Morphological Modeling of Tidal Inlet Migration and Closure

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ABSTRACT


Inlet migration and closure usually occur in micro-tidal, wave-dominated coastal environments with strong seasonal variations in river flow and wave climate. In the last decades, efforts have been undertaken to identify, classify and quantify these phenomena using conceptual models, empirical relationships and behavior-based models. However, to obtain further insight into the dominant physics requires the application of a process-based model. This study investigates the migration and closure of an idealized tidal inlet system due to wave driven longshore sediment transport. The process-based morphodynamic modeling system Delft3D is applied for this purpose. The ratio of wave energy over tidal prism was changed systematically, through varying the tidal amplitude, tidal basin area and wave characteristics, to investigate the morphological response of the inlet (e.g. closure and migration). The results were compared with Bruun’s empirical criteria for overall stability and with Escoffier stability concept. The results clearly indicate that a process-based model is able to reproduce a morphological inlet response consistent with Bruun’s criteria and Escoffier’s closure curve. A typical example of a migrating tidal inlet due to oblique waves is presented which includes features such as ebb channel formation, migration and welding to the downdrift barrier, and bypassing of ebb shoals. In other cases, inlet closure due to prolongation of the inlet channel and infilling with littoral-drift material is also reproduced.

ADDITIONAL INDEX WORDS: inlet evolution, inlet stability, process-based model, Delft3D, sand bypass

INTRODUCTION

Barrier islands and associated tidal inlets are highly dynamic and sensitive areas in the coastal environment. Tidal inlet migration and closure is linked to barrier growth/erosion, the movement of offshore shoals and the evolution of tidal channels. In many natural (non-jettied) inlets, the formation and development of sand spits govern the migration and closure of a coastal inlet and its tidal channels. In the last decades, many studies have been carried out on the complex nature of these systems and particularly, on the evolution and natural behavior of the inlet channel and ebb shoals as one of the most dynamic parts of a tidal inlet system. Studies on migration and closure of a tidal inlet system are imperative to provide background knowledge to understand and predict the morphological changes of the system before any engineering solution can be applied.

This study is focused on the migration and closure of an idealized tidal inlet system due to wave driven longshore sediment transport in a wave dominated environment. The evolution of barrier islands, associated inlet channels, and sand by passing through the inlet channels are reproduced by the process-based morphodynamic modeling system Delft3D (LESSER et al., 2004) for a number of scenarios in which hydrodynamic forcing conditions were varied. The model results were subsequently used to compare with the criteria for overall stability of tidal inlets given by BRUUN et al. (1978) and channel evolution towards equilibrium, which is known as ESCOFFIER’S (1940) closure curve.

INLET MIGRATION AND SAND BYPASSING

Inlet migration and barrier spit development are common features at many coasts in the world where wave induced longshore sediment transport is dominant in one direction. The migration process of a tidal inlet associated with barrier spit development is schematized in Figure 1. When wave-induced longshore sediment transport adds sand to the updrift side of the inlet, the inlet flow area is constricted resulting in increasing flow velocities through the inlet and a greater scouring capacity at the inlet throat. As the tidal currents scour the channel to remove sand, the downdrift side of the inlet channel is eroded and the inlet migrates in downdrift direction.

In general, the migration rate is dependent on several factors including the magnitude of littoral drift (sediment supply and wave climate), the ebb tidal current velocity (tidal prism and depth of the main channel), other currents (riverine generated currents) and on the composition of the channel bank (FITZGERALD, 1988). According to DE ALTERIS and BYRNE (1975), the channel bank composition is a particular important parameter because if an inlet becomes entrenched in consolidated sediments the less erodable sediments will impede further migration. In contrast, when channels of inlets have eroded to a more or less equilibrium
situation the barrier spits frequently migrate. The depth of the inlet throat that is eroded by tidal currents and other currents is one factor that seems to separate migrating inlets from stable inlets. FITZGERALD et al. (1978) in their analysis on historical development of tidal inlets along the South Carolina coast indicated that inlets deeper than 8 m have been stable during the past 100 years while inlets shallower than 3-4 m have a history of migration and spit breaching.

Whether an inlet migrates along the coast, or remains in a fixed position is very much related to the stability of the inlet system and is forced partly by the mechanism of natural sand bypassing through the inlet channel. Natural sand bypassing, as first introduced by BRUUN et al. (1978), is a process by which material (mainly sand), after a short interruption caused by an inlet channel, a jetty or another type of littoral barrier, is absorbed by the normal littoral drift zone some distance downdrift of the inlet. BRUUN and GERRITSEN (1959) described three natural mechanisms by which sand bypasses a tidal inlet: (a) wave-induced transport along the outer edge of the ebb delta (the terminal lobe), (b) transport of sand in channels by tidal currents, and (c) migration of tidal channels and accretion of sandbars. They related the different mechanisms of sediment bypassing to the ratio r between tidal prism (P) at the inlet during spring tide and the total amount of material (M_{tot}) arriving at the inlet in one year. They concluded that inlets with high ratios (r > 150) bypass sand via mechanism (a) along the terminal lobe, while for inlets with low ratios (r < 50) the channel location is highly variable. The bypass of sand is then through mechanism (b) and (c).

