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Journal of Marine Science
http://ojs.bilpublishing.com/index.php/jms

ARTICLE

Managing Tidal Inlets

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ARTICLE INFO

Article history
Received: 17 May 2019
Accepted: 11 June 2019
Published Online: 30 August 2019

Keywords:
Inlet
Littoral drift
Shields parameter
Tidal prism
Cobble armoring
Coastal

ABSTRACT

Sandy inlets are in a dynamic equilibrium between wave-driven littoral drift acting to close them, and tidal flows keeping them open. Their beds are in a continual state of suspension and deposition, so their bathymetry and even location are always in flux. Even so, a nearly linear relationship between an inlet's cross-sectional flow area and the inshore tidal prism is maintained - except when major wind and/or runoff events act to close or widen an inlet. Inlet location can be stabilized by jetties, but dredging may still be necessary to maintain a navigable channel. Armoring with rock large enough to resist erosion can protect an inlet bed or river mouth from excessive storm flow erosion. Armoring can also be used as a stratagem to close inlets.

1. Introduction

Ocean coastlines are dynamic. Waves, large and small, crash against the coast with great and relentless force, grind rocks into sand, and push the sand along the shore. Tides raise and lower the whole ocean twice a day, by a few centimeters or by multiple meters. Inland, rivers flow toward the sea and either enter it directly or pool in tidal bays before discharging through inlets. In extreme weather, new inlets can be cut through a sandy barrier beach by storm waves, or can be temporarily enlarged by storm runoff from a tributary river.

This paper is a review of some of the behaviors of sandy tidal inlets, with mention of some measures employed to manage their stability, based on the author's study and experience.

2. Definitions

Figure 1 is a definition profile sketch for some of the terms used herein. A tidal bay is a body of water separated from the ocean by a sandy beach, except for an inlet, which is a gap in the beach.

The tide range is the vertical distance between high and low tide in the tidal bay.

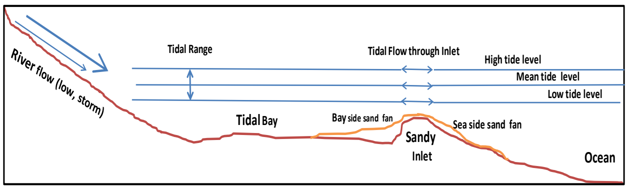

Figure 1. Definition profile sketch for sandy inlets

Littoral drift is the movement of sand along the ocean beach, driven by wave action.

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 DOI: https://doi.org/10.30564/jms.v1i2.850

"Fair weather equilibrium" is a term coined to describe a dynamic equilibrium in which normal ocean wave action drives littoral drift along the shore tending to fill and close the inlet, but which is countered by tidal flow (flood on a rising tide, ebb on a falling tide) that scours the new sand and maintains the inlet cross-section. The sand scoured from the inlet is deposited in submarine sand fans both inland and offshore of the inlet (Shore Protection Manual [1]).

3. The Area/Prism Relationship

Many years ago coastal oceanographers[2,3,4] realized that there is a nearly linear relationship between the cross-sectional flow area, A, of an inlet (below mean tide level) and the tidal prism, P, the product of the tide range and the surface area of the tidal bay inland of the inlet. From Figure (2),

$$3.5E4 \text{ ft} < P/A < 7.2E4 \text{ ft, or}$$

$$1.1E4 \text{ m} < P/A < 2.2E4 \text{ m}, \qquad (1)$$

a relatively narrow range despite A ranging over two orders of magnitude.

The semidiurnal tidal period, T, equals 12.5 hours = 45,000 seconds. The mean flow rate, Q, through the inlet equals P divided by half of T. Thus the range of mean flow velocity V = Q/A is

$$0.5 < Q/A < 1 \text{ m/s} \qquad (2)$$

throughout the range of Figure 2.

