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# COASTAL INLET FUNCTIONAL DESIGN: ANTICIPATING MORPHOLOGIC RESPONSE

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**Abstract**: Inlets are part of the coastal sediment-sharing system, and the presence of a new inlet will greatly modify the nearshore and bay morphology, as well as the up-drift and down-drift shorelines. Morphologic response to an inlet varies over several time and spatial scales. This paper analyzes general morphologic responses to the presence of a new coastal inlet in the context of functional design considerations that typically must balance navigation and shore-protection requirements.

## INTRODUCTION

Construction of new coastal inlets with jetties is rare. As coastlines have become more developed, however, environmental and engineering consequences for new or modified inlets have never been greater. For example, the jetties at many of the larger stabilized coastal inlets in the Unites States were constructed around the turn of the 20th Century, with federal jetties in the Great Lakes being the oldest in dating to the 1840s. When these early jetties were constructed, knowledge of coastal processes was limited. Main concerns were to furnish a reliable navigation channel and the feasibility of construction in the marine environment (The Engineer School 1932). Many of the earlier inlet stabilization projects were built on the shifting sediments of tidal flats and estuaries, far from infrastructure and development. The coast of the United States was relatively unpopulated, so consideration of the beaches adjacent to the inlets was minimal. This paper attempts to be an introductory resource of information about inlet engineering and morphologic responses, with focus on navigable inlets. Small breaches in barrier islands and in river mouths are made for environmental enhancements (Wamsley and Kraus 2005) and as a means of providing sand to the beach through relocation typically by closing and reopening the inlet up drift of the original location (e.g., Kana and

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14. ABSTRACT

**Inlets are part of the coastal sediment-sharing system, and the presence of a new inlet will greatly modify the nearshore and bay morphology, as well as the up-drift and down-drift shorelines. Morphologic response to an inlet varies over several time and spatial scales. This paper analyzes general morphologic responses to the presence of a new coastal inlet in the context of functional design considerations that typically must balance navigation and shore-protection requirements.**

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McKee 2003; Erickson et al. 2003). Such typically ephemeral inlets are not considered here.

Jetties are constructed to stabilize the position of the inlet, confine the current, protect the channel from sedimentation by longshore transport, and allow vessels to transit through the wave-breaking zone under non-stormy conditions. It is now well known that jetties and associated dredging operations to maintain the navigation channel will alter the position of the shoreline, eroding or advancing the beach, depending on various factors. These include the net and gross rates of longshore sediment transport, length of the jetties, depth and width of the navigation channel, bypassing practice at the inlet, and occurrence and strength of storms. An ebb shoal and flood shoal will form from material that would otherwise be available to the beach, and more complex morphology can develop (Fig 1), such as bypassing bars to the ebb shoal and attachment bars where bypassing sediment leaves or returns to the beach on either side of the inlet (Kraus 2000). Navigable inlets with large tidal prisms form ebb shoals containing millions to hundreds of millions of cubic meters of sediment. Because of the large change anticipated with construction of a new inlet with its navigation channel and jetties, modern design must account for both navigation reliability and future state of the nearshore morphology, adjacent beaches, and bay morphology. Morphologic change can occur over many years to centuries, and coastal response and engineering responsibility may extend far up drift and down drift of the inlet.

