INLET STABILISATION USING FLOW REGULATION,
A NUMERICAL APPROACH USING PROCESS-BASED MODELING

T. T. Tung 1

ABSTRACT: The central coast of Vietnam has more than sixty inlets and river mouths discharging into the East Sea. They are often unstable due to entrance shoaling, channel migration and seasonal inlet closure and breaching. These phenomena cause a number of social and environmental problems, such as risk of flooding in the low lying coastal plain, negative impacts on navigation, fisheries and changes to the water environment and ecological system and thereby harming the social-economic development of the region. Using river flow for flushing sediment accumulation at the inlet mouth and in the inlet channel of a tidal inlet system is an alternative non-structural solution that may be used in micro tidal inlets in a wave dominated environment. In this paper, using river flow for flushing an unstable inlet will be simulated in a series of simulation scenarios using process-based modeling (Delft3D) in order to estimate the effectiveness of the solution and to find the optimum way in using river flow for flushing. The model results show that with the same amount of flushing volume, the scenario that has a longer flushing duration and a sufficient flushing discharge is more efficient than the scenario that uses a high flushing discharge over a short duration. This means that the flushing efficiency is closely related to the flushing duration rather than the flushing discharge.

Keywords: Tidal inlet, river flushing, sediment transport, Delft3D, central coast of Vietnam.

INTRODUCTION

Seasonal closure and migration of tidal inlets and estuaries usually occur in micro-tidal, wave dominated coastal environments where strong seasonal variations of river flow and wave climate are experienced. These inlets and estuaries close every year for a number of months due to the formation of a sand bar across the entrance or due to the growth of a sand spit from updrift to downdrift. (Ranasinghe and Pattiaratchi, 2003). The phenomenon of seasonal closure of inlets or estuaries can be found at many coasts such as at the southern coasts of Australia, the southern coast of South Africa, the south-easter coastal of Brazil, and the south-western coasts of India and Sri Lanka and Vietnam.

Situated in the monsoon-prone humid tropical region, Vietnam is affected by both the oceanic and continental climates causing disasters to the country like riverine flooding and storm induced damage. The natural disasters occurring in the coastal strip in the central part of Vietnam, caused by meteorological and oceanographical factors, are intensified by human interventions, like damming of rivers for various purposes or the extensive deforestation for agricultural lands. Along 3,200 km of coastline of Vietnam, the central coast has more than sixty inlets and river mouths discharging into the South China Sea. These systems play vital roles in social-economic activities in the region. The steep rivers with abundant natural flows but unevenly distributed during the year make the low-lying coastal plains in the region prone to inundation by flooding, while the river is almost dry during the rest of the year. Specific topographical features and hydrological characteristics of the region produce a particular highly seasonal variation of tidal inlets and river mouths, from narrowing, shoaling or entirely closing in the dry season to widening or breaching in the flood period. Frequent disasters set back development efforts in this poorest region of Vietnam and trap people in a cycle of poverty.

Stabilizing inlets in the central coast of Vietnam therefore is recognised as one of priority tasks to mitigate potential risks caused by natural disasters, especially by floods and storms on low-lying coastal plains, and to promote a safe and stable condition for social-economic development in the region. Additionally, strong seasonal variation of inlets and estuaries also contribute to the complexity of problems and raise a necessity to implement a strategy for inlets and river mouths stabilization under the constraints of lacking capital investments and shortage of knowledge and resources. It is also essential to integrate the strategy for inlet stabilization into the coastal zone management plan, water resources management plan and the social development plan in the region.

Using river flow for flushing sediment accumulation at the inlet mouth and in the inlet channel of a tidal inlet

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system is an alternative non-structural solution that may be used in micro tidal inlets in a wave dominated environment. Examples of such alternative solutions for such inlet stabilisation measures can be found in South Africa, in Malaysia, in Australia, and in Florida coast of USA.

In this paper, using river flow for flushing an unstable inlet will be simulated in a series of simulation scenarios in order to estimate the effectiveness of the solution and to find the optimum way in using river flow for flushing.

THE NUMERICAL MODEL

Model settings
To calculate the morphological changes in the tidal inlet the process-based model Delft3D is used. The model consists of the modules Delft3D-FLOW and Delft3D-WAVE. In this application the depth-averaged (2DH) version of the FLOW module is used to solve the shallow water wave equations. Sediment transport is calculated using the method proposed by Van Rijn (1993).

The Delft3D model simultaneously solves the shallow water equations, the sediment transport and bed evolution equation (Lesser et al., 2004). The hydrodynamic module is coupled to the SWAN wave model (Booij et al., 1999) by means of communicating the water levels, current velocities and bathymetry from the flow to the wave module and updated wave forcing from the wave to the flow module at a regular user-defined interval. The model includes formulations for bed slope and dry bank erosion (Lesser et al., 2004) for which default parameters are used (see Tung, 2012).

