THE APPLICABILITY OF A 3D HYDRODYNAMIC MODEL ON FLOW AROUND HYDRAULIC STRUCTURE IN VIETNAM

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ABSTRACT: Hydraulic structures such as spur dyke or embankment are popular in river training engineering. The flow around hydraulic structures definitely has complicated three-dimensional nature and has been the subject of studies using numerical models. The current 3D model has been applying on many experiments in laboratory but the applicability to the real river is still in question. This paper shows some results of 3D simulation of flow around structure in a natural river. The original 3D model for bed sediment load was improved by including the suspended sediment in order to adapt with rivers in Vietnam then it was applied to a segment of Red river nearby Hanoi city.

INTRODUCTION

In almost all the cities of Asian countries, there is lots of vulnerability for flood disaster from natural and social conditions. Especially, in the Red River, which runs through the center part of Hanoi city in Vietnam, the river bed materials consists of fine sand and silt. Then, severe damages such as bank erosion and dike break are possible to occur easily, since the river bed and channel deforms much during floods. Therefore the construction of structure to protect the bank like immerged and submerged spur dyke or abutment is needed. But the flow around hydraulic structures definitely has complicated three-dimensional nature and the characteristics of local flow and bed deformation are different among each river basin.

As engineers become involved in managing rivers, the reliable prediction tools, or models, must be available to compare the expected performance of various design options for structure. When something more than an analytical solution is required, physical and numerical models have been used to address sediment transport problems (Chanson, 1999). A physical model is a scaled-down representation of the prototype geometry, fabricated and investigated in a laboratory under controlled conditions. Physical models are commonly used to optimize structure design or ensure that a structure can operate safely (Chanson, 1999; Hassan, 2003). Over the past few decades, problems related to flow and bed deformation processes around river hydraulic structures have been studied mostly by physical modeling of a spur dike, an abutment, and a bridge pier (Nagata et al., 2005). The studies on the spur dike and the abutment are considered to be alike due to their relatively similar shapes. The investigations on this type of obstruction have been presented by Garde et al. (1961); Laursen (1963); Gill (1972); Rajaratnam and Nwachukwu (1983a,b); Melville (1992); Kwan and Melville (1994); Lim (1997); Rahman et al. (1998); and Kuhnle et al. (1999). Based on the experimental results, the flow characteristics have been examined, and several formulas for estimating local scour depth have been proposed by means of dimensional analyses (e.g., Garde et al. 1961; Melville 1992) or the analytical approaches (e.g., Laursen 1963; Lim 1997; Rahman et al. 1998).

Numerical models are computer programs that solve basic fluid mechanics and sediment transport equations (Martin and McCutcheon, 1999; Abbott, 1992). Fluid mechanics equations can be solved in one-dimensional (1D), two-dimensional (2D), or three-dimensional (3D) spatial schemes (Martin and McCutcheon, 1999; Abbott, 1992). Solving these equations in their three-dimensional forms for flow and sediment transport is extremely difficult and has become feasible only as increased computer power makes numerical solutions practical (Martin and McCutcheon, 1999). Recently, several numerical models have been developed to calculate the phenomena around river hydraulic structures, however, the number of test cases utilized to validate these numerical models is not adequate in understanding their general applicability to river hydraulic structures (Nagata et al., 2005) such as three-dimensional models with the hydrostatic assumption by Mayerle et al. (1995), Jia and Wang (1993, 1996) cannot reliably compute flow field near the structure; or the turbulence model under the assumption of local isotropic turbulence is not considered to be suitable for the simulation of flow around the obstacle where three-dimensional flows are dominant. In addition, a common assumption in these bed deformation model is the local equilibrium of sediment transport over the one-step length scale of particle movement. However, a nonequilibrium condition of sediment transport dominates around the structure significantly affect sediment movement, rapidly change due to the presence of the flow obstacle and the scour hole. Nagata et al. (2005) developed a fully (non-hydrostatic pressure distributions) three-dimensional, Reynolds-averaged Navier–Stokes equation (RANS) closed with the nonlinear k-ε turbulence model for the flow calculation and introduced the effect of nonequilibrium sediment transport processes into the bed-deformation model and the moving grid system was employed to conform numerical grids to both bed and water surfaces. However, this model has been validated and applied to the laboratory experimental data (Nagata et al., 2005) such as flow around the spur dike (Muneta and Shimizu 1994); local scour around the spur dike (Michiue and Hinokidani 1992); flow and local scour around the cylindrical pier (Melville 1975; Melville and Raudkivi 1977).