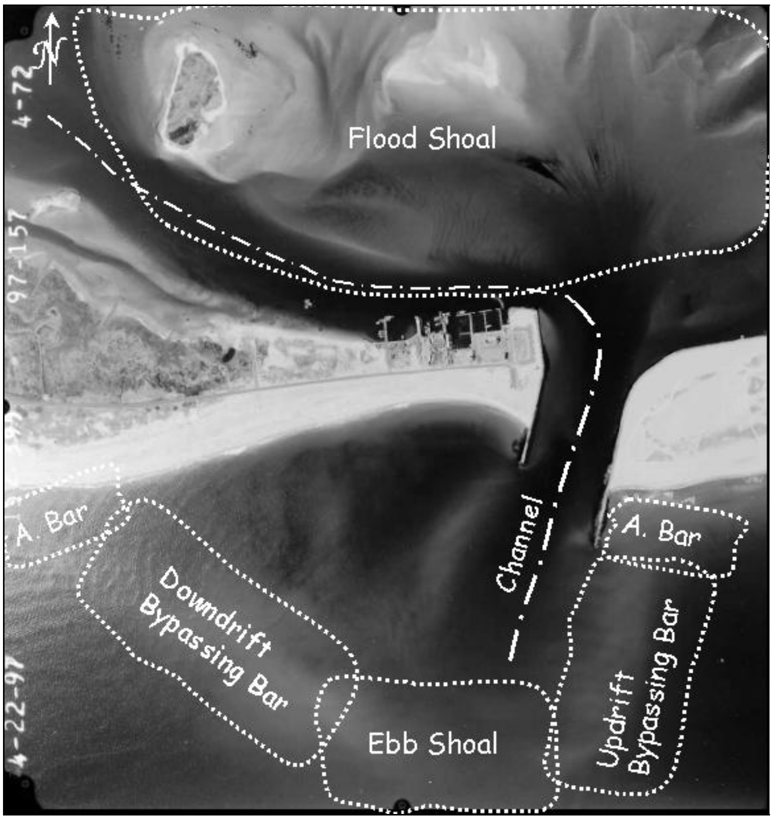

Fig. 1. Morphologic features, Shinnecock Inlet, New York

This paper presents an integrated summary of coastal inlet functional design and the various morphologic processes that must be taken into account in treating the ocean, inlet, adjacent beaches, and bay as a sediment-sharing system. The paper is based on experience in designing two inlets (including Packery Channel, Texas, under construction; Fig. 2), as well as study of many inlets on the four coasts of the United States ranging from largest to smallest. The objectives of this paper are to summarize major morphologic responses to coastal inlets and to give guidance for inlet functional design as it relates to navigation considerations and morphologic responses.

Fig. 2. Packery Channel (Inlet), Texas, under construction, March 2005

## INLET FUNCTIONAL DESIGN CONSIDERATONS

Inlet functional design must balance conflicting requirements of maintaining inlet stability, promoting natural sediment bypassing, and maximizing navigation reliability. Navigation reliability means providing safe navigation for the common wave and tide conditions. Considerations of inlet functional design with respect to interaction of the inlet, coast, and bay depend on the type of engineering action to be taken as:

1. Creation of a new inlet or relocation of an existing inlet.
2. Stabilization of an existing inlet by construction of jetties.
3. Modification of an existing inlet as by rehabilitation of the jetties, relocation of jetties, allowing existing jetties to deteriorate (a passive modification), deepening or widening the channel, and other similar activities.

These three classes of engineering actions induce different magnitudes and time scales of morphologic change. Although specific morphologic response and navigability conditions depend on the waves, tide, wind, bay area, channel depth, distance between jetties, length of jetties, amount of dredging, location of dredged material placement, and other factors, certain general morphologic responses will occur. Principal morphology and navigation issues relating to such engineering actions are:

1. Response of adjacent beaches.
2. Formation of ebb shoal and flood shoal.
3. Interruption of natural bypassing.
4. Inlet stability.
5. Navigation reliability.
6. Response of bay.
7. Ebb shoal collapse.
8. Cost of construction and maintenance dredging.

For each of these, one must consider the time scale, magnitude, and spatial extent. Development of inlet and regional sediment budgets is a first step in inlet functional design (e.g., Kana and Mason 1988; Rosati and Kraus 1999, 2001; Byrnes et al. 2003; Rosati 2005). A carefully formulated sediment budget provides information on the balance of net and gross longshore transport rates for different physical extents of the coast, long-term trends in shoreline change, and sediment sources and sinks. It also identifies gaps in needed information for assessing the present and future morphology.

