

CHAPTER 150

COMMENTS ON TIDAL ENTRANCES ON SANDY COASTS

by

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FLOW AREA-TIDAL PRISM

The information necessary for computation of the tidal prism is available in charts and tide tables for many inlet-bay systems. Empirical correlations have been developed by Le Conte in 1905, O'Brien in 1931 and 1969, and others, which showed the flow area to be a unique function of the tidal prism for the sets of data studied. However, the data underlying these correlations were derived from inlets with semi-diurnal tides, typical of the Atlantic and Pacific Coasts of the United States. Jarrett in 1976 showed that such correlations are not valid for diurnal and mixed tides, such as occur along the Gulf Coast.

Stevenson in 1874 pointed out that the scouring capacity of the tide must include the number of tidal cycles per year. Since the number of tidal cycles in any period of time is inversely proportional to their duration, the integrated scouring capacity of the tidal flow through an inlet channel should be independent of the duration of the tidal cycle and should depend primarily on the tidal discharge. If the maximum rate of tidal discharge (Q_{\max}) and the variation of discharge throughout the tidal cycle are identical for two inlets subjected to tidal cycles of different duration, the scouring capacity of the two inlets would be the same over equal periods of time. The conclusion is that Q_{\max} should provide a more generally valid basis for correlation with the flow area than does the tidal prism alone and one which may be valid at hydraulic model scale and for inlets maintained by the seiching of nontidal lakes, as at Duluth. Bruum (1978) used the correlation of the flow area with Q_{\max} in his studies.

Keulegan's (1951) analysis of inlet flow yielded the relationship

$$Q_{\max} = \pi CP/T \quad (1)$$

Here, C is a coefficient which ranges from 0.81 to 1.0, with 0.86 as a generally applicable value. The minimum flow area A_C should be correlated with either Q_{\max} or (P/T) to be applicable to diurnal, semi-diurnal, and mixed tides and to periodic flows in general.

If the maximum rate of discharge to be correlated with the flow area has been measured directly, rather than derived from the tidal prism through Eq. 1, this value must be corrected to that which would occur on a standard range of tide. This correction will require, in

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effect, the establishment of a rating curve, or discharge coefficient for the inlet. Furthermore, the corrected maximum rates of discharge on flood and ebb are seldom equal and a choice must be made as to which phase is generally more effective in maintaining the flow area. The first correlations were based on Pacific Coast data where the tide shows a diurnal inequality, with the "long-runout" following higher high water and the diurnal range, and the related strong ebb current was selected for the correlation. This characteristic is not found in Atlantic and Gulf coast tides and, for these inlets, the spring range has usually replaced the diurnal range. Although the ratio of the spring range to the mean range is numerically about equal to that of the diurnal range, the hydraulic effects may be very different, since ebb may not be dominant over flood at the time of the spring range. In future studies of the correlation between tidal discharge and flow area, use of the mean tidal range would probably be more significant. The generalized correlation between tidal flow and flow area might be

$$A_c = f(Q_{\max}) \text{ or } f\left(\frac{\pi CP}{T}\right) \quad (2)$$

depending upon whether the measured flow or the or the tidal prism, from charts and tide gages, is the source of data.

HYDRAULIC CHARACTERISTICS

Brown-Keulegan Analysis - Brown (1928) analyzed the flow through a tidal inlet on the basis of the following simplifying assumptions:

- The tidal variations in both ocean and bay are sinusoidal.
- The flow area of the inlet channel (below MSL) is constant (prismatic) from ocean to bay.
- The surface area of the bay does not vary with the tide stage in the bay.
- The surface of the bay remains horizontal throughout the tidal cycle.
- The depth of the inlet channel is large as compared with the range of tide.
- The difference in head necessary to accelerate the mass of water in the inlet channel is neglected.
- There is no surface runoff into the bay.

