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Lagrangian Discrete Parcel Simulation of River Ice Dynamics

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ABSTRACT

A coupled two-dimensional model for river ice dynamics is developed for simulating ice movement and jamming in river reaches with complex geometries. For the hydrodynamic simulation an Eulerian finite element method is used. A Lagrangian discrete parcel scheme, based on the smoothed particle hydrodynamics method, is used to simulate the movement of surface ice. The model is applied to the Grass Island Pool area of the upper Niagara River.

INTRODUCTION

The existence of ice in rivers in cold regions can have significant detrimental conseguences. Of particular concern is the formation of ice jams. The analytical formulation of floating surface ice jams was first developed by Pariset and Hausser (1961). This was followed by a number of theoretical and laboratory studies (Uzuner and Kennedy, 1976; Tatinclaux, 1977; and Beltaos, 1983). This type of formulations was developed for static accumulations of floating granular ice masses. They can not describe the dynamics of ice jam formation. As a result, the time and location of ice jam initiation can not be determined. Recently, Shen et al. (1990) developed an analytical framework for dynamic ice transport and jam initiation in rivers. The basic concept of river ice dynamics is similar to that of sea ice and lake ice (Hibler, 1979; Wake and Rumer, 1983). However, river ice transport is more dynamic than lake or sea ice. River ice transport usually has large convection terms, and large variations in velocity and concentration. Important river ice phenomena, such as underturning, grounding, undercover transport, and freezing between ice floes, can not be easily described analytically in the surface ice transport equations. An accurate and flexible numerical method is needed for river ice transport. In this study, a two-dimensional numerical model for river ice dynamics is developed. The ice transport is simulated using a Lagrangian discrete parcel scheme developed based on the smooth particle hydrodynamics method (Lucy, 1977; Monaghan, 1985). The model is applied to the Grass Island Pool area of the upper Niagara River.

GOVERNING EQUATIONS

The movement of surface ice in a river is governed by current and wind drags, gravity, interaction between ice elements, and their interactions with river boundaries. The governing equations for the water current as well as ice transport are presented.

Hydrodynamic Equations

Hydrodynamic equations for free surface flows in shallow waters have been well-established. The two-dimensional depth-integrated equations for free surface flows (e.g. Connor and Brebbia, 1978; Wake and Xiao, 1989), modified to include the effect of surface ice, are (Shen and Chen, 1992):

$$\frac{\partial(\rho H')}{\partial t}+\frac{\partial(\rho q_x)}{\partial x}+\frac{\partial(\rho q_x)}{\partial y}=0 \tag{1}$$

$$\frac{\partial q_x}{\partial t}+\frac{\partial}{\partial x}\left(\frac{q_x^2}{H'}\right)+\frac{\partial}{\partial y}\left(\frac{q_x q_y}{H'}\right)=-\frac{\partial \overline{N}_p}{\partial x}+\frac{1}{\rho}\left(\frac{\partial N_{xx}}{\partial x}+\frac{\partial N_{yx}}{\partial y}\right)$$
$$+\frac{1}{\rho}\left(\tau_{s_x}-\tau_{b_x}\right)+g\eta'\frac{\partial h}{\partial x}-\frac{H'}{\rho}\frac{\partial p_i}{\partial x} \tag{2}$$

and

$$\frac{\partial q_y}{\partial t}+\frac{\partial}{\partial x}\left(\frac{q_x q_y}{H'}\right)+\frac{\partial}{\partial y}\left(\frac{q_y^2}{H'}\right)=-\frac{\partial \overline{N}_p}{\partial y}+\frac{1}{\rho}\left(\frac{\partial N_{yy}}{\partial y}+\frac{\partial N_{xy}}{\partial x}\right)$$
$$+\frac{1}{\rho}\left(\tau_{s_y}-\tau_{b_y}\right)+g\eta'\frac{\partial h}{\partial y}-\frac{H'}{\rho}\frac{\partial p_i}{\partial y} \tag{3}$$

with

$$N_{ij}=<\tau_{ij}+\rho u_i'u_j'>\equiv\int_{-h}^{\eta'}\left(\tau_{ij}+\rho u_i'u_j'\right)dz$$
$$\cong\varepsilon_{ij}\left(\frac{\partial q_i}{\partial x_j}+\frac{\partial q_j}{\partial x_i}\right)\quad i,j=x,y \tag{4}$$

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KEY WORDS: Ice dynamics, ice jam, Lagrangian method, numerical simulation, river ice.