## 1. Response of Adjacent Beaches

If an inlet experiences a dominant direction of longshore sediment transport, the typical response of the adjacent beaches is up-drift accretion and down-drift erosion. If the inlet is in a nodal region of longshore transport such that the long-term net rate is zero, shoreline response as accretion on both sides can result from jetty construction. However, as opposed to the situation where jetties interrupt appreciable longshore sediment transport (large net transport rate), an equilibrium shoreline configuration at nodal points may be reached within relatively few years, as found by Komar et al. (1976) for Pacific northwest coast inlets. Porous jetties can cause erosion of the up-drift beach by allowing sediment to leak through to the inlet channel, increasing dredging maintenance, and this loss is especially deleterious to the down-drift beach. Sand tightening of porous jetties near to shore can provide an immediate beach-growth enhancement (Creed et al. 1994).

Jetty construction at an existing inlet will confine the ebb-tidal current and push the ebb shoal offshore from its original location. Flanks of the ebb shoal not located in the ebb-tidal jet may migrate onshore and give the appearance of accretion by longshore transport on the down-drift side of the inlet, until the abandoned portions of the ebb shoal disappears, removing this sand source. The down-drift and, possibly, up-drift beaches will then begin to erode. The morphologic consequence of this abandonment is called ebb-shoal collapse or deflation, and it is discussed further in Section 7.

Bruun (1995, 2005) distinguishes the near-field adjustment and far-field adjustment of the down-drift shoreline at inlets. The near field is the shoreline reach between the down-drift (and possibly up-drift) jetty and the attachment bar (Fig. 3) and at many inlets near-field recession of the shoreline is chronic and requires special measures of shore protection (Hanson and Kraus 2001). This erosion may thin barrier islands to the point that breaching adjacent to the inlet is a concern. The far-field shoreline response can extend many kilometers beyond the inlet. The existence and extent of the shoreline adjustment depend in great part on (a) length of the jetties, (b) placement frequency and location of material dredged from the channel or bypassed mechanically, (c) balance of net and gross longshore sediment transport rates, and (d) elapsed time after jetty construction. Shoreline-change numerical models can give an estimate of adjustment of the shoreline to be expected. Such modeling must include the anticipated configuration of the ebb-tidal shoal in the wave transformation.

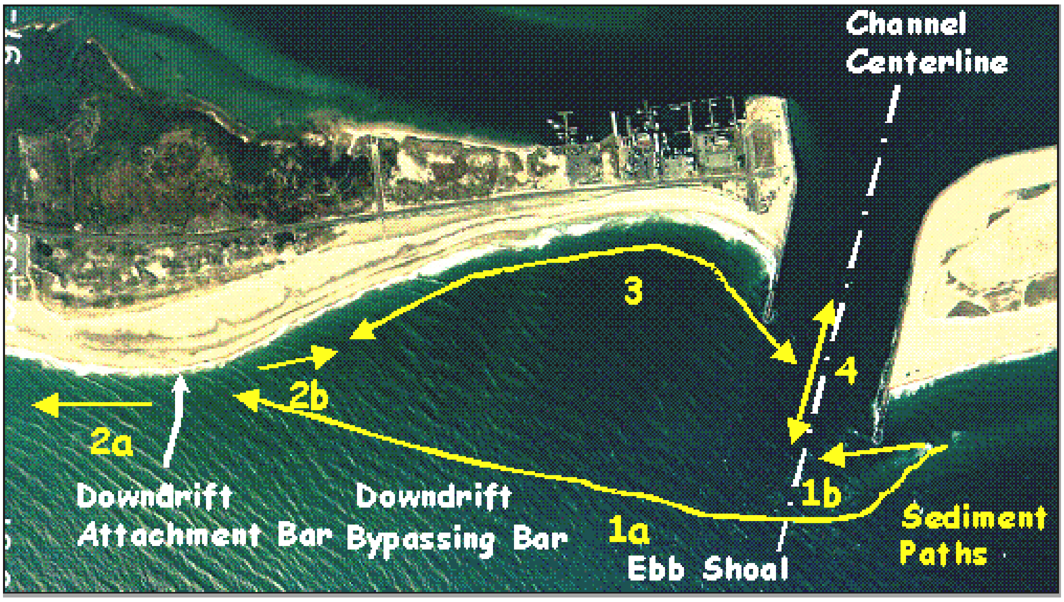

Fig. 3. Inferred sediment pathways and chronically eroding, isolated down-drift beach (area “3”), Shinnecock Inlet (from Hanson and Kraus 2001)

