975). After several apparently unsuccessful attempts beginning in 1886, this inlet was finally opened in 1924, with two short jetties flanking the entrance. The inlet was shallow, and the jetties could not prevent a gradual shoaling up and eventual closure in the mid-ninteen forties. The inlet was reopened in 1948-49 with a new alignment. Jetty improvement and extensions were carried out in 1955, 1959 and 1969-70. A channel was dredged in 1962. The throat cross-section in Fig. 4 reflects the history of the inlet. A stable section appears to have been attained.

II. LONG-TERM STABILITY CRITERIA

Prism-Area Relationship

The tidal prism is the volume of water that enters the bay during flood and leaves during ebb. Following the original observation by O'Brien (1931)

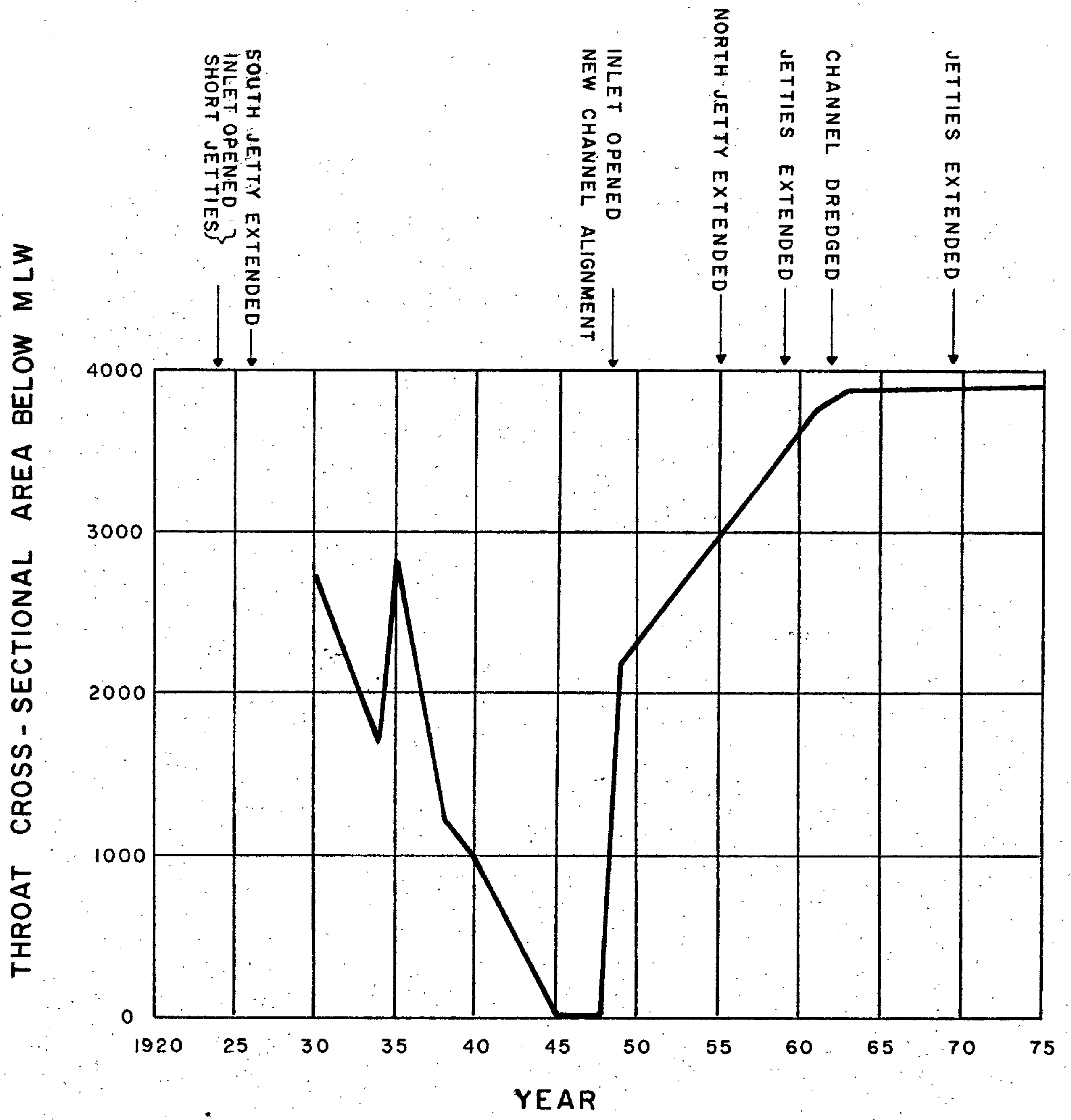

Fig. 4. History of Sebastian Inlet as Reflected by the Throat Section.

and others later, empirical relationships between the prism P_m (cubic feet) on the mean range of tide and throat cross-sectional area, A_c (square feet), below mean water level[3] may be expressed as

$$\frac{P_m}{A_c} = 5.3 \times 10^4 \text{ ft. (for unimproved inlets)} \qquad (2\text{-}1)$$

$$\frac{P_m}{A_c} = 5.0 \times 10^3 \, P_m^{0.10} \text{ (for one and two jettied inlets)} \qquad (2\text{-}2)$$