These assumptions are repeated here to emphasize the degree to which Brown's inlet-bay system was idealized; the configurations of almost all real inlets differ markedly from these assumptions.

Keulegan (1951) recognized that a sinusoidal tide in the ocean would not produce a sinusoidal tide in the bay because the flow through the inlet channel is proportional to the square root of the difference in head; otherwise, he made the same assumptions as Brown. He found

that the ratio of the tide in the bay to that in the ocean, the lag of slack water in the inlet channel after HW or LW in the ocean, and the maximum velocity in the inlet channel could be represented as functions of a dimensionless quantity which he designated as the repletion coefficient,

$$K = \frac{T}{2\pi a_0} \frac{A_C}{A_B} \sqrt{\frac{2ga_0}{F}} \quad (3)$$

The quantities in Eq. 3 are the major variables affecting inlet flow. This coefficient provides a useful means of ordering and analyzing inlet flow data, even though it is based on highly idealized assumptions. Keulegan compared his results with those of Brown in the high range of K-values, where the difference should be greatest, and found that Brown's method yielded values of maximum velocity between 10 and 15 percent greater than did his method. Probable errors in the data usually available are of the same magnitude as the difference between the relationships developed by Brown and Keulegan and Brown's method is much simpler in application. Following Brown, assume that the tidal fluctuations in the bay are sinusoidal. High water in the bay occurs at slack water in the inlet channel; the amplitude of the bay oscillation (a_b) is related to the ocean amplitude (a_0) and the lag of slack water after HW or LW in the ocean (ϵ , deg) as

$$a_b = a_0 \cos \epsilon \quad (4)$$

If the flow conditions in the inlet are as assumed, the difference, Δ , defined as

$$\Delta = \frac{a_b}{a_0} - \cos \epsilon \quad (5)$$

should be zero. When Δ is plotted as a function of inlet size, small inlets show a random scatter about the zero line but, with increasing size of inlet, the values of Δ become increasingly positive. Refinement of the value of Δ by using the more precise method of Keulegan plus corrections for the effects of variations in the flow area and the bay area with tide stand and of the inertia of the mass of water in the inlet channel would probably reduce the scatter of points somewhat but would not explain the systematic increase of Δ for large entrances. The entrances included in this study show fairly good agreement with the flow area-tidal prism correlation.

The explanation of the increasing value of Δ with size of inlet is believed to be that the flow through the inlet channel is not wholly of the "hydraulic" type assumed but is, in some degree, that of a long wave. A good illustration of this difference is the flow at the mouth of the St. Johns River (Florida) where the value of Δ is approximately 0.95; the strength of flood very nearly coincides with HW and the strength of ebb with LW; the lag of slack water is 92° and the ratio of the ranges, a_b/a_0 is 0.90. This entrance leads into a river channel leaving substantially constant average depth and width; the characteristics of the flow are those of a long wave in shallow water.

Considering tidal entrances of increasing width, the depth does, in general, not increase in proportion to the width, and it seems reasonable that the tide should enter large entrances primarily as a wave. If this is the case, the average velocity in the channel should follow approximately the equation

$$u = a_0 \left(\frac{g}{h} \right)^{1/2} \quad (6)$$

Comparing Eq. 6 with the average of flood and ebb currents reported in the Current Tables for a few representative entrances:

	Mean Ocean Range (ft)	Mean Inlet Range (ft)	Lag Slack Water (deg)	Average Depth (ft)	u_w (ft/sec)	From Tables
Narrows	4.5	4.5	64	61	3.3	3.1
Delaware	4.4	4.1	44	38	2.0	3.1
Chesapeake	3.5	2.9	116	25	2.0	2.1
Port Royal	6.4	6.4	51	40	2.9	3.0
St. Johns R.	5.4	4.9	92	31	2.7	3.5
San Francisco	4.2	4.0	56	176	0.9	5.3

The ocean range shown in this table is the range on the outer coast remote from the entrance; the range at "inlet" is that at the station at or inside the throat. At San Francisco, the throat section (Golden Gate) is bounded by rock and the width there is small in proportion to the depth.