In this study, in order to examine the applicability of 3D model for flow and bed deformation around hydraulic structure in the Red river, the model developed by Nagata et al. was adopted to include the module for suspended sediment transport which is considered as dominant part of total sediment load in Vietnamese river particularly Red river. The model was applied to a river segment crossing Hanoi City with the surveyed bathymetric data including an immerged spur dyke. This paper showed some initial results with qualitatively reasonable characteristics of flow around structure as well as the evolution of river bed which encourages us to further study with quantitatively validation.

NUMERICAL MODEL

Flow model

The 3D RANS equations and the continuity equation expressed in the moving boundary-fitted coordinates are as follows (Nagata et al., 2005):

Continuity equation

$$\frac{\partial}{\partial \xi^j}\left(\frac{U^j}{J}\right) = 0 \tag{1}$$

Momentum equation

$$\frac{\partial}{\partial t}\left(\frac{U^i}{J}\right) + \frac{\partial}{\partial \xi^j}\left(\frac{\left(U^j - U_G^j\right)U^i}{J}\right) - \frac{\left(U^j - U_G^j\right)\mathbf{u}}{J}\cdot\frac{\partial}{\partial \xi^j}\left(\nabla \xi^i\right) - \frac{\mathbf{u}}{J}\cdot\frac{\partial}{\partial t}\left(\nabla \xi^i\right) = -\frac{g^{ij}}{\rho J}\frac{\partial p}{\partial \xi^j} + \frac{\mathbf{f}}{J}.\nabla \xi^i + \frac{1}{J}\frac{\partial \xi^j}{\partial x^m}\frac{\partial \xi^i}{\partial x^l}\frac{\partial}{\partial \xi^j}\left(\tau^{lm} - \overline{u'^l u'^m}\right) \tag{2}$$

in which

$$\nabla = \left(\frac{\partial}{\partial x^1}, \frac{\partial}{\partial x^2}, \frac{\partial}{\partial x^3}\right) \tag{3}$$

$$g^{ij} = \nabla \xi^i \cdot \nabla \xi^j \tag{4}$$

$$U^i = \left(\frac{\partial \xi^i}{\partial x^j}\right)u^j \tag{5}$$

$$U_G^i = \left(\frac{\partial \xi^i}{\partial x^j}\right)u_G^j \tag{6}$$

$$\tau^{ij} = \nu\left(\frac{\partial \xi^m}{\partial x^j}\frac{\partial u^i}{\partial \xi^m} + \frac{\partial \xi^m}{\partial x^i}\frac{\partial u^j}{\partial \xi^m}\right) \tag{7}$$

where t=time; $\left(x^1, x^2, x^3\right)$ Cartesian coordinates (x^3 denotes the vertical coordinate in this paper); $\left(\xi^1, \xi^2, \xi^3\right)$: boundary-fitted coordinates; ρ : fluid density; ν: kinematic viscosity of fluid; p: pressure; J: Jacobian of transformation; g^{ij} : contravariant metric tensors; U^i: contravariant components of velocity; U_G^i : contravariant components of grid velocity; $\mathbf{u}$: velocity vector $\left[\mathbf{u} = \left(u^1, u^2, u^3\right)\right]$; u^i : velocity components in Cartesian coordinates; u_G^i : grid velocity components in Cartesian coordinates; $\mathbf{f}$: gravitational vector $\left[\mathbf{f} = (0, 0, g)\right]$; g : gravitational acceleration; τ^{ij} : viscous stress tensors; và $-\overline{u'^i u'^j}$: Reynolds stress tensors.

