Influence of river mouth sand spit level on the time variation of river stage and bed topography

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Abstract

Presence of sand spits at river mouths interrupt effluent flood flow into the sea. An appropriate flushing of the sand spit could reduce flooding intensity in the adjoining areas. Initial sand spit elevation influences initiation and development of flushing through a complex interaction of effluent flood discharge, tidal level and sediment transport processes. Present paper describes the influence of initial sand spit level on the time variation of river stage and corresponding development of bed topography under the actions of both tide and high flood flows. Model results show that initial sand spit level influences the magnitude of peak water level and its arrival time. The over-topping of sand spit and initiation of its flushing, however, show only little difference in time owing to very steep rise in effluent flood discharge. Sediment transport with low tide has been found to be higher than that with high tide as low tide forces lower water level at high discharges, therefore, causing high velocities. The sand spit has been seen to flush down into the sea forming a new channel section.

1 Introduction

Coexistence of various external forces such as waves, tidal actions and river discharges constitute a very complicated phenomenon at a river mouth. Formation or flushing of sand spits at river mouths takes place based on the predominance of wave action or of effluent river discharge respectively. While
environmental aspects and disaster prevention are concerned, formation of sand spits has advantages as it prevents salinity and wave intrusions. However, these sand spits interrupt effluent flood flow into the sea causing undesirable flooding and damage to structures. At overflowing river discharges flushing of sand spits also occur. This would reduce flooding intensity if appropriate flushing of the sand spits could be maintained. As such, in order to achieve maximum benefits, a proper planning for sand spit management could greatly contribute to flood and disaster prevention, and to proper utilization of coastal structures like jetties etc.

In order to investigate sand spit flushing by overflowing river discharge, many experimental studies have been carried out (e.g. Fukuoka et al.[1]). However, these were mostly carried out for two-dimensional phenomenon in laboratory flumes. Several numerical computation methods have also been developed in recent years to reproduce three-dimensional flushing process of sand spit at a river mouth (Deguchi and Sawaragi[2]; Hatanaka and Kawahara[3]; Tanaka and Qin[4]; Sato et al.[5]; Tanaka et al.[6]). These models were validated either with experimental data or against field observations. Development of these models facilitated the investigation of sand spit flushing process under extreme events. Also it is possible to study the influence of individual parameters on the complex interaction of effluent flood discharge, tidal levels, and resulting sediment transport and local scouring which governs the flushing process.

Present paper describes the influence of initial sand spit level on the time variation of river stage and corresponding development of bed topography under the actions of both tide and high flood flows. Computations have been carried out applying the method proposed by Tanaka et al.[7] for plane two-dimensional turbulent flows. The model took into account the flushing of the sand spit at a river mouth due to overflowing river discharges and local scouring caused by secondary currents.

2 Numerical modeling and computation methods

The modeling approach consists computation in two phases; a) computation of river hydrodynamics applying depth-averaged equations of flow and momentum conservation, and b) bed evolution computation by applying standard sediment transport and mass conservation equations. The effects of bottom slope and spiral current are also considered in the computation.

2.1 Governing equations for flow dynamics

The governing equations for hydrodynamic model are expressed in terms of water surface elevation and depth-averaged quantities as follows:

$$\frac{\partial \eta}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0$$

(1)
\[
\frac{\partial M}{\partial t} + \frac{\partial}{\partial x} \left( \frac{M^2}{D} \right) + \frac{\partial}{\partial y} \left( \frac{MN}{D} \right) + gD \frac{\partial \eta}{\partial x} + \frac{g n^2}{D^{7/3}} M \sqrt{M^2 + N^2} = 0
\]  
(2)

\[
\frac{\partial N}{\partial t} + \frac{\partial}{\partial x} \left( \frac{MN}{D} \right) + \frac{\partial}{\partial y} \left( \frac{N^2}{D} \right) + gD \frac{\partial \eta}{\partial y} + \frac{g n^2}{D^{7/3}} N \sqrt{M^2 + N^2} = 0
\]  
(3)

where \( \eta \) is water level about still water level, \( t \) time, \( x \) and \( y \) horizontal coordinates along and across the river axis respectively, \( M \) and \( N \) flow flux per unit width in \( x \)- and \( y \)-directions respectively, \( g \) gravitational acceleration, \( D \) total depth \((D=h+\eta, h: \text{still water depth})\), and \( n \) is Manning friction coefficient.