If the calculation of the lag angle and of the ratio of ranges is refined by considering the effects of inertia, flow area, bay surface area and surface runoff, the positive value of Δ may be an indicator of the extent to which the flow through the inlet channel is "hydraulic," as assumed by Brown and Keulegan, or "long wave."

Corrections for the effects of deviations from the simplifying assumptions of Brown and Keulegan have been studied by Oliveira (1970), King and Shemdin (1974), Seelig and Sorensen (1978), Mehta and Ozsoy (1978), Escoffier and Walton (1979), and others.

Other useful approximate relationships, derived on the assumption that the tide in the bay is sinusoidal, are that the maximum head difference between ocean and bay and the maximum channel velocity

$$h_{\max} = 2a_0 \sin \epsilon \quad (7)$$

$$V_{\max} = \left(\frac{2ga_0 \sin \epsilon}{F} \right)^{1/2} \quad (8)$$

Equation 8 is a convenient means of determining the impedance of an entrance because a_0 , ϵ , and V_{\max} can be obtained for many entrances

from the tide and current tables. If ϵ and V_{\max} are not available, they may be measured at the throat section with little difficulty.

O'Brien and Clark (1973) used Eq. 8 to compute the value of the impedance (F) for a number of inlet channels having simple geometry and to determine the value of the friction coefficient (f) and the Manning roughness coefficient (n) from

$$F = 1 + \frac{fLc}{4Rc} \quad (9)$$

$$n = 1.48 Rc^{1/6} \left(\frac{f}{8g} \right)^{1/2} \quad (10)$$

Entrances	Lc(H)	Rc(H)	F	f	n
Fire Island	33,100	13.8	16	0.025	0.022
E. Rockaway	11,100	13.7	10.5	0.047	0.022
Indian River	4,200	10.6	15.3	0.143	0.051
St. Marys	15,200	32.8	7.6	0.057	0.039
Lake Worth	1,900	20.9	5.9	0.220	0.071
Humboldt B.	2,690	17.9	5.1	0.110	0.049
San Diego	18,860	40.9	6.7	0.049	0.038

Keulegan measured the friction loss in the relatively uniform inlet channel at Indian River between the ocean and the seaward side of the bridge; his value of n was 0.046. The value in the table included the head loss through the bridge piers. No direct measurements were available for comparison with the other figures in the table, but the close agreement for Indian River lends credence to the other values.

STABILITY OF INLETS

Escoffier (1940) treated the stability of an inlet from the purely hydraulic standpoint by assuming progressive changes in the flow area and hydraulic radius and computing the corresponding maximum tidal velocity during a tidal cycle. He showed that there is a critical flow area at which the maximum tidal velocity is greatest and concluded that, at larger areas, the inlet will be stable because a decrease in area will cause increases in the maximum velocity and in the scouring capacity. Conversely, at areas less than the critical area, an inlet will be unstable because a decrease in area will cause a decrease in velocity. O'Brien and Dean (1972) modified this approach by making assumptions regarding the manner in which sediment encroachment would change the effective length as well as the flow area and hydraulic radius. Their results also showed a critical flow area and maximum tidal velocity with implications regarding stability similar to those of Escoffier.

Bruun (1978) treats inlet stability in terms of the balance between the scouring capacity of the tidal flow, represented by

Q_{\max} , and the magnitude of the littoral transport. This approach, which is believed to be basically sound, considers the two major factors affecting inlet stability, but its quantitative application is limited by the uncertainty over the magnitude of the littoral transport at many inlets, especially regarding the local sand movement under storm wave intensity. Oliveira (1970) broadened the Brown-Keulegan analysis of inlet flow by including the effects of varying both flow area and lagoon surface area during the tidal cycle and computed the scouring capacity of the tidal currents; he showed that the bed load capacity reached a maximum value when the Keulegan coefficient of repletion was within the range $0.6 < K < 0.8$. His other results of significance were that the duration of the ebb phase exceed the flood and that the mean level in the bay was above that in the ocean.

