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Three-dimensional experiment and numerical simulation of the discharge performance of sluice passageway for tidal power plant

Sang-Ho Oh [a, b, *], Kwang Soo Lee [a], Weon-Mu Jeong [a]

[a] Coastal Engineering Division, Korea Institute of Ocean Science and Technology, Ansan 15627 Republic of Korea
[b] Department of Convergence Study on the Ocean Science and Technology, Ocean Science and Technology School, Korea Maritime and Ocean University, Busan 49112, Republic of Korea

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ABSTRACT

In this study, the discharge performance of the sluice passageway of tidal power plants was investigated based on the experiments conducted in a planar open channel and three-dimensional numerical simulations. By conducting the experiments in a planar channel, it was possible to reproduce the three-dimensional flow field around the sluice passageways similar to the field condition. The discharge capability of the passageway was estimated under various flow conditions with five different channel bathymetries. The estimates of the discharge coefficient generally ranged from 1.3 to 1.45, which are significantly smaller than the values obtained from the previous study based on the two-dimensional experiment. In addition, the experimental results showed a considerable difference in the discharge coefficient among the test cases, demonstrating an apparent influence of channel bed topography on the discharge performance. Based on an intensive parametric study carried out using the numerical simulations, an optimal configuration of the width, slope, and bottom length of the apron section was suggested for maximizing the discharge capability of the sluice passageway.

1. Introduction

Tidal barrage power generation is a traditional method for generating electricity by utilizing the periodic changes in the sea level due to tides. This power generation system comprises a barrage for enclosing a tidal basin, sluice structures for controlling the tidal flow across the barrage, and turbines for generating electricity. Only a few power plants of this type have been commercially operated in the world including the Rance power station in France and other relatively smaller plants in Russia, Canada, and China [1,2]. Recently, the largest tidal barrage power station was constructed at the Sihwa lake in Korea [3–5], whose capacity (254 MW) is slightly higher than that of the Rance plant (240 MW). In Korea, several other sites are being considered suitable for constructing additional tidal power stations [6–8].

With regard to the technology of tidal barrage power plants, the design of sluice caissons or the housing structures containing the flow controlling gates is significantly relevant to the efficiency of power generation because the flow discharge through the caisson depends on its shape. Hence, an enhancement in the discharge capability of sluice caissons leads to an increase in the power generation capacity of tidal power plants because more water can be allowed for generating electricity [9,10].

A sluice gate is one of the widely used hydraulic structures for controlling water levels or flow rates in rivers or regulated streams [11]. The flow characteristics across sluice gates have been investigated by many researchers [12–15], so the hydraulic performance of the gate is well understood. When a sluice gate is used for controlling the tidal flow around a tidal barrage power plant, the gate is typically housed inside a caisson whose shape is similar to a culvert or venture-tube. Because the elevation of the ceiling at the opening of a caisson is typically lower than the ambient tidal water level, the flow is likely to pass the caisson passageway filling up the opening with water. For this reason, the inner cross-sectional shape of the caisson passageway, rather than the sluice gate itself, is the principal factor for determining the discharge capability through the passageway. Hence, it is required to design the interior shape of the sluice passageway favorable to the tidal flow through it.

Only a few studies have been reported so far concerning the discharge performance of the sluice passageway of tidal power

* Corresponding author. Coastal Engineering Division, Korea Institute of Ocean Science and Technology, Ansan 15627, Republic of Korea.
E-mail address: coast.oh@gmail.com (S.-H. Oh).

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plants. A series of hydraulic tests [16] were carried out in order to improve the sluice passageway design as a part of the pre-feasibility study for the Severn barrage. More recently, two- and three-dimensional hydraulic model tests [17] were conducted to examine the sluice conveyance of the tidal barrage to be constructed at the Garolim bay, Korea. The objective of these two studies was to improve the design of the sluice passageway fitted to the tidal barrage of the specific site. Meanwhile, a change in discharge capability of the sluice caisson with respect to the variation in its geometrical shape was investigated by conducting experiments in a two-dimensional open channel flume [18]. It seems to be the first extensive study investigating the performance of the sluice passageway by considering the major design parameters including the general shape of the structure. In their study, however, it was only possible to estimate the discharge capability of a single caisson unit because the experiment was performed in a long narrow two-dimensional open channel. Moreover, the bottom geometry of the caisson upstream and downstream was entirely horizontal, which is a less realistic condition in the actual field. To the knowledge of the authors, there is no literature available examining the effects of the three-dimensionality as well as the variation in topography of the neighboring sea bed on the discharge performance of the sluice passageway.