Sediment transport is calculated using the method proposed by Van Rijn (1993). Van Rijn’s formula was selected because it allows wave effects and the effects of bed slope to be included. The morphological prediction is accelerated by upscaling the predicted bed changes with a user-defined factor (so-called online approach, Roelvink, 2006). This upscaling factor, MorFac, is O(1) for dynamic situations in which the hydrodynamic and morphodynamic time scales are similar (e.g. during storm events) and may be O(100) for relative stable in which the morphological response varies on much longer time scales compared to the hydrodynamics (Ranasinghe et al., 2011). For the considered cases the MorFac was varied systematically to determine its upper limit. In all cases MorFac values in the range of 25 ÷ 50 were found to result in reliable predictions which were unaffected by the upscaling.

The uniform horizontal eddy viscosity and eddy diffusivity coefficients are both set to 0.1 m²/s. The Chézy friction coefficient is constant over the computational domain with a value of 65 m²/s. Bottom sediments consist of a single-fraction of non-cohesive sand with a density of 2,650 kg/m³. The computed wave field is calculated every 30 minutes to account for changes in water levels, velocities and morphology. For additional information on model set-up and parameters reference is made to Tung (2011).

![Fig. 1: Model domain and bathymetry of the idealized tidal inlet, the legend bar on the right indicates depth below SWL.](image)

The model configuration consists of an idealized tidal inlet system in which a 500 m long tidal channel connects a rectangular basin to the ocean (Figure 1). Initially, the tidal basin has a flat bed with a uniform depth of 2 m below the still water level (SWL). The prismatic inlet channel has a trapezoidal cross-section with a uniform depth of SWL-2 m. At the seaward side, inside the surf zone, the bathymetry has a concave equilibrium profile (Dean, 1991). Outside the surf zone a gentle profile with a constant slope of 1:200, until a water depth SWL-13 m is reached about 3.5 km offshore, is used. The elevation of the barrier islands on both sides of the inlet channel is set to SWL+3 m. To allow for an unrestricted widening and/or migration of the inlet channel the barrier islands are defined as erodible banks. The rectangular grid has a resolution of 30 m in the inlet region which is gradually increased to about 200 m in the offshore and basin areas.

A shore-normal propagating tide is prescribed in the form of a single 12 hour harmonic component at the shore-parallel seaward boundary The lateral boundaries are open, non-reflective Neumann boundaries, where zero alongshore water level gradient are prescribed (Roelvink and Walstra, 2004). Waves in the form of a JONSWAP spectrum are prescribed at the offshore boundary. The spectrum is characterised by a significant wave height, peak period and mean wave direction.

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**Simulation scenarios**

First, the design rate of river flow for flushing an unstable inlet is computed based on overall stability parameters of a tidal inlet (Bruun et al., 1978). The river flow adding into the system is calculated from the P/Mtot ratio, in which P is total volume ebb flow during the ebb phase and Mtot is the annual littoral sediment transport. The total volume of ebb flow includes the ebb tidal prism and the volume of river discharge added into the tidal basin during the ebb phase.

Table 1. Summary of simulation scenarios in zero option and flow option

<table>
<thead>
<tr>
<th>Model settings</th>
<th>Zero Scenario</th>
<th>Flow Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basin area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial channel area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tidal char. a0 (m)</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>T (hrs.)</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Sed. char. D50 (mm)</td>
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<td>250</td>
</tr>
<tr>
<td>Wave char. Hb (m)</td>
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<td>1.5</td>
</tr>
<tr>
<td>θ (deg.)</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Simulation duration days</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>FLOW-1</td>
<td>Q (m³/s)</td>
<td>600</td>
</tr>
<tr>
<td>FLOW-2</td>
<td>Q (m³/s)</td>
<td>1200</td>
</tr>
<tr>
<td>FLOW-3</td>
<td>Q (m³/s)</td>
<td>2400</td>
</tr>
</tbody>
</table>

According to Bruun et al. (1978), a tidal inlet with P/Mtot ratio in between 20 and 50 is considered to be stable but to be highly variable in terms of channel location and channel cross-sectional area. For optimising the volume of river flow that is needed for flushing the inlet channel, the middle value of the P/Mtot ratio of 40 is selected. Both ebb tidal prism (Pebb) and annual littoral sediment transport (Mtot) are estimated from the model results in the simulation scenario ZERO. The simulation scenario ZERO is a base scenario that used to investigate inlet evolution without stabilisation. Model settings, boundary conditions of the scenario ZERO are described in Table 1. Detail of the simulation results of the scenario ZERO can be found at Tung (2012).