### 2.2 Governing Equations for Morphological and Sediment Transport Computation

The morphological model is based on two-dimensional equation of sediment mass conservation given as:

\[
\frac{\partial z}{\partial t} + \frac{1}{1-\lambda} \left( \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} \right) = 0
\]  
(4)

where \( z \) is elevation of the bottom surface from still water level, \( \lambda \) sediment porosity, and \( q_x \) and \( q_y \) are sediment transport rates per unit width per unit time in the \( x \)- and \( y \)-directions respectively.

Bed load transport rates have been computed applying Einstein-Brown (Brown[8]) bedload formulation with a correction factor of 0.8. For suspended sediment Lane and Kalinske[9] model has been applied. Details of the selection of sediment transport formulae can be found in Tanaka et al.[7].

### 2.3 Computation Method

Hydrodynamic model has been computed using leap-frog scheme, as proposed by Goto and Ogawa[10] for numerical simulation of tsunamis, with a uniform square mesh spacing. In order to improve model stability, non-linear convective terms are expressed through upwind difference method. A staggered mesh scheme is employed for morphological model. The hydrodynamic and morphological models are coupled to compute water level, velocity field, sediment transport and subsequent bed level evolution at a time step.

Model accuracy is further improved by considering predominance of secondary spiral current near the river mouth, as proposed by Shimizu and Itakura[11], and by introducing sediment sorting over sloping bottom considering Watanabe et al.[12] method. Details of computation method can be found in Tanaka et al.[13].
The solution has been achieved using spatial grid increments of 15m and with a time increment of 0.8sec.

3 Computation domain and field data

The model has been applied at the Natori River mouth in northeastern Japan (Fig. 1). The river has a length of 55km and a catchment area of 939km². There are two jetties at the river mouth and the sand spit on the left-hand side normally remained attached to the northern jetty. In recent years frequent flushing of the sand spit caused concern and the present model was calibrated against measured data after such a flushing of the sand spit had occurred (see Tanaka et al.[7], [13]). All relevant data was collected by field measurement conducted by the Ministry of Construction, Japan and data from most recent surveys has been used in the present paper.

Table 1. Sequence of model simulation

<table>
<thead>
<tr>
<th></th>
<th>Base Run</th>
<th>Option 1</th>
<th>Option 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case A</td>
<td>Actual sand spit data</td>
<td>2.0m max. sand spit level with high tide</td>
<td>2.5m max. sand spit level with high tide</td>
</tr>
<tr>
<td></td>
<td>with high tide</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case B</td>
<td>Actual sand spit data</td>
<td>2.0m max. sand spit level with low tide</td>
<td>2.5m max. sand spit level with low tide</td>
</tr>
<tr>
<td></td>
<td>with low tide</td>
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</tbody>
</table>

Figure 2 shows the model computation domain. At the upstream boundary a synthesized inflow hydrograph, assessed from measured data with 1 in 150 year probability of exceedence, has been used. At the offshore boundary two extreme tidal conditions were used for two different cases, high and low tide coinciding flood peak, with 0.30m additional effect due to storm surge. No flow through the side boundaries was considered. Boundary water levels and inflow hydrograph for different model simulations are shown in Fig. 3. To investigate the influence of initial sand spit level, two additional sand spit topography have been considered apart form actual data. Option 1 defined maximum initial sand spit level as 2.0m and for Option 2 a maximum level of 2.5m has been used (Fig.2). Different simulation sequences are shown in Table 1.
Figure 2. Model Computation domain and bathymetry options; a) measured bathymetry, b) bathymetry for Option 1 and c) bathymetry for Option 2

Figure 3. Tidal and inflow discharge boundary time series.
4 Results and discussion

4.1 Influence of initial sand spit and tidal levels on flooding

Figures 4 and 5 show water level and sediment transport time variation at points A and B respectively, as referred in Fig.2. At point A it can be seen that initial sand spit level influences the peak water level and its arrival time. A reduction in sand spit level decreases flooding intensity as can be seen in Fig.4. It also causes the peak to arrive early. For Case A high tide coincides flood peak and therefore, resulting water level is much higher than that can be observed for Case B.