Eqs. (2-1) and (2-2) are plotted in Fig. 5. Eq. (2-2) is due to Johnson (1973). They are valid, strictly speaking, for stable inlets, i.e., those that are in non-silting, non-scouring sedimentary equilibrium. If the actual P_m/A_c at a given inlet is substantially different from the curves of Fig. 4, the following two possibilities exist:

1. P_m/A_c is much smaller. This is the case of an inlet in which the throat section is larger than the equilibrium size, and therefore the inlet will contract until equilibrium is established according to Eq. (2-1) or (2-2). Example - a newly cut inlet.
2. P_m/A_c is much larger. In this case A_c is too small. The inlet in this case could go either way, i.e., expand until equilibrium is attained, or contract further until a probable closure. To determine which of these two courses the inlet will follow, the following computations must be made.

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[3] Add the product of surface width times one-half the mean tide range in the inlet or vicinity, to convert cross-section below mean low water to mean water level.

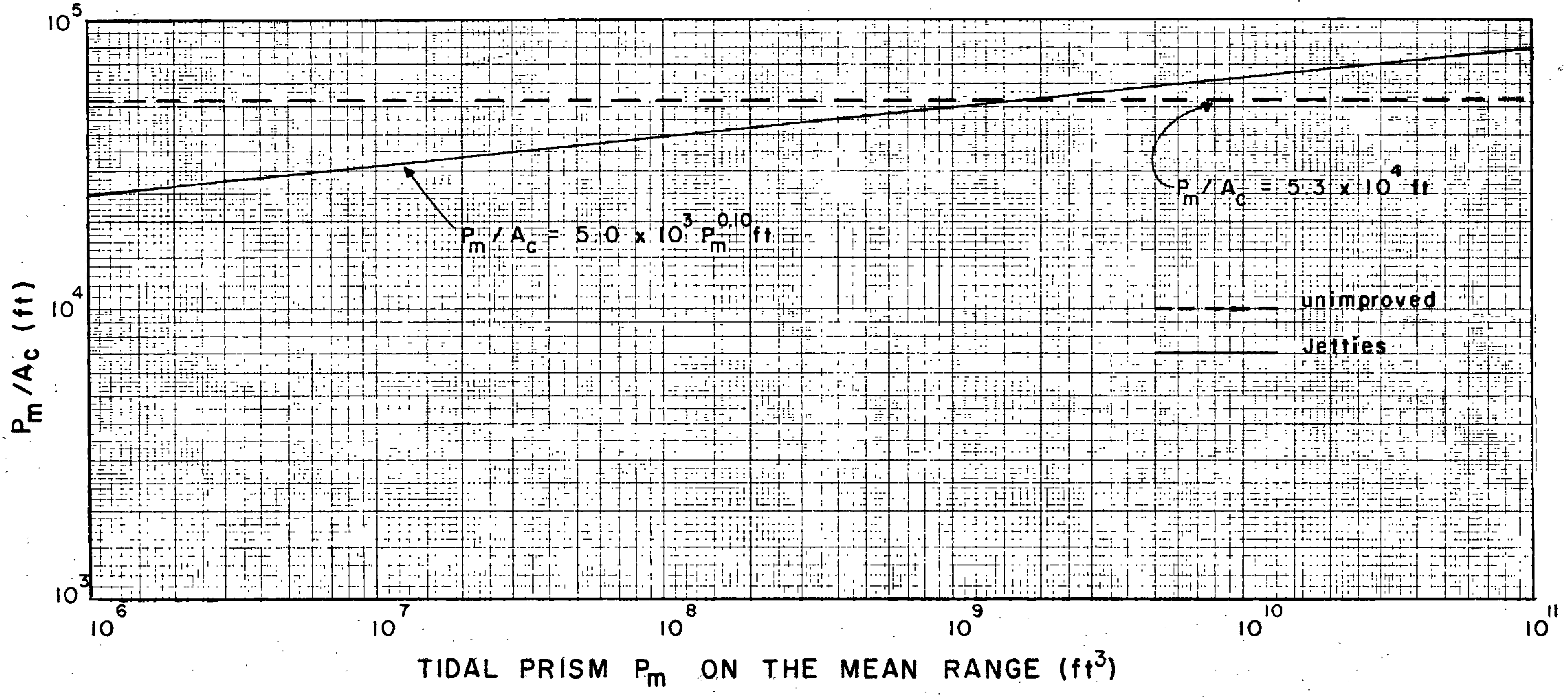


Fig. 5. Prism-Area Relationships for Inlets in Sedimentary Equilibrium.

Critical Cross-sectional Area

Escoffier (1940), and later Dean (1971a) and O'Brien and Dean (1972) noted that the hydraulics of an inlet-bay system determines a critical throat cross-section, A_c^*, given the inlet-bay geometry, ocean tide characteristics and head losses in the inlet. If the actual $A_c > A_c^*$, the inlet is stable, and if $A_c < A_c^*$, the inlet will be unstable.

