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Computation of Filling Time of a Ship Lock

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Abstract: In this paper, Steady-flow Integration Approach (SIA) and Volume of Fluid (VOF) method are both used to calculate the filling time of a ship lock. The values of filling time derived from these two different methods have the same order of magnitude. SIA is only used to give a quick but coarse estimation; however in the application of more time-consuming VOF approach, the fluctuations of water surface are additionally considered and computed, It provides a more precise estimation of the filling time and a more realizable details about the filling process. In practical engineering, the geometry of ship lock will be far more complex than here; the SIA is not enough to satisfy the demands for a desired design. The VOF method will be a nice choice and give reasonable predictions of filling time, water fluctuations and velocity fields in the ship lock.

Introduction

Ship lock is a common type of hydraulic structure in hydraulic engineering. The filling or discharge time of a ship lock, water fluctuations and velocity field in the ship lock are the concerns of engineers and managers[1]. In some text books, the involved estimation of filling or discharge time for a simplified ship lock is solved using a Steady-flow Integration Approach (SIA) [2,3]. In this paper, Volume of Fluid (VOF) method is used to solve this essentially unsteady problem. Compare is also done between the SIA and VOF method. The study results can be used as a reference in engineering design.

Problem Descriptions

Suppose a simplified planar ship lock is 12m long with vertical sides, shown in Fig.1. The Blue represents the water, and the red stands for the air. The water surface in the lock is initially 2.5m below the level of the surface of the water upstream. Water enters the ship lock through a conduit with cross-sectional area A (A=1m^2/m). The question is how long the ship lock will be filled from the initial status to the final status? Two approaches of SIA and VOF are given here in the following paragraphs for this problem.

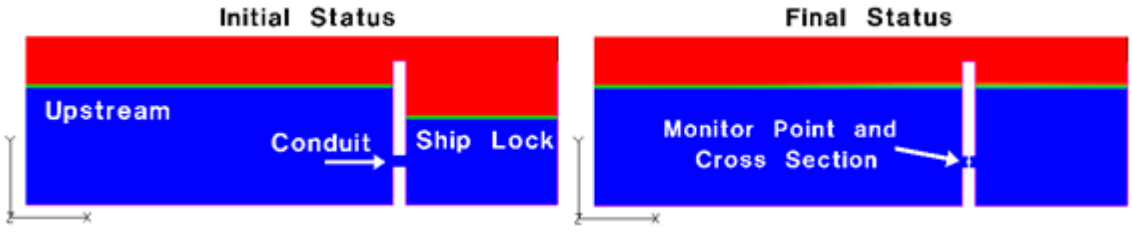

Fig.1 Problem Descriptions

Steady-flow Integration Approach (SIA)

In many textbooks of hydraulics, an approximate solution for this simplified engineering problem of ship lock is introduced under two hypotheses. The first hypothesis is that the unsteadiness of this flow is not too rapid, unsteady flow can usually be approximated by assuming the flow is steady at different rates over successive time periods of short duration. The second hypothesis is that the discharge coefficient C_d for the conduit is a constant (0.5 used here, in fact, this value is a variable and should be given by specific physical tests). Thus, the flowrate Q through this conduit at different instant is given by following equation,

$$Q = C_d A(2gy)^{1/2} \tag{1}$$

where y is the variable difference in level between the water surface in the lock and that outside. The change in volume of ship lock during a small time interval dt can be expressed as $dV=Qdt$, if A_s is denoted as the area of the surface of the volume when dy is the change in level of the surface during the filling process, then dV can also be written as $dV=A_s dy$, so integrating of equation $A_s dy=Qdt$ gives an estimation for t, which is the time for the water level in the lock to change from y_1 to y_2.

$$t = \int_{y_1}^{y_2} \frac{A_s dy}{C_d A(2gy)^{1/2}} = \frac{2A_s}{C_d A\sqrt{2g}}(y_2^{1/2} - y_1^{1/2}) \tag{2}$$

Substitute the quantities into the above equation, the calculated result t of filling time is 6.3 seconds.

VOF Approach

In software FLUENT, The VOF model can model two or more immiscible fluids by solving a single set of momentum equations and tracking the volume fraction of each of the fluids throughout the domain. Two-phase domain (water in the ship lock with a region of air above) is solved using VOF method in order to resolve the variation of the water surface and the time consumed during the filling process. Two continuity equations are solved to account for each phase, for the q^{th} phase, the equation has the following form:

$$\frac{\partial \alpha_q}{\partial t} + u_i \frac{\partial \alpha_q}{\partial x_i} = 0 \tag{3}$$

where α_q represents the volume fraction of the q^{th} phase in the control volume; t is the time; u_i represents velocity in the x_i direction; A single momentum equation is solved throughout the domain as following:

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i \tag{4}$$

ρ is the average local density in the control volume computed as $\rho=\Sigma\alpha_q\rho_q$, p is the static pressure, τ_{ij} is the stress tensor consisting of kinematic molecular and turbulent viscosity effects, g_i is the gravitational acceleration in the i-direction; The volume fractions of all the phases in each cell should be summed up to unity[4].