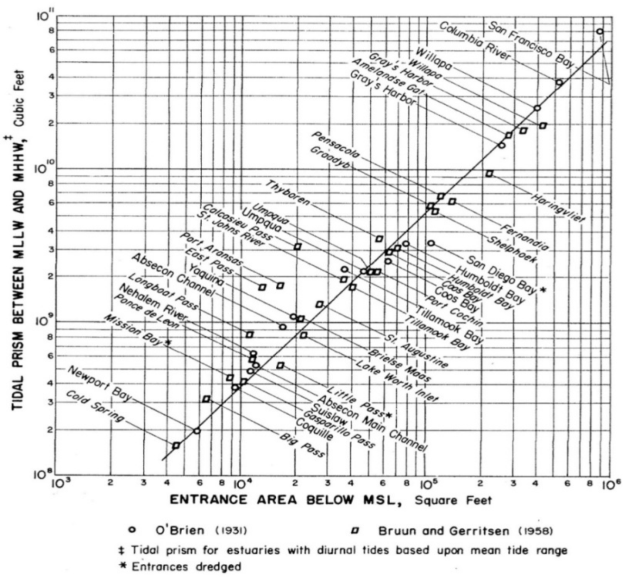

Figure 2. Empirical Plot of Tidal Prism vs Entrance Area (O'Brien[2] and Bruun and Gerritsen[3] as reported in Wiegel[4])

4. Sediment Suspension; Threshold for Erosion

The tendency to erode sediments of various grain diameters can be estimated by use of the Shields [5] relationship (Figure 3):

$$\tau/(\gamma[s_s - 1]d) = \tau/(\rho g[s_s - 1]d) = f(d[\tau/\rho]^{0.5}/\nu) \qquad (3)$$

in which $\tau/(\gamma[s_s - 1]d)$, or $\tau/(\rho g[s_s - 1]d)$, is a dimensionless ratio of the shear stress exerted on sediment grains of specific gravity s_s and diameter d, and $d(\tau/\rho)^{0.5}/\nu$ is a Reynolds number for the flow. (For sandy inlets, $d(\tau/\rho)^{0.5}/\nu$ ranges from about 10 to 400.)

Furthermore:

τ = the shear stress that the flow through the gap exerts on the granular bed,

ρ = the density of the seawater, about 1025 kg/m^3;

g = the acceleration of gravity, 9.81 m/s^2;

$\gamma = \rho g$ = the unit weight of water;

s_s = the specific gravity of the sediment grains, about 2.65 for silica and for calcium carbonate sands;

d = the characteristic diameter of the sediment grains;

R = the inlet hydraulic radius = the ratio of A to the wetted perimeter (bottom and walls) of the inlet cross-section. (R is slightly greater than the mean inlet flow depth, y);

ν = the kinematic viscosity of the seawater, about 10^{-6} m^2/s.

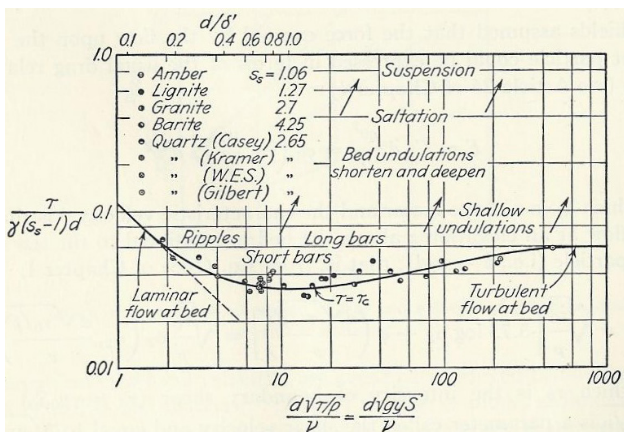

Figure 3. Shields Sediment Movement Threshold Diagram (Shields[5], cited in Rouse[6])

The ordinate, $\tau/(\rho g[s_s - 1]d)$, sometimes called the Shields parameter, is the dimensionless ratio of dynamic forces on the sediment particles to the gravitational forces. The greater this ratio, the more likely the sediment particles are to be suspended in the flow. The solid curve in the figure denotes the experimentally determined threshold below which particles will not be moved by the current in the flow. Note that