The Reynolds stress tensors have the following expressions (Yoshizawa 1984):

$$-\overline{u'^i u'^j} = D_t\left(\frac{\partial \xi^m}{\partial x^j}\frac{\partial u^i}{\partial \xi^m} + \frac{\partial \xi^m}{\partial x^i}\frac{\partial u^j}{\partial \xi^m}\right) - \frac{2}{3}k\delta^{ij} - \frac{k}{\varepsilon}D_t\sum_{\beta=1}^{3}C_\beta\left(S_\beta^{ij} - \frac{1}{3}S_\beta^{\alpha\alpha}\delta^{ij}\right) \tag{8}$$

in which

$$S_1^{ij} = \frac{\partial u^i}{\partial x^r}\frac{\partial u^j}{\partial \xi^r} \tag{9}$$

$$S_2^{ij} = \frac{1}{2}\left(\frac{\partial u^r}{\partial x^i}\frac{\partial u^j}{\partial x^r} + \frac{\partial u^r}{\partial x^j}\frac{\partial u^i}{\partial x^r}\right) \tag{10}$$

$$S_3^{ij} = \frac{\partial u^r}{\partial x^i}\frac{\partial u^r}{\partial x^j} \tag{11}$$

Sediment model

Suspended sediment equation:

$$\frac{\partial C_k}{\partial t} + \frac{\partial uC_k}{\partial x} + \frac{\partial vC_k}{\partial y} + \frac{\partial\left(w - w_{s,k}\right)C_k}{\partial z} = \frac{\partial}{\partial x}\left(\varepsilon_{s,x}\frac{\partial C_k}{\partial x}\right) + \frac{\partial}{\partial y}\left(\varepsilon_{s,y}\frac{\partial C_k}{\partial y}\right) + \frac{\partial}{\partial z}\left(\varepsilon_{s,z}\frac{\partial C_k}{\partial z}\right) \tag{12}$$

where: C_k : suspended sediment contents (*k* equal to 1 and 2 corresponding to cohesive and non-cohesive sediment); *u,v,w* are velocities in *x, y* and *z* directions; $\varepsilon_{s,x}$ and $\varepsilon_{s,y}$ are diffusion coefficients in horizontal plan;

$\varepsilon_{s,z}$ is diffusion coefficient in vertical direction; $w_{s,k}$ are settling velocities.

Bed deformation

The volume of sediment pickup per unit time from a numerical mesh on the bed surface, V_p, is given by

$$V_p = \frac{A_3 d}{A_2} p_s S_p \tag{13}$$

where p_s: pickup rate; d: diameter of sediment particle; A_2, A_3: shape coefficients of sand grain for two- and three-dimensional geometrical properties (=π/4, π/6), respectively; and S_p: area of the bed-surface mesh projected onto the horizontal (x_1–x_2). The pickup rate p_s is from Nakagawa et al. (1986) as follows:

$$p_s \sqrt{\frac{d}{(\sigma/\rho - 1)g}} = F_0 G_* \tau \left(1 - \frac{k \Phi \tau_{*c}}{\tau_{*k}}\right)^{m_p} \tag{14}$$

The deposition volume $V_d(j,n)$ of the sediment moving from point j at the time it reaches the position of $p_{sed}(n)$ can be obtained from (Nagata et al., 2005):

$$V_{d(j,n)} = V_{p(j)} f_s\left(s_{(n)}\right) \left|u_{sed(n)}\right| \Delta t \tag{15}$$

$$f_s\left(s_{(n)}\right) = \frac{1}{\lambda} \exp\left(-\frac{s_{(n)}}{\lambda}\right) \tag{16}$$

where $V_{p(j)}$: volume of sediment pick-up at point j; $f_s(s(n))$ probability density function of step length; λ: average step length. More detailed descriptions about the parameters might refer to Nagata et al. (2005).

