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Morphological and Navigational Aspects of Tidal Inlets on Littoral Drift Shores[1]

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ABSTRACT

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Tidal inlets and fjords have always been important navigational arteries because they provide natural harbors. As vessel sizes increased, depth requirements also grew and on littoral drift shores shallow bars in front of inlets became obstacles to navigation. Even if in some cases the gorge channel, the smallest section of the channel, had sufficient depth, the bar section was invariably shallower and wave action over the bar increased navigation problems. Research has long concentrated mainly on the gorge section with its simplified hydraulic conditions adaptable to the hydraulic engineers' way of thinking. This article pays attention to the overall stability with particular reference to the bar section and its combined flow and sediment conditions. Certain practical conclusions on improvements for navigation are drawn. This article also summarizes and updates the book *Stability of Tidal Inlets* (BRUUN, MEHTA, and JONSSON, 1978).

ADDITIONAL INDEX WORDS: *Alluvial (sand) coast, bed load transport, gorge channel, inlet stability, ocean bar, sediment transport, tidal inlet.*

INTRODUCTION

Most literature on tidal inlets only considers the gorge channel, defined as the cross section of minimum area. A tidal inlet on an alluvial (sand) coast, however, is not just a gorge channel. It also has an "entrance" and "bay" section with the gorge channel situated in between. In many cases shoals or bars hamper navigation; bay or lagoon shoals cause similar problems. Ocean shoals or bars are usually located seaward of the gorge, an "intermediate section" connects the gorge with the bar section.

The hydraulics of these four sections are all different due to variable exposures to wave action and current patterns. In the final analysis their behavior is seen to depend on as well as influence the sedimentary budget, transport and bathymetry. Most tidal hydraulics committees and authors (as mentioned later) have tended to concentrate solely on problems related to flow in the gorge channel. Others have focussed on jet flows at either end of the gorge section introducing such simplified assumptions that results have limited practical importance or they became very "special cases" of rare, if any, occurrence. Nevertheless, a number of practical experiments have been conducted that considered the inlet as an integrated system. The following review, which considers flow and sedimentary stability for a tidal entrance on an alluvial shore, details the overall stability of both gorge and entrance conditions. Furthermore, practical improvements in relation to basic aspects of flow and sediment transports are discussed.

GORGE CHANNEL THEORIES

An introduction to gorge channel theory was made by O'BRIEN's (1931) diagram relating cross-sections to the tidal prism. Attempts to correlate inlet flows to inlet sedimentary stabilities have, however, been few and meager. ESCOFFIER's (1940, 1972) approach represented a step forward because it correlated consequences of sedimentation with flow modes. It is, however, basically a "static" approach that concentrates solely on the gorge channel and does not include the hydrodynamic interaction between flows

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and sediment transport. Wave action is not considered in ESCOFFIER's model.

Escoffier presented a diagram in which the mean channel velocity (ordinate) was plotted against the channel cross-sectional area (abscissa) for a range of areas starting from zero. He assumed that a constant channel velocity (horizontal line) defines equilibrium conditions for the inlet, and its intersection point with the first curve defines the stable inlet area. ESCOFFIER (1972) used O'BRIEN's (1931, 1969) prism-area relationship to show that the equilibrium velocity is not constant but increases with channel area. He presented the new version of his diagram (Figure 1) as a plot of dimensionless mean velocity, Vm, versus KEULEGAN's (1950) repletion coefficient, K, to yield the inlet stability point B.

In his 1972 paper, ESCOFFIER further reasoned that an indication of the stability of an inlet is given by:

$$\lambda = Vm/Ve_{maxVm}$$

When $\lambda > 1$ no channel area could be stable for the given channel length, bay area and ocean tide. When a stable channel is possible, the degree of stability is indicated by the magnitude of λ. An evaluation of this concept using data for a series of inlets of known historic stability is needed, however, and this is difficult to obtain due to the lack of proper surveys. The theory, therefore, largely remains an attractive "philosophy."

As pointed out by BRUUN (1978) the Escoffier model has several similarities with BRUUN's (1968) approach, as seen for example, from Figure 2 by referring to the gorge channel per se. The problem with Escoffier's perfect *Hydraulic model* is that it does not consider overall stability of the inlet. Bars and shoals, which are associated with tidal inlets on littoral drift coasts, are not incorporated into the model. Furthermore, the shape of the curve (see Figure 1) may not be fully correct. As shown by BRUUN and GERRITSEN (1960) and BRUUN (1968, 1978) and confirmed by many field surveys *e.g.* MAYOR MORA (1977), NELSON (1980), RIEDEL and GOURLAY (1980), BYRNE *et al.* (1980), VAN DE KREEKE and HARING (1980) and multiple Dutch experiences (BRUUN, 1968, 1978), the Vmax is fairly close to 1 m/sec or 0.9-1.1 m/sec (Figure 2) and stays that way regardless of the size of the cross sectional area [only weak dependency was found by BRUUN (1968) of $R^{1/4}$-$R^{1/6}$ where R is hydraulic radius]. The flow for stability conditions during max flow at spring tides always seem to be in the transition phase from rippled-dune bottom to plane bottom for inlets on littoral drift shores. This fact, derived from numerous investigations, and its implications is discussed in detail by BRUUN (1967, 1968, 1978) who shows that for the particular velocity range of 1m±0.1m (3.3 ft±) the bed load transport is independent of depth — a "wise decision" by nature (Figure 3). The practical importance of this fact in relation to the handling of stability problems in inlets on littoral drift shores is pointed out subsequently.

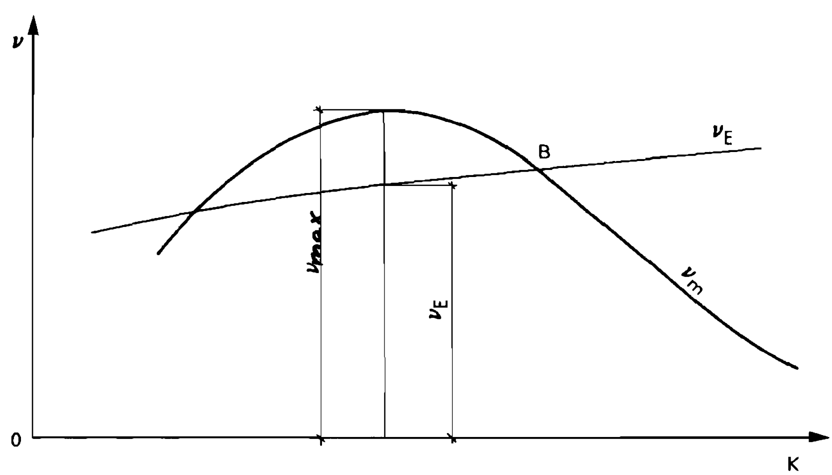

Figure 1. Escoffier Inlet Stability Diagram (from ESCOFFIER, 1972).

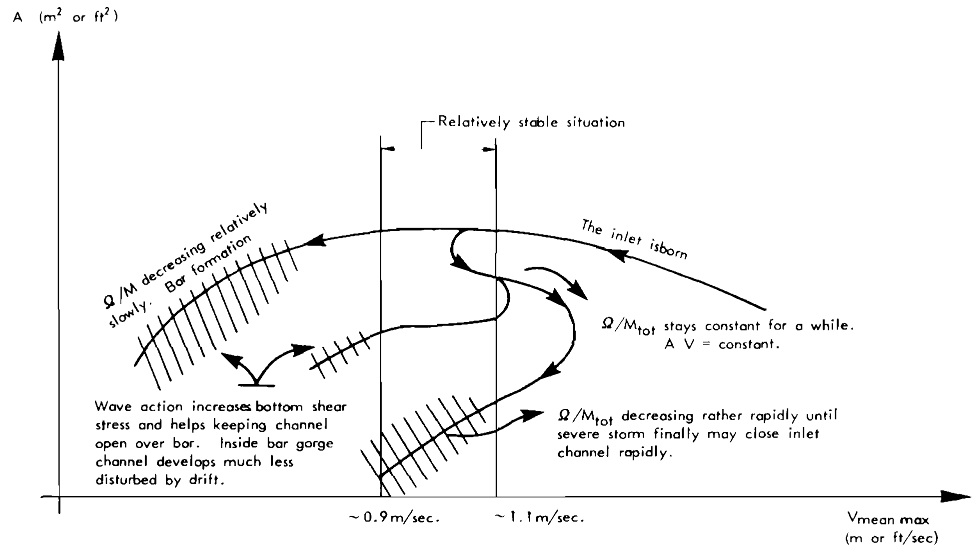

Figure 2. Development of inlet channel under various assumptions (from BRUUN, 1978).

Escoffier was not concerned with the problem of sedimentation. He and other followers concentrated on the flow in the gorge channel not considering sediment transport which, in the BRUUN and GERRITSEN approach (1960, 1968, 1978), are all-important just as they are in nature.

O'BRIEN and DEAN (1973) considered both hydraulic and sedimentary stability. Based on Escoffier's stability concept (as illustrated in Figure 1), they developed a method to calculate the stability of an inlet as affected by deposition. the theory assumes that a "critical" gorge area exists carrying a corresponding critical V_{max}. Furthermore, a "stability index" number is defined as:

$$\beta = \int_{A_C}^{A_{CE}} (V_{max} - V_t)^3 \, d\, A_c$$

where A_C is the gorge cross sectional area, A_{CE} = the "equilibrium area," A_C = the critical area (Figure 1), V_{max} is max current velocity and V_t = threshold velocity.