  DOI: https://doi.org/10.30564/jms.v1i2.850

$$\tau/(\rho g[s_s - 1]d) = SR/([s_s - 1]d). \quad (4)$$

The solid spoon-shaped curve in Figure 3 marks the experimentally determined threshold between non-erosive conditions (below the curve) and conditions (above the curve) in which the sediment grains will roll, form ripples, bounce, or simply be suspended in the overlying current. Several example grain sizes are listed in Table 1. Under the sandy inlet conditions of Equation (2), only grains 1 cm or larger will resist scour. Since sand grains are much finer than 1 cm, an inlet bed is in a continual state of suspension and deposition. The bathymetry shifts from tide to tide, and if not constrained, the inlet position can gradually migrate along the shoreline.

Table 1. Shields Parameter for the Propensity for Suspension in "Fair Weather Equilibrium" Conditions in a Sandy Inlet, for a Range of Grain Sizes

SR =	SR,m =	1.41E-04	6.25E-04	
	V,m/sec	0.5	1.0	
0.00015	d=0.15mm	0.571	2.525	Saltation, suspension
0.0005	d = 0.5mm	0.171	0.758	Saltation
0.001	d = 1mm	0.086	0.379	Ripples, dunes
0.005	d = 5mm	0.017	0.076	Threshold of erosion
0.01	d = 10mm	0.009	0.038	Resists scour

5. Examples of Sandy Inlet Behavior

Case 1: Ca Cong, Vietnam. Figures 4a and 4b show two photographs of an inlet, taken 3 years apart. The inlet appears to have migrated along the coast by about 400m in that time. Note, however, that the dimensions of the inlet have remained approximately constant. Submerged sand fans can be seen.

Figure 4a. Ca Cong inlet, Vietnam, in 2014

Figure 4b. Ca Cong inlet in 2017

Case 2: Shinnecock Inlet on the south shore of Long Island, New York is shown in Figure 5. The sides of the inlet have been lined with rock jetties, to stabilize the location (prevent migration), but not to attempt to alter the natural width of the inlet. A submerged sand fan is clearly visible in the tidal bay, and less clearly visible offshore of the inlet. Because of the constantly shifting bathymetry, power boat pilots must use extreme caution and keen observation to avoid grounding on shoals.

Figure 5. A sandy inlet between the sea and a coastal bay

In cases of strong littoral drift and a commercial need for deep-draft navigability, dredges have been employed at some inlets to move the sand accumulating updrift of a jetty (such as seen in Figure 5) past the inlet for deposition downdrift of the inlet (Shore Protection Manual[7]).

Case 3: The Mahlongwa River, in South Africa, flows to the Indian Ocean. In Figure 6a, littoral drift has moved sand nearly the whole way across the river mouth. At this site, the tidal prism of the tidewater part of the river is insufficient to keep the inlet open, and in fact the inlet can

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close fully during the low-flow season of the river. When the rainy season in the catchment resumes, the river flow breaks across the inlet, and erodes a new wide channel, as seen in Figure 6b.

Figure 6a. Mahlongwa River mouth with small tidal prism, nearly closed by littoral drift

Figure 6b. Mahlongwa River mouth opened by seasonal storm flow

Case 4: In a coastal city, urban development included cutting a new outlet for a river with a small tidal prism, resulting in a tidal flow of about 3 m^3/s (but a large storm flow of several hundred m^3/s in monsoon season). The new river mouth is bounded by retaining walls 66 m apart (Figures 7a, 7b, and 7c).

The river discharges to a sandy beach with littoral drift. The tidal part of the river has a tidal prism of about 100,000 m^3. The local ocean tides are predominantly semi-diurnal, with a range of 0.5 to 1.0 m; a typical velocity for tidal rise or fall is about $3x10^{-5}$ m/s. The mean tidal flow rate is thus about $3m^3$/s. The sand grain size is about 0.15mm. The hydraulic radius is of the order of 1 m.

From Equation (1) the fair weather equilibrium area A is about 7 m^2. With an hydraulic radius, R, of 1m, the channel width can only be about 7 m. Indeed, the flow width is far less than the constructed width of 66m between retaining walls, as seen in the several views of Figures 7.

6. Hard Boundaries, Rapid Flow

When the sediment grain size is large enough to withstand erosion, i.e. is larger than the "threshold" size for sediment movement; or the flow boundaries are in fact concrete or monolithic rock, the flow velocity may be much larger than the gentle 0.5 to 1m/s of sandy inlets in fair weather equilibrium.

Figures 7a, b, and c. A river mouth with tidal inlet area much smaller than the width between constructed retaining walls

Case 4 continued: In monsoon season, the stormwater flow in the river shown in Figures 7 can grow to several hundred cubic meters per second, and the velocity in the channel, even using the full 66-m width, is 2 m/s or more. This is sufficient to erode the sandy bed of the river mouth down by several meters. Such erosion can threaten the integrity of the retaining walls, and the soils behind them.

A means to inhibit such damage is to armor the bed with cobbles of d = 20 mm, 100 mm, or larger, particularly along the base of the retaining walls.

Case 5. In the northeast USA, it was desired to reduce the salinity in a tidal bay by constricting the entrance of a natural inlet, using side retaining walls. Yet the engineers did not consider the sandy inlet bed, which of course eroded down to recover the cross-sectional area lost by installation of the walls, "obeying" Equation (1). Negligible change to tidal bay salinity was achieved (Spaulding [8]). Some structural peril to nearby shore structures may

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have occurred. Paving the inlet with appropriately sized cobbles to resist erosion would have been a more effective way to constrict the inlet (though with increased flow velocity, and challenge to navigation) .

Case 6: "The Horries," Australia. An interesting exception to the gentle tidal flows through sandy inlets is the "horizontal waterfall" phenomenon on the coast of the Kimberley Wilderness in Western Australia. The narrow inlets are formed between rock hills, not easily eroded, and the resulting energetic white-water tidal flows are popular as tourist attractions (Figures 8a and 8b.)

Figure 8a. White-water rapids flood through a "horizontal waterfall" inlet, Western Australia

Figure 8b. White-water rapids ebb through the hard rock inlet

7. Closure of a tidal estuary

In the limiting case of nearly total constriction, the tide range in a tidal bay approaches zero, and headloss across the inlet approaches the sea's tidal amplitude, H, i.e. half its tidal range:

Surface elevation difference = Headloss = Entry Loss + Exit Loss + Friction Loss

$$H = 0.2\ (Q/A)^2/2g + 1.0\ (Q/A)^2/2g + SL \quad (5)$$

In which S is the friction slope (i.e. the water surface slope) across the inlet and L is the flow length of the inlet.

The Manning friction formula (in SI units) is $V = R^{2/3}*S^{1/2}/n$, where n is a roughness coefficient. This may be written $(Vn)^2 = R^{1/3}(SR)$, or $SR = Q^2n^2/(A^2R^{1/3})$, so

$$SL = LQ^2n^2/(A^2R^{4/3}),\ \text{and} \quad (6)$$

$$H = (Q/A)^2/2g*(1.2 + 2gLn^2/R^{4/3}). \quad (7)$$

For erosion threshold conditions (Figure 3), the Shields parameter takes a value of about 0.06. In that case $SR = [s_s - 1]d*0.06$; but also $SR = Q^2n^2/(A^2R^{1/3})$, so we can eliminate $(Q/A)^2$ from Equation (7):

$$H = ([s_s - 1]d*0.06*R^{1/3}/2gn^2)*(1.2 + 2gLn^2/(R^{4/3}). \quad (8)$$

Rearrange to solve for d:

$$d = 2gn^2H/\{([s_s - 1]*0.06*R^{1/3})*(1.2 + 2gLn^2/(R^{4/3})\}. \quad (9)$$

With $s_s = 2.65$ and $g = 9.81\ m/s^2$,

$$d = 198n^2H/[R^{1/3}*(1.2 + 19.8Ln^2/(R^{4/3})]. \quad (10)$$

Note that in this limiting condition the threshold grain size, d, is directly proportional to the tidal amplitude, H, but independent of Q or A. However, there is a dependence on R.