The geometry of the computational domain is shown in Fig.1. The grids and the boundary conditions are shown in Fig.2.

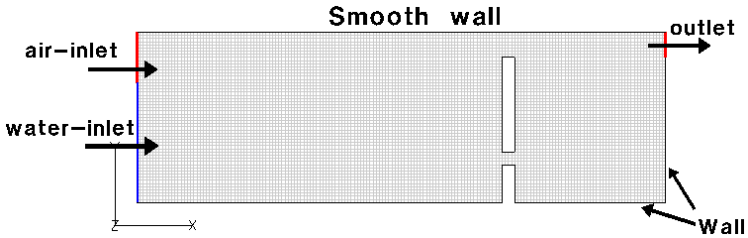

Fig.2 Grids and Boundary Conditions

8904 rectangular cells are used to mesh the domain. Four kinds of boundaries provided by Fluent are used here in order to simulate the physical features of the real flow boundaries. At the upstream side of the domain, the "pressure-inlet" boundaries named "air-inlet" and "water-inlet" are specified. The pressure at the air inlet boundary is the operating pressure, the value is 101325 Pa, the phase at this boundary is only the air. At water-inlet boundary, the phase is only water, the pressure distribution obey the static pressure distribution of water, the velocity is omitted here due to its smaller value compared to the other items in the governing euqation. The top "Smooth wall" boundary of the domain is the "Wall" type of boundaries of Fluent, zero shear stress is specified at this place, so a smooth wall is obtained in order to let the flow pass along the wall. At the upper part of the right side of the domain, the "pressure-outlet" type of boundaries of Fluent named "outlet" is specified, the values at this place are computed from the domain during the computing process. The remaining boundaries are all defined as the "Wall" type of boundaries of Fluent, the no-slip condition must be satisfied at these places, the roughness height and constant are 0.0002 m and 0.5 respectively.

The realizable k-ε model is selected to simulate the turbulence effect and standard wall functions are used to treat the near wall flow. The other parameters are the default values provided by Fluent without modification. The flow is unsteady, the time step size is 0.1s, the velocity of a point in conduit and the volume flow rate through the cross section of the conduit are monitored and recorded respectively during the computing process. The locations of the monitor point and the corss section are also shown in Fig.1.

Results and Discussion

Filling Time. The history of x-component velocity of monitor point is shown in Fig.3, this irregular line looks like a damping curve. It means the fluid in the ship lock has a periodic motion due to the inertia, this cause the unwanted fluctuations of the water level in the ship lock. The amplitudes of the fluctuations reduce gradually because of energy dissipation, and it will take a considerable time to decay off the fluctuations finally.

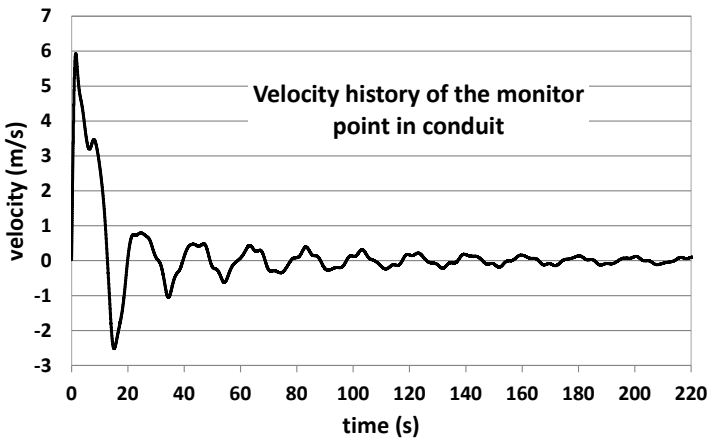

Fig.3 Velocity History of the Monitor Point

Variation of Water Surface. The intuitional variation of water surface in the ship lock is shown in Fig.4. Due to the paragraph, only five pictures are shown here, correspond to five instants of the maximum, minimum velocity (i.e. the maximum negative x-component velocity) and three zero velocities occurred in the first period at the monitor point. At the instant of 12.5s, also shown in Fig.3, the velocity in conduit is zero and the ship lock is over-filled, its counterpart computed by the SIA method is 6.3s, the values by two methods are have the same order of magnitude, but the VOF method includes the inertia effect of the flow motion, so it provides more precise estimation of the filling time and more realizable details of filling process.