Although the philosophy presented by ESCOFFIER (1940, 1972) has definite similarities to the stability concept proposed by BRUUN and GERRITSEN (1958-1960) and by BRUUN *et al.* (1974, 1978, see Figure 2) the further development by O'BRIEN and DEAN (1973) concentrated mainly on the definition of an "equivalent length" for the gorge channel, assuming a deposit of length Δl in the outer part of the entrance. This theory suffers from the following drawbacks:

(a) Calculations of currents are based on Keulegan's ideal assumptions which, as pointed out by KEULEGAN (1950), are generally not valid except for preliminary evaluation. The method of DRONKERS (1964) or similar approaches, *e.g.* the numerical method by AMEIN (1975), are much more reliable. It is well known that most large inlets deviate from the Keulegan hydraulic behavior model. CHERNIAK (1977) used the method for two connected inlets on the Long Island coast and found an agreement, but this, so far, seems to be the only known case of that nature and it may be coincidental.

(b) The depositional behavior model, which is based on just a few air photos, is not realistic when seen from a practical engineering point of view because it only considers deposition in the outermost entrance area and entirely ignores deposition which takes place elsewhere in the channel and on shoals in the bay or lagoon. This does not disclose its possible usefulness for some Long Island inlets and others. which mainly shoal in the outer entrance over a certain length of the outer channel where the

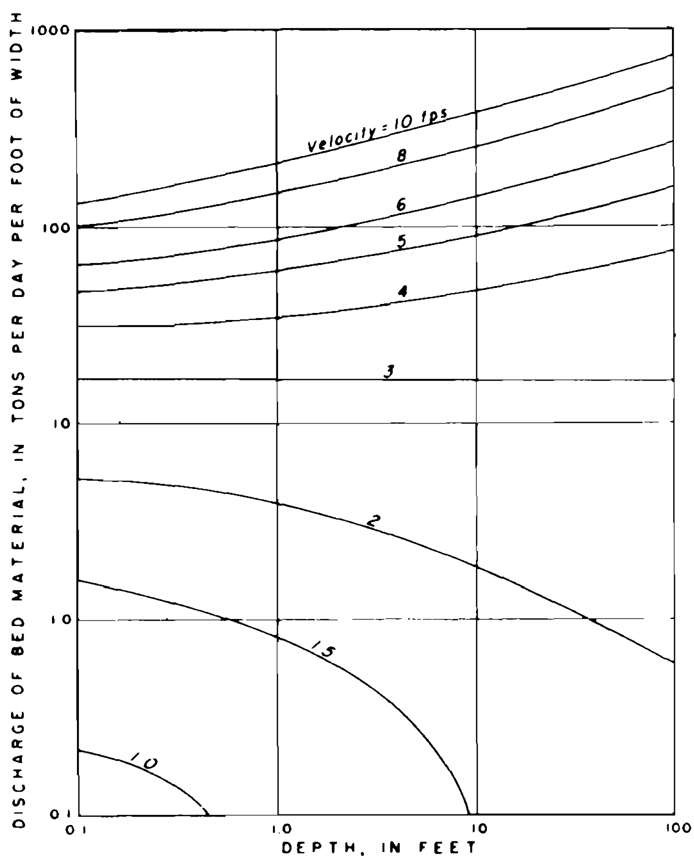

Figure 3. Effects of depth on the relationship between mean velocity and empirically determined discharges of bed material (0.3 mm diameter) at 60° F (from BRUUN, 1978 after COLBY, 1964).

pattern of flood currents always tends to leave some "vacuum" of calmer areas close to the outer ends of the jetties. It is well known, however, that the bulk of the material is washed bayward by flood currents and oceanward by ebb curents. How else should bay and ocean shoals come into existence and expand? The "depositional length," $\Delta\iota$ is, however, claimed to be a factor of "marked influence" on the stability results. This may be true in a hydraulic sense for cases where wave action is rather weak. Generally, the actual mechanics experience is not described due to the limitation on deposition areas.

(c) The dubious assumption that the development of the cross sectional area is $A_C = k\ A_{CE}$ (A_C = reduced cross sectional area due to the deposits, A_{CE} the "equilibrium" area, k is a parameter of area reduction). This assumption is an over-simplification of natural conditions because the postulated single area of entrance deposits is unrealistic. There is also a conflict here with the assumption about $\Delta\iota$. From a great number of practical cases, as mentioned in the following, it is well known that a cross section in a tidal inlet does not develop as assumed by O'BRIEN and DEAN. The cross-sectional shape is a function of the transfer of material from one or both sides. Consequently, a squeezed cross section always tends to increase depth and thereby its efficiency width decreases. This is nature's way of defending its position, well known from river technology and from theories on meandering, *e.g.* ENGELUND (1975, 1976). It should also be noted that it is not in agreement with nature's practice to define a certain gorge area as "critical." This is too general. "Critical" must always be seen in relation to flow capacity versus the ability of the flow to flush the quantity of sediment that is carried to the channel at any time. If the offshore bottom is very steep, all of the littoral drift from either side of the surrounding ocean shore may be carried into the gorge channel. Even though cases are rare, they do occur where canyon heads come close to shore and where waves on either side refract away from the centerline of the canyon. In such cases material that is carried to the entrance may be partly deposited on bay shoals by flood currents and partly flushed out in the ebb flow and lost in the canyon. ESCOFFIER's views (1940, 1972), however, are probably valid where wave action is limited and where littoral drift is relatively small and concentrated in a narrow nearshore area, as along the shores of the Gulf of Mexico where Escoffier did his excellent pioneering work.

NIELSEN and GORDON (1980) in a very practical paper on "Inlet Behavior" express similar views as BRUUN (1968, 1974, 1977, 1978). Regarding "the equivalent length" by O'BRIEN and DEAN (1973), the following is expressed by NIELSEN and GORDON (pp. 2468-2469):

> "In particular, major difficulites are encountered in determining the equivalent length and cross-sectional area of a long and complex entrance channel system. However, the major failing of the model is that it cannot be used as a predictive tool in situations where significant perturbations such as those associated with the construction of breakwaters are or will be made to the entrance bar of the inlet. Moreover, if it is desired to predict the effect of such perturbations the O'Brien and Dean model cannot be used for the reason that an Escoffier diagram representing the range of future likely hydraulic characteristics cannot be constructed if more than one parameter (A_C and consequently R) is varied".

Following on from the O'Brien and Dean approach, BRUUN (1978) shifted the emphasis to sediment transport considerations on the basis that stability must reflect the ability of sediment to move through the inlet in such a way that net deposition does not occur. Bruun suggests that inlet analysis be undertaken by calculating sediment transport: (1) in the gorge (entrance channel), (2) in the region between the inlet and ocean bar, (3) in the ocean channel increasing its passage over the bar, and (4) in the bay channels. It is then possible to construct a quantitative sediment budget from which erosion and depositional areas may be identified, hence a model of estuary/inlet behavior can be constructed.

> "The limitations of the Bruun approach are less obvious than those of O'Brien and Dean. There are difficulties in accurately carrying out many of the required calculations. The sediment budget determination may in many cases be very sensitive to these inaccuracies. Further, there is no well-documented method to determine sediment transport in the region of the ocean bars for differing inlet configurations. Finally the method is not readily adapted to situations where relatively long channels connect the bay to the ocean."

Next NIELSEN and GORDON (1980) presented an "Inlet Behavioural Approach" which is practical and not biased by purely hydraulic views. Using the sediment transport analyses by ENGELUND and HANSEN (1967) as also applied by BRUUN (1968, 1978) they express inlet geometries and velocities as functions of max discharges (see also BRUUN and GERRITSEN, 1960) to predict the slope development which comes out with a very weak dependency of changes in Q (only −0.107 power), compared to BRUUN and GERRITSEN (1960) who obtained somewhere between −0.1 and −0.2.

For a specific field test program at Forster/Tuncarry, New South Wales in Australia, NIELSEN and GORDON presented a sediment budget analysis based on a sediment transport versus flow rate equation:

$$Q = k \times V^n$$

where Q is the sediment transport rate, k = constant, B = average channel velocity, n varied from 4 to 6 over the monitoring stations in their test. They found good aggrement between detailed measured and predicted results. Further, a very interesting analysis of Ocean Bar/Inlet Morphology and Flow Patterns is presented by which entrance head losses are computed. In conclusion, the major feature of their inlet behavioral approach is summarized by them as follows:

"The construction of a northern breakwater at Forster/Tuncurry converted the previous single breakwater entrance into a double breakwater entrance. This perturbation, unlike the previous one occasioned by the construction of the first breakwater, caused significant changes to the tidal prism, the inlet entry and exit head loss characteristics and the entance bar morphology. Existing stability theories were unable to describe the changes or predict the future consequences of the perturbation. The long and complex estuary channel system connecting the ocean inlet to the "bay" region, Wallis Lake, provided additional complications."

"It was necessary to adopt a new approach of

"Inlet Behavioural Analysis" which was based on a combination and extension of past methods.

The major features of this approach included: Examination and description of changes to ocean bar morphology, current patterns and entrainment condition in order to identify the relevant parameters and their importance with respect to the changes.

Determination of the impact of the perturbation on ocean bar/inlet efficiency. That is, determination of head loss variation caused by changes to bar morphology, flood/ebb current pattern and cross-sectional optimality at the entrance — particularly between the breakwaters.

Use of a regime type approach to predict the propagation and distribution of the changed hydraulic conditions at the entrance throughout the inlet-estuary system. The development of a predictive sediment budget model is based on sediment transport formula and the calculated hydraulic conditions from the regime analysis. The use of this sediment budget model and conceptual hydraulic model to chart the future of the estuary and determine the time span over which impacts from the perturbation will occur.

