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NUMERICAL INVESTIGATION ON WATER DISCHARGE CAPABILITY OF SLUICE CAISSON OF TIDAL POWER PLANT

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The design methodology of the sluice caisson structure is one of important factor that is close related to the efficiency in tidal power generation. When the sluice caisson is designed to maximize the water discharge capability, it is possible to minimize the number of sluice caissons for attaining the water amount required for achieving the target power generation, which results in reduction of the construction cost for the sluice caisson structure. The discharge capability of sluice caisson is dependent on the geometrical conditions of an apron structure which is placed in both sides of the sluice caisson. In this study, we investigated numerically the variation of water discharge capability of sluice caisson according to the geometrical conditions of apron. Flow fields are simulated with FLOW-3D software using VOF method.

1. Introduction

The economy of the Republic of Korea (hereafter referred to as “Korea”) has been growing rapidly for the last 30 years. Because of the limited domestic energy resources, Korea has been almost entirely dependent on imports to meet its energy consumption needs. In the early years, the imported energy resources were mostly fossil resources such as petroleum and coal. Even after two oil crises, fossil resources still represent a significant share of the total energy resources.

It is well known that these fossil resources are gradually being depleted, resulting in reduced price stability. In addition, CO_2 emissions caused by the consumption of massive amounts of fossil energy have a great influence on the global environment. Nuclear energy, which is still relatively low cost, carries potential risk of catastrophe through contamination resulting from radiation leakage accident. In this context, reducing the dependence on these traditional energy sources and preserving the environment have become significant goals for all human beings.

Renewable energies have the potential to overcome the gradual depletion of traditional fossil energies and their associated environmental impacts, while simultaneously solving the issues of energy sustainability, economic development, and environmental protection; consequently, the development and application of renewable energies have accelerated during the last decade. Among the renewable energies, ocean energy refers to that carried by ocean waves, tides, and ocean temperature differences. The ocean has a tremendous amount of energy as it covers more than 70% of the Earth’s surface, making it the world’s largest solar collector. In addition, tidal and wave energy driven by the gravitational pull of the moon and by the winds, respectively, are substantial energy resources in the ocean.

The potential energy associated with tides can be harnessed by building barrage structures built across the mouth of a bay or an estuary in an area with a large tidal range. As the level of the water changes with the tides, a difference in hydraulic heads develops across the barrage. Sea water is allowed to flow through the barrage via turbines, which can provide power during either the ebb tide or flood tide or during both tides. This generation cycle means that, depending on the site, power can be delivered twice or four times per day on a highly predictable basis.

The design methodology of the sluice caisson is one of important factor that is closely related to the efficiency in tidal power generation. If the sluice caisson is designed to maximize the water discharge capability, it is possible to minimize the number of sluice caissons for attaining the water amount required for achieving the target power generation, which results in reduction of the construction cost for the sluice caisson structures. In this respect, it is necessary to investigate the variation of water discharge capability of sluice caisson according to its geometrical shape. Lee *et al.* (2010) conducted a precise laboratory experiment with a total of 32 different sluice caisson models of tidal power plant, and investigated the influence of the respective shape parameters of the sluice caisson on the water discharge capability.

Until now, almost numerical and laboratory experiments on the sluice caisson model were conducted for 2D sectional case assuming the infinite array of sluice caissons, which allows the two dimensional flow pattern. However, in real cases, the number of sluice caisson is limited that makes the flow pattern to three dimensional phenomenon. In this study, we investigated the influence of the length and slope of apron and three dimensional considerations on the water discharge capability.

2. Numerical model

A well-known computational technique, VOF (Volume of Fluid) method was developed by Hirt (1994), and was implemented in the CFD code, FLOW-3D. The program solves the Navier–Stokes equation by the finite difference method. It utilizes a true volume of fluid method for computing free surface motion (Hirt and Nichols, 1981) and the fractional area/volume obstacle representation (FAVOR) technique to model complex geometric regions (Hirt and Sicilian, 1985). The true VOF method tracks the sharp interface accurately and does not compute the dynamics in the void or air regions. The portion of volume or area occupied by the obstacle in each cell (grid) is defined at the beginning of the analysis. The fluid fraction in each cell is also calculated. The continuity, momentum or transport equation of fluid fraction is formulated using the FAVOR function. A finite difference approximation is used for discretization of each equation. Unlike some finite element/volume or boundary fitting grid methods, this meshing technique does not require re-meshing and would not induce any mesh distortion during transient analysis. Hence an accurate solution algorithm can be applied easily.