Under the assumption that the flow through the inlet results from the head difference between the ocean and the bay, and that the rise and fall of the water level in the bay is in phase, i.e., the bay water level remains horizontal at all times, a relationship is obtained (see Part I) between the maximum velocity V_{max} through throat cross-section of the inlet and the repletion coefficient K (Keulegan, 1967), defined here according to O'Brien and Clark (1973) as,

$$K = \frac{T}{2\pi a_o} \frac{A_c}{A_B} \sqrt{\frac{2ga_o}{F}} \qquad (2\text{-}3)$$

where

T = tidal period,
$2a_o$ = ocean tide range,
A_c = throat cross-sectional area below mean water level,
F = impedance.

The impedance F reflects a summation of all the head losses through the inlet. F may be obtained from

$$F = 1 + \frac{fL_c}{4R_c} \qquad (2\text{-}4)$$

Here,

f = Darcy-Weisbach friction factor,

R_c = hydraulic radius at the throat,

L_c = equivalent channel length, as defined in Part I.

In Fig. 6, Keulegan's solution of the dimensionless maximum velocity, V'_{max}, where,

$$V'_{max} = \frac{T}{2\pi a_o} \frac{A_c}{A_B} V_{max} \tag{2-5}$$

as a function of the repletion coefficient K is presented. The application of this curve for determining a critical throat cross-section will be illustrated by an example.

Example 2-1

Consider the case of a pilot channel which is being excavated across a barrier island to a bay of particular size. Assume the following values of the relevant parameters (Dean, 1971a):

$2a_o$ = 3.0 ft.

A_B = 10^8 ft^2.

f = 0.03 (a reasonable value)

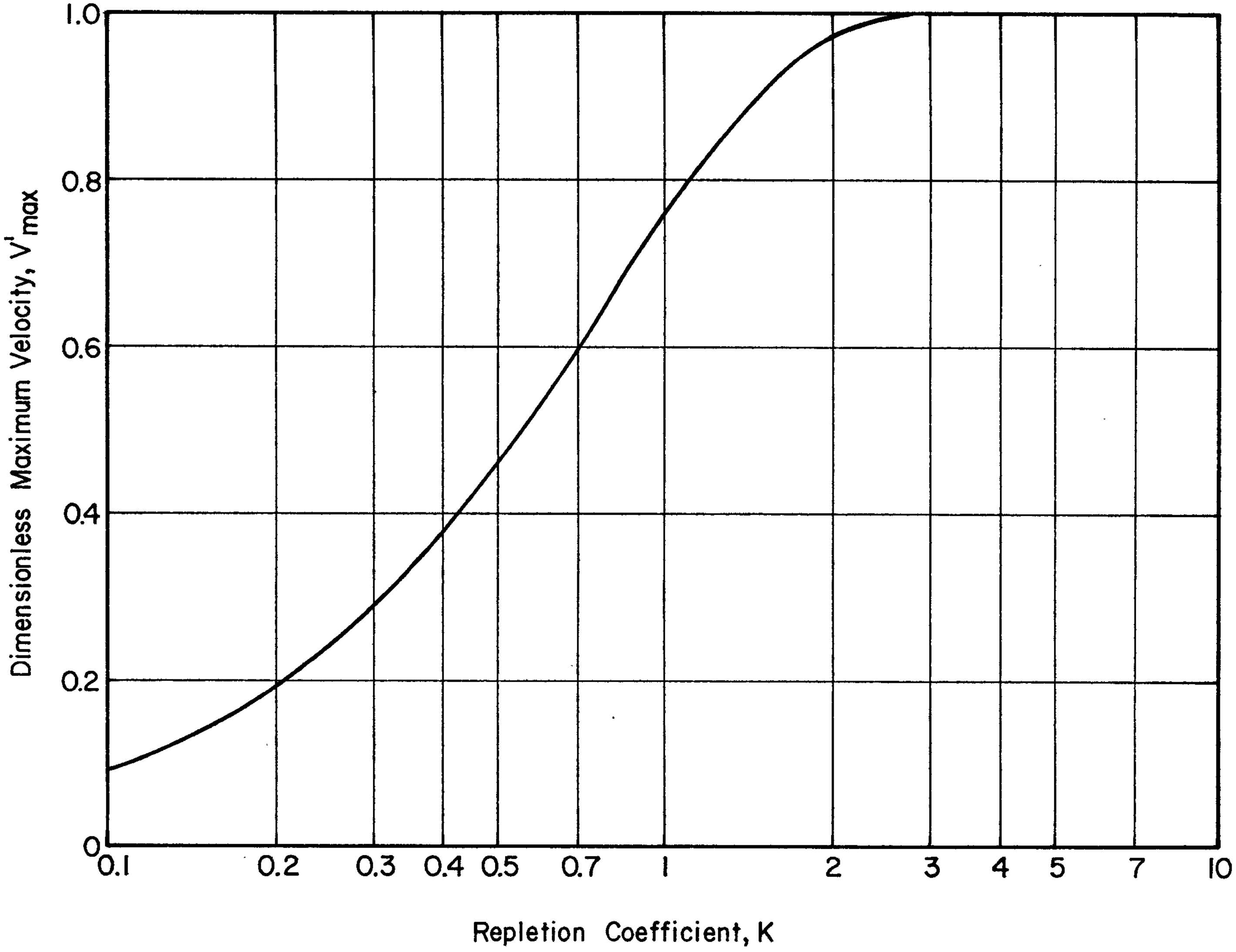
L_c = 2500 ft. (equal to barrier width)

$$W_c = A_c/R_c = 20\ R_c \tag{2-6}$$

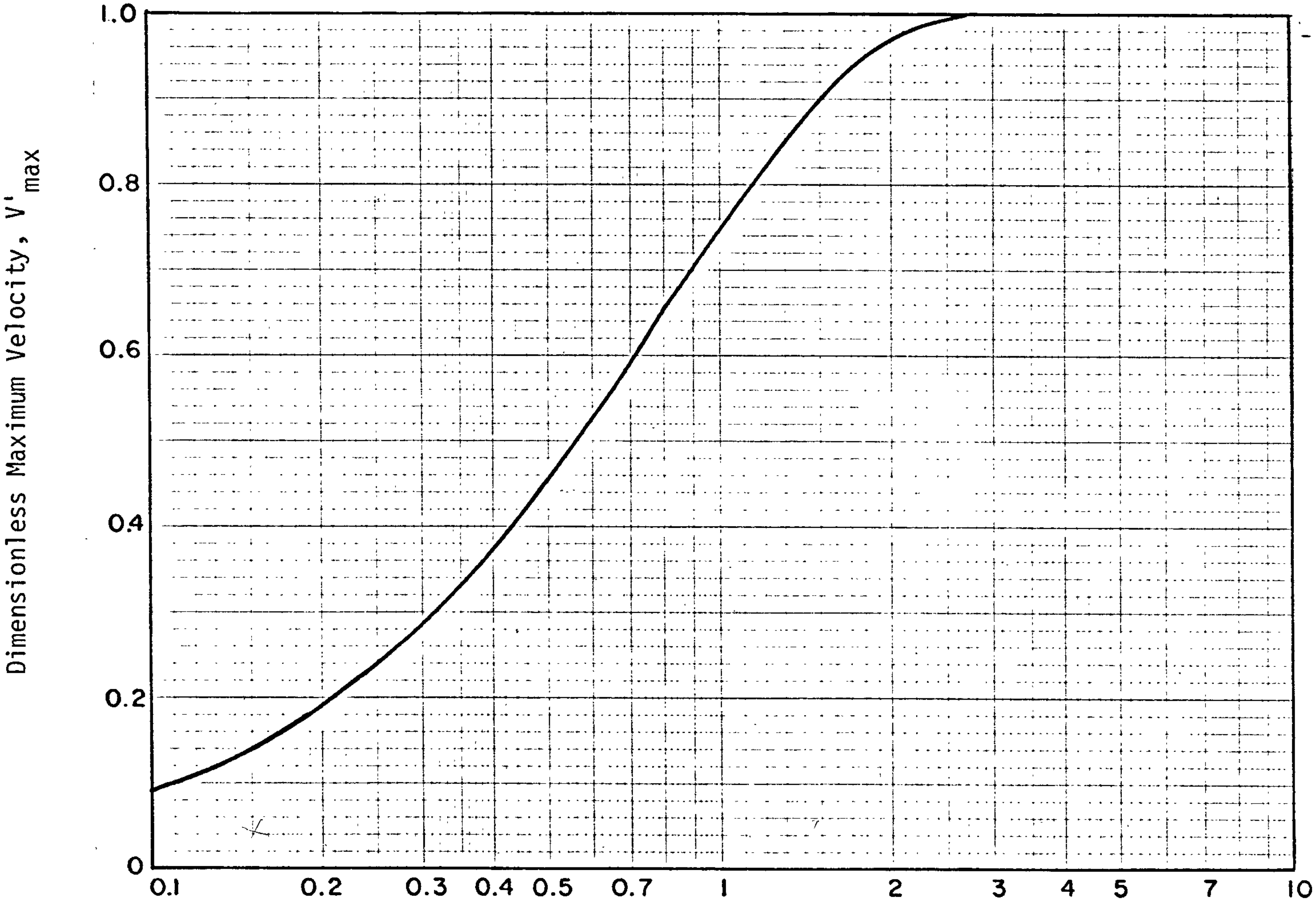
T = 44640 sec.

where W_c is the width at the throat of this wide channel and is assumed to be twenty times the hydraulic radius. This yields,

$$K = \frac{4.66 \times 10^{-4} A_c}{\sqrt{1 + \frac{83.85}{\sqrt{A_c}}}} \tag{2-7}$$



1.0
0.8
0.6
0.4
0.2
0
Dimensionless Maximum Velocity, V'_{max}
0.1
0.2
0.3
0.4
0.5
0.7
1
2
3
4
5
7
10
Repletion Coefficient, K



Repletion Coefficient, K

Fig. 6. Dimensionless Maximum Velocity, V'_{max}, as a Function of Keulegans Repletion Coefficient.