Based on the pioneering work of BRUUN and GERRITSEN (1959), numerous conceptual models for sediment bypassing processes along barrier coastlines have been proposed. FITZGERALD (1988) proposed three models to summarize the mechanisms of tidal inlet migration through sediment bypassing on micro-tidal coasts and meso-tidal coasts. These models are based on the relationship between stability of the inlet throat and the migration of the inlet channels, and have shown to be valid for a wide range of mixed-energy tidal inlets.

The conceptual model for inlet migration and spit breaching most relevant for this paper is summarized as follows. The tidal inlet is mostly a tide-induced channel. Channel migration and spit breaching is strongly related to longshore sediment transport processes. Longshore sediment transport adds sand predominantly to the updrift side of the channel. It results in a constriction of the inlet throat and commonly extends the inlet channel. Elongation of the inlet channel increases frictional resistance of the tidal flow thereby reducing the tidal range in the bay. Differences in height and phase of water levels between the ocean and backbarrier basin can induce breaching of the spit and formation of a new (relocated) tidal inlet. The new inlet is commonly located along the updrift spit at a position where the barrier is narrow and the backbarrier tidal prism is easily accessed. The hydraulically favorable position of the new inlet promotes capture of the old inlet's tidal prism and the old inlet will eventually close.

MODEL DESCRIPTION AND SIMULATION

Model description

The process-based model used in this study is the 2DH version of the Delft3D model. The Delft3D-Flow model was used in depth-averaged mode to solve the unsteady shallow-water equations. The equations consist of the continuity equation, the horizontal momentum equations, and the transport equation under the shallow water and Boussinesq assumptions on a staggered grid using an Alternating Direction Implicit method. Recently, the computations of sediment transport and bed level change have been fully integrated in the Delft3D flow module. This approach for morphological modeling is called the ‘online’ approach, described by ROELVINK (2006). The Delft3D-Wave model employs the fully spectral third generation wave model SWAN. The sediment transport is based on the depth integrated advection diffusion equation for suspended-sediment transport. The bed load transport is separately computed (LESSER et al., 2004). The Delft3D-Flow model and Delft3D-Wave model are operating on different computational grids, but the flow grid is used as the basis for data exchange between the models.

Grids, forcing, and bathymetry

This study focuses on inlet evolution forced by tides and waves. Other driving processes such as caused by wind or by density differences due to non-uniform salinity distribution are neglected. Computational grids for both flow and wave models were constructed. In the area of interest, the inlet channel and the surfzone, a high-resolution grid was designed. In both grids, the cell size dimensions varied from 30 m at the inlet gorge and shoreline to 200 m at the seaward boundary in cross-shore direction and at two lateral boundaries in longshore direction. The wave grid has 150 grid cells in M-direction (in west-east direction) and 50 grid cells in N-direction (in north-south direction) and cover an area of 13 km long by 3.5 km wide. The flow grid has 80 grid cells in M-direction and 100 grid cells in N-direction. Dimensions of the tidal basin in the flow grid are 4 km by 3.75 km. The inlet is located in the center of the computation grid and has a trapezium shape.

The model has three open boundaries: an offshore boundary at the seaside and two lateral boundaries (Figure 2). The offshore boundary is defined at the 13 m depth contour line as a water level boundary, while the lateral boundaries are open, non-reflective Neumann boundaries, where the alongshore water level gradient is prescribed (ROELVINK and WALSTRA, 2004). Tidal forcing for the
Simulation scenarios and model setting

As indicated by Bruun and Gerritsen (1959), the natural sand bypassing mechanisms and the stability of tidal inlet are strongly related to the \((P/M_{tot})\) ratio between tidal prism and annual littoral sediment transport. In this study, 5 simulation scenarios were set up in which the dimension of the inlet channel at the initial state of each simulation is 850 m². Table 1 summarizes the simulation scenarios with the tidal range, tidal basin surface area and significant wave height variations. In each simulation scenario, the same computational grid and initial bathymetry was used and identical model settings were employed. Tidal inlets in the simulation scenarios with low \((P/M_{tot})\) ratio (< 20) are expected to be unstable, and the inlet channel may close due to elongation of the sand spit. Tidal inlets in the simulation scenarios with high \((P/M_{tot})\) ratio (50 < \(r\) < 150) are considered to be stable with a clear main inlet channel and well developed ebb shoals. Tidal inlets in simulation scenarios with \((P/M_{tot})\) ratio in between 20 and 50 are expected to be highly variable in terms of channel location and channel cross sectional area. Thus the five simulation scenarios in this study are designed to have the \((P/M_{tot})\) ratios in the 3 different ranges mentioned above.

