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The Numerical and Experimental Investigation of Froude Number in Bottom Outlet Channel

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ABSTRACT

The bottom outlet is a series of structures that are used to transfer water from the dam reservoir to the downstream. The purpose of the present study was to numerically and experimentally investigate the Froude number in the bottom outlet channel. In this research, the physical model of conduit and gates constructed in the laboratory of the Soil Conservation and Water Management Research Institute (SCWMRI) was applied, and the necessary tests were performed. The numerical model of the discharger was simulated using the Flow 3-D software and the experimental and numerical results were compared with each other, and also, the previous results were compared in this research. Based on the obtained results, the change of Froude number at different heads was similar. The rate of change in the initial openings was high, and the intensity of the changes increased with the increase of the reservoir head. Then, the Froude number decreased with increasing opening, and after the 50% opening, it tended to be linear with almost identical slopes at different heads.

Keywords: *Transfer of dam water, bottom outlet channel, Froude number, reservoir head*

1. INTRODUCTION

Designing the bottom outlets is one of the most important issues for dam designers, who need to ensure sufficient discharge capacity, proper conduit operation, hydraulic installations such as gates, and hydromechanical installations. In the bottom outlets, there is a pressurized valviferous conduit with two service and emergency side gates. The main variables in the pressurized conduit include geometric parameters such as length, width, height, and slope, and hydraulic parameters such as velocity, flow rate, upstream head, and pressure. Due to the momentum and high rate of the fluid flow, the pressure decreases along the bottom surface of the gate and behind it in each position of the gate, while the pressure upstream of the gate changes slightly. In cases where the water depth in the dam reservoir is high, bottom outlets are used for downstream water consumption, discharging of the dam in emergency situations, and in some cases for discharging the sediments accumulated in the dam reservoir (Hosseini and Abrishami 2008). Basically, the bottom outlet channel operates under pressure, and it is necessary to consider the drop values in the hydraulic design of a pressurized conduit. The energy drop in a pressurized flow is primarily due to the frictional resistance of the conduit wall against the flow, and the lateral drops such as curves, valves, gates, transitions and etc. are other causes of energy loss. If a gate is installed at the inlet of the conduit that does not interfere with the flow lines when fully open, the drop due to the gate can be considered "0". When the installed gate in the conduit is in such a way that the walls, floor, and ceiling of the conduit in upstream and downstream of the gate are in a similar level with the gate opening, the drop due to the installation location of the gate can only be considered. Many flow regimes in nature and industry are two-phase flows.