Numerical Procedure

The momentum equations and the transport equations of k and ε were discretized by the finite-volume method on a staggered grid system. In order to satisfy local continuity, the highly simplified mark-and-cell (HSMAC) method (Hirt and Cook 1972) was applied with the convective terms were discretized by employing the quadratic upstream interpolation for convective kinematics (QUICK) scheme (Leonard 1979), and the diffusion terms were discretized using the central differencing scheme.

TEST CASE

In Nagata et al. study (2005) concerning the numerical simulation of flow and morphological changes around the structure, the models referenced previously were tested with only several types of hydraulic structure in laboratory experiment, which makes it difficult to evaluate the model's applicability. In order to validate the recent improved model, in this study it was applied in a real river segment of Red river near by the center of Hanoi City. The computations were performed using an Pentium IV CPU with 2Gb RAM, and it required approximately 30 days of computation time for 30 minute real phenomenon.

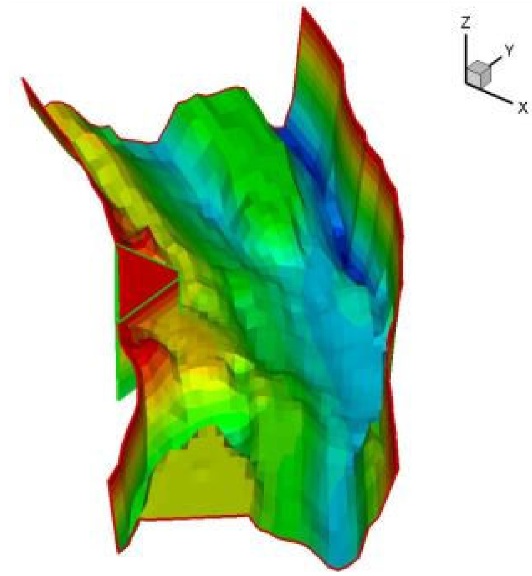

Figure 1 Bathymetry in the study river segment

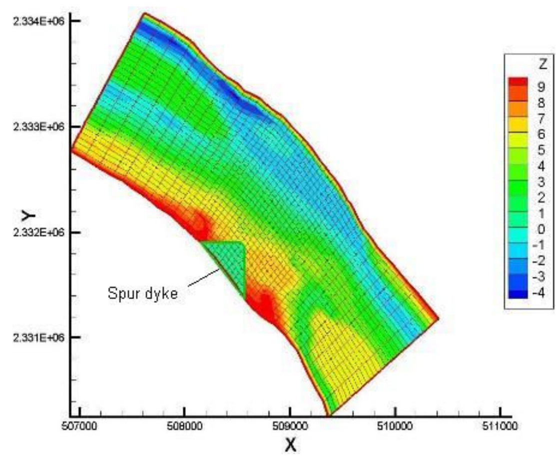

Figure 2 Illustration of computational mesh in 2D plain

Model setup

The study area was selected base on the available bathymetry data, which located near the center of Hanoi City (Fig 1) with dimension of about 4000 m (in length) and about 1650 m (in width). In the right side of the river there is an immerged triangle spur dyke with the dimension of each side is about …m. The curvilinear mesh was adopted in the river segment to 46x30x11 cells (Fig 3) with the finer resolution in the location nearby spur dyke. The initial and boundary conditions were extracted from the 2D simulation results using TREM model (Giang N.T, 2010).

