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Sedimentation Dynamics of Tidal Inlets

Clifford R. Merz1 and Panagiotis D. Scarlatos2, M.ASCE

Abstract

Tidal inlets are very dynamic systems subject to continuous morphological changes under the action of tides, waves and transported sediments. Although flow and sediment dynamics are interactive, for simplicity, they can be decoupled. By accounting only for astronomic tidal effects, the flood cycle can be approximated by means of potential flow toward a sink while the ebb by the hydrodynamics of a plane jet. Using flow field simulation data, the amount and distribution of the moving sediment can be quantified by employing existing methods for estimation of bedload and suspended sediment transport. The applicability of the model is tested against field data from the Jupiter Inlet in S.E. Florida.

Introduction

Tidal inlets are narrow natural or artificial openings that connect protected coastal waters (i.e., lagoon, bay) with the open sea. Tidal inlets are very dynamic systems. Naturally, they occur as the result of severe erosion and failure of a coastal barrier inland caused during a severe storm. Thereafter, wave action and littoral drift tend to deposit sediments in the vicinity of the inlet. This eventually leads either to a complete closure and disappearance of the inlet or to its migration along the coast (Bruun and Gerritsen, 1958). Generally, a detailed simulation of tidal inlet dynamics requires a time–dependent, three–dimensional coupled hydrodynamics–sediment transport model. However, for many practical applications the system can be simplified by using a number of approximations and by decoupling flow dynamics from sediment transport.

There is a number of mathematical models developed for simulation of inlet behavior (van de Kreeke, 1988). Some of these models describe flow within the inlet using as boundary conditions the conditions at the open sea and the connecting inland water body (Seelig, et al., 1977). Other models simulate the flow in the offshore area using as boundary conditions the flow at the inlet mouth (Özsoy and Unluata, 1982).

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The model developed in this study belongs in the latter category. Analytical solutions were applied for the description of both flood and ebb cycles. Sediment budget, including bedload and suspended matter was estimated on a finite spatial grid. The results were tested against data from the Jupiter inlet in S.E. Florida.

Methodology

The model developed in this study incorporates three separate computational components: ebb hydrodynamics, flood hydrodynamics and sediment transport.

Ebb Hydrodynamics. Flow during the ebb cycle can be simulated by means of jet dynamics (Purandare, 1977; Wang, et al., 1983). Assuming a uniform velocity distribution along the depth and negligible buoyancy effects, the governing equations for a tidal jet are given as (Özsoy, 1977)

\[
\frac{\partial (uh)}{\partial x} + \frac{\partial (vh)}{\partial y} = 0
\]

(1)

\[
\frac{\partial (u^2h)}{\partial x} + \frac{\partial (uvh)}{\partial y} = -Fulul - \frac{\partial (u'v')}{\partial y}
\]

(2)

where \( h \) is the water depth, \( u, v \) are the depth-averaged velocities in the \( x \) and \( y \) directions respectively, \( F \) is a friction factor, \( u', v' \) are the turbulent velocity fluctuations, \( x \) is the offshore direction and \( y \) is the alongshore direction. Employing the self-similarity feature of jet flows, the velocity is expressed as

\[
\frac{u}{u_c} = f(\eta), \quad \eta = \frac{y}{b(x)}
\]

(3)

where \( u_c \) is the centerline offshore velocity, \( b(x) \) is the jet width and \( f(\eta) \) is the similarity function. In the zone of flow establishment (ZOFE) the similarity function is defined as (Stolzenbach and Harleman, 1971)

\[
f(\eta) = \begin{cases} 
0 & \text{if } \eta > 0 \\
(1 - \eta^{1.5})^2 & \text{if } 0 < \eta < 1 \\
1 & \text{if } \eta < 0
\end{cases}
\]

(4)

where \( r(x) \) is the width of the undisturbed core (Figure 1). In the zone of established flow (ZOEF) the similarity function is obtained from eqn (4) by setting \( r = 0 \). The centerline velocity and the jet width are estimated as functions of the geometric features, frictional effects and initial velocity (Özsoy, 1977).