## 2. Formation of Ebb Shoal and Flood Shoal

Inlets are sinks of sediment through formation of ebb and flood shoals that are supplied predominantly by longshore sediment transport. Creation or relocation of an inlet will cause formation of new ebb and flood shoals. Likewise, modification of jetties, such as lengthening one or both, or changing the distance between them, will alter the tidal current and, therefore, the locations of the shoals. Because it is understood that jetties interrupt longshore sediment transport, typically the material removed in cutting a new inlet channel is placed on the down-drift beach or stockpiled to do so in the case of highly variable longshore transport direction. As an example, Fig. 2 shows material dredged during inlet cutting that was pumped down drift (white strip of dry sand in bottom of photograph), in front of a seawall and condominium.

Empirical predictive formulas are available to calculate the volume of the ebb shoal complex (Walton and Adams 1976) and, with less reliability, the volume of the flood shoal (Carr de Betts 2000). These formulas are based on the tidal prism $P$, which is the amount of water entering through an inlet on ebb or exiting on flood, exclusive of river flow and wind-generated currents. These predictive expressions have the form:

$$V_F = BP^k \tag{1}$$

in which $V_F$ = equilibrium volume of the given inlet morphologic feature (ebb shoal or flood shoal), and $B$ and $k$ = empirical coefficients. The values of the empirical coefficients for prediction ebb shoal volume depend weakly on a wave-energy parameter as determined for the three ocean coasts of the United States and in recognition that greater wave energy will tend to transport material off the shoal. The formulas of Carr de Betts (2000) were derived only for Florida inlets and do not have a wave dependence.

The time scale for growth of inlet morphologic features is long and can require centuries because (a) the supply of sediment is limited by the longshore transport rate at the site, (b) the ebb shoal will bypass sediment down drift and to other inlet morphologic features while it is growing, and (c) storms can reduce the size of shoals. The Inlet Reservoir Model (Kraus 2000) can estimate the time rate of volume growth and natural bypassing of inlet morphologic features. The characteristic time scale $\tau$ of this model is:

$$\tau = \frac{V_e}{Q_g} \tag{2}$$

where $V_e$ = equilibrium volume of the ebb and flood shoal complex, and $Q_g$ = gross rate of transport arriving at the inlet. This ratio expresses the capacity of the ebb shoal to hold sediment to its rate of supply.

## 3. Interruption of Natural Bypassing

The modes of natural sediment bypassing at natural and stabilized inlets have been discussed by FitzGerald et al. (2001). Sediment pathways for natural bypassing depend on the wave conditions, particularly between typical seas and storms (Militello and Kraus 2003). If the jetties are long relative to the surf zone, thereby pushing the ebb shoal outside the active littoral zone, or if the navigation channel is dredged very deep, total interruption of natural bypassing is possible, as reported by Olsen (1977) for St. Marys Entrance, Florida. Sediment must then be bypassed mechanically, as part of maintenance dredging. The time scale for natural bypassing is long, perhaps extending to hundreds of years, and it depends on $\tau$. Applications of the Inlet Reservoir Model for decadal and century-long calculation of natural bypassing have been made by Kraus (2000), Kraus et al. (2003), Zarillo et al. (2003), and Dabees and Kraus (2005).

Bruun and Gerritsen (1959) introduced a classification and empirical relation for inlet bypassing and morphologic state of the channel based on a quantity:

$$r = \frac{P}{M_{tot}} \tag{3}$$

in which $M_{tot}$ = volume of material carried to the inlet entrance by the longshore transport in 1 year. Because the formula of Walton and Adams (1976) relates tidal prism to ebb shoal volume, and $M_{tot}$ is closely related to the gross longshore transport in a year, the parameter $r$ is directly connected with the characteristic time scale $\tau$ for inlet morphology change, bypassing, and suitability of the channel for navigation.

Ebb shoals and, possibly flood shoals (Militello and Kraus 2001a) offer a source of material for beach nourishment. Mining of the ebb shoal disrupts natural bypassing and must be done with caution (Cialone and Stauble 1998). Ebb shoals can also be reconfigured by storms (Mehta et al. 1996), which will also disrupt natural bypassing. The Inlet Reservoir Model can be applied to estimate such processes. Dabees and Kraus (2005) describe the general methodology of the Reservoir Model, embedded in regional modeling of the tidal hydrodynamics and analysis of inlet morphology and shoreline change, through several epochs with different forcing and engineering actions.

## 4. Inlet Stability

Stability can refer either to inlet plan-view location or to inlet channel cross-sectional area. Jetties stabilize inlet location; however, the inlet navigation channel can migrate in response to changes in the jetties (Cialone et al. 1999) or in the forcing conditions (Militello and Kraus 2001a, 2001b). The desired cross-sectional area is determined by tidal prism and other water discharges (such as by wind and rivers), distance between jetties, length of jetties, longshore sediment transport rate, wave height (which figures directly in sediment bypassing), and sediment type as the leading factors. O'Brien (1931), Jarrett (1976), Hume and Hendendorf (1992) and others have found a simple empirical relation between tidal prism and minimum channel cross-sectional area below mean sea level of stable inlets $A_C$ as:

$$A_C = CP^n \tag{4}$$

in which $C$ and $n$ (~ 1) are empirical coefficients. Kraus (1998) derived a theoretical form for the coefficient $C$ to be:

$$C = \left( \frac{\alpha \pi^3 m^2 W_e^{4/3}}{Q_g T^3} \right)^{0.3} \tag{5}$$

in which $\alpha$ = empirical sediment transport coefficient of order unity, $m^2$ = Mannings coefficient squared (units of $\sec^2/\mathrm{m}^{2/3}$), $W_e$ = equilibrium or minimum width of inlet, and $T$ is the main tidal period as diurnal or semidiurnal. Values of $C$ obtained with this formula are of the order of magnitude as those empirically determined. Assuming qualitative validity of Eq. 5, the cross-sectional area depends weakly, but inversely on the gross longshore transport rate, meaning that for all other factors being equal, the inlet channel cross-sectional area will be larger for areas with smaller transport rate.

Inlet channel stability is promoted by a smaller ratio of its width to hydraulic radius at mean sea level, $W/R$. As a first approximation, $R$ can be replaced by average depth in the entrance channel. Jarrett (1976) found that most dual-jettied inlets had $W/R < 100$. Such channels tend to be deep and, therefore, more hydraulically efficient.

A classical approach to inlet stability is that of Escoffier (1940), in which a "stability curve" is developed relating channel cross-sectional area to the velocity through the inlet. Empirically, a mean-maximum velocity (mean of maxima of spring tides, for example) of 1.1 m/sec is necessary to maintain a minimal channel cross-sectional area, and the Escoffier analysis is compatible with that result. A PC program is available to perform this analysis (Seabergh and Kraus 1997).

## 5. Navigation Reliability

Jetties are typically extended seaward to at least the depth of the navigation channel to protect the channel against intrusion of longshore sediment transport and to shelter vessels from breaking waves and the longshore current in the surf zone under non-storm conditions. Channels may be dredged deeper over the entrance bar or ebb shoal because of the presence of breaking waves there. Jetties are sometimes oriented and configured with doglegs to provide protection against higher waves from their incident direction. Therefore, jetty length and orientation, wave height and direction, and channel depth and orientation are three sets of interconnected parameters entering functional design of navigable inlets. As the ebb shoal grows at a new or modified inlet, it will reach a limiting depth that may be a concern to navigation channel design. Guidance is available to predict this minimum depth (Buonaiuto and Kraus 2003).

A design conflict may arise in that small $W/R$, preferable for scouring the channel and maintaining cross-sectional area, also promotes a strong ebb and flood current. A strong ebb current increases wave steepness (wave height divided by wavelength) in the inlet entrance, degrading navigation reliability. A strong tidal current reduces rudder control of larger vessels, which approach inlets at moderate speed.

If feasible, channel orientation is into the predominant waves, typically "straight out." However, if there is a saddle in the ebb shoal, vessel captains will tend to maneuver through it toward deeper water, which gives greater under-keel clearance and is typically an area of reduced wave height because of the deeper water. Price (1952) advocated taking advantage of the natural orientation of the main (ebb) inlet channel for navigation, but such an orientation may put vessels abeam to incident waves. Ship simulations based on computed waves and currents can assist in designing channel orientation.

## 6. Response of Bay

This functional design consideration covers such aspects as (a) change in magnitude, phasing, and duration of storm water levels; (b) change in bay flushing, (c) salinity change; and (d) elimination of natural bay bottom by the footprint of the new flood shoal. If a new inlet is cut, the perimeter of the bay, estuary, or lagoon that it connects to the ocean will experience a change in water level, circulation pattern, and, perhaps, salinity, under both typical and storm sea conditions. These responses are readily evaluated with numerical simulations models of tidal circulation and storm surge (e.g., Brown and Militello 1996; Kraus et al. 2003). Results will depend on the existence of other inlets to the bay system, relative cross-sectional areas and locations of the other inlets, phasing of the tide, and track and wind of the storm, among other factors. Figures 4a and 4b give an example of calculation of the tidal circulation for hypothetical relocation of Fire Island Inlet, New York.