The phase is represented as one of the physical states of matter (solid, liquid, and gas). According to the above, two-phase flows are divided into three states: liquid-gas, liquid-solid, and gas-solid. A two-phase flow means that two compressible and incompressible fluids flow into a pipeline. If the water and air are subjected to the same hydraulic gradient, the gas phase moves faster than the liquid phase. The large difference between the compressibility of the liquid and gas phases causes the gas to expand and slide rapidly over the liquid phase (Falloy, 1980). Numerical methods for solving governing equations and rules for these types of flows are very complex and in most cases, two-phase flows show an inherent oscillating behavior that requires solving costly algorithms (Gray, 2006). In 2007, Safavi investigated the amount of required air for flow after the gate in the bottom outlet tunnels of the dam. In his experiments, the mechanism of flow aeration and the effect of air conduit diameter, tunnel length, tunnel filling percentage, flow rate on the amount of air entering the tunnel, and negative pressure behind the gate were studied. By examining the amount of aeration on the model of outlets such as Siazakh and Gotvand in 2010, Kavianpour et al. could provide the experimental relationships for the number and diameter of aerator tunnels. According to the investigations, if the flow rate in the outlet tunnel is more than 10 m/s, the flow should be aerated to prevent cavitation (Khosrojerdi and Kavianpour, 2001). Despite recent advances in the designing and calculation of dams and their installations using computational software, obtaining accurate results by theoretical modeling for many things is practically impossible due to the complexity and 3-D flow patterns. The cause is mainly due to the complexity of the flow path geometry in the areas around the gate. So, it will not give the designer and builder full assurance of proper performance. Hence, due to the high costs of construction of dams and their installations and damage and loss of life and property due to possible failure of gates, testing the hydraulic model for the outlets of many elevated dams is practically necessary. Therefore, in our country, in cases such as Alborz, Gavoshan, Jegin, Gotvand dams, etc., the required models of bottom outlets have been made and their performance has been evaluated. Despite recent advances in the design and calculation of dams and their installation using computational software, due to the complexity and 3-D flow pattern, which is mainly due to the complexity of the flow path geometry around the gate, accurate results from theoretical modeling It is practically impossible for many people and will not give the designer and builder full assurance of proper performance. Therefore, due to the high cost of construction and installation of dams and the loss of life and property due to possible damage to the gates, testing the hydraulic model for the output of many high dams is practically necessary. Therefore, in our country, in cases such as Alborz, Gavoshan, Jagin, Gotvand dams, etc., the required models of lower outputs have been built and their performance has been evaluated. Thus, in order to investigate the hydraulic performance of the bottom outlet channel of dams, the outlet model of the Narmashir dam was developed in the present study and tested in the laboratory of the Soil Conservation and Water Management Research Institute (SCWMRI). Then, the effective parameter on the flow field (Froude number) was investigated. The aim of the present study is to numerically and experimentally investigate the Froude number in the bottom outlet channel.

2. Materials and methods

2.1 Design and construction of laboratory model

The pressurized conduit model can be designed based on the Froude principle when the Reynolds number of the flow is greater than 10^5. In the present investigation, the Reynolds number of the flow was calculated using the design flow rate provided by the design consultant as follows, in which the Reynolds number was in the above range. Thus, the model was designed based on the Froude scale. For a Froude model, the scale relationships were as follows:

$$L_m = \frac{L_P}{\lambda} \qquad (1)$$

$$P_m = \frac{P_P}{\lambda} \qquad (2)$$

$$V_m = \frac{V_P}{\lambda^{0.5}} \qquad (3)$$

$$Q_m = \frac{Q_P}{\lambda^{2.5}} \qquad (4)$$

$$T_m = \frac{T_P}{\lambda^{0.5}} \qquad (5)$$

Where,

L: Length
P: Pressure
Q: Flow rate
T: Time
V: Speed
λ: Geometric scale

The simultaneous similarity of Reynolds and Froude numbers requires the construction of a model with the original sample size. Because of this impossibility, models are usually based on the Froude number in engineering operations. Also, in high Reynolds numbers (more than 10^5) the similarity of Reynolds can be ignored (Novak, 1981) and only the Froude number can be used as a criterion of similarity.

$$R_e = \frac{V_p y_p}{\nu} = \frac{30.36 \times 2}{10^{-6}} = 61 \times 10^6$$

It should be noted that the above condition, according to the following calculations, is valid for up to 72 times reduced prototype:

$$Q_{\max} = 85 m^3/s \Rightarrow V_p = 30.36 m/s$$

$$\mathrm{Re}_p = \frac{V_p y_p}{\upsilon} = \frac{33.36 \times 2}{10^{-6}} = 6.1 \times 10^7$$

$$\mathrm{Re}_m = 10^5$$

$$\lambda_r^{1.5} = \frac{\mathrm{Re}_m}{\mathrm{Re}_p} = \frac{10^5}{6.1\times10^7} = \frac{1}{610} \Rightarrow \lambda_r = \frac{1}{72} \langle \frac{1}{15}$$

Where,
Re_p: Reynolds number of prototype (actual sample)
y_p: Conduit height at the service gate location
V_p: Flow rate in the conduit, immediately after the service gate

Thus, it is observed that the scale of the selected model was 1:15 larger than the minimum acceptable scale and so was appropriