Field application of a numerical model for river mouth topography change

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Abstract

The authors have proposed a two-dimensional hydrodynamic and morphological model for predicting river mouth topography change during a flood, in which sediment movement due to secondary current as well as that induced by streamwise current is considered. (Tanaka et al. [1]). Although the model has been successfully applied to a river mouth in Japan, however, the applicability of the model to other flood events and to other rivers has not been yet examined thoroughly. The purpose of the present study is to investigate predictive ability of the authors’ model when it is applied to other big floods.

1 Introduction

Considerable change in river mouth topography sometimes occurs in a very short time due to predominant external forces acting at a river mouth. Among them, a big flood causes flushing of sediment at a river mouth and resultant deposit in the sea area. This phenomenon is, of course, important from a viewpoint of flood control. Nowadays, further attention has been paid by coastal engineers to this event from a viewpoint of sediment supply from a river mouth to surrounding coastal area.

The authors have been involved in development of a numerical model for predicting topography change at a river mouth during a flood (Tanaka et al. [1], Sato et al. [2]). In the latest model of Tanaka et al. [1], the sediment movement due to streamwise flow as well as that induced by secondary current in a channel bend is considered. However, the applicability of the model has been examined using only one data set of flood event in Japan. In the present study, further investigation is carried out to examine field applicability of the model.
2 Study area

The numerical model will be applied to the Natori River mouth in Japan, being same as the previous work of the authors (Tanaka et al. [1]). A map of the study area is shown in Fig. 1.

It had been considered until the beginning of 1980's that the sand spit at the Natori River mouth is too stable to be eroded by flood, though, remarkable flushing of the spit has been observed six times in these fifteen years: September 1982, August 1986, August 1989, August 1993, September 1994 and September 1995. Among these, the second one was employed in the previous verification of Tanaka et al. [1], while the first and the third ones will be used in the present computation. The maximum discharge attained to 2,187m³/sec and 2,660m³/sec in 1982 and 1989, respectively.

The water level variation measured at the Yuriage Station (★ in Fig. 1) and aerial photographs taken at the river mouth will be used for model verification.

3 Computation method

Time-variation of water level and corresponding velocity field can be obtained by solving the following governing equations.

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

(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 the water level above the still water elevation, $t$ the time, $x$ and $y$ the horizontal coordinates, $M$ and $N$ the flow flux per unit width in $x$- and $y$-direction, respectively, $g$ the gravitational acceleration, $D$ the total water depth ($D = h + \eta$, $h$: still water depth), and $n$ is Manning’s friction coefficient. Using $M$, $N$ and $\eta$ thus obtained, the sediment transport rate is calculated by means of Einstein-Brawn’s formula [3] for bed load along with Lane and Kalinske’s formula [4] for suspended sediment. Following the previous study of the authors (Tanaka et al. [1]), 0.8 is multiplied to Einstein-Brawn’s formula in the present computation, instead of the original expression. The bed elevation, $z$, can be computed by the equation for mass conservation.

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

(4)

where $\lambda$ the porosity of sediment and $q_x$ and $q_y$ the sediment transport rate per unit width per unit time in $x$- and $y$-direction, respectively.

It is here noted that there are two jetties at the Natori River mouth and it has curvature towards the north as illustrated in Fig. 1, resulting in possible predominance of secondary current (spiral flow). Thus, sediment will be
**Fig. 1** Study region at the Natori River mouth

**Fig. 2** Schematic explanation of secondary flow
transported not only to the downstream direction, but also to the cross-stream direction. In this computation, the sediment movement caused by secondary current will also be considered, following Shimizu and Itakura’s method [5]. In a curve-linear coordinate system \((s,n)\) depicted in Fig.2, the near-bottom velocities, \((u_b, v_b)\) can be correlated with the cross-sectional mean velocity, \((u,v)\) (Engelund [6]).

\[
\begin{align*}
  u_b &= \gamma u, \quad v_b = \gamma v \\
  \gamma &= 3(1-\beta)/(3-\beta), \quad \beta = 3/(\phi_0\kappa + 1), \quad \phi_0 = (u^2 + v^2)^{1/2}, \quad u^* \text{ the shear velocity,} \\
  \kappa &= \text{the Karman constant} (=0.4). \quad \text{Using } u_b \text{ in Eq.(5), the corresponding velocity due to secondary current } v_b' \text{ can be estimated.}
\end{align*}
\]

\[
  v_b' = -N_r \frac{D}{r} u_b
\]

where \(N_r = 11.5 \) (Rozovskii [7]), and \(r\) the curvature of the channel bend. Finally, the sediment transport rate in \(n\)-direction due to combined primary and secondary currents can be evaluated.

\[
  q_{bn} = q_{bs} \frac{v_b + v_b'}{u_b}
\]

Furthermore, the correction method for sand movement on sloping bottom proposed by Watanabe et al. [8] is employed to achieve stable computation, and the slope of sand surface is adjusted so that it does not exceed the immersed angle of repose.