For a range of A_c values, Eq. (2-7) gives the corresponding K, Fig. 5 yields V'_{max} and Eq. (2-5) gives V_{max}. Fig. 7 shows the plot of V_{max} versus A_c. The value of A_c (= 2000 ft^2) at the peak V_{max} of 5 ft/sec is defined as A_c^*. For any $A_c > A_c^*$, a reduction ΔA_c in A_c due to sand deposition will increase the maximum velocity V_{max} by ΔV_{max}, thus increasing the scouring capability of the flow and therefore the deposited sand will be flushed out. Likewise, any increase ΔA_c will result in a reduction ΔV_c in the velocity, thus aiding in the shoaling of the throat, until the throat-section returns to A_c. This is the case of a stable inlet. For any $A_c < A_c^*$, a reduction ΔA_c will mean a corresponding reduction ΔV_{max} and will enhance the possibility of further sand deposition. Thus the inlet in this case is unstable.

In the case of a stable inlet, the actual value of A_c is determined by the sedimentary equilibrium relationship, i.e., Eq. (2-1) or (2-2).

Assume that this example is one of an unimproved inlet. Note that the tidal prism P_m may be expressed as (See Part I):

$$P_m = \frac{V_{max} A_c \; T}{\pi C_K} \tag{2-8}$$

where $C_K = 0.86$. Combining Eq. (2-8) with (2-1) gives,

$$V_{max} = \frac{5.3 \times 10^4 \; \pi C_K}{T} \tag{2-9}$$

which gives

$$V_{max} = 3.21 \text{ ft/sec} \tag{2-10}$$

This value of V_{max} occurs along the stable part of the curve of Fig. 6 at A_c = 7000 ft^2, which is the hydraulically stable throat cross-section under