Point B is located on the sand spit, and it can be seen also that (Fig.5) the overtopping depends on its initial elevation. However, owing to very steep rise in inflow discharge at the time of overtopping, this time difference is not significant. A steep drop in the water level can be observed at the time of overtopping. This could be caused by rapid development of bottom topography due to small depth and high velocity.

The tidal level also has significant influence on flooding extent along with sand spit elevation. While in Case A, the effect of lowering of sand spit level is clearly evident on peak water level, for Case B, the phenomenon is rather over shadowed.

![Figure 4. Time series of water level and sediment transport rate at Point A for both the cases](image)
4.2 Sediment transport and resulting bed evolution

At Point A high variation of sediment transport rates can be observed between Case A and Case B. Low tide forces the water levels to be low in the river resulting in a higher flow velocity near the river mouth. As such, the sediment transport rate in the later case is much higher (Fig.4). During overtopping very high velocities over very small water depths are likely on the sand spit. A sharp rise in sediment transport rate is therefore expected as can be seen at Point B (Fig.5).

Sequential bed topography development in all the cases are presented in Fig.6. Simulation results correspond to a time of 17 hours, the time of first inflow peak, 23 hours, corresponds to the time of peak discharge, and at the end of simulation period, i.e. 48 hours from the beginning of simulation has been presented. For both the cases erosion of sand spit started after the passage of first discharge peak.

After the commencement of flushing, the main channel has been diverted on to the sand spit area. The width of the new channel section generally increases with decreasing initial sand spit level, while the depth decreases with decreasing level. As such Base Run produces more scouring depth than other options. Both Cases
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A and B show similar trend in cross section development only that in Case B volume of eroded material is more indicating higher sediment transport rate. The influence of secondary current can be well observed in the river within the jetties.

Figure 7 shows the comparison of initial and simulated batheymetry maps corresponding to the peak inflow discharge for Base Run and Option 1 with high tide (Case A). The difference in scour extent at the sand spit can be observed comparing the contours of 5m and 6m depths. For Option 1 more erosion of the sand spit has taken place, at the time of peak discharge, because of lowered initial sand spit level.

**5 Conclusions**

Several simulation runs have been carried out with different sand spit levels along with two extreme tidal conditions to assess the influence of initial sand spit level on flooding extent and sand spit erosion process. The river inflow has been considered based on measured data which has a return period of 1 in 150 years.

Tides at the offshore boundary dominate the flood levels near the river mouth, however, generally a reduction in sand spit level reduces the flooding intensity. During low tide very high velocity in the vicinity of the river mouth can be
Figure 7. Bathymetry map showing the bed topography development; solid line (---) : at the time of peak inflow (23 hrs.), dashed line (-- -- --): initial bathymetry; a) Base Run for Case A and b) Option 1 for Case A.

observed resulting in a higher sediment transport rate than that with high tide. Selection of initial sand spit level influences the time of overtopping and arrival time of peak flood owing to the complex scour development. Here the overtopping and subsequent flushing of sand spit are mainly guided by the steep rise in effluent flood discharge.

It was observed that the width of scoured channel over the sand spit increases with a decrease in sand spit level. It also reduces the scour depth near the northern jetty. This indicates that a trade-off between allowable scouring limit and extent of lateral erosion is possible in selecting the sand spit level.

Acknowledgment
The authors are indebted to Sendai Construction Office, Ministry of Construction, Japan for their kind supply of field data.
References