If now $n = 0.025$, $R \approx 3m$, $L = 25m$, and $H = 1.5m$,

$$d = 0.1856/(1.441*1.271) = 0.101m \approx 100mm, \quad (11)$$

the size of sediment units (grains) required to withstand erosion.

Case 7: Cobble armoring to help dam a tidal estuary. A small tidal estuary was to be dammed to create a fresh-water reservoir. The 850-m long dam was to consist of an impermeable slurry wall, contained on each side by sand fill and shouldering rockfill bunds (French and Harley [9]).

The bed of the estuary consists of fine sands and silts. The estuary opens to a "sea" that is tidal but with minimal wave energy, causing negligible littoral drift. The semidiurnal tidal exchange caused only very small flow velocity in and out of the wide-mouthed estuary.

Ultimately, of course, the completed reservoir would have no tidal rise and fall.

It was recognized that as dam construction progressed across the mouth of the estuary, the tide range in the estuary would be gradually constricted, leading to increasing water surface differential elevations between the estuary and the “sea.” There would be increasingly rapid flow, and increasing potential to scour the bed, through the gap not yet dammed.

The selected closure strategy was:

(1) To construct the dam, working from each shore, until there remained a gap of width and depth that would just begin to erode the native bed material;

(2) To estimate the greatest shear stress on the bed of the gap;

(3) To pave the gap with rock of a size adequate to resist movement under that maximum shear stress;

(4) To quickly fill the gap with that size rock, completing a temporary closure to enable completion of the rockfill-sand-slurry-sand-rockfill dam cross-section throughout its span of the estuary mouth.

Accordingly, after dam construction left a gap somewhat less than 100 m wide, it was noticed that the fine sands of the natural bed were indeed beginning to scour. Rocks with a median diameter of about 500 mm, and not more than 10 percent finer than 100 mm, were placed in the gap as quickly as possible, carpeting the bed, and halting the scour. Continued rockfill formed a temporary closure to enable the contractor to complete construction of the dam without the nuisance of high-energy tidal flow rushing through.

8. Discussion

Despite the very dynamic behavior of an ocean’s sandy coastline, where inlets to tidal bays can close, open, and shift location, a “fair weather equilibrium” of tidal ebb and flow through an inlet counters the tendency of wave-driven littoral drift to close it. The inlet cross-sectional area, A, is nearly directly proportional to the tidal prism, P. The mean flow velocity through a sandy inlet is commonly about 0.5 to 1.0 m/s, over a wide range of A and P.

Engineering attempts to increase the area, A, or to constrict it, will be frustrated if the A:P ratio is not adequately considered. Examples are given.

When flow velocity is increased, by design or by storm runoff, sandy inlet beds will scour. Erosion can be checked by armoring the inlet bed with cobbles of adequate size.

This paper describes a few of the ways that water and sand behave at tidal inlets, and of measures that can be considered in managing the location and bathymetry of inlets. Structures and dredging as routinely practiced elsewhere may be extremely expensive, ineffective or even counterproductive, at inlets. Successful inlet management consists of assessing the tidal prism of a tidal bay, the anticipated storm discharge of a river, and the magnitude and direction of the local littoral drift. The commercial and societal benefits of management measures can be weighed against their cost. Ineffective management efforts can be avoided altogether.

This advice is familiar to coastal civil engineers. Yet it may well be of ancillary interest to “blue-water” oceanographers, and of essential interest to land-bound engineers tasked with a coastal engineering challenge.

Satellite images of inlets were acquired via Google Earth Pro.

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