Each simulation scenario in this study was run for 10 days. To speed up the simulation time and to overcome the difference between the time scales of morphological changes and flow, a morphological factor of 40 is used. It means that 10 days simulation equals a morphological prediction of 400 days. The time step for the flow computations was set to 12 seconds in order to fulfill the numerical stability criterion of the maximum Courant number. Simulations start from a uniform water level at SWL and uniform velocity of 0 m/s in the whole computation domain. The Van Rijn (1993) formula was used for the computation of the bed load and suspended load in the model.

MODEL RESULTS AND DISCUSSION

Varying tidal ranges, tidal basin areas and wave heights in 5 simulation scenarios yield different hydrodynamic conditions that cause the idealized tidal inlets to evolve towards a stable condition or to become unstable and migrate or to become unstable followed by an entire closure. The model results and overall stability conditions of the inlet systems as well as the mechanisms of sand bypassing in the five simulation scenarios are presented in Table 1. In each simulation, the channel flow areas \((A_c)\) at different cross sections, the mean tidal velocities \((V_m)\) and the tidal prism \((P)\) of each tidal cycle are extracted from the model results. A time series of flow patterns, inlet bathymetry, geometry of the gorge, mean longshore and cross-shore sediment transport of each simulation have also been evaluated.

Model results have shown to be consistent with the Bruun empirical criteria for overall stability of a tidal inlet as described in Table 1. Simulation scenarios SIM1, SIM2, and SIM4 with \((P/M_{tot})\) ratios in between 20 and 50 have illustrated a clear trend of channel migration and growth of a sandspit in downdrift direction (Figure 4 and 6). The evolution of the tidal inlet in the simulation scenario SIM3 (Figure 3) confirms that inlets with a low \((P/M_{tot})\) ratio are unstable and the inlet channel in this scenario entirely closes after 240 days. Simulation scenario SIM5

![Figure 2. Flow grid bathymetry of the idealized tidal inlet](Image)

Delft3D-Flow model was represented as a harmonic wave, which is defined at the offshore boundary and assumed perpendicular to the shoreline. The tidal amplitudes vary from 0.25 m to 0.75 m and periods are 12 hours in various simulation scenarios.

The Delft3D-Wave model is forced by constant offshore wave conditions, which are defined at the offshore boundary with a wave height \((H_s)\) of 1.5 m and 0.75 m, a wave period of 7 seconds and a wave direction \((\varphi)\) of 25 degrees relative to the North. The waves were updated every 30 minutes to accurately represent the changing flows due to tide and morphological development.

The initial bathymetry of the idealized tidal inlet in this study consists of a uniform depth in the basin and a gentle slope at the seaside (Figure 2). At the seaside, the bathymetry was divided into two parts. Inside the surf zone area, the beach has Dean’s equilibrium profile (Dean, 1991). Outside the surf zone area, a profile with slope of 1:200 is used. The tidal basin and the inlet channel initially have a flat bed with uniform depth of 2 m below still water level (SWL) to allow waves and tides to change the equilibrium profile (Dean, 1991). Outside the surf zone area, a two parts. Inside the surf zone area, the beach has Dean’s equilibrium profile (Dean, 1991). Outside the surf zone area, a profile with slope of 1:200 is used. The tidal basin and the inlet channel initially have a flat bed with uniform depth of 2 m below the still water level (SWL) to allow waves and tides to change the inlet channel and build the ebb and flood shoals. The sand barriers are defined as erodable banks in the model with a top elevation of SWL +3 m in order to allow for an unrestricted widening and/or migration of the inlet.

Table 1: Simulation scenarios, model results with initial inlet dimension of 850 m² \((H_s = 1.5m; 0.75m, T = 7s, \varphi = 25^\circ ;\text{Tidal period} = 12\text{ hrs})\)