In order to overcome these two limitations of the previous studies, three-dimensional experiments and numerical simulations were conducted by changing the geometry of the channel at the upstream and downstream of the sluice passageway. The physical experiments were carried out in a three dimensional open channel with 10 passageway models that were installed in a parallel manner. By analyzing the experimental data, the discharge performance of the sluice passageway obtained from this study was compared with the results based on the two-dimensional physical experiment [18]. Then numerical simulations were conducted for the laboratory setup to validate it with the corresponding experimental results. The effect of the channel bed geometry accompanied by other changes related to the shape of the sluice passageway was quantitatively assessed based on the further simulation results that were performed with the prototype conditions.

2. Experimental setup

2.1. Experimental facilities and test cases

A planar open channel of length 23.6 m, width 16.0 m, and height 1.0 m was used for the physical experiment. The length of test section used for the measurement was 19.9 m. At the upstream of the test section, multiple rectifiers were installed in order to minimize water surface fluctuations as well as to facilitate uniform lateral distribution of the flow at the inlet. The water surface level in the open channel was controlled by a flap-type weir placed at the end of the channel. A schematic diagram of the open channel including a barrage model and sluice caissons are illustrated in Fig. 1.

The cross-section of the sluice caisson model was designed based on the shape of a prototype structure adopted in the feasibility study of the Incheon tidal power plant project. The geometry of the sluice caisson model is shown in Fig. 2. The scale of the model was determined to be 1/70 of the prototype considering all the relevant factors in relation to the scale of the model based on the Froude similarity law, which is defined as

$$F_r = \frac{U}{\sqrt{gL}} = \frac{U_M}{\sqrt{gL_M}} = \frac{U_P}{\sqrt{gL_P}}$$

where F_r is the Froude number, U is the characteristic flow velocity,

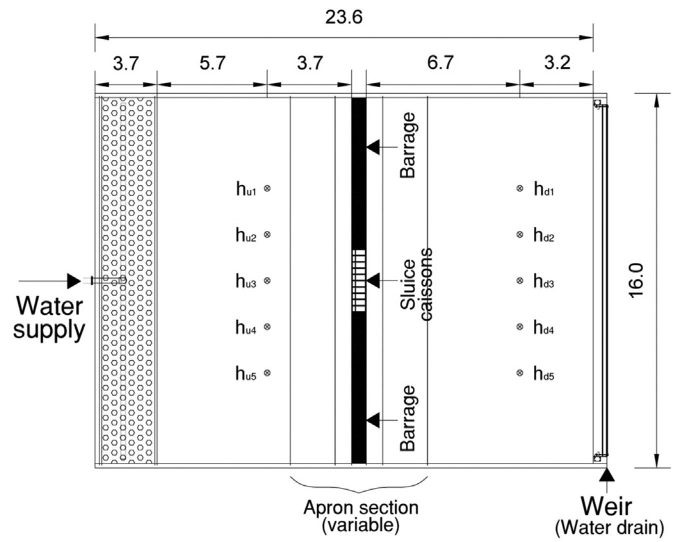

Fig. 1. A diagram of the planar open channel (unit: m).

g is the gravitational acceleration, L is the characteristic length. The subscripts M and P stand for the model and prototype, respectively. Equality in the Froude number in model and prototype scale ensures that inertia and gravity forces are correctly scaled. If the geometrical scale between the model and prototype is denoted as λ, the velocity and time are scaled as λ, while the mass and force are scaled as λ^3, for example.

Among the experimental parameters related to the determination of the model scale in the present experiment, the flow rate was the most influencing physical quantity because it varied in proportion to the 2.5th power of the scale based on the Froude similarity law. Considering the flow rate conditions and the capacity of the water supply system, 1/70 was found to be the most feasible scale in the present experiment. An experiment with a greater scale than this was not possible because it required more water supply than the capacity of the facility. As shown in Fig. 3(a), 10 models of the sluice caisson and two connecting structures made of acrylic plates were installed in the planar channel. The caisson models were placed parallel to each other at a location 9.4 m downstream from the test section inlet, approximately the half point of the test section length. The general view of the experiment in the planar open channel is illustrated in Fig. 3(b).

Five test cases were considered in this study depending on the geometrical difference in channel bed bathymetry in the streamwise direction and/or the shape of sluice passageway used in the experiment. Fig. 4 illustrates the side view of the five test cases corresponding to the scale of the model. As seen in the figure, the first two cases (case A and case B) differ in their slope of transition. Meanwhile, case C is discriminated from case A in that the caisson models are placed in the reverse direction. In case D, the shape of the caisson passageway differs from those of case A to C: the lower inner wall of the passageway is horizontal as shown in Fig. 4. In addition, the channel bed configuration is also changed with higher elevation (from −0.32 m to −0.25 m) and longer flat sections at the upstream and downstream of the passageway (from 0.71 m to 1.46 m). Finally, case E differs from Case D in that the diffuser soffit of the passageway is inclined 3° upwards to the horizontal. The vertical distance at the throat section is 0.18 m for all the five test cases.

2.2. Flow conditions and measurement

The experiment was carried out under 15 test conditions with