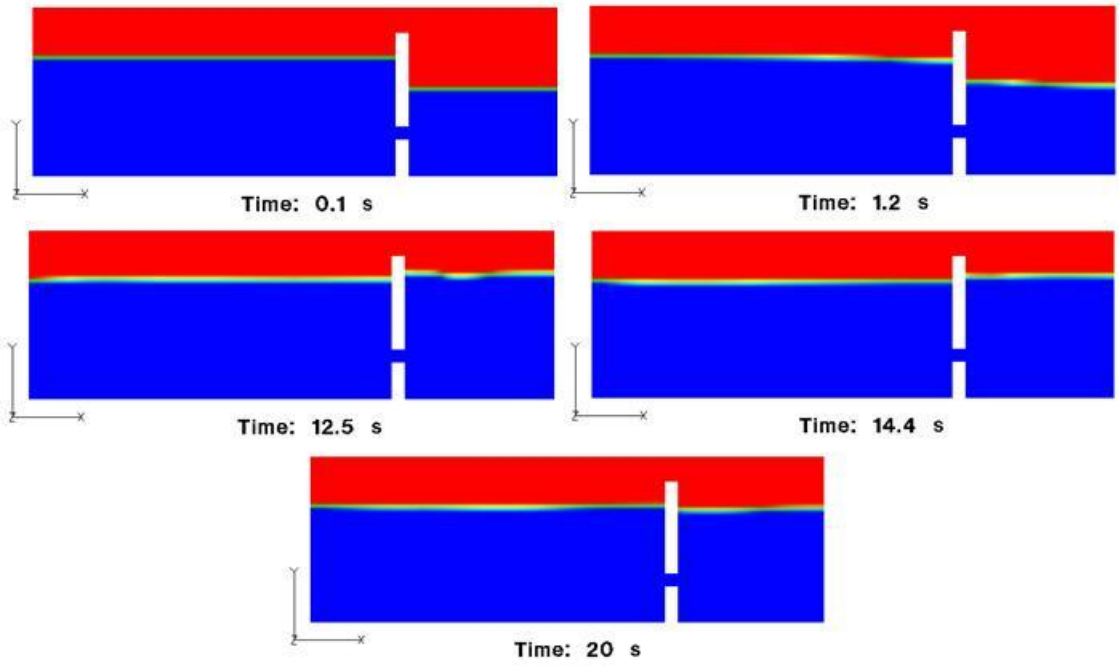

Fig.4 Variations of Water Surface in First Period

Mass Balance. The history of volume flow rate through the cross section of conduit is shown in Fig.5. In spite of the fluid will flow in and out of the ship lock during the filling process, finally the amount of water entering into the ship lock is 30m^3 corresponding to the statements of this problem, so by integrating of the volume flow rate over the time, the result can be used to check the mass balance, and also to validate this numerical model. The value of integral spanning from 0s to 236s is 30.16m^3, with a satisfied precision.

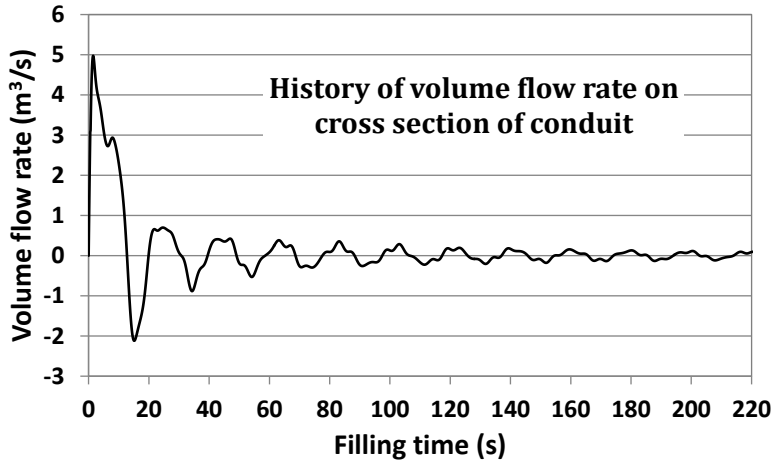

Fig.5 History of Volume Flow Rate through the Cross Section of the Conduit

Conclusions

In this paper, Steady-flow Integration Approach (SIA) is used to give a quick but coarse estimation of a ship lock with simple geometry, the corresponding time of full filling is 6.3s. While in the VOF approach, the fluctuations of water surface are considered and computed, so a longer time of 12.5s is the solution of this problem, if only considering the first period.

The values derived from two methods have the same order of magnitude. The more time-consuming VOF method reasonably tenders a more precise estimation of the filling time and a more realizable filling process. In practical engineering, the geometry of ship lock will be more complex, the SIA is not enough to satisfy the demands for a good design. The three dimensional VOF method will be a nice choice, it will give more precise predictions of filling time and other concerned flow details, such as water fluctuations and velocity fields in the ship lock.

Acknowledgements

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References

[1] MENG Xiang-wei, ZHOU Hua-xing and GAO Xue-ping: Application of basic equation of water filling-emptying for ship lock. Water Resources and Hydropower Engineering Vol. 39 (2008), p.45 (In Chinese)

[2] E. John Finnemore, Joseph B. Franzini: *Fluid Mechanics with Engineering Applications* (McGraw-Hill Science, USA 2001)

[3] Melvyn Kay:*Practical Hydraulics* (Taylor & Francis, UK 2008)

[4] Fluent Inc.: *FLUENT 6.3 User's Guide* (Fluent Inc., Lebanon, NH 2006)