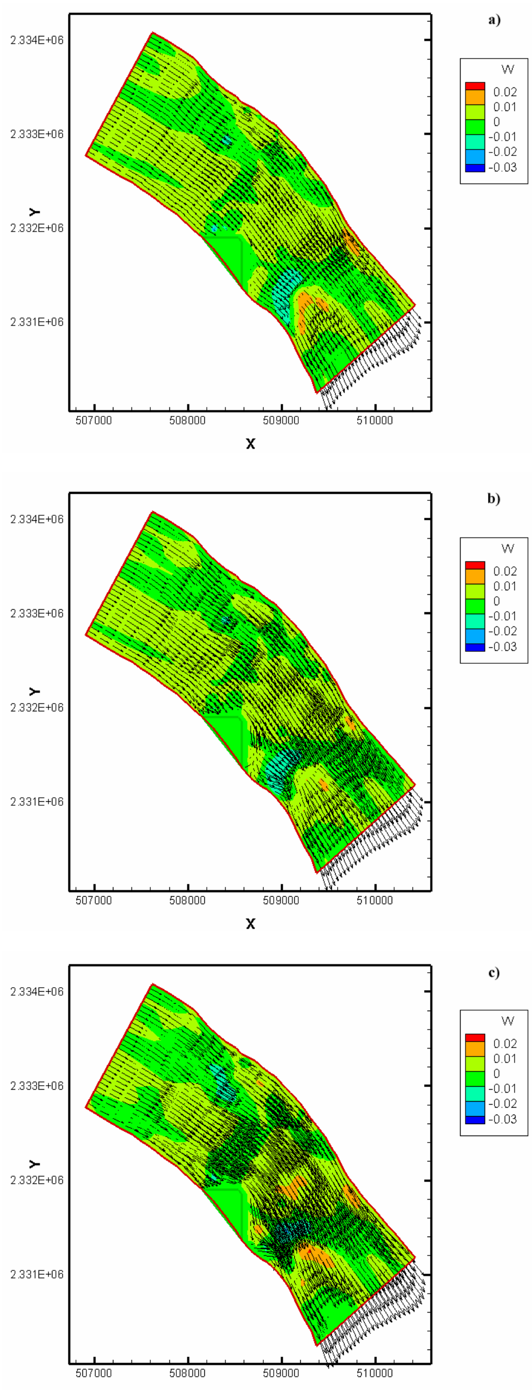

Figure 3 Velocity field at the surface layer
a) at t=5 minutes; b) at t=30 minutes; c) at t=60 minutes.