The continuity and momentum equations are as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(u\rho) + \frac{\partial}{\partial y}(v\rho) + \frac{\partial}{\partial z}(w\rho) = RSOR + RDIF \tag{1}$$

$$\frac{\partial u}{\partial t} + \left\{ u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} \right\} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + G_x + f_x - b_x - \frac{RSOR}{\rho}u \tag{2}$$

$$\frac{\partial v}{\partial t} + \left\{ u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} \right\} = -\frac{1}{\rho}\frac{\partial p}{\partial y} + G_y + f_y - b_y - \frac{RSOR}{\rho}v \tag{3}$$

$$\frac{\partial w}{\partial t} + \left\{ u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} \right\} = -\frac{1}{\rho}\frac{\partial p}{\partial z} + G_z + f_z - b_z - \frac{RSOR}{\rho}w \tag{4}$$

where ρ is the density of fluid, $RSOR$ is the mass source term, $RDIF$ is the turbulent diffusion term, G is the body acceleration, f is the viscous acceleration, b is the energy dissipation by passing through the porous structure.

3. Numerical test

3.1. *Sluice caisson models*

With regard to the design of the sluice caisson, a number of design parameters can be brought out that are related to the three-dimensional shape of the sluice caisson. Lee *et al.* (2010) conducted intensive laboratory experiment and found the best sluice caisson model. In this study, we adopted the same sluice caisson to investigate the effect by the slope and length of aprons. Figure 1 shows the plan and side views of the sluice caisson model.

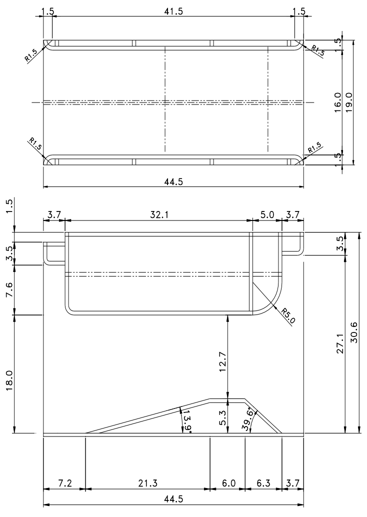

Figure 1. Plan and side views of the sluice caisson model (unit: m).

In order to consider the effect of the apron slope and the enlargement of the channel (B’), we set up the computational conditions as Table 1.

Table 1. Computational conditions.

Head difference	Apron slope	B’
0.3m, 0.6m, 0.9m	S0(0), S1(1:2), S2(1:5), S3(1:10)	B0(0), B1(1), B2(2), B(3)

3.2. *Estimation of head difference and discharge coefficient*

The water discharge capability of the sluice caisson is commonly assessed by using the discharge coefficient (C_d), which are defined as follows.

$$C_d = \frac{Q}{A_t \sqrt{2g\Delta H}} \tag{5}$$

where A_t is the area of the throat section, g is the gravitational acceleration, and ΔH is the head difference between both sides of the sluice caisson defined as

$$\Delta H = \left(h_{UP} + \frac{V_{UP}^2}{2g} \right) - \left(h_{DN} + \frac{V_{DN}^2}{2g} \right) + h_f \tag{6}$$

where V_{UP} and V_{DN} denotes the mean velocities on upstream and downstream of the sluice caisson, respectively, which is calculated by dividing the water discharge rate with the respective cross-sectional area. h_f denotes the head loss in the open channel, which was taken into account to compensate the natural gradient of water level in the channel due to the friction at the bottom and both side walls that are scarcely present in the field condition. In general, the head loss is almost linearly proportional to both the distance between the upstream and downstream measurement locations and the water discharge rate. As shown in Eq. (5), the discharge coefficients are related to the relative discharge rate per unit area of the throat section.

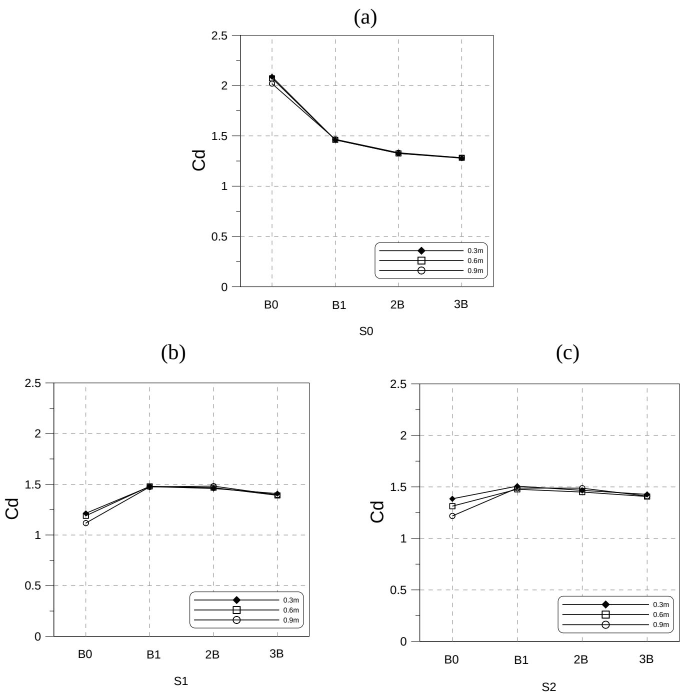

Figure 2. Discharge coefficients for the apron slope of 0 (a), 1:2 (b), 1:5 (c).