Given the ebb tidal prism at beginning state of unstable condition of the inlet channel from simulation results in the scenario ZERO, the Pebb is about 7.5 \(10^6\) m³, and annual littoral sediment transport (Mtot) = 0.5 \(10^6\) m³ per year, the P/Mtot before flushing is about 15. According to Bruun et al. (1978), a tidal inlet in this case is highly unstable and may close. Assuming the duration of the ebb phase (Tebb) is about 6 hours for semi-diurnal tide, the river flow discharge (Qriver) needs to be added into the system for obtaining a higher P/Mtot ratio is computed by formula:

\[
Q_{\text{river}} = \left( \frac{M_{\text{tot}} \times P}{M_{\text{tot}}} \right) - P_{\text{ebb}} \frac{T_{\text{ebb}}}{T_{\text{ebb}}} \quad (1)
\]

in which:

- \(M_{\text{tot}}\): annual littoral sediment transport (m³/year)
- \(P_{\text{ebb}}\): ebb tidal prism (m³)
- \(T_{\text{ebb}}\): duration of the ebb phase (second)
- \(P/M_{\text{tot}}\): inlet stability ratio (-)

In this paper, to obtain the (P/Mtot) ratio of 40, the selected river discharge needed to be added into the system is 600 m³/s.

River flow for flushing the inlet can be added into the tidal basin at the beginning of the simulation period or can be added into the tidal basin at the moment before inlet going to close. In this paper, river flow is added into the tidal system at the moment the inlet is going to close. The model results in the simulation scenario ZERO are used to estimated the moment when the inlet channel is going to close. A set of simulations for inlet flushing using river flow is implemented in the study and described in Table 1.

Three simulation scenarios (denoted as FLOW-1, FLOW-2 and FLOW-3) are designed in the FLOW simulation in which different flushing discharges (Q) and flushing durations are defined (see Table 1). These settings are aiming to find effectiveness in using river flow for flushing in terms of flushing discharge and duration. Using the same flushing volume, the first simulation scenario (FLOW-1) adding a constant flushing discharge of 600 m³/s in 40 days, the 2nd scenario (FLOW-2) adding 1,200 m³/s in 20 days and the 3rd scenario (FLOW-3) adding 2,400 m³/s in 10 days. To speed up the simulation, a morphological factor (fMOR) of 40 has been used in these simulations. All three simulation scenarios were run for 400 days and in each scenario flushing starts at the day 200th, at the moment inlet channel is going to close.

Because the sediment transport is about a power two of the velocity, the higher the flushing discharge, the larger sediment transport will be. But the flushing discharge should not be too large to overcome the discharging capacity of the basin and the inlet channel. In the flow domain of the process-based model, flushing flow is defined at the open boundary in the tidal basin as a localised discharge of water.
A discharge in the flow domain is characterised by the name and its position in the flow grid. The discharge rate can be assigned for each discharge name as time dependent input data. In this paper, river flow used for flushing is assigned as discharge boundary for 20 grid cells at the open boundary in the basin. In each cell, a similar time series of discharge rate is used. The total discharge of 20 cells corresponds to the total discharge that will be used in the each simulation scenario.

**MODEL RESULTS AND ANALYSIS**

**Model results**

Figure 2 presents the evolution of the inlet channel from the moment when the inlet has been flushed till the end of the simulation time (at the day 200th after flushing) in three simulation scenarios FLOW-1, FLOW-2, and FLOW-3.

Fig. 2 Series of bathymetry maps over time after flushing, of 3 simulation scenarios FLOW-1, FLOW-2; FLOW-3. The X and Y coordinates are in metre.
The model results in three simulation scenarios (FLOW-1, FLOW-2 and FLOW-3) indicate that the inlet channel in the first scenario still remains opening at the end of simulation time meanwhile the inlet channels in the two others scenarios (FLOW-2 and FLOW-3) were closed at the day 100th and the day 140th after flushing (see Figures 2b and 2c and 7). Using a same amount of flushing volume, the scenario which has longer flushing duration seems to maintain the inlet channel open longer.

In the scenarios FLOW-2 and FLOW-3, the flushing velocities were much higher compare to velocities in the scenario FLOW-1, but the flushing durations were not long enough to maintain the opening state of the mouth and are not be able to overcome the advancing of the updrift sand spit after flushing. Thus, the inlet channel in the both scenarios (FLOW-2 and FLOW-3) after flushing was turned and bend to the downdrift direction (see Figures 2, the middle row and bottom row).

In the scenario FLOW-1, the inlet channel after flushing is aligned more or less perpendicular to the shoreline for a period of more than 50 days (see the top row in Figure 2). The evolution of the inlet system at the day 67th after flushing in the scenario FLOW-1 in Figure 2 indicates that the flushing current has cut through the sand spit which developed across the inlet mouth. A new inlet channel has formed after flushing and created a better inlet channel in terms of hydraulic efficiency.

In Figure 3, the maximum depth of the inlet throat after flushing is also related to the flushing discharges and the flushing durations. The scenario FLOW-1 has a maximum depth of about 8 m after flushing, meanwhile, the scenarios Q-1200 and Q-2400 have maximum depths of about 10 m and 12 m after flushing.

Figures 4 and 5 present the temporal variation of the total instantaneous discharge and the cumulative discharge through the inlet throat after flushing in three simulation scenarios. The model results in these Figures agree well to the evolution of the inlet channel as shown in Figures 2, 6, and 7. It indicates that in the scenarios FLOW-2 and FLOW-3, there is no tidal exchange via the inlet channel at the day 140th after flushing. The same cumulative flushing discharges (about $2.5 \times 10^7$ m$^3$) via the inlet throat of the three scenario was found in Figure 5.

Model results in the 3 simulation scenarios indicates that given the same flushing volume, the flushing efficiency is closely related to flushing duration rather than flushing discharge. Using the same total flushing volume, a flushing scheme that has a longer flushing duration and sufficient flushing discharge is more efficient than a flushing scheme that uses a high flushing volume.
discharge in a short duration. Moreover, the flushing moment (at high tide or low tide) is also contributing to the flushing efficiency and needs further study in future.

Fig. 6 Cumulative sediment transport through the inlet throat before flushing in 3 scenarios: FLOW-1, FLOW-2 and FLOW-3

Fig. 7 Cumulative sediment transport through the inlet throat after flushing in 3 scenarios: FLOW-1, FLOW-2 and FLOW-3

Figures 6 and 7 present the cumulative sediment transport through the inlet throat in the three scenarios in the period before flushing and in the period after flushing. The negative value of cumulative sediment transport means landward transport of sediment. The dominated in landward transport in the three scenarios in Figure 6 implies that the tidal inlet system in the three scenarios are flood dominated.

As mentioned in the simulation setting section, sediment transport is about a power two of the velocity. Thus the higher flushing discharge, the larger sediment transport will be. These analyses are well illustrated in Figures 6 and 7. The amounts of sediment which were flushed out to the sea in the scenario FLOW-1, FLOW-2 and FLOW-3 are approximately 3,200 m³; 5,500 m³ and 9,250 m³, correspondingly. The temporal development of cumulative sediment transport via the inlet throat after flushing in Figure 7 of the scenario FLOW-2 and FLOW-3 is also presenting the moment when the sediment transport via inlet throat is stopped. They are in well agreement with results as in Figure 4, 5 and with the evolution of the inlet channel over time in Figure 2.

Discussions

Within a limited number of the simulation scenarios, the model results of the three scenarios FLOW-1, FLOW-2 and FLOW-3 were used to find the effectiveness way for flushing an unstable tidal inlet channel using the same flushing volume. An inlet channel which was flushed by river flow in longer duration with sufficient flushing discharge maintains its opening state longer than an inlet channel which was flushed by a high flushing discharge in a short duration. Using the same amount of total flushing volume, the flushing efficiency is closely related to flushing duration rather than flushing discharge. The sufficient flushing discharge in this paper is computed based on the minimum value of the P/Mtot ratio of 40 according to the stability criteria of Bruun et al. (1978). Moreover, the flushing moment (at the beginning of the ebb phase or at the beginning of the flood phase) will also contribute to the efficiency of the solution but needs more study.

CONCLUSIONS

The central coast of Vietnam is characterised by a dense river network, various types of coast and many small and medium size inlets/estuaries formed along the 1,500 km of coastline. The barrier lagoon inlet and inlet formed at the mouth of a wave dominated estuary in the central coast have an important role for fishery, aquaculture, navigation and tourism. It provides direct sources of living to the local inhabitants living in the surrounding areas. Not only contributions to the social-economic development of the region, but they also have an important function in coastal ecology and water environment. Inlet closure, sedimentation and breaching are types of natural disasters which often occur in the central coast of Vietnam.

To investigate inlets stabilised by using river flow for flushing an inlet, a set of simulation scenarios in which different flushing discharges and flushing durations is implemented. Within a limited number of simulation scenario, the model results show that with the same amount of flushing volume, the scenario that has longer flushing duration and sufficient flushing discharge is more efficient than the scenario that using high flushing...
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discharge over a short duration. It means using the same amount of total flushing volume the flushing efficiency is closely related to flushing duration rather than flushing discharge. Moreover, the flushing moment (at the beginning of the ebb phase or at the beginning of the flood phase) will also contribute to the efficiency of the solution and needs more study in the future.

REFERENCES