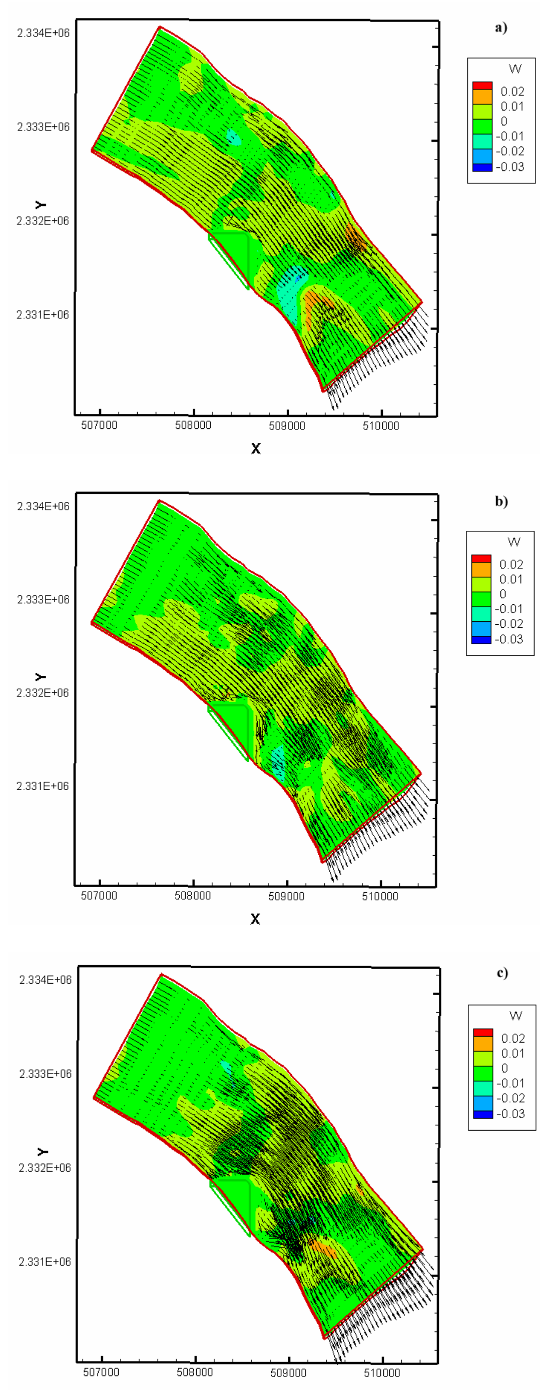

Figure 4 Velocity field at the middle layer
a) at t=5 minutes; b) at t=30 minutes; c) at t=60 minutes.

Results

Fig 3-5 showed the current filed in computational domain at different moments and layers, and generally the flow tends to concentrate in the right bank. The impacts of spur dyke was significant on the velocity field.

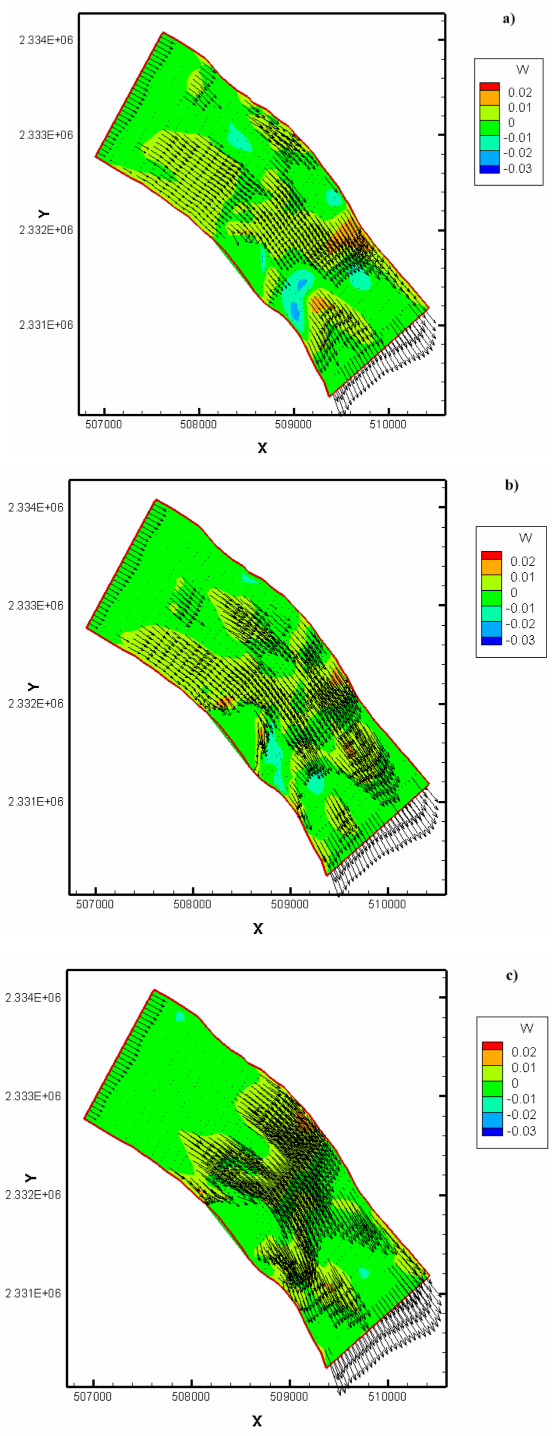

Figure 5 Velocity field at the bed layer
a) at t=5 minutes; b) at t=30 minutes; c) at t=60 minutes.