Application of this approach to Forster/Tuncurry produced interesting results which now — 14 years after the perturbation — are in good agreement with field observations. That it is the discharge, thereby the cross-sectional area and not its geometry which is the determining factor for stability is also obvious from the field results published by SORENSEN (1980) with reference to results by CERC. He states:

> "the parameters defining the gross scale dimensions and shape of the ebb tidal delta and the channel showed a strong relationship to the minimum width channel cross-sectional area (represented by the product of average depth and width). However, there was no strong correlation with either the channel width or average depth separately. Apparently, the channel width and depth at the minimum width are free to adjust to the wave climate while the cross-sectional area is controlled by the tide (tidal prism)."

This result confirms the importance of Qmax by BRUUN (1968, 1971). The importance of wave action is realized by Sorensen but without an attempt to analyze the basics of the subject as in BRUUN (1978, Chapters 3 and 4).

COASTAL MORPHOLOGICAL AND NAVIGATIONAL DEFINITION OF STABILITY

General Discussion

The gorge stability criteria are hydraulic. Little or no concern is given to sedimentary aspects other than the hydraulic computation admits an entrance head loss (KEULEGAN, 1950). This model does not consider bars, shoals, their locations and configuration, it pays no attention to sediment movements and espresses no interest in the very practical sedimentary aspects of inlet stability which are the navigational problems in entering or leaving the inlet. Wave action is not included although it is a most important parameter for the behaviour of an entrance on a littoral drift shore. The advocates of the gorge hydraulic philosophy were and still are largely satisfied with the tidal prism versus gorge area relation and flows through its cross-section. Innumerable papers have been written on the subject, considered by committees that deal with tidal hydraulics, and published in proceedings of conferences on coastal engineering (1980, 1982, 1984). One is thus tempted to ask whether these researchers that deal with hydraulics have ever seen a tidal inlet on a littoral drift shore. If they had, they might start thinking in terms of a larger perspective.

BRUUN and GERRITSEN (1960) were among the first to note the "large scale stability" of tidal inlets on littoral drift shores. In their work on coastal erosion problems in Holland, Denmark, and Florida they recognized the different behavior of inlets on downdrift erosion. Some inlets had bars in their entrance which "bar-bypassed" material. Because others had smaller bars and seemed to bypass material by a more complicated flow and wave action during ebb currents, they were called "flow-bypassers." The difference in behavior could, according to Bruun and Gerritsen, be described largely by considering the ratio between the max discharge volume Qmax and the predominant drift quantity M to the entrance $M/Qmax = r$. When $r > 200\text{-}300$ bar bypassing occurs. With $r < 10\text{-}20$ tidal flow bypassing is predominant. Later (BRUUN, 1968, 1974, 1978) this ratio was converted to the Ω/M_{tot}, Ω = tidal prism, M_{tot} = the total amount of material carried to the entrance. As described in the following pages, Ω/M_{tot} seems to describe well the "overall stability" of a tidal entrance that encounters littoral drifts in the morphological sense and with respect to sediment transport. The practical importance of the Ω/M_{tot} ratio was that it also related inlet flow and sedimentary characteristics to practical navigation aspects inasmuch as "bar-bypassers" were much less suitable for navigation than "tidal flow bypassers" which were less obstructed by bars or shoals in their entrance.

The Ω/M_{tot} ratio is concerned with the total flow (prism) versus the total quantity of material affecting the entrance, *i.e.* whether it remains in the entrance on shoals or is bypassed laterally along the shore, or oceanward or bayward. The ratio also incorporates aspects of coastal inlet morphology and sedimentary conditions of great importance to navigation as well as to the ability of the inlets to transfer material downdrift. The latter aspect is particularly relevant to coastal erosion. As such, the Ω/M_{tot} criteria serves the needs of navigators, fishermen, and coastal engineers. It also is the coastal geologist's criteria for studying drifts on shoals, as diligently investigated by BYRNE *et al.* (1974, 1980), FITZGERALD (1977), HAYES *et al.* (1970, 1976) and others (reviewed by BRUUN, 1978). Regarding the Ω/M_{tot} ratio, where Ω refers to spring tide conditions, it should be observed that Ω/M_{tot} undergoes seasonal fluctuations (*e.g.* monsoons). On a long term basis, Ω/M_{tot} is also decreasing slowly with a decrease in Ω which is most likely due to sedimentation while M_{tot} may stay unchanged for long periods of time unless man starts interfering by making "improvements" that change the local drifts or circulations. The slow rise of sea level, however, favors a slow increase of the tidal prism, which in some places may neutralize the sedimentary development.

The tidal hydraulics field, therefore, seems to have become too "narrow" because it only dealt with the simplest aspects of hydraulic stability. Proponents of simplified tidal hydraulics failed to recognize that for tidal inlets on alluvial shores, it is not possible, in a scientific analysis, to separate flows from sedimentary aspects. Such considerations are important to the navigator as well as the coastal engineer who is concerned with maintenance and protection of beaches against erosion and storm tides. Field observation of how tidal entrances function under storm conditions provides compelling evidence to give up "static considerations" which only consider flow volumes and cross-sectional areas in gorge channels. It is, therefore, somewhat surprising to see that some coastal geologists, particularly those who have otherwise contributed to studies of shoals and bars at tidal inlets, occasionally "submit" to Ω/A relationships without considering the sedimentary and dynamic aspects which provide for understanding of the entire problem (FITZGERALD, PENLAND, and NUMMEDAL, 1984).

Is the Ω/M_{tot} a "sensible parameter" for the overall stability? BRUUN (1968, 1978) explains that V_{max} in the gorge channel during spring tide is almost independent of depth or $V \sim R^{1/6}$ found by field data. This observation is contrary to Escoffier's rounded diagram (Figure 1) for the development of V_{max}. Bruun's figure $1m \pm \Sigma (\Sigma \sim \pm 0.1m)$, described in several papers and books (BRUUN, 1968, 1974, 1978), is based on sedimentary phenomena in the transition zone which spans rippled-duned bottom to plane bottom. It allows a fairly easy calculation of an inlet's ability to flush gorge deposits, *e.g.* using ENGELUND-HANSEN's (1967) bed load transport formula.

The importance of the ratio Ω/M_{tot} is emphasized by the fact that the quantity of material transported as bed load is independent of depth when the mean velocity is about 1 m/sec (see Figure 3).

This means that the total bed sediment transport is proportional to the width (W) of the gorge channel (cross-sections of similar geometry considered). As calculated by BRUUN (1974), an average of 80% of the transport takes place when the max velocity is between 85% to 90% and 100% of the peak velocity. For inlet channels of mean depth D one has:

$$S + M_g \sim W$$

or drift of "native material" (S) plus input of littoral drift material (M_g) is proportional to the width of the channel. But

$$W \times D = A \; (= \pi \Omega C_2/T)$$

where D = depth of channel

$W \sim D$ for similar cross-sections considering inlets of the same size class of relatively small size.

$$W^2 \sim \Omega$$

$$W = S + M_g \sim \sqrt{\Omega}$$

$$\Omega/M_g \sim (M_g + S)^2/M_g$$

From this expression it may be seen that Ω/M_g is high when $M_g \ll S$ and Ω/M_g is low when $M_g \gg S$. From these relationships it follows that the Ω/M_g ratio may be expected to be a useful parameter to describe the relative stability of the gorge cross-section area for at least relatively small and medium size channels. This, however, also seems to be true for larger inlets with wider channels when $S + M_g$ is proportional to $A \sim \Omega$ which means that $\Omega/M_g \sim (M_g + S)/M_g = 1 + S/M_g$, which in turn supports the conclusion for small channels. It should be remembered that on exposed shores, the quantity of suspended load may also be high but probably proportional to $A \sim Q$; this relationship refers particularly to the ocean channel. In a gorge channel with moderate or little wave action, bed load transport remains predominant.

An evaluation of the Ω/M_g ratio must of necessity include an evaluation of the overall material transport in the gorge. The general rule is that in the gorge almost all transport of sand>about 0.1 mm takes place as bed load transport. Finer-sized particles, *i.e.* <0.06 mm including silt and clay, if present, are transported in suspension during high flows, possibly also influenced by wave action.

BRUUN (1978) showed that it is possible to explore and calculate drift quantities in an entrance and also explains the fact that inlets on shores with a greater littoral drift have the highest Vmean max at spring tides (*e.g.* 1.1 m/sec). A high Vmean max is necessary to clean away the additional drift material carried to the channel from the longshore drifts. This observation also explains some differences between Atlantic, Pacific, and Gulf coast inlets, as described by JARRETT (1976), and accounts for the fact that Atlantic inlets tend to be widest in relation to depth because they have to push more material away.

That, as stated by JARRETT (1976, p.29), "the equation for jettied Atlantic coast inlets varies considerably from O'BRIEN's (1931, 1973) is just another proof, among many, of how dangerous generalization is." "Formulas" must always be considered with some suspicion, and O'BRIEN's Ω versus A relationship, as earlier mentioned, is undoubtedly an oversimplification. But it was "a first step." A weakness in Jarrett's analyses is that they ignore the length of jetties. Jetty length could be a major consideration because it influences current transport to the entrance.

Overall Stability of Tidal Entrances

Overall stability must include all sections of a tidal entrance as divided by BRUUN (1978) in "Ocean Bar," "Gorge" and the "Intermediate Section." Because each of these sections is influenced by combinations of current and wave forces, their sediment transports need to be considered accordingly. BRUUN *et al.* (1978) give preliminary advice using theories by JONSSON (Chapter 3 of BRUUN *et al.*, 1978) MADSEN and GRANT (1976, Chapter 4 of BRUUN, 1978), and NIELSEN (1978). The slow but steady progress in the exploration of these sorts of problems is punctuated by major steps forward, as derived from NIELSEN and GORDON's work (1980). But the question arises as to what is the best way to handle the problems of "sedimentary budgets" at inlets so that geoscientists will be able to understand the actual morphological stability in greater detail while at the same time still explaining the "stamina" of entrances that sometimes survive for hundreds or even thousands of years.