Figure 2 showed the discharge coefficient for various apron slopes, extended widths and head differences. For the case of B0, where the experiments were treated as 2D case, the discharge coefficients showed very different values according to the slope of apron, but the discharge coefficients were estimated as approximately 1.4 for the large extended widths (B’>B).

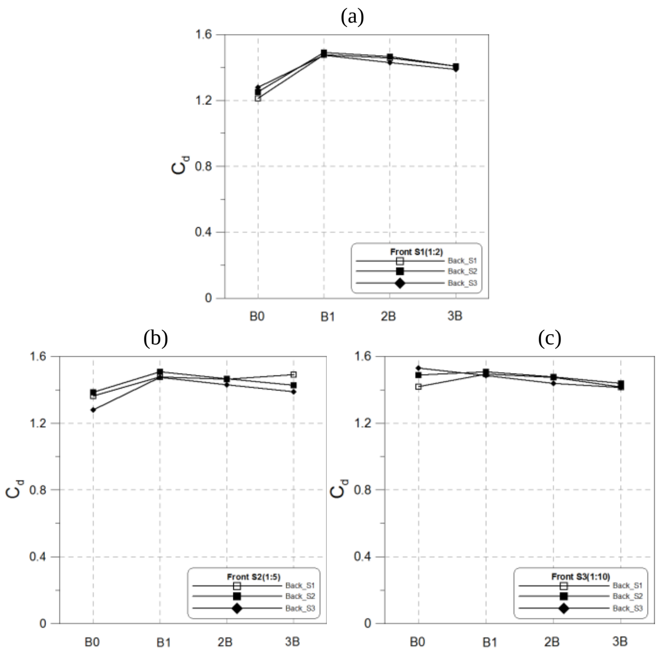

Figure 3. Discharge coefficients for the front slope of 1:2 (a), 1:5 (b), 1:10 (c).

Figure 3 showed the discharge coefficient for the various apron slopes and extended widths. In this experiment, the apron slopes at upstream and downstream could be different. However, for the extended width, the effect by the apron slope was negligibly small. For the all cases, the discharge coefficients were estimated as 1.4-1.5.

For the case of $B' = 3B$, figure 5(a) and (b) showed the streamline for the slope of 1:2 and 1:10. Although the apron is equipped evenly, the stream line pattern at upstream and downstream is very different. At the upstream, the streamline approached to the sluice caisson very slowly without constituting any eddy at the apron, whereas jet-like streams are formed with making a large eddy.

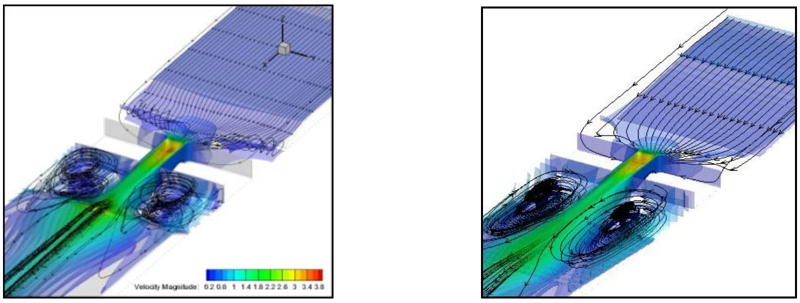

Figure 4. Streamline around the sluice caisson ((a): slope=1:2, (b): slope=1:10).

4. Conclusions

Renewable energy associated with tides is usually able to be harnessed by building barrage structures built across the mouth of a bay or an estuary in an area with a large tidal range. The discharge capability of sluice caisson is dependent on the geometrical conditions of an apron structure which is placed in both sides of the sluice caisson. In this study, we investigated numerically the variation of water discharge capability of sluice caisson according to the geometrical conditions of apron. Flow fields are simulated with FLOW-3D software using VOF method. The numerical results showed that the discharge coefficient for a certain sluice caisson can be estimated as a value by considering the three-dimensional effect with enlarged channel. The effect by the slope of apron was negligibly small.

Acknowledgments

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