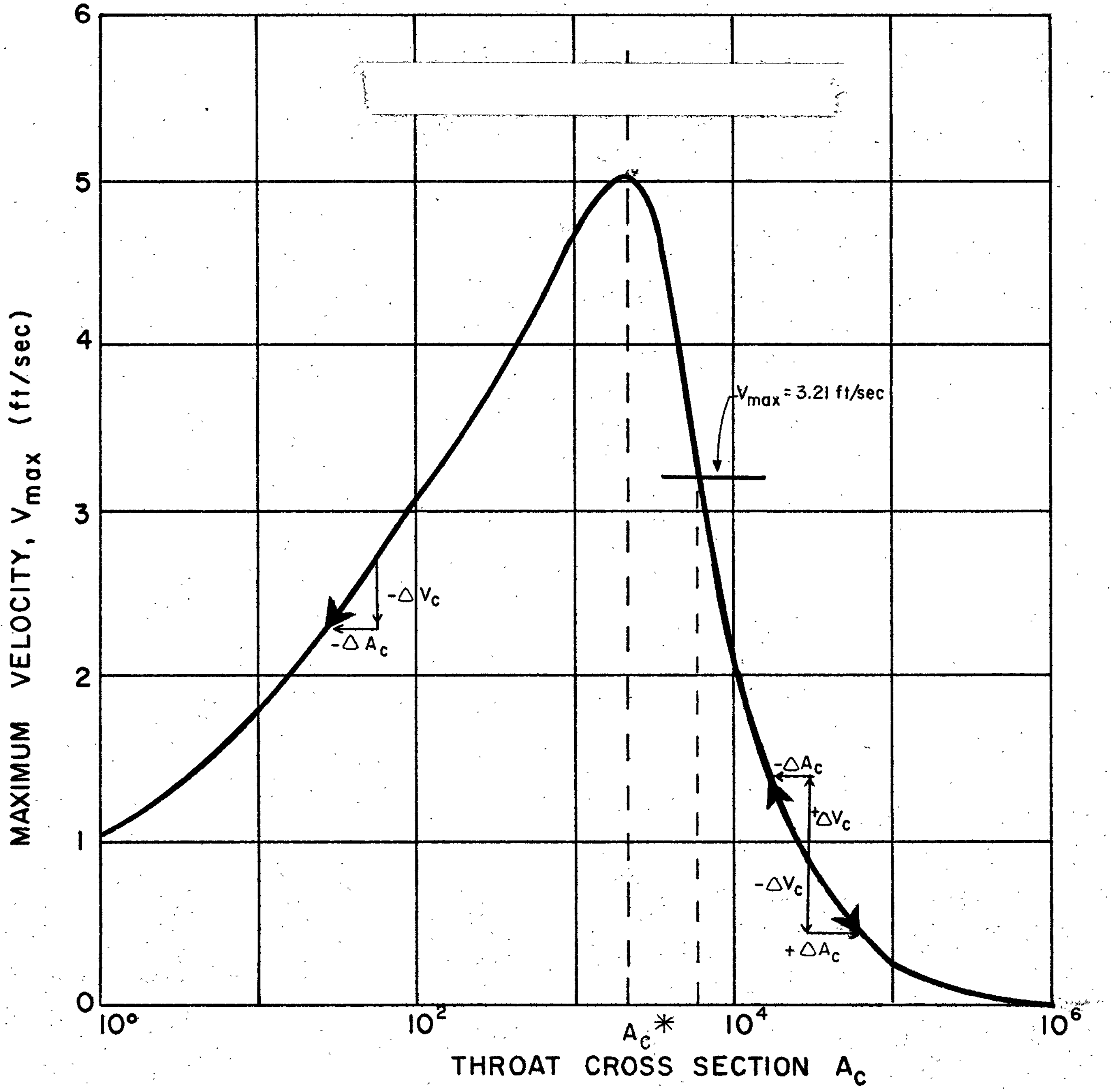


Fig. 7. Relationship between V_{max} and A_c; Determination of Critical Cross-section.

sedimentary equilibrium.

Note that if the cross-section of the new pilot channel is between 2000 and 7000 ft^2, sedimentary equilibrium requirement will cause the channel to enlarge to 7000 ft^2. Likewise, an initial cut larger than 7000 ft^2 will contract to that value. If however, the initial cut is less than 2000 ft^2, it will be hydraulically unstable, and therefore will contract indefinitely.[4]

A Semi-empirical Approach

One of the limitations of the hydraulic computations described above is that they do not explicitly involve the effect of wave intensity on stability. Clearly, high energy waves generate more littoral drift, which in turn will cause greater stability problems for an inlet (Bruun, 1966; O'Brien, 1971; Johnson, 1973). Recognizing the opposing roles of the waves and of tidal flow through the inlet in establishing the long-term stability regime, the following dimensionless coefficient M has been introduced as a stability criterion (Mehta, 1975),

$$M = \frac{P_a T}{2\gamma A_c W} \tag{2-11}$$

where

P_a = annual average longshore wave power,

γ = unit weight of ocean water (64 lbs/ft^3).

and

$$W = \int_0^{T/2} V_c S \, dt \tag{2-12}$$

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[4] Dean (1971b) and Mehta and Brooks (1973) have applied the method described in this section to long lagoons with three inlets.

where

t = time,

V_c = velocity at the throat,

S = slope of the energy grade line in the inlet of cross-section A_c and hydraulic radius R_c.

The numerator of Eq. (2-11) is the longshore wave energy over the tidal period per unit length of the shoreline. The denomenator is the flow energy over a tidal cycle, per unit length of the inlet. Note that $\gamma V_c A_c S$ is the power per unit length available in the flow in the channel. We assume a sinusoidal variation of V_c

$$V_c = V_{max} \sin \sigma t \tag{2-13}$$

where $\sigma = 2\pi/T$. S is related to the Chezy discharge coeffieicnt C through

$$S = \frac{V_c^2}{C^2 R_c} \tag{2-14}$$

Substitution of Eqs. (2-13) and (2-14) into (2-12), integration, and finally, elimination of V_{max} using Eq. (2-8) leads to

$$W = 4.2 \frac{P_m^{\ 3}}{C^2 R_c T^2 A_c^{\ 3}} \tag{2-15}$$

Eq. (2-15) defines W for computing M in Eq. (2-11). The Chezy coefficient C may be obtained from Fig. 9 of Part I. The straight line shown there may be expressed as,

$$\log C = 1.40 + 4 \times 10^{-4}\, L_s/R_c \tag{2-16}$$

Where L_s has been defined in Fig. 10 of Part I as the distance between the outer bar and the junction of the channel near the inner shoal.

The longshore wave power P_a is related to the rate of littoral drift Q_L according to

$$P_a = 0.48\ Q_L \tag{2-17}$$

where P_a is in foot-pound per foot per hour and Q_L is in cubic yards per year. In view of the possibility of sand entering the inlet from both sides, as shown in Fig. 3 (c), P_a should be based on the "gross" rate of drift, i.e., the sum of the drift from the left and from the right.

Mehta (1975) has computed M for a number of inlets and has defined regions of good, intermediate and poor long-term stability in a plot of M versus P_m, by classifying known stability condition of each of the inlets into these three catagories. The stability regions are indicated in Fig. 9.

Example 2-2

Consider John's Pass and Blind Pass, Florida, both of which connect north Boca Ciega Bay to the Gulf of Mexico (Mehta and Adams, 1975). In the past approximately 100 years, John's Pass has widened and is a stable inlet at the present time. Blind Pass, on the other hand, has contracted and has poor stability. This change has been brought about, to a great extent, by the reduction in the surface area of north Boca Ciega Bay due to the construction of dredge fill islands, some of which are particularly close to Blind Pass. Fig. 8 shows this reduction. Throat characteristics of the two inlets are given below.