Reference is made to Figure 4 which shows a situation where the inlet receives the quantities M_n and M_s from either side. If $M_n > M_s$, it may be assumed that the corresponding bar drifts and drifts to the gorge have $M_{nb} > M_{sb}$.

The gorge receives the quantity $M_{ng} + M_{sg}$. Of this quantity, $\propto_b(M_{ng} + M_{sg})$ is flushed bayward while another part $\propto_o(M_{ng} + M_{sg})$ is carried out on the bar by ebb currents. While the total result for the stable gorge is ΣM_g = zero, the situation may be different on the bar. The bar receives $\propto (M_n + M_s)$. $\propto$ is assumed to be the same in either direction. A certain part of the material bypasses the bar $= (M_n - M_s)\beta\propto$ where β approaches unity in a completely stable situation. The ebb currents during their crossing over the bar, more or less dispersed in accordance with entrance geometry, have to cope with the following loads:

$$M_{ob} = (M_n + M_s) \propto = (M_{ng} + M_{sg})\propto_o \quad (1)$$

To this, however, must be added an unknown factor representing "local material circulation," M_{local}, which always represents an "additional material trouble" (Figure 5). It is likely that M_{local} depends upon M_{nb} and M_{sb} as it was derived from these sources and therefore may be said to be included in $\propto$ increasing the actual "transfer-$\propto$" by a factor >1 and perhaps in certain cases $\gg 1$. $\propto$, of course, does not necessarily need to have the same value for north and south drifts. It may be split in $\propto_n$ and $\propto_s$. For entrances on exposed shores $\propto_o$ would normally be relatively small and perhaps close to zero due to high suspension loads. $\propto$ may still be large. For less exposed shores $\propto_o$ may be relatively large, particularly at high tidal ranges while β and $\propto$ may

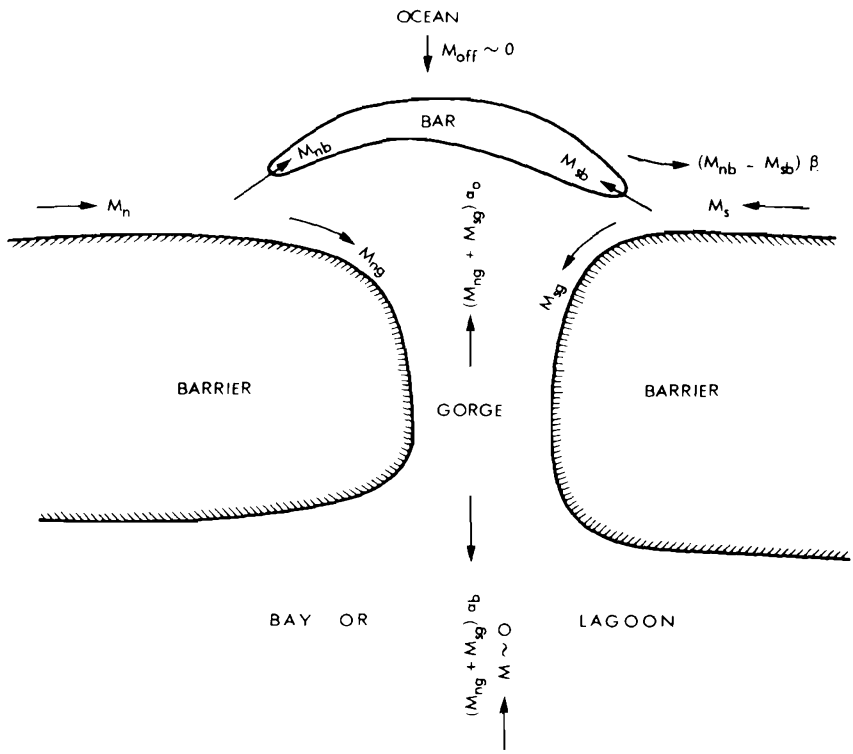

Figure 4. Material transport pattern of an inlet entrance (BRUUN, 1978).

be relatively smaller. This leaves two equilibrium conditions for the ocean bar:

$$\text{Exposed: } M_{ob} = M_{(n+s)g}\ \propto_o \quad \text{relatively small} \tag{2}$$

Less Exposed:

$$M_{ob} = M_{(n+s)g} \propto_o + (M_n + M_s) \propto_{\text{relatively small}} \tag{3}$$

$\propto$ is the important factor for exposed and $\propto_o$ for less-exposed conditions. $\propto$ depends upon the degree of exposure, the slope and configuration of the offshore bottom and also upon material characteristics. $\propto_o$ in turn also depends upon wave exposure, offshore bottom slope, material characteristics and upon inlet channel hydraulics, which include bay and channel morphology and tidal flows.

Referring to Figure 4, there is also a possibility that the bar may receive some material from offshore by "bottom creep." In this respect, reference may be made to a paper by CARTER *et al.* (1973), which mentions mass transport by waves and offshore bedforms. Such mass transport may take place as a result of wave action with bottom slope and grain size being important parameters. Swells and gentle bottom slopes favor onshore transport. Mass transport is, however, relatively small; if the transport was not minor the offshore bottom would deepen (erode) severely.

BRUUN (1978) (Figure 5) explains how it is possible to obtain detailed information about the distribution of drifts at a tidal entrance by using (fluorescent) tracers. The method requires the use of three different tracers, including one for studying the circulation on the ocean bar. For details, the reader is referred to BRUUN *et al.* (1978). Drift from updrift and downdrift sides may be estimated by available techniques and experiences. Knowledge about dredging quantities will provide information of qualitative value, as seen from examples at Ft. Pierce Inlet and South Lake Worth Inlet in Florida (BRUUN, 1968, 1978). In addition, reference is made to NIELSEN and GORDON (1980).

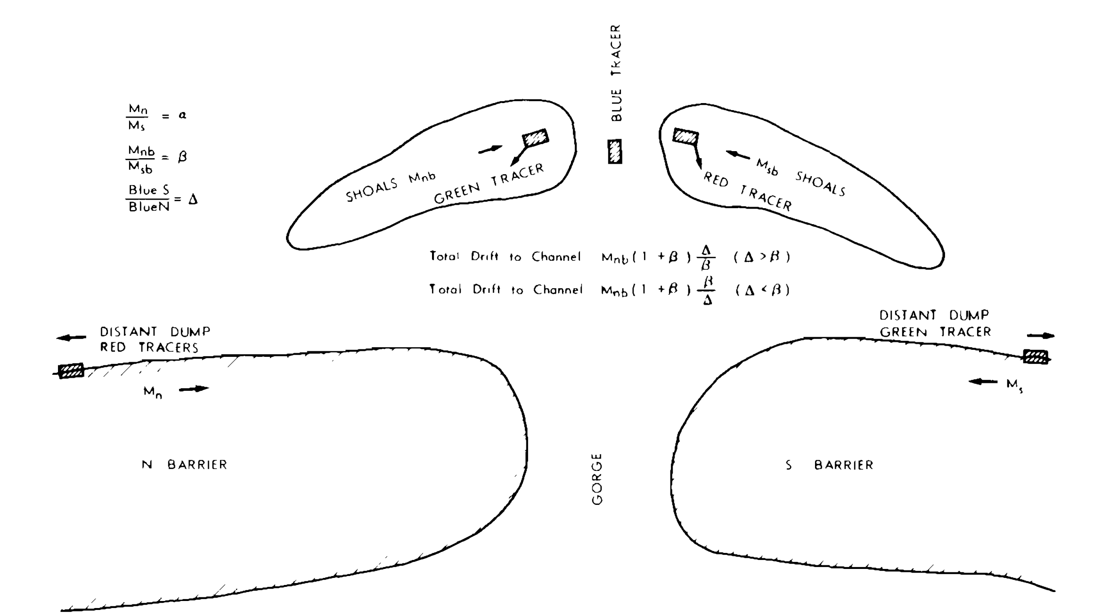

Figure 5. Drift at entrance with offshore shoal (BRUUN, 1978).

Review of Practical Data on Overall Stability

A tidal inlet on an alluvial shore includes four different sections, all of which have to be stable. The term "stable" in this morphodynamic context, means relatively little change over long periods of time. If a stable (not changing) condition of ocean bar transfer becomes established, the only development in the general stability condition could be a slow growth of the bay shoal by flood current deposition. Bay channels gradually increase in length as shoals extend into the bay. Over a long term, this causes a slow decrease of the tidal prism. In order to study this phenomenon (without surveys) over a long period of time, one has to examine tidal entrances which, presumably have slowly deteriorated without reaching the final stage of closing — and they may never do so. In this respect, one should consider the slow but continuous rise of mean sea level. It should also be noted that estuarine flow alters or offsets a closing trend, as occurs in India due to monsoonal flows.

No country in the world exhibits a larger collection of such entrance conditions as does India. Most of the tidal entrances on the Arabian Sea and Bay of Bengal are very ancient and were used throughout history by invaders. Table 1, BRUUN *et al.* (1978) is a review of gorge, tidal prism and littoral drift characterisitcs for twelve tidal inlets in India. Some of them are only "part-time estuaries." Tidal prisms (Ω) are indicated in relation to an approximated quantity of drift M_{tot} carried to the entrance on the ocean side providing the Ω/M_{tot} factor. The corresponding entrance condition is described by the condition of the entrance bar. Table 2 is a similar review based on figures from various tables of BRUUN *et al.* (1978) together with some new information. When the two tables are combined in Table 3, it is seen that the Ω/M_{tot} factor is suitable for the description of entrance condition.