Flood Hydrodynamics. During the flood cycle, the flow converges towards the inlet and can be simulated by means of potential flow towards a sink (Wolanski and Imberger, 1987). Under steady-state conditions and linearized frictional effects, the governing equation reads (DelCharco and Mehta, 1993)

\[
\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} - 2\frac{\partial \psi}{h \partial x} = 0
\]

(5)
where $\psi$ is the streamline function defined as

$$u_h = -\frac{\partial \psi}{\partial y}; \quad v_h = \frac{\partial \psi}{\partial x}$$

(6)

After some mathematical manipulations eqn (5) can be rewritten as

$$(1 + s^2)\frac{d^2\psi}{ds^2} + 4s \frac{d\psi}{ds} = 0$$

(7)

where the variable $s$ is given by

$$s = S_0z, \quad z = \frac{y}{h}; \quad h = h_0 + S_0x$$

(8)

where $S_0$ is the bottom slope, and $h_0$ is the water depth at the mouth of the inlet (Figure 1). Based on the above equations the flow velocities are estimated as (Merz, 1995)

$$u = -\frac{Q_0h_0}{bh^2(s^2 + 1)^2}, \quad v = -\frac{Q_0h_0yS_0}{bh^3(s^2 + 1)^2}$$

(9)

where $Q_0$ is the discharge at the inlet. Eqns (9) account for the selective flow convergence due to bottom slope effects.

**Sediment Transport.** The sediment budget was estimated on a finite element grid superimposed on the offshore area in the vicinity of the inlet. The bedload model was calculated using either the Einstein and Brown or the Meyer–Peter and Muller method. For estimation of the suspended sediment flux, the Einstein modified Rouse formula was employed (Chang, 1988). Using the simulated sediment data, the bathymetry of each finite element was corrected at each time step. However, it was assumed that the bathymetric changes do not affect the flow.

**Application**

To evaluate its applicability, the model was tested against available field data of the sedimentation pattern at Jupiter Inlet in S.E. Florida. Jupiter Inlet connects the Atlantic Ocean with the Loxahatchee River (Figure 2). The inlet mouth has a cross area of 435 m$^2$, a surface width of 122 m, and an average flow velocity of 1.5 m/s. The centerline velocity at the mouth was estimated at 2.1 m/s. The discharge during flood tide was measured at 770 m$^3$/s (1/28/83 at 06:14) and during ebb at 1,060 m$^3$/s (1/28/83 at 11:36) (Buckingham, 1984). The flow discrepancy between flood and ebb is attributed to the fact that during ebb there is a significant contribution of flow from the adjacent Intra-coastal waters. The average linear offshore slope of the coast is approximately $3.8 \times 10^{-3}$. The sediment is comprised of sand with a mean particle diameter of 0.4 mm. The model was applied using a 30 min time step.

The simulated data predicted an offshore deposition pattern which qualitatively matches the location and shape of the ebb tidal shoal of Jupiter Inlet (Figure 3). Field measurements along the offshore centerline axis documented deposition occurring at a distance off the inlet mouth of approximately 110 to 650 meters. The maximum deposi-
tion was found at about 350 meters. The simulated data indicated a maximum deposition occurring at a distance of 260 meters.

In order to assess the sensitivity of the model to certain physical parameters involved, a number of runs were conducted with different values for those parameters, i.e., bed friction and bottom slope (Merz, 1995).

Conclusions

The conclusions of this study are as follows:

1. During the ebb cycle, the location of transition point between the ZOFE and ZOEF of the jet moves towards the inlet for increasing bottom slope and increasing bed friction.

2. The shape of the ebb shoal becomes shorter, more narrow and thicker for increasing bottom slope and increasing bed friction.

3. The Einstein and Brown bedload formula estimates sediment transport rates of about one order of magnitude higher than those estimated by the Meyer–Peter and Muller formula.

4. The simulation predicted a horse–shoe ebb shoal that qualitatively resembles the sedimentation pattern of Jupiter Inlet. This indicates that overall, tidal effects are the main factor controlling the shape of the inlet area. However, a more accurate description would definitely require incorporation of wave action and littoral drift effects.

References


Figure 1. Configuration of ebb tide (after Özsoy, 1977).
Figure 2. Jupiter Inlet.

(Qebb = 1060, Qflood = 770 m$^3$/sec; Bottom slope = 0.0038; Darcy-Weisbach $f = 0.02$; Meyer-Peter-Muller)

Figure 3. Deposition pattern after a tidal cycle (after Merz, 1995).