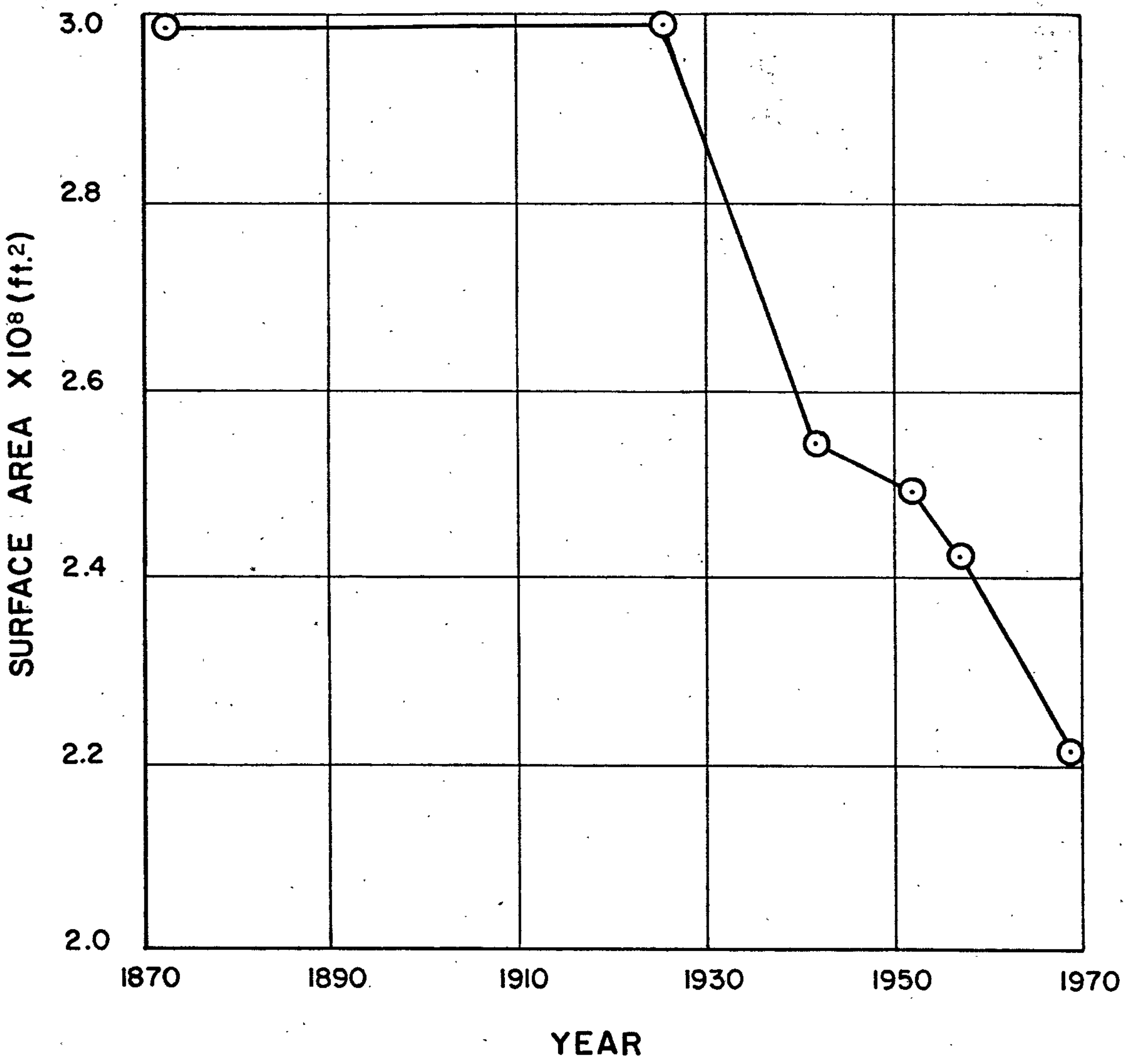

Fig. 8. Reduction in North Boca Ciega Bay Area (after Mehta and Adams, 1975).

Year	John's Pass A_c (ft^2)	 W_c (ft)	Year	Blind Pass A_c (ft^2)	 W_c (ft)
1873	5100	425	1873	5790	510
1883	4640	370	1883	5340	540
1926	5720	445	1926	2250	355
1941	6850	510	1936	2420	510
1952	9140	600	1952	1690	195
1974	9500	590	1974	440	85

We will assume here that the ratio P_m/A_c obtained from recent measurements is applicable at all times in the past. The Chezy coefficient C will be assumed to be constant and equal to values obtained from recent measurements. The annual average longshore wave power P_a has been derived from handcast wave statistics, and will also be assumed to be the same over the years. The tidal period T = 12 hours will be assumed. Numerical values of the parameters for the two inlets are as follows:

Parameter	John's Pass	Blind Pass
P_m/A_c (ft)	3.79×10^4	4.98×10^4
A_c (ft^2)	variable	variable
P_a (ft-lb/ft/hr)	1.04×10^5	1.04×10^5
T (hr)	12	12
$R_c = W_c/A_c$ (ft)	variable	variable
C ($ft^{1/2}$/sec)	32	37
γ (lb/ft^3)	64	64

The prism P_m is obtained by multiplying P_m/A_c by the A_c at the given year. M values are computed through Eqs. (2-15) and (2-11).