From this evidence it is obvious that a whole series of equilibrium or stability conditions exist at tidal entrances on littoral drift coasts. Each represents a balance between flow and sediment movement, and supplies to the entrance but this balance changes with time and seasonal conditions. One situation may, however, be just as stable as another under normal weather situations. Because a gorge section changes its area it does not mean that it becomes less stable. In practice, it is known that inlets with relatively small flows tend to close up during the most severe storm tide conditions. During periods of storminess the bar-transfer mechanism might be unable to "follow up" with the sediment supply to the channel due to wave action on the

Table 1. Tidal entrances at India. Hydraulic and cross sectional characteristics related to overall stability (BRUUN, GERRITSEN, and BHAKTA, 1974).

Name of entrance or inlet	Ω $10^6 m^3$	$A \sim$ m^2 at MSL	Q_{max} m^3/sec	M* net	M* total	Depths, m gorge MLW	Depths, m bar MLW	Ω/M	Note stability situation
Beypore (estuary)	16 m 5nm	1,000 300			0.2	6-7 5-6	1.5-2	~8.0 m	p Comprehensive bar
Chandipur (estuary)	5 (e)				0.25		0.9-1.2	~20	p Comprehensive bar very shallow
Honavar (estuary)	≤20 (su)	800 nm 1,400 m 1,000 su			0.2	5-7 su	2 su	50-100	pf Bar
Kalingapatam (estuary)	1 nm (e)				0.1 (nearshore)			10-20	p Comprehensive bar very shallow
Krishnapatam (estuary)	(10) (e)	500 m 500±nm			0.5-0.7	(0.5-1)	~0.5	10-20	p Comprehensive bar very shallow
Machilipatam (estuary)	10 (e+su)				0.2 (nearshore)	~2	~1	20-50	p Comprehensive bar very shallow
Malpe (estuary)	5.8 (su)	350±su	350 su	0.1	0.15	2-3	1-1.5 su	~60	pf Bar
Neandakara (estuary)	(9) (e+su)	(600)			0.2			~50	pf Bar
Nizampatam (estuary)	1-1.5 (su)	70 su			0.1 (nearshore)	3 su	max 1.5 su	10-20	p Comprehensive bar very shallow
Ponnani (estuary)	~3 (e)	300 m +nm			0.2	0.5-1 m	2-2.5 nm	10-20	p Comprehensive bar very shallow
Sapati (estuary)	~15 (e)				0.1 to the entrance	3		100-150	f Protected by rock reefs
Versova (estuary)	~6 (e)	400±		0.05-0.1	0.05-0.1	3-4		100-150	f Protected by shore rock

m = monsoon; n = non-monsoon; su = surveyed; e = estimated by computation; s = spring
*Drift is almost unidirectional $M \sim M_{tot}$

Table 2. Entrance Conditions Described by Ω and M_{tot}.

Location	Ω $10^6 m^3$/cycle	M_{tot} $10^6 m^3$/year	Ω/M_{tot}	Condition Depth Gorge	Ocean Bar
Calibogue Sound South Carolina, USA	200	0.2	1,000	12 m (40') no protection	6 m (20')
Penang Harbour at Georgetown, Malaysia	700	0.5	1,400	18 m (60') no protection	9 m (30')
Eyerlandse Gat Holland	200	0.5-1	300	12 m (40') no protection	6 m (20')
Port Aransas Texas, USA	40	0.2	200	Dredged and jetty protected to provide greater depth	
Longboat Pass Florida Gulf Coast	15	0.1	150	4.5 m (15') groin updrift	2.7 m (9')
Thyborøn Denmark	100	0.8	125	12 m (40') short jetties	9 m (30')
Gasparilla Pass Florida Gulf Coast	10	0.1	100	4.5 m (15') groin updrift	1.2 m (4')
Masonboro Inlet, North Carolina (before improvement	20	0.3	70	4.5 m (15') unprotected	3 m (10')
North Inlet South Carolina, USA	10(20)	0.4	25(50)	6 m (20') varying unprotected	3 m (10')
Oregon Inlet North Carolina, USA	60	1	60	9 m (30') unprotected	3 m (10')
Ponce de Leon Inlet Florida Atlantic Coast	15	0.4	40	5 m (17') unprotected	3.6 m (12')
Sarasota Pass Florida Gulf Coast	3	0.1	30	7 m (23') unprotected	1.5 m (5')

Table 3. Entrance Conditions in Relation to Ω/M_{tot}.

Ω/M_{tot}	Entrance Conditions
$\Omega/M_t > 300$	Little or no ocean bar outside gorge (ocean shoals may occur further out)
$150 < \Omega/M_t < 300$	Little ocean bar
$100 < \Omega/M_t < 150$	Low ocean bar, navigation problems usually minor
$50 < \Omega/M_t < 100$	Wider and higher ocean bar, increasing navigation problems
$20 < \Omega/M_t < 50$	Wide and shallow ocean bar, navigation difficult
$\Omega/M_t < 20$	Very shallow ocean bar, navigation very difficult

Note: The condition on the ocean bar also depends upon the wave climate involved $M_t = M_{tot}$

beaches on either side of the inlet. Consequently, the channel may become overloaded with material and, in the worst case, close up. It is thus concluded that the smaller the gorge in relation to material transport, [M_{tot} (extreme condition)], the greater the chances are for clogging or closing up. This situation occurs because there is not enough flow capacity in reserve to flush the entrance. Such relationships are demonstrated at some tidal entrances in India where some inlets close up during the monsoon while others remain open due to the effects of increased fresh water flow.

The necessity for considering all sections of a tidal entrance, not just the gorge, therefore should be obvious to field observers. BRUUN's (1980) discussion of ESCOFFIER and WALTON's (1980) paper maintains that overall inlet stability must, of necessity, include all sections of the inlet because this is the most common and practical case. JARRETT's (1976) results anticipated this conclusion without discussing basic aspects of the current/wave problems, although the importance of this combination is clearly indicated by the differences in the behavior of inlets on the east, west, and Gulf coasts of the United States.

Although WINTON and MEHTA (1981) also concentrate on the gorge channel, their work is a continuation of earlier work by BRUUN (1968) and BRUUN *et al.* (1978) who suggested that *the part of the littoral drift* (regardless of the actual transfer mechanism) that winds up in the gorge must also be flushed from the gorge. The sediment transport capacity of inlet currents can be computed by the use of proper bed load and suspension load expressions as shown by BRUUN (1968, 1978) and by NIELSON and GORDON (1980). WINTON and MEHTA (1981) do not consider the direct contribution by wave action to sediment transport. Their conclusions were based on a practical test case for a small coastal lagoon on the west coast of Florida. The shallow 0.3 m gorge depth resulted because wave action was largely eliminated before reaching the entrance. There is little wave action in any case on that part of the Florida Gulf coast.

A basic researcher like FREDSOE (1984) emphasizes that in order to calculate the sediment transport, the following hydrodynamic part of the problem must be solved:

(1) Description of the wave motion outside the wave boundary layer.
(2) Description of the turbulent wave boundary layer due to the motion obtained from item (1).
(3) Calculation of the vertical mean current distribution in the combined wave-current motion.

These three items cannot be solved separately due to interactions between wave and current motion. How it can be done was most recently shown by FREDSOE *et al.* (1985).

After these items have been determined, the following information can be applied to the solution of the sediment transport part of the problem that involves (a) the instantaneous value of the bed shear stress, and (b) the variations in time and space of the eddy viscosity.

The instantaneous value of the bed load transport can be found by applying a bed load transport formula from the steady state case into which the instantaneous value of the bed shear stress is inserted. This was suggested ,for example, by MADSEN and GRANT (1976) and, analyzing the effect of inertia of particles moving as bed load, FREDSOE and RASMUSSEN (1980) showed that it was correct to within a few percent error. The instantaneous value of bed concentration may be found by applying principles developed by ENGELUND and FREDSOE (1976). The vertical distribution of suspended sediment can be obtained by means of diffusion equations as described by FREDSOE (1984).

Various Attempts on Exploration of Overall Stabilities

Another attempt to explain overall stability of tidal entrances was made by JOHNSON (1973), with special reference to tidal entrances in California. His attempts were based on the P_w/A_g ratio where P_w is the annual wave power (lbs/ft^2/yr) and A_g is the area of the lagoon (ft^2) making the P_w/A_g ratio having the dimension lbs/ft^2/yr (16.7 kg/m^2/yr). Analysis of 46 entrances in California for this ratio (which is not dimensionless) provided data from which it was concluded that wave power is the single most important factor affecting the stability of tidal inlets. Whether an inlet is always open or closed, or open occasionally appears to be related to the ratio of wave power to potential or actual tidal power, which JOHNSON (1973) assumes to be the tidal prism. BRUUN and GERRITSEN (1974) express different views on this theory by reference to their work published in 1960 and 1968 using Ω/M_t. Analyses of results derived from their comprehensive field research suggest that it is unlikely that just one parameter can be classified as "the single most important factor affecting stability of tidal inlets." Johnson's figures also demonstrate considerable scattering compared to BRUUN and GERRITSEN (1960) and BRUUN (1968, 1978). It also seems to be less logical to compare a cross section (in square feet) or a tidal prism in (cubic feet) to a wave power (feet-pounds per year) even in deep water, and to include all directions with a shoreward component at the same weight, regardless of the great importance of longshore components for littoral drift carrying material to the inlet, interferring severely with its stability.