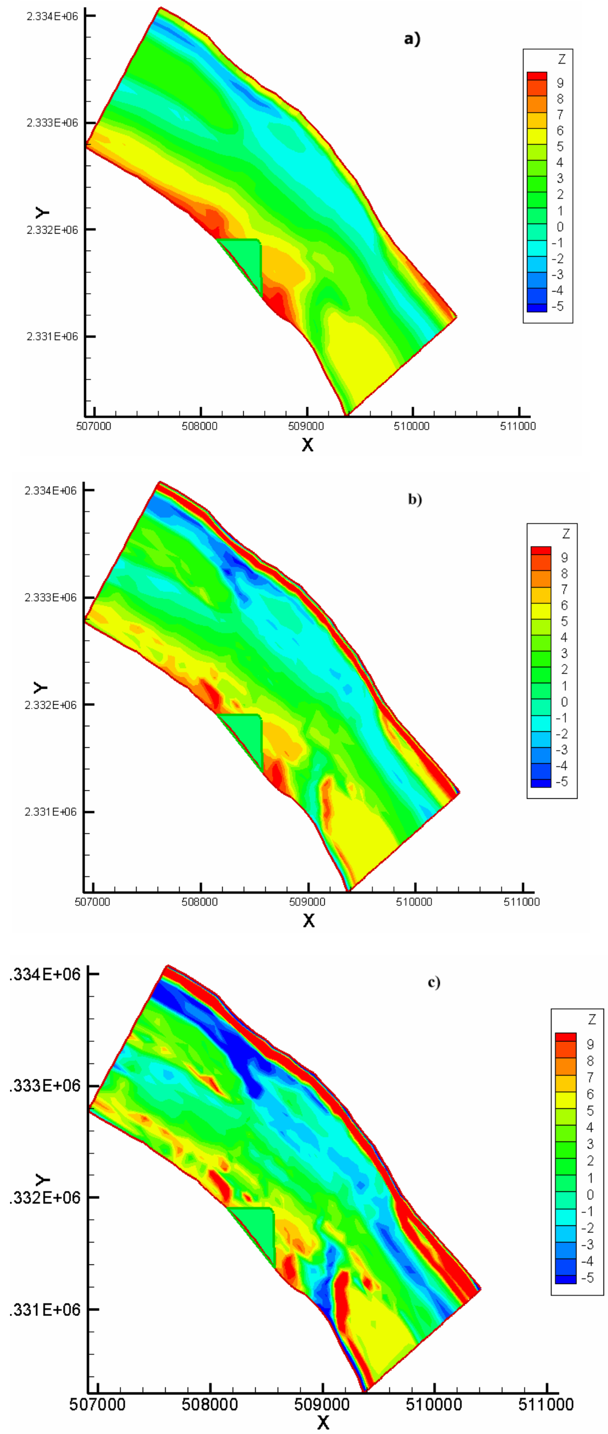

Figure 6 Bed bathymetry results
a) at t=5 minutes; b) at t=30 minutes; c) at t=60 minutes.

The study area was bend segment, the flows at upstream was likely stronger in concave bank side then it caused the serious bed erosion as seen in Fig. 6. It also can be seen that, due to the increased flow speed in the right bank side the river bed was also eroded then tends to attract more flow in this side. The bed variation is reasonably simulated with serious erosion near the left bank in upstream and near the right bank in downstream part of the study area. Some small deposition could be observed at the head of small submerged island downstream of structure. These results were qualitatively in agreement with some previous survey in this region.

CONCLUSION

A numerical model for simulating flow and bed variations around river hydraulic structures has been developed to describe the flow field and river bed evolution in Vietnamese condition. Furthermore, the model incorporates the effect of suspended sediment transport into the original Nagata et al. model. The proposed model was applied to a field case of river segment and showed a qualitatively reasonable characteristics of flow and bed deformation around immerged triangle spur dyke. The numerical results suggest that the present model could be a useful tool for simulating the flow and river-bed features around hydraulic structures in Vietnamese river. Further studies may be needed in order to clarify the sensitivity of the coefficient appearing in the bed-deformation model as well as to improve the computation time by converting the source code into parallel simulation.

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