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GENERALIZED THREE-DIMENSIONAL CURVILINEAR NUMERICAL MODELING OF LAMINAR AND TURBULENT FREE-SURFACE FLOWS IN A VORTEX SETTLING BASIN

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IN THE NAME OF GOD

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Dedication

This dissertation is dedicated, with great affection and gratitude, to my wife

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ABSTRACT

GENERALIZED THREE-DIMENSIONAL CURVILINEAR NUMERICAL MODELING OF LAMINAR AND TURBULENT FREE-SURFACE FLOWS IN A VORTEX SETTLING BASIN

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A three-dimensional numerical model has been developed to study the complex flow situations with air-water interface in a vortex settling basin. This model is based on solving Navier–Stokes (N.–S.) equations. For turbulence modeling, the Reynolds Averaged Navier–Stokes (RANS) equations were adopted. The standard k-ε and k-ω, were used to provide the information of turbulent eddy viscosity. A computer code was developed to solve above equations using finite volume approach in general curvilinear coordinates. The well-known SIMPLE algorithm was implemented to solve N.–S. or RANS equations. The free-surface motion is tracked by using piecewise linear volume of fluid (VOF) method.

The different parts of the numerical model were first validated by a number of laminar and turbulent single phase flows. Then free-surface tracking approach was verified using some simple analytical flow fields. The free-surface coupled with the equations of motion was also validated using a laminar liquid jet filling a thin rectangular mould. Then the code was applied to model some laminar and turbulent free-surface flows including a 3-D dam-break wave striking with a square cylinder, a hydraulic jump with different upstream Froude numbers and the water entry of a sphere with constant velocity. In order to study the flow field in the vortex settling basin (VSB), first a simplified cubic VSB was considered and

its outlet boundary conditions were investigated. Vorticity open boundary condition was introduced and applied for the outlets of this simplified geometry and advantages of this kind of BC were discussed. A preliminary assessment of the turbulence model performance in this geometry was then conducted.

Finally the code was used to study the unsteady flow behavior in a circular cylindrical VSB with a central clock-wise vortex. However, to keep the problem tangible and to save the computational time, only the flow filed inside the basin were modeled and the inlet channel omitted from the computational domain and an overflow weir was considered at the beginning of outlet channel. The detailed discussions about complex three-dimensional flow patterns, velocity fields, and free-surface deformations in the cylindrical VSB have been presented and discussed. These helped to shed more light on the very complicated flow structure in a VSB.

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Chapter 1

Introduction

Except for mountainous rivers or large dams, diverted water usually carries considerable amounts of sediment that produce problems in distribution networks. The sediment particles decrease the discharge capacity of conveyance canals, clog sprinklers and drippers, and erode canals and hydropower tunnel linings, penstocks and turbines. Moreover, they produce complication by necessity to clean away sediment deposited and arrange for their disposal, which are costly and time consuming.

To overcome the above problems, sediment removal devices are widely used. These devices are divided in two main categories: intermittent and continuous operation systems. Continuous systems utilize a fraction of the diverted flow to flush out the extracted sediment particles from the sediment chamber. These systems obviate the need to clean away the deposited sediment in the settling basin. A vortex settling basin (VSB) is a continuous flushing system which is used to remove sediment from diverted water. Since the size of a VSB is small, the construction cost of a VSB is just a fraction of the cost required for the construction of a classical settling basin to extract comparable particles (Mashauri, 1986). A schematic diagram of this device and a simplified model (to be employed in numerical simulations to be described below) was presented in Ziaei *et al.* (2007) and repeated here as Figure 1.1. A VSB is an efficient device that uses a vortex motion with vertical axis to remove sediment from water. In a VSB, flow is introduced tangentially into a cylindrical chamber having an orifice at the center of its bottom. The induced combined vortex (combination of free and forced vortices) within the chamber causes sediment particles that are heavier than water to move towards the periphery of the chamber due to centrifugal force. Secondary flows move the fluid layer near the basin floor toward the central orifice. Since the sediment particles move with the flow along a helical path, they have a settling length that is longer than the basin dimensions. This feature makes the VSB more efficient than ordinary settling tanks.

Elaborate studies were made on different properties of the VSB mostly by physical modeling. Therefore, our knowledge of VSB flow structure relies heavily on laboratory experiments and empirical or semi-empirical correlations. However, it is well known that laboratory experiments suffer from constraints on the range of applicable physical parameters and scaling effects, not to mention the cost associated with performing careful experiments. Due to recent rapid advancement of computational power, 3-D Navier–Stokes solvers to simulate flow in hydraulic structures have been developed. These numerical models have the potential to become useful research tools for better understanding the physical processes and engineering tools to design these structures.

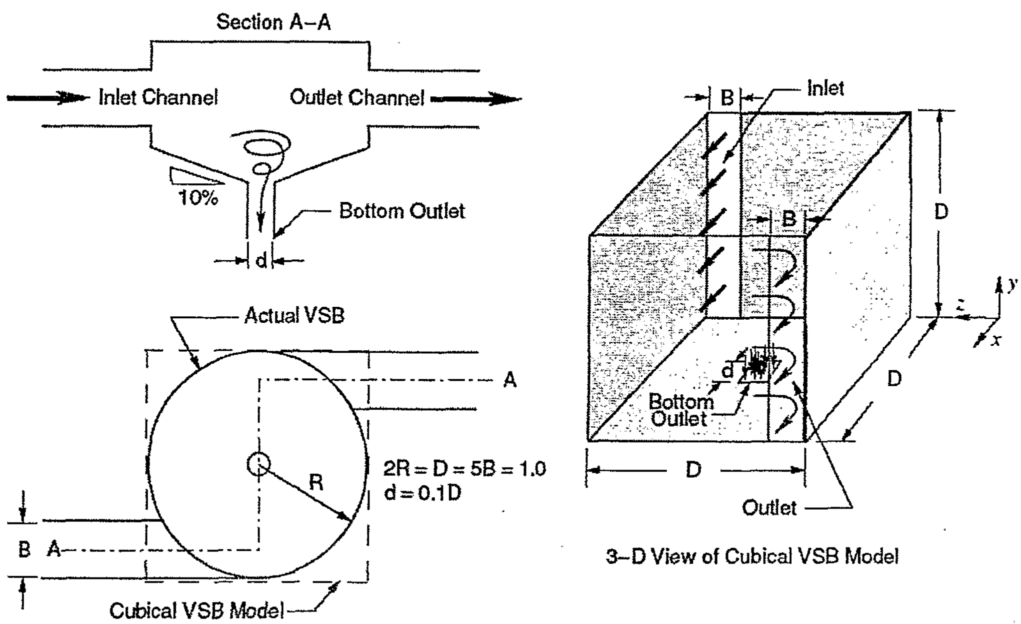

Figure 1.1. Schematic diagram of a vortex settling basin (left) and the simplified model (right).

In this study, a numerical tool which is able to simulate three-dimensional complex flow situations with air-water interfaces in a vortex settling basin will be developed. The accuracy of this numerical model will be examined and validated by different test cases in terms of turbulence characteristics, free surface profiles and velocity fields. Some useful results that are difficult to be measured by the experiments will be presented and discussed.