<table>
<thead>
<tr>
<th>Scenario name</th>
<th>Boundary conditions</th>
<th>Model results ((A_c = \text{channel flow areas} ; P = \text{tidal prism}; M_{tot} = \text{total sediment arriving at the inlet} ; V_m = \text{mean tidal velocities}))</th>
<th>Overall stability condition and mechanism of sand bypassing</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIM1</td>
<td>15 0.50 1.5</td>
<td>(1,003 \times 10^5) (147) (8.3) (1.00) (18)</td>
<td>Ebb channel migration, clear bar bypassing</td>
</tr>
<tr>
<td>SIM2</td>
<td>30 0.50 1.5</td>
<td>(2,016 \times 10^5) (294) (7.0) (1.05) (42)</td>
<td>Channel gorge stable, bar bypassing</td>
</tr>
<tr>
<td>SIM3</td>
<td>15 0.25 1.5</td>
<td>(531 \times 10^5) (34) (8.3) (0.97) (25)</td>
<td>Inlet closure after 240 days, spit elongates across the entrance and blocks the mouth</td>
</tr>
<tr>
<td>SIM4</td>
<td>15 0.75 1.5</td>
<td>(1,702 \times 10^5) (217) (8.8) (0.85) (138)</td>
<td>Ebb channel migration, bar bypassing</td>
</tr>
<tr>
<td>SIM5</td>
<td>15 0.50 0.75</td>
<td>(1,415 \times 10^5) (149) (1.1) (0.85) (138)</td>
<td>Main channel stable at fixed position, sand bypass along terminal lobe of ebb tidal delta</td>
</tr>
</tbody>
</table>
with a \((P/M_{tot})\) ratio of 138 is representative for a tidal inlet in a stable condition in terms of inlet location and channel cross sectional area. A clear main channel with a fixed position is formed and maintained by tidal currents while ebb shoals are well developed and pronounced in the foreshore. A series of geometrical cross-sections of the scenario SIM5 in Figure 6 supports the statement about channel cross sectional areas.

Figure 4 presents a cyclic pattern of ebb channels migration and ebb shoals formation, bypassing and welding to the downdrift barrier. After 80 days, the inlet maintains two main channels which are bound by ebb shoals in between. The channel on the right side of the inlet is more pronounced than the one on the left side. In the next state (after 120 days), the left channel has terminated due to the attachment of the ebb shoal to the downdrift barrier. The remaining channel has cut through the ebb tidal delta and is realigned nearly perpendicular to the shoreline. The ebb channel then was curved to the right after 240 days due to the build-up of sand spit in combination with enlargement of ebb shoal on the left side of the inlet. Due to the evolution of the sand spit to the left, the main channel is gradually confined and loses hydraulic efficiency. Consequently, a new channel has formed orientated towards the left after 320 days. The old channel gradually diminished and has completely filled in at the end of the simulation. On inlet scale this implies that shoals deflect the main ebb channel towards the downdrift direction. Thus, the cyclic pattern of ebb channels migration is primarily forced by the evolution of the sand spit from the updrift to the downdrift barrier and by the ebb shoals formation, bypassing and welding in the downdrift barrier.

Figure 5 presents the development of cross sectional areas versus mean velocities for the 5 scenarios. Cross sectional areas in the scenario SIM2 and SIM4 show inlet channels of the gorge evolving toward equilibrium accordance with the stability concept of ESCOFFIER (1940) in which mean velocities are fairly close to the critical velocity of 1 m/s and stay that way regardless of channel cross sectional areas. Meanwhile, cross sectional areas in the scenarios SIM 1 and SIM 5 show a clear trend of channel evolution of the gorge toward equilibrium at a lower mean velocity (0.75 m/s). This occurs due to the fact that the inlet channels of the gorge in the SIM2 and SIM4 have been maintained by tidal currents at a relatively larger depth (up to –16 m), while the inlet gorges in the SIM1 and SIM5 have been eroded no deeper than –8 m by tidal currents (see Figure 6). In SIM3, the
growth of a sand spit across the inlet entrance gradually reduces the mean velocities through the main ebb channel and fills the channel with littoral-drift material till it finally blocks after 240 days without make any significant changes to the flow areas of the gorge (Figure 3). This explains the vertical line of the \((V_m-A_c)\) relationship in this simulation scenario in Figure 5.

**CONCLUSIONS**

This study provides better understanding of the underlying processes that govern the migration and closure of a tidal inlet. It is shown that tidal inlet behavior is linked to the natural sand bypassing mechanisms and partly governs the stability of a tidal inlet system. The model results demonstrate that the process-based model is able to reproduce morphological evolution of a tidal inlet consistent with Bruun’s criteria and Escoffier’s stability concept. A typical example of a migrating tidal inlet due to oblique waves which includes features such as ebb channel migration, shifting and diminishing, and the bypassing of ebb shoals from the updrift to the downdrift barriers is illustrated by a series of bathymetry maps in Figure 4. In another case inlet closure due to prolongation of the ebb channel and infilling with littoral-drift material in the foreshore is also observed. Furthermore, the model result indicate that, Escoffier’s closure curve is solely applicable to the channel gorge and thus insufficient to explain the closure of a tidal inlet due to littoral sand infilling into the main ebb channel as illustrated in Figure 3.

**LITERATURE CITED**


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