Year	John's Pass		Year	Blind Pass	
	P_m (ft^3)	M		P_m (ft^3)	M
1873	1.93×10^8	0.19	1873	2.88×10^8	0.094
1883	1.76×10^8	0.22	1883	2.67×10^8	0.089
1926	2.17×10^8	0.18	1926	1.12×10^8	0.14
1941	2.60×10^8	0.16	1936	1.21×10^8	0.094
1952	3.46×10^8	0.14	1952	8.42×10^7	0.25
1974	3.60×10^8	0.14	1974	2.19×10^7	0.58

M versus P_m from the above table are plotted in Fig. 9. The trajectory of the data for John's Pass shows that in the 100 year period covered, this inlet has improved its stability, moving from a state of intermediate to good stability during 1880's. Conversely, Blind Pass, which was a stable inlet up until the early 1920's became rapidly unstable from then on, in direct response to dredge fill operations near its bayward end, as indicated by the overall reduction in the bay area in Fig. 8.

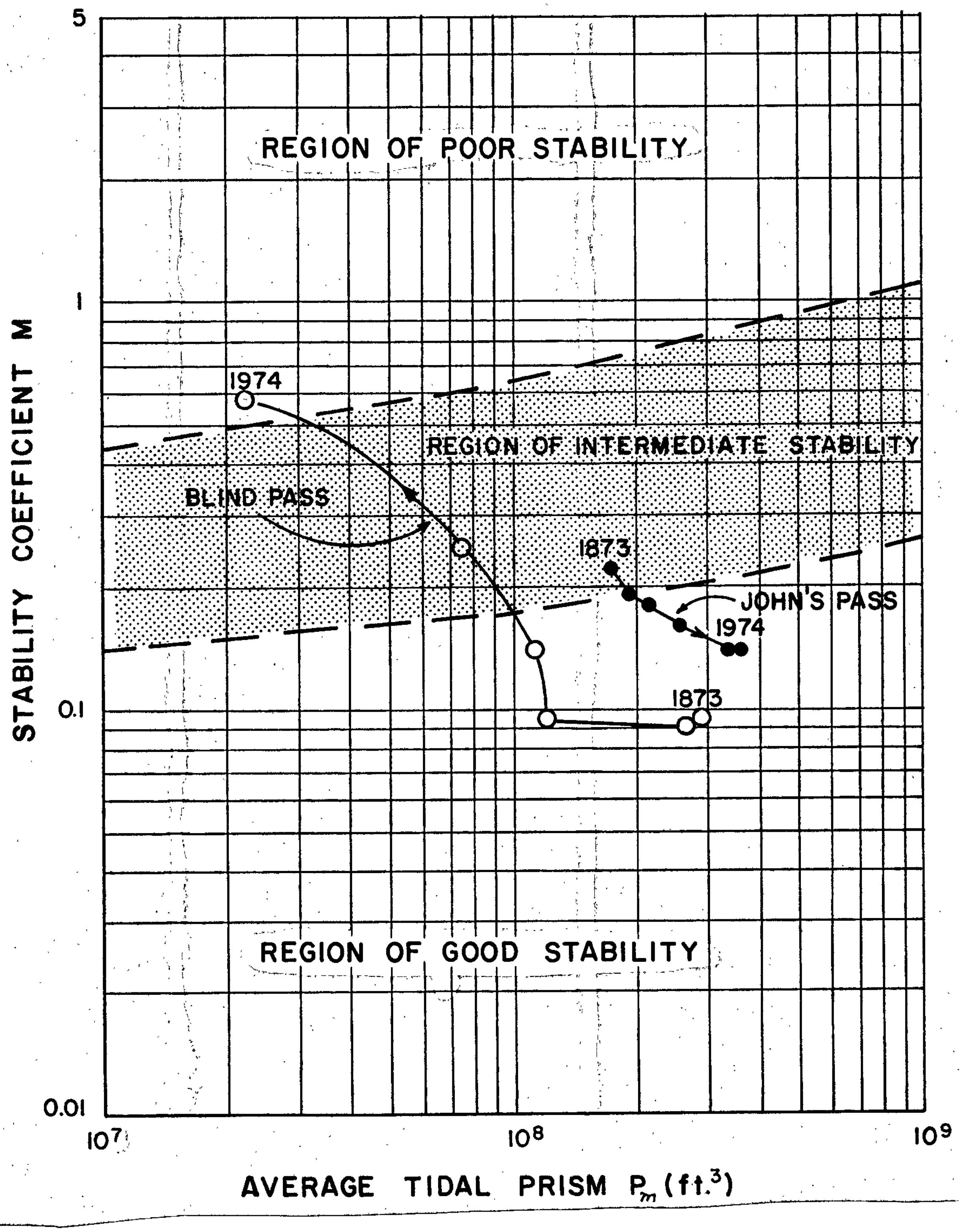

Fig. 9. Historical Stability Progression of John's Pass and Blind Pass (after Mehta and Adams, 1975).

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