Energies behave very differently in relation to water depths and thereby to flows. They are also highly dependant upon wave height over depth ratio. Together with the wave period they determine the depth and mode of wave breaking thereby influencing shoal formation. Shoals in turn additionally affect the mode and pattern of wave breaking. A comprehensive summary of wave breaking, relating wave characteristics to depth and slope characteristics, is given by BRUUN *et al.* (1985, Ch.2). It is customary to relate littoral drift to longshore flux of wave energy (CERC, 1973-1984); various empirical methods are available (BRUUN, 1981). In this way energies may be converted to sediment transport. The propagation of energies, however, undergo dramatic changes during waves passage from deep to shallow water. Energies that are finally released in wave breakings often occur one after another. Furthermore, the hydrodynamic sedimentary action is highly dependent upon the interrelation between wave "orbital currents," wave-generated currents, and other currents such as tidal flows. Complexities may be noted when considering littoral drift theories of BIJKERS and SVASEKS (1969), MADSEN and GRANT (1976), FREDSOE *et al.* (1984) and NIELSEN's (1978-1984) comprehensive works. Consequently, an energy-based approach must be classified as doubtful and outdated if it does not convert energy to actual transport.

It is difficult to compute drifts at the entrance of a tidal inlet that involves detailed wave analyses of all wave characteristics. In an attempt to overcome this difficulty, BRUUN (1978) indicated a field approach using tracers. It is likely that some entrances not only receive material from either side by longshore drift, but, as claimed by JOHNSON (1973) they may also receive material from the offshore bottom, particularly if the bottom slopes gently seaward. The modes of flood and ebb currents, however, tend to increase the longshore drift to the entrance (flood channels) and decrease the bottom creep towards the inlet channel (ebb channel) (See Figures 6 and 9). If a substantial bottom creep exists the offshore bottom tends to deepen, but this, according to experience, represents an anomalous situation. Bottom creep towards the entrance outside the bar or surf zone could, however, contribute to formation of a bar with rather steep slopes, as in the Gulf of Mexico and along coastal India during the dry season. The bar is usually segmented by one or more ebb flow channels. Energies, of course, must be known for all sections of the entrance in order to perform a scientific analysis.

JOHNSON (1975), discussing the US Pacific coast, proposed that as the littoral drift to some inlets may not be very strong, it is natural to relate the stability of the inlet to the total wave power regardless of the direction of input. However, heavy wave energy inputs cause stunted bars and a considerable increase in energy flux and sediment load in bayward directions. Flood current velocities increase, while ebb current velocities decrease, during periods of high wave exposure. This results in elevated tides in the bay during storms. After the storm, an increased ebb current velocity flushes the gorge even more strongly. The final result is a balance in water masses moving in and out. Increased sedimentation occurs on the bay shoals in such cases but not in the gorge. Consequently, the relation to wave power is unclear. If wave power is related to drifts, including local circulations, the Ω/M_{tot} ratio may change with wave power. But, as shown by numerous cases mentioned earlier, this does not necessarily change Ω. Why should it? An inlet entrance with a rather heavy input of littoral drift materials from the sides (BRUUN, 1968, 1978) will usually have a smaller gorge area than a corresponding inlet with less drift for the same Ω, regardless of the existing wave power. Currents may run about 10% stronger, increasing flushing ability by about 30%. Variances in drift, therefore, do not necessarily cause any change in prism but may only change the efficiency of the prism hydraulically. This contradicts JOHNSON's (1973) wave power/prism relationship and may explain the large scattering of his California-inlet results.

If drifts at the inlet entrances are relatively small, cross sections may increase during storms due to wave motion increasing bottom velocities, thereby exerting a greater shear stress on the bottom, increasing its mobility and transport of material (BRUUN, 1978, Ch.3). This explains why the cross sectional area decreases from the ocean section (flow plus wave action) to the gorge (mainly flow). Examples of this are, for example, the Thyboron Channel in Denmark (BRUUN, 1978) and the St. Mary's River

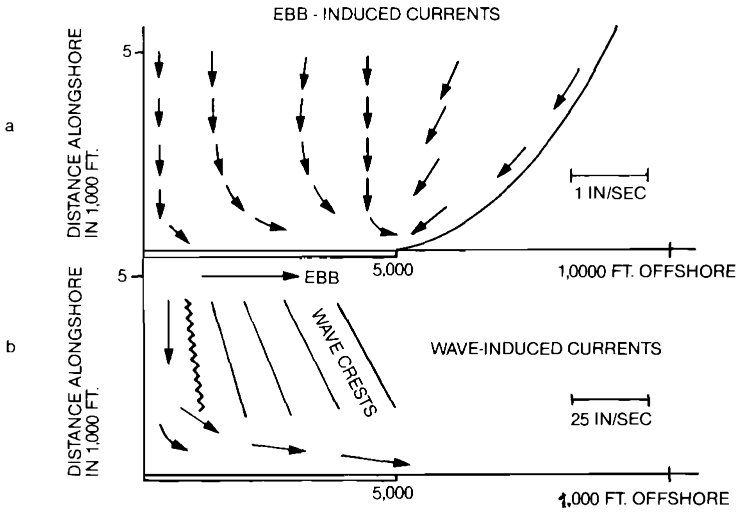

Figure 6. (a) Jet-induced flow field for Ft. Pierce Inlet, Florida. Schematics (JOSHI and TAYLOR, 1983). (b) Wave-induced currents superimposed.

entrance in Florida (BRUUN and GERRITSEN, 1960). One may, therefore, conclude that generally it is wave-induced longshore drifts and tidal currents *combined* with waves which are the important parameters for inlet stability. This subject is reviewed by BRUUN (1978) referring to results by Jonsson, Madsen and Grant, and others.

Consequently, it is also interesting to note that Johnson's ratios between wave power and cross sectional areas (JOHNSON, 1973, Table 3, used by Bruun and Gerritsen to compute ratios) range from 1.3×10^{-6} to $2{,}750 \times 10^{-6}$ for open channels and from 0.7×10^{-6} to 15.2×10^{-6} for closed or closing channels. These ranges are much larger than (and even overlap) those used by BRUUN and GERRITSEN (1960, 1968, 1978) to classify relative stability in many Ω/M_{tot} ranges and overall as "good," "fair," or "poor." JOHNSON (1977), in another closure on the same article (1973) and addressed to A.J. Mehta (1977), lists a number of cases where the P_w/P (wave power per year over tidal prism) was computed (without consideration to refraction, although it is very important). Scattering is, however, still considerable compared to the BRUUN and GERRITSEN (1960) approach which has general application and many ranges which were developed under *practical* entrance conditions.

BYRNE *et al.* (1974) indicated similar approaches already explained and demonstrated by BRUUN and GERRITSEN (1960), BRUUN and BATTJES (1966), BRUUN (1966), and BRUUN, GERRITSEN, and BHAKTA (1974). A "channel maintenance ratio," $\propto$, is defined as

$$\propto = Q_E \times R_E / H^{2.5} \times F$$

where

Q_E = mean ebb discharge (prism x duration of ebb)
R_E = ebb tide range
H = wave height
F = "wave duration weighting factor"
F = 3: waves approach 0 to 70°
F = 2: waves approach 80° to 110°
F = 1: waves approach 110° to 180°

Results were based on detailed surveys of the Wachapreague Inlet, Delaware, a downdrift offset inlet on the Delaware Atlantic coast (BRUUN, 1978).

With reference to these results, it was concluded that: "A qualitative correlation exists between short-term channel cross-section area change and the ratio of ebb tidal power on the ebb-tidal delta, *i.e.* the quantity of material stirred up by the wave action. The $H^{2.5}$ relationship is the relationship for longshore transport $H^2 \times T$ (CERC 1973-1984). With $T = \sqrt{H}$ one gets $H^2 \times T \sim H^{2.5}$ as in the denominator of their maintenance ratio, $\propto$. If $H^{2.5}$ is $\sim M_{tot}$ they thereby re-introduce a variety of the

Ω/M_{tot} ratio by Bruun and Gerritsen as described earlier.

MEHTA and HOU (1974) define a "stability coefficient" as

$$C_2 = E_a \times T / 2\propto \times A_c \times W$$

where E_a is *longshore energy*
T = tidal period
A_c = inlet cross-sectional area
W = work done by friction against inlet currents per/lb of water
$\propto$ = unit weight of water

There is actually little difference between this criteria and BRUUN's (1968, 1978) Ω/M_{tot} criteria. When $E_a \sim M_{tot}$ and $A_c \times W \sim A_c \times u$ where u is the current velocity, $A_c \times u = Q \sim \Omega$. Consequently, $A_cW \sim \Omega$.

The MEHTA-HOU (1974) approach, however, does not differentiate between various degrees of stability in relation to morphological and sediment transport factors inherit in the bottom configurations of various inlets, including offshore bars and shoals. But the theory admits — maybe involuntarily — that the Ω/M_{tot} factor is a useful stability criteria, unfortunately without taking the step from longshore energies to drifts of material, M_{tot}, which relates quantities of flow, Ω, to quantities of drift; this would be the most logical ratio which has no dimension!

If as discussed by WARD (1982), inlets have to "share" Ω (like Texas inlets) or are capturing Ω from each other (also observed in Texas) the situation worsens for one or both as sharing means a lower Ω/M_{tot} for one (BRUUN, 1983). And one inlet's hunger is the other one's "satiety" (VAN DE KREEKE, 1985).