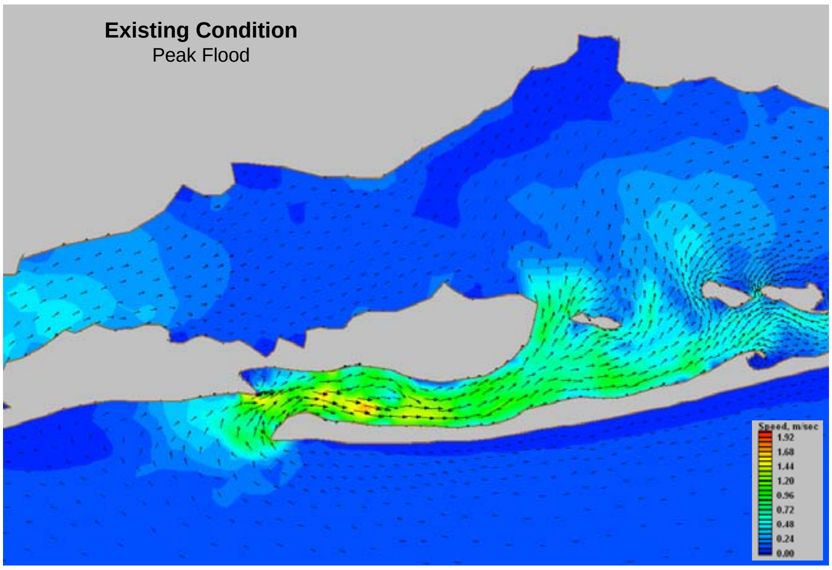

Fig. 4a. Existing inlet

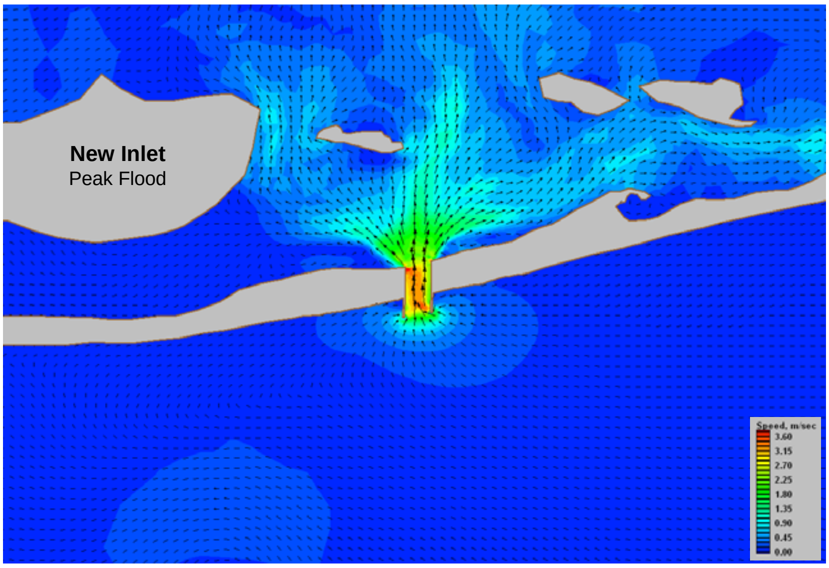

Fig. 4b. Hypothetical relocated inlet

Fig. 4. Simulation of flood current at Fire Island Inlet, New York (Kraus et al. 2003)

Burial of a portion of the bay bottom by the new flood shoal may be viewed as an environmental enhancement if the bay bottom is not productive or as an environmental degradation if the bottom is a resource. Often, the flood shoal will form near or at the intra-coastal waterway passing parallel to the coast in the bay. In such a case, dredging requirements for the intra-coastal waterway will increase.

## 7. Ebb Shoal Collapse

Ebb shoal collapse or deflation means migration of portion or the entire ebb shoal onshore, alongshore, and offshore because of loss of the ebb-tidal current (abandonment) over the shoal (Hansen and Knowles 1988; Pope 1991). The shoal can collapse because of jetty construction or modification, or because an inlet is relocated. Pope (1991) developed a conceptual framework (see Pope Fig. 5) of the morphologic evolution of an ebb-dominated jettied inlet that moves from natural bypassing in its original state to collapse of the ebb shoal and subsequent erosion of the ebb-shoal platform with elapsed time. Byrnes et al. (2003) document collapse of the southern (up drift) and northern (down drift) flanks of the ebb shoal at Grays Harbor, Washington, and seaward translation of the central portion of the ebb shoal in response to construction of long jetties at the turn of the 20th Century. Kana and McKee (2003) discuss the twice-relocated Captain Sams Inlet in South Carolina, for which collapse of the ebb shoal at the closed inlet was anticipated to nourish the beach (Kana and Mason 1988).

## 8. Cost of Construction and Maintenance Dredging

Jetty construction costs thousands of dollars per meter of length. As jetties extend into deeper water, construction cost greatly increases because it is proportional to stone volume, and larger physical plant is required for the construction. Long jetties relative to the navigation channel depth or typical width of the surf zone will intercept greater amounts of longshore sediment transport, requiring more planning and expense in replacing natural bypassing with mechanical bypassing.

Maintenance dredging may offer the least-cost means of bypassing sediment, if the waves and currents allow nearshore placement or pumping to the beach. Seabergh and Kraus (2003) review bypassing techniques and engineering design considerations. There is a tradeoff between the one-time construction cost to protect the channel from sedimentation and constructing shorter jetties, but dredging more. Thus, jetty weirs, jetty spurs, and channel deposition basins are strategies developed that combine consideration of protecting the navigation channel from infilling while stockpiling or directing sediment incident to the inlet to a convenient location for bypassing action.

## CONCLUDING DISCUSSION

Maintenance of coastal inlet navigation channels and the adjacent beaches brings conflicting requirements. For example, jetties are built in part to confine and strengthen the current, but the resultant seaward translation of the ebb shoal interrupts natural sediment bypassing. In turn, interruption of the natural bypassing rates and pathways compromise the integrity of the adjacent beaches, with potential feedback to destabilize the jetties and inlet navigation channel. Recognition of these conflicts will aid the engineer in design of an optimal channel for navigation within a systems approach for management of dredged material and its distribution to the adjacent beaches.

Inlet morphology evolves over decades to centuries, and shoal development and change can be complex. Thus, the consequences of modifications to an existing inlet may not be noted for many years. Predictive technology is emerging that can address issues related to short-term and long-term morphology change at engineering inlets.

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