As boundary conditions, measured time-variation of discharge is imposed at the upstream end of the computation domain, while the measured tidal variation is used at the offshore end.

The governing equations described above are solved by means of finite difference method with a leap frog scheme (see, e.g., Tanaka and Qin [9]), using spatial increment \(\Delta x = \Delta y = 15m\), and time increment \(\Delta t = 0.9\text{ sec}\). Before the computation over movable bed, a preliminary computation is made for fixed bed so that it reaches steady state under constant discharge condition.

### 4 Results and discussions

#### 4.1 Flood in September, 1982

Time-variation of water level in the mouth during the first flood is shown in Fig.3, along with the river discharge and the tidal elevation. Although we can observe slight discrepancy between the computation and the measurement, the overall agreement is excellent. According to the computation, there is a small peak of water level around 23:30 on September 12 immediately before the next peak at 2:00. This might be caused by the backwater effect behind the sand spit and is followed by rapid lowering of the water level induced by intense sediment movement and resultant erosion on the sand spit. However, this phenomenon can not be confirmed in the measurement, since the water level was measured every one hour, longer than the duration of the small peak.
September, 1982

- measured
- calculated

tidal variation

- discharge

Fig 3 Water level variation (September, 1982)

Fig 4 Topography change (September, 1982)
Figure 4 depicts the computed bottom topography in the vicinity of the mouth before and after the flood, respectively shown by solid and broken lines. It is seen that the left sand spit was eroded to form a sand terrace in the sea area. The width of the breaching is about 50m, being quite comparable to the actual phenomenon observed in Photo 1.

The process of sand terrace formation along the a-b-c section (see Fig. 1) is illustrated in Fig. 5, along with the water surface profile at each instant. The bottom profile at 2:00 on September 13, corresponding to the arrival of the peak discharge, shows adverse slope in the sea area. This is due to the sediment deposit owing to abrupt reduction of the tractive force with the increase of the width of the jet formed in the sea. At the final stage of the flood, i.e., 24:00 on September 13, the surface of the sand terrace becomes flatter due to sediment transport in the offshore direction. Similar development of sand terrace at a river mouth has already been reproduced by one of the authors for small-scale laboratory experiment (Tanaka and Qin [9]).

4.2 Flood in August, 1989

During the second flood, semi-diurnal variation of the tide is more predominant (Fig. 6) as compared with the former one shown in Fig. 3. Furthermore, the maximum of the discharge was about 20% higher than the previous flood in 1982.

Temporal variation of the water level can be seen in Fig. 6. The water level in the mouth also shows semi-diurnal property in accordance with the tidal variation. Being same as the previous case in 4.1, the accuracy of the present model with regard to the water level is almost perfect. It is noted that a small peak can be seen again at 23:00 on August 6.

According to the computation shown in Fig. 7, the width of the sand spit breach attained to 80m, slightly bigger as compared with the previous case. This might be due to the difference of the maximum discharge between these two floods. The breached width based on the computation shows reasonable agreement with the reality seen in Photo 2.

Scouring and deposition of sediment in the vicinity of the river mouth and corresponding water surface profile can be more clearly observed in Fig. 8. In contrast to Fig. 5, higher flood discharge in this case caused more severe erosion of the sand spit up to -6m, resulting in more considerable development of the sand terrace towards the offshore direction.

5 Conclusions

The numerical model for river mouth topography change developed by the authors is applied to two floods at the Natori River mouth in 1982 and 1989. The model consists of hydrodynamic and morphological portions, and it can be solved numerically by using a finite difference method. The computed time-variation of water level in the mouth showed excellent agreement with the
Photo 1 Aerial photograph (September 12, 1982)

Fig. 5 Computed cross-section (September, 1982)
Fig. 6 Water level variation (August, 1989)

Fig. 7 Topography change (August, 1989)
Photo 2 Aerial photograph (August 7, 1989)

Fig. 8 Computed cross-section (August, 1989)
measurement in both cases. Furthermore, the breach of the sand spit can also be reproduced with sufficient accuracy. Especially, the difference of width of the breach, which reflects the difference of the magnitude of flood discharge, can be well predicted. Thus, it can be concluded that the applicability of the present model is sufficient for practical uses.

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