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ScienceDirect
Journal of Hydro-environment Research 2 (2009) 228–238
Journal of Hydro-environment Research
www.elsevier.com/locate/jher

Inundation analysis of the effectiveness of an estuary gate in Hori River

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Received 3 April 2007; revised 19 November 2008; accepted 3 December 2008

Abstract

Storm surges and floods around bays in Japan frequently result in water disasters. Both dikes and estuary gates can be constructed in urban areas near bays as counter measures. Estuary gates at the mouth of a river are intended to protect the upstream areas from storm surges and tsunamis. The sewer systems in urban areas also decrease the inundation. In this study, a numerical simulation is carried out to examine the effectiveness of the estuary gate and performance of the sewer system. A synthetic analysis model of inundation phenomena is developed and applied to the behavior of water in the urban area near the Nagoya Port and the estuary region of the Hori River. The developed model consists of models for the sea, river, sewer, overland flood flow, and typhoon. The inundation analysis model is validated by a comparison of analytical and observed results. The features of the inundations in the urban area caused by various conditions are discussed.

Keywords: Inundation analysis; Estuary gate; Water disaster; Storm surge; Sewer system

1. Introduction

Every year, typhoons hit Japan and cause both heavy damage to infrastructure and the loss of lives. Because of Japan's topography, storm surges are among the most dangerous water events. Storm surges and floods may occur simultaneously and lead to inundation of coastal areas. This study focuses on inundation phenomena in the area around the Shonai River and the Hori River in the city of Nagoya, in central Japan. The Hori River passes through the downtown area of Nagoya, and empties into the Nagoya Port. An estuary gate was constructed at the mouth of the Hori River to protect the upstream area against storm surges and tsunamis. Since the embankments constructed along the left and right banks of the Hori River were only designed to prevent flooding from river runoff, the top elevation of the river embankment is lower than the estuary gate. If the estuary gate is not closed during a storm surge, overflow and inundation may occur.

The aim of this study is to evaluate both the effectiveness of the estuary gate in the Hori River against water disasters and the performance of the sewer system in the urban area. For this purpose, a synthetic analysis model is developed, and a numerical simulation of inundation phenomena in the study area is performed. The developed model consists of a two-dimensional sea model, a one-dimensional river flood model, a two-dimensional urban model with an unstructured grid, and a one-dimensional sewer model based on the slot model. A typhoon model is also used to simulate the distribution of atmospheric pressure and wind in the storm surge analysis.

The flood during the Tokai Heavy Rain in 2000, and a storm surge from the Ise Bay Typhoon in 1959, caused extensive inundations in the study area. This work analyzes the water behavior during these two events. The model is validated by a comparison of results with flooding and inundation data from the Tokai Heavy Rain in 2000. In addition, the features of the inundation, the effectiveness of the estuary gate, and the performance of the sewer system are discussed

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1570-6443/$ - see front matter
doi:10.1016/j.jher.2008.12.001

for various conditions, such as flood only, storm surge only, and both conditions combined.

2. Numerical analysis model

The inundation analysis model consists of models for the sea, the river, overland flood flow, and the sewer. The governing equations and numerical simulation method of each model are provided below.

2.1. Sea model

A two-dimensional planar model based on the shallow water equations is used for the analysis of the sea area. The continuity and momentum equations are as follows:

$$\frac{\partial h}{\partial t}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial y}=0 \tag{1}$$

$$\frac{\partial M}{\partial t}+\frac{\partial uM}{\partial x}+\frac{\partial vM}{\partial y}=-gh\frac{\partial(h+z_b)}{\partial x}-\frac{h}{\rho}\frac{\partial P}{\partial x}+\frac{\partial}{\partial x}\left(\varepsilon_x\frac{\partial M}{\partial x}\right)+\frac{\partial}{\partial y}\left(\varepsilon_y\frac{\partial M}{\partial y}\right)+\frac{\tau_{sx}}{\rho}-\frac{\tau_{bx}}{\rho} \tag{2}$$

$$\frac{\partial N}{\partial t}+\frac{\partial uN}{\partial x}+\frac{\partial vN}{\partial y}=-gh\frac{\partial(h+z_b)}{\partial y}-\frac{h}{\rho}\frac{\partial P}{\partial y}+\frac{\partial}{\partial x}\left(\varepsilon_x\frac{\partial N}{\partial x}\right)+\frac{\partial}{\partial y}\left(\varepsilon_y\frac{\partial N}{\partial y}\right)+\frac{\tau_{sy}}{\rho}-\frac{\tau_{by}}{\rho} \tag{3}$$

where x, y represent the axis of the plane, h is water depth, z_b is mean sea level, t is time, u, v are the flow velocities in the x, y directions, respectively, M, N are the flux of flow rates in the x, y directions, respectively ($M=uh$, $N=vh$), P is atmospheric pressure, τ_{sx}, τ_{sy} are the components of shear stress at the water surface in the x, y directions, respectively, τ_{bx}, τ_{by} are the components of shear stress at the water bottom in the x, y directions, respectively, ρ is the density of water, g is the acceleration of gravity, and ε_x, ε_y are the eddy viscosities in the x, y directions, respectively.