DEAN and WALTON (1973) and WALTON and ADAMS (1976) attempted to correlate volume of material stored in offshore bars or shoals with tidal prisms. Based on studies of some American inlets, they found a linear relationship. The validity of their results, based on a relatively few American cases, seems to ignore certain facts about inlet and coastal morphology as observed in nature. First they concentrate on inlets with ocean shoals but most inlets in the world have bay shoals as well. Some inlets have large bay or lagoon shoals but small ocean shoals. The placement and magnitude of the shoals quite obviously is related not just to the tidal prism but also to the magnitude of wave action and the availability of space (room) for deposits in the bay or lagoon regardless of tidal prism. Coastal geologists and geographers have studied ocean shoals and their behavior (BYRNE, 1974; FITZGERALD, 1977; HAYES, 1976) to the neglect of bay shoals, which are less "dramatic." But, in fact, Thyboron Inlet in Denmark has all its shoals in the bay; Haldia Entrance in India has mostly bay shoals; Chilka Lake Entrance in India has mostly bay shoals; most Fresian inlets (Holland and Germany) have bay shoals; so have some Mexican inlets on the Pacific; Omaha Inlet, New Zealand has mostly bay shoals; and Mecox Inlet, New York, among many other US east coast inlets, including those on Long Island, all have mostly bay shoals.

Many other inlets have mainly ocean shoals, for example Golden Gate (California), Indian inlets on the Bay of Bengal, Mantanzas Inlet (Florida), Macquary Harbor (Tasmania), North Inlet (South Carolina), Panamora Inlet (Delaware), Ponce de Leon Inlet (Florida), Price Inlet (South Carolina), Sarasota Inlet (Florida), Skull Inlet (South Carolina), and Tubbs Inlet (South Carolina).

Most tidal inlets on littoral drift shores still, however, have shoals on either side of the gorge, such as: most Alaskan inlets, Columbia River (Oregon), Florida inlets in general (if space is available for bay shoals*), most South Carolina inlets (particularly large ones), North Carolina inlets in general, Texas inlets in general, many inlets in Australia (Gold Coast), many inlets in Pakistan (*e.g.* Sumoniami), and many inlets in India (*e.g.* Honovar).

In sum, if the sea is rough and space is available in the bay, sand will be carried by flood currents and deposited on the bay side. Conversely, if the sea is not rough and the bay is narrow with a relatively long channel connecting sea and bay, sand will accumulate on the ocean side, perhaps following a roundtrip in the gorge channel. A generalization such as the one by WALTON and ADAMS (1976), therefore, may not have wide application. However, their relation *is* valid for some inlets. DEAN and WALTON (1973) and WALTON and ADAMS (1976) suggest that it may be practical to distinguish between "moderately esposed" and "mildly exposed" coasts.

IMPROVEMENT OF TIDAL ENTRANCES ON LITTORAL DRIFT SHORES

Navigational improvements for inlets that include a variety of jetties, training walls, and sediment traps,

*Recent surveys have demonstrated that the Florida coastal inlets in their ocean shoals store almost one billion cubic meters of sand. Their importance for the erosion downdrift is thereby well demonstrated.

apply to the entire length of the inlet channel where an increase or stabilization of depth is desired. Using the Ω/M_{total} ratio for evaluation of the overall stability condition, and improvement requires an increase or decrease of M_{total}. Knowing these two values it is possible to establish relative stability in regard to bar conditions (BRUUN, 1978) defined as "poor," "fair," or "good."

It is often possible to obtain some (usually smaller) increases of Ω if this is not going to cause an unacceptable increase of floodings in the bay or lagoon area or increase drainage problems. A major improvement, however, calls for a reduction of M_{total} and its variances. That means a decrease of the total amount of littoral drift material carried from either side to the entrance channel. Basically, this may be obtained by trap dredging or by entrance jetties.

Trap dredging is a solely defensive method which has the weakness of not providing protection against the "big surprises" in the form of overwhelming material supplied during extreme storms. The most popular improvement, jetties or training walls, protect the entrance channel from deposits of material drifting into the entrance from the sides.

Innumerable jetty improvements have been undertaken (see, *e.g.* BRUUN, 1978; for numerous references to actual cases). Such efforts are commonly unable to reduce M_{total} to an extent that no further improvements or maintenance are necessary. Additional dredging was required. This situation may be understood from the following.

Figure 6a is a schematic plan based on JOSHI and TAYLOR's (1983) results that were presented in a paper "Circulation Induced by Tidal Jets." This article considered idealized conditions of jet-induced flows associated with tidal ebb current jets, disregarding wave generated and wind driven currents. However, their research clarified the potential significance of jet-induced currents entering the ocean. The major significance of these currents lies not in the order of magnitude but in their persistence and interaction with other ongoing processes.

> "Whereas wind, wave, and wave-current induced mass transport phenomena are highly variable and dependent upon the climatological conditions of the movement, the jet-induced transports are present roughly 12 hours a day, every day of the year. Moreover, if even the gentlest swell upon breaking at the shoreline is capable of putting sediment in suspension, then these persistently weak currents can act to slowly move this material towards the inlet entrance" (cit.).

The authors identify the persistence of such small currents. The importance of various shoaling agents, however, depends upon the relative magnitudes of the various factors contributing to the shoaling. When inlets are located in low energy areas it becomes practical to largely ignore currents produced by breaking waves. Therefore, the tidal jet current analyzed by the authors probably describes the actual conditions quite well under such conditions. Details of ebb depositional currents are given by ÖZOY (1977; see also ÖZOY's contribution to BRUUN *et al.* 1978). However, on high-energy shores wave currents are predominant. Under such conditions the wave induced currents, regardless of any tidal flow, develop as indicated schematically in Figure 6b. In the case of wave action, the ebb jet will be subject to a spreading by opposing waves similar to the case theoretically dealt with by ISMAIL and WIEGEL (1983).

For flood currents, the situation is indicated schematically in Figure 7 where scales of current velocities are realistic for prototype conditions. Both ebb and flood currents carry material into the inlet and conversely, currents flush material away from the entrance channel after forming a shoal or bar. The bar may also receive some material from offshore by bottom creep, particularly during swell conditions (see *e.g.* CARTER *et al.*, 1973). Due to the modes of ebb and flood entrance currents, ebb currents mainly influence offshore-bar configuration. Offshore bar shape and depth are combined results of current and wave action. The bar, in turn, functions as a transfer-"bridge" for material to the downdrift side as shown in Figure 4. The details of this mechanism are not well known but the patterns may be observed in aerial photographs: see Figure 8 of Jupiter Inlet, Florida (BRUUN *et al.*, 1978); Figure 9 — Ponce de Leon Inlet, Florida (PURPURA, 1977); and refraction diagrams like Figure 10 (HAYES *et al.*, 1976), or by tracing as attempted by BRUUN (1978) and TELEKI (1975) at Port Corinto, Nicaragua, 1975. Any man-made effort to break the natural transfer pattern is doomed to failure and will cause erosion problems downdrift if the natural drift is not fully reestablished. As deposits in the inlet channel are going to interfere with navigation, the most effective solution to the problem is to temporarily store the drift material on the updrift side and transfer it mechanically/hydraulically to the downdrift side.

Storage may be provided by "traps" with or without structures or a combination of both. A review of these methods is given by BRUUN (1978). Unfor-

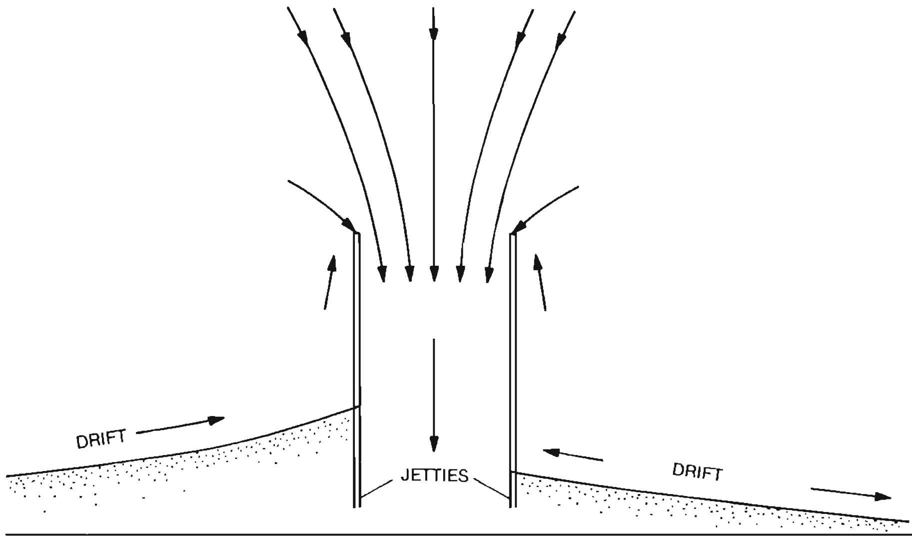

Figure 7. Flood Tides draw currents from all sides to a tidal entrance. Schematics.

Figure 8. Jupiter Inlet, Florida (BRUUN *et al.*, 1978).