Consider first an inlet-bay system which fulfills the Brown-Keulegan assumptions. The maximum hydraulic power available for scouring the channel occurs when the head and the related rate of discharge are at their maximum values; the maximum head available is a function of the phase difference between the ocean and bay tides.

$$P_{\max} = w Q_{\max} h_{\max} \text{ (Max. Power)}$$

$$Q_{\max} = \frac{\pi C P}{T}; \quad P = 2 a_b A_B$$

$$a_b = a_o \sin \epsilon; \quad h_{\max} = 2a_o \cos \epsilon$$

$$P_{\max} = \frac{4w\pi C}{T} A_B a_o^2 \sin \epsilon \cos \epsilon \quad (11)$$

Consequently, the maximum hydraulic power would be available in the inlet channel under the idealized conditions assumed if the lag angle ϵ is 45° , corresponding to $K \cong 0.63$. The total energy available on either the flood or ebb phases would be

$$E = \frac{8}{\pi} \cdot A_B a_o^2 \cos \epsilon \sin \epsilon \quad (12)$$

Again, the maximum value corresponds to $\epsilon = 45^\circ$ and $K \cong 0.63$.

These relationships are pertinent to the analysis of the stability of an inlet because the energy available will increase or decrease as changes in the geometry or the hydraulic characteristics change the value of K . If $K > 0.64$, a decrease in K would cause an increase in the energy available for scouring the channel; such a decrease might be caused by a choking down of A_b , or an increase in F , or both. Conversely, if $K < 0.64$, a decrease in K will bring a decrease in the energy available, which may then lead to a further decrease in the value of K .

The obvious disparity between the simplifying assumptions made by Brown and Keulegan and the configuration of real inlet-bay systems and between their theoretical results and field measurements has led to studies of the effects of deviations from the assumed conditions, as

mentioned earlier, and it is now possible to correct, at least approximately, for such effects as are caused by variations in the surface area of the bay, the inertia of the mass of water in the inlet channel and so forth. The coefficient of repletion

$$K = \frac{T}{2\pi a_0} \frac{A_C}{A_B} \sqrt{\frac{2ga_0}{F}} \quad (13)$$

includes the major variables affecting the hydraulics of an inlet-bay system, and it appears to be the most illuminating single descriptor of such systems. Of the variables entering K, the impedance, F, is usually that one most in question; its value may be determined, at least approximately, by methods described earlier.

The coefficient of repletion should be regarded as one of a number of dimensionless parameters which may be used to describe quantitatively real inlet-bay systems. Used in this sense, the quantitative relationships between K and the magnitude and occurrence of maximum energy and other variables will probably be altered to some degree by the interaction with the other parameters. As mentioned earlier, Oliveira (1970) employed a numerical model to determine the effect of systematic variations of the flow area and the surface area on the scouring capacity at the throat and found that this capacity had a maximum value in the range $0.6 < K < 0.8$ for the conditions he considered, indicating that the maximum for real inlets may not lie far from that of the idealized models of Brown and Kuelegan.

It should be emphasized that this discussion has dealt only with the energy available for maintaining an inlet channel. The effectiveness of this energy in doing so will depend upon the initial configuration and hydraulic conditions and on the character of the changes which occur subsequently. A large value of the coefficient of repletion should signify a strong capability for maintaining a stable channel and a low value, the reverse; corrections for the effect of variations in flow area, inertia and other effects will improve the accuracy in predicting the actual value of K at which the energy would be a maximum. Such calculations require, however, assumptions regarding changes in the configuration or the hydraulic conditions which would induce a change in K; the uncertainty here is of the same nature as that involved in the other approaches to stability, previously discussed.