The shear stress at the water surface is given by equations (4) and (5):

$$\tau_{sx}=\rho_a\gamma^2 W_x\sqrt{W_x^2+W_y^2} \tag{4}$$

$$\tau_{sy}=\rho_a\gamma^2 W_y\sqrt{W_x^2+W_y^2} \tag{5}$$

where ρ_a is the density of air, W_x, W_y are the wind velocities in the x, y directions, respectively, and γ^2 is the drag coefficient at the free surface of water.

The shear stress at the bottom is presented below using Manning's roughness coefficient f:

$$\tau_{bx}=\rho g f^2 u\sqrt{u^2+v^2}/h^{1/3} \tag{6}$$

$$\tau_{by}=\rho g f^2 v\sqrt{u^2+v^2}/h^{1/3} \tag{7}$$

The finite volume method (FVM) is used for the numerical calculations of the sea model. Fig. 1(a) shows the spatial locations of the unknown variables in a two-dimensional staggered scheme. Fig. 1(b) shows the temporal location of variables in the leap-frog scheme.

The finite difference forms of equations (1) and (2) are given as equations (8) and (9), respectively:

$$h_{i,j}^{n+1}=h_{i,j}^{n-1}-\frac{2\Delta t}{\Delta x}\left(M_{i+1/2,j}^{n}-M_{i-1/2,j}^{n}\right)-\frac{2\Delta t}{\Delta y}\left(N_{i,j+1/2}^{n}-N_{i,j-1/2}^{n}\right) \tag{8}$$

$$\begin{aligned}M_{i-1/2,j}^{n+2}=&M_{i-1/2,j}^{n}-\frac{2\Delta t}{\Delta x}\left(uM_{S_{\mathrm{I}}}-uM_{S_{\mathrm{II}}}\right)-\frac{2\Delta t}{\Delta y}\left(vM_{S_{\mathrm{III}}}-vM_{S_{\mathrm{IV}}}\right)\\&-gh_{i-1/2,j}^{n+1}\frac{2\Delta t}{\Delta x}\left(h_{i,j}^{n+1}+Z_{b_{i,j}}-h_{i-1,j}^{n+1}-Z_{b_{i-1,j}}\right)-\frac{h_{i-1/2,j}^{n+1}}{\rho}\frac{2\Delta t}{\Delta x}\left(P_{i,j}-P_{i-1,j}\right)\\&+\frac{2\Delta t}{\Delta x}\left(\varepsilon_{x_{i,j}}\frac{M_{i+1/2,j}^{n}-M_{i-1/2,j}^{n}}{\Delta x}-\varepsilon_{x_{i-1,j}}\frac{M_{i-1/2,j}^{n}-M_{i-3/2,j}^{n}}{\Delta x}\right)\\&+\frac{2\Delta t}{\Delta y}\left(\varepsilon_{y_{i-1/2,j+1/2}}\frac{M_{i-1/2,j+1}^{n}-M_{i-1/2,j}^{n}}{\Delta y}-\varepsilon_{y_{i-1/2,j-1/2}}\frac{M_{i-1/2,j}^{n}-M_{i-1/2,j-1}^{n}}{\Delta y}\right)\\&+2\Delta t\left(\frac{\rho_a\gamma^2 W_{x_{i-1/2,j}}\sqrt{\left(W_{x_{i-1/2,j}}\right)^2+\left(W_{y_{i-1/2,j}}\right)^2}}{\rho}\right)\\&-2\Delta t\left(\frac{0.5gf^2\left(M_{i-1/2,j}^{n+2}+M_{i-1/2,j}^{n}\right)\sqrt{\left(u_{i-1/2,j}^{n}\right)^2+\left(v_{i-1/2,j}^{n}\right)^2}}{\left(h_{i-1/2,j}^{n+1}\right)^{4/3}}\right)\end{aligned} \tag{9}$$