Figure 9. Ponce de Leon Inlet, Florida (BRUUN *et al*, 1978).

tunately no updrift trap is perfect because currents run out along the jetties for both ebb and flood flows. Practical ways of putting brakes on these currents are: (1) flared entrances, (2) spurs, and (3) weirs combined with various kinds of transfer plants or arrangements as indicated schematically in Figure 11. None of these methods, however, are considered "foolproof." Some material exchange into and out of the inlet will continue to be moved by tidal currents. Consequently, the ideal solution appears to be an arrangement which includes: (1) channel stabilizing training works, (2) jetty-configurations which turn currents away from the entrance, and (3) an ebb current "lift-arrangement" (see WEISMAN *et al*, 1982 and BRUUN, 1984). As indicated in Figure 12 a hydraulic lift arrangement can be provided in the channel gorge by increasing the flushing ability of ebb currents; possibly further supplemented by a transfer-lift arrangement in the potential shoal area when ebb jet currents are slowed by wave orbital motions, thereby causing settling and shoaling. Whether these two lift arrangements need to be joined or operated intermittently, *e.g.* by other types of agitation dredging, is a matter for detailed research and planning, but navigation interests will undoubtedly prefer arrangements with few interruptions. This means weirs in the jetties, perhaps a flared entrance, and a permanent lift arrangement that extends across all potential trouble areas in the entrance. (Tests by Weisman are now in progress: 1985).

Where tidal ranges are high (>3 meters) head pressure for fluidization (about 2 ts/m^2 or more) may be provided by gated storage basins, if areas for such basins are available. At locations where steep rivers flow to the sea as in Columbia, Ecuador, Iceland, New Zealand, Japan, Norway, Pakistan, and Venezuela) water may be extracted upstream from these rivers and carried in pressure pipes (steel or concrete) to the entrance to provide the necessary pressure for fluidization.

One of the most interesting recent proposals for

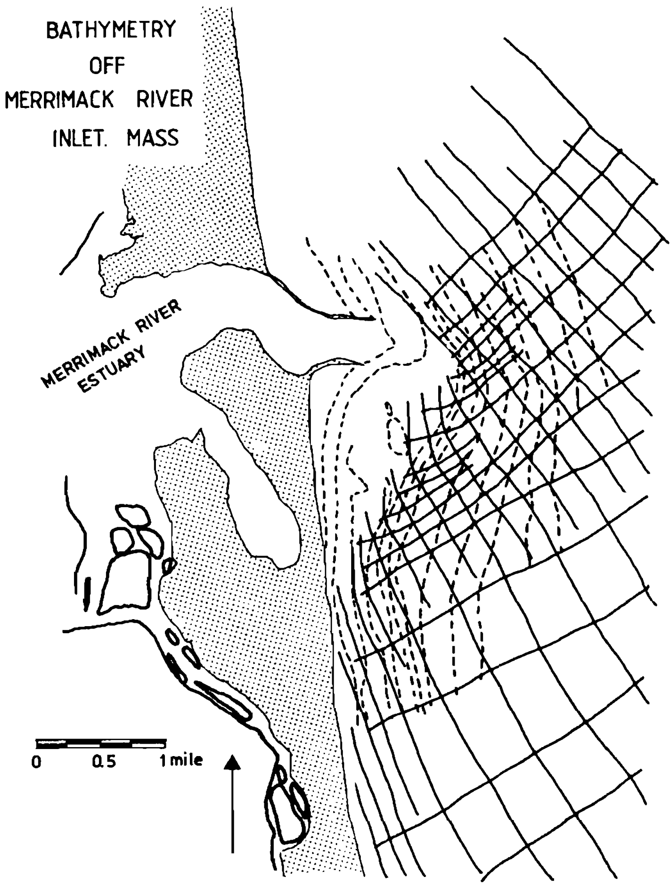

Figure 10. Wave refraction diagram at the mouth of the Merrimack Inlet, Massachusetts (HAYES *et al*, *1977*).

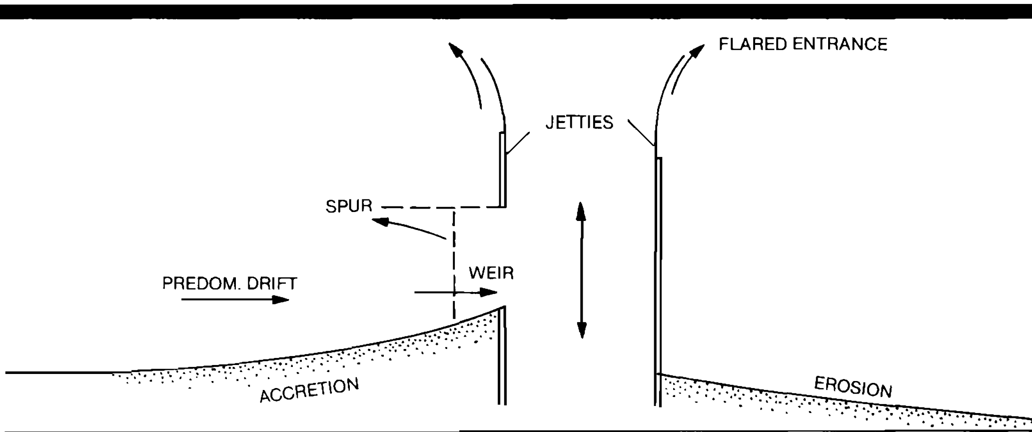

Figure 11. Various training and trapping arrangements for tidal entrances including weir, spur and flared jetties.

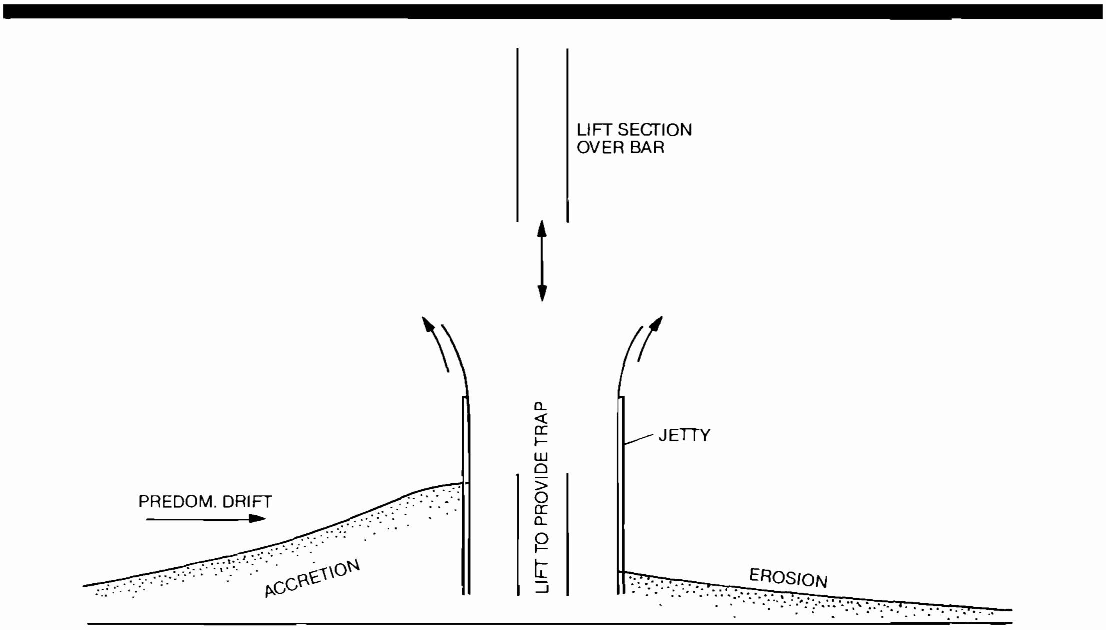

Figure 12. Hydraulic lift arrangements for critical sections of a tidal entrance.

improvements by training walls was reported by DRUERY and NIELSEN (1980). They describe a stabilization of the Hastings River, New South Wales, Australia as follows:

> "For over 40 years the entrance to the Hastings River was host to a large swash bar the presence of which created hazardous navigation conditions. The recent construction of a northern entrance jetty in 1977-1978, triggered an unprecendented onshore movement of the swash bar. The cause can be related to the elimination of a daily circulation of sand which had previously aided the dynamic stability of the swash bar."
>
> "Monitoring of post-construction changes has indicated that the swash bar will not return to its former size and there has been a substantial reduction in the width of the bar."
>
> "The long term configuration of the entrance bar and swash bar is linked to the occurrence of major floods. It was possible to discern past cycles of deposition by floods and subsequent slow onshore movement of the flood deposits."
>
> "It was possible to construct a conceptual model of entrance sedimentary processes which was suitable for predictions of morphological response. Although the model was based on elementary considerations of sediment budget, it was a highly effective tool for elucidating the subtleties of sediment transport relationships between the gross morphologic features of a tidal entrance."
>
> "Considerable fundamental research is necessary before full process understanding of tidal entrances will be achieved. Conceptual models as put forward in this paper are a useful interim step which combine the art and the science of coastal engineering and offer a means for assessing the impact of coastal works on macro coastal processes."

The explanation of this phenomena may not be as distant as the Australian authors thought. Actualy they closed a "swash" flood channel. Such closing always works that way! The Dutch also closed some of their tidal inlets and received, as a benefit, the spreading of ocean shoal material to either side of the entrance!

SUMMARY AND CONCLUSION

(1) Overall stability of tidal entrances on alluvial shores must consider all sections of the inlet channel, not just the gorge channel.

(2) Overall stability is related to the Ω/M_{tot} ratio by which the various degrees of overall stability may be described in a practical way related to shoals, bars, and navigational conditions.

Techniques are under development for determination of M_{total} which may be related to wave energies.

(3) Inlet ebb as well as inlet flood currents cause material transport to the entrance from either side of the inlet — all of the time — and even if they are weak currents.

(4) Protection of an inlet entrance against littoral drift deposits should take advantage of the flushing effects by ebb currents. These effects should decrease the adverse effects of secondary ebb currents and primary flood currents in flood channels by a combination of rejecting structures, traps, and natural or engineered lift arrangements in the navigation channel. These methods are suitable when greater depths are desired for reasons of navigation.

(5) Offshore bars and shoals should be subjected to much more study of their behavior and drifts.

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