The energy considerations discussed here may shed some light on the method of formation of barrier islands and inlets. If an embayment is gradually enclosed by the growth of a sand spit, the value of the repletion coefficient would be very large initially but would decrease as the spit continued to grow and to reduce the flow area; this process would increase the energy available for scouring the opening and presumably this process would continue until the tidal discharge becomes capable of sweeping away the littoral transport and establishing an equilibrium condition. However, the maximum energy potentially available for maintaining an inlet might not be sufficient to balance the littoral transport, in which case the spit would continue to grow and gradually close

the opening, passing through a condition of marked instability before closure. On the other hand, if the barrier has been developed as a continuous ridge, such inlets as are formed in it might have any initial coefficients of repletion.

INLET CLOSURE

The final closure of natural inlets occurs primarily under storm conditions. It is also true that waves and surge from extreme storm conditions occasionally enlarge or open inlets. These notes deal with the closure of inlets by wave conditions which are abnormal relative to the local wave climate but which are not so extreme as to overwash or break through the adjacent sand spits. There are examples of inlets which have been closed under non-storm conditions by a persistent or excessive littoral transport, but these inlets were, for the most part, small artificial cuts; under such conditions of excessive transport, natural inlets are usually found to be long-since closed, leaving a fresh-water lagoon as the evidence that an inlet once existed.

An important factor in the conditions which determine whether or not an inlet will be closed is the configuration of the shore and bottom seaward of the throat; the volume of sand in offshore shoals, jetties, overlapping or offset spits, rocky headlands and other natural or artificial features in the vicinity of the channel may affect both the volume of sand movement required for closure and the rate of deposition. The variety of such conditions is almost unlimited; data on the conditions which have caused closure should be categorized under inlet configurations. These notes consider a simple inlet channel without jetties through a straight, sandy shoreline with ebb-tide outer bar and zero offset. On a segment of coast exposed to essentially the same wave climate under normal weather conditions, storms may produce substantial differences in winds, wave characteristics and surge within relatively short distances and over short time intervals. Observations on the conditions which actually caused closure are subject to considerable uncertainty and much scatter of the data is to be expected. The duration of storms is at most a few days and is the same for small and large inlets on the same segment of coast. Closure of an inlet requires time for the movement of material and the closure of a large inlet should require either a longer duration or a greater intensity of wave-induced sand movement than for the closure of a small one.

There have been a number of studies of the conditions under which inlets close. Johnson (1974), Sedwick (1975) and Mehta and Hou (1974) have proposed criteria which differ in detail but which, in essence, compare the sand-transporting capacity of the wave climate with the potential scouring capacity of the tide and have located a boundary zone between closed and open inlets by examples from the Pacific Coast, Florida and Long Island. Data on this phenomenon are not plentiful and almost none pertain to the actual conditions at the time of closure. If an inlet has been closed for some time, the data regarding tidal prism and scouring capacity consist of the surface area of the lagoon and the tide range and duration in the ocean; hydraulic analysis of the flow

conditions would be questionable, and the potential tidal prism has been used. On the other side of this boundary are the small inlets which are still open; the specific wave intensities to which they have been subjected is usually uncertain, and a representative figure has been derived from the wave climate. Apparently, there is only one example of the measurement of waves and tides during closure of a natural inlet, and that a very small one (Mehta and Hou, 1974); there is one set of laboratory tests on closure (Saville and Simmons, 1957). However, despite these limitations these studies have served to define approximately criteria which separate closed and open inlets and which clearly show an upward trend in the required wave intensity with increasing tidal prism.

The studies of closure just mentioned yielded criteria which were based upon average or representative conditions, such as the tidal prism on a mean range of tide or the annual or seasonal average wave intensity; they are not representative of the actual conditions existing at the time of closure and, consequently, they should be regarded as an indication of the vulnerability of an inlet to closure; over an extended period of time, an inlet with a value of the criterion in the "closed" region will probably close sometime, but it may not do so. The equilibrium condition of an inlet is really the statistical average of conditions which change somewhat with every change in incident waves and tide range; perhaps what is visualized as the equilibrium conditions is the bathymetry "frozen" in a survey. If the concept of equilibrium as the balance between wave-induced sand movement and tidal scour is correct, even the most stable inlets must experience continuous changes under the influence of the sequence of tidal ranges and the variations in normal wave conditions. Littoral transport along the adjacent shore moves sand toward or away from the vicinity of the inlet; waves plus flood and ebb currents bypass sand across the inlet, store it in ebb or flood shoals, or carry it to deep water. What is the nature of the changes in this regimen caused by an abrupt transition to storm conditions? The littoral transport is a function of the alongshore component of wave power per unit length of shore. The tidal currents may be altered slightly by the storm surge and consequent super elevation of the bay. The volume of sand movement onshore or offshore from the ebb shoal and bottom is probably some function of the tidal currents plus the component of wave power perpendicular to the shore, multiplied by the width of the inlet opening. Under the normal range of wave and tide conditions, sand movements balance and change is minimal but a drastic increase in wave power probably results in a strong shoreward sand movement, which is large as compared with the concurrent littoral drift. Considering the conditions existing at the time of closure, a criterion suggested is

$$M = \frac{W \cdot I_p \cdot T_F}{P_E a_b} \quad (14)$$

where:

- W = width of throat
- I_p = component of wave power perpendicular to shore per unit length
- T_F = duration of flood

a_b = range of tide in bay
 P_E = volume of the ebb tide.

This criterion is the ratio of the energy delivered by wave action during the flood phase of the tidal cycle studied to the energy available in the ebb flow of the same tidal cycle. Since the tide range and the wave intensity will vary during a storm, this criterion should be computed, if possible, for each cycle during a storm. Other quantities might be substituted, if more convenient. The concept represented is that the wave energy delivered over the width of an inlet will dominate the sand movement during a storm and will be the principal agent of closure.

Data necessary for developing a quantitative criterion of closure will be extremely difficult to obtain in nature. Hydraulic models may offer a means of establishing, at least qualitatively, the relative importance of the variables, such as the onshore component of wave power. Although surface wave models may not be distorted and this requirement leads to large models, a compensating factor is that the turbulence of breaking waves seems to permit smaller models for similarity. The experiments of Mayor-Mora (1973) and the CERC-WES program (Saville and Simmons, 1957) seems to show that movable-bed wave models of reasonable size responded to waves and currents in a manner similar, in flow characteristics, to the behavior of natural inlets.

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SYMBOLS

a_b	range of tide in bay
a_o	amplitude of the ocean tide (range = $2a_o$)
a_B	amplitude of tide in the bay
A_B	surface area of the bay
A_C	flow area at the throat below MSL
b	surface width of inlet throat at MSL
c	Keulegan coefficient to correct the tidal prism for nonsinusoidal tide in bay
E	potential tidal energy available for scouring the channel on either phase of the tide
F	impedance of the inlet channel ($= \Sigma k + f L_c/4 R_c$)
f	friction coefficient
g	gravitational force per unit mass
h	difference between surface elevations of ocean and bay
I_p	component of wave power shore normal per unit length of shore
k	coefficient of velocity head loss
K	coefficient of repletion
L_c	length of hypothetical channel of area A_C having same friction loss as real channel
M	criterion of closure
n	roughness coefficient in Manning's equation
P_{max}	maximum tidal power
P	volume of the tidal prism
P_E	volume of a particular ebb tide

Q_{\max}	the maximum rate of discharge during either phase of the tidal cycle
R_c	hydraulic radius of A_c
T	duration of the tidal cycle
T_F	duration of flood
W	width of throat
ϵ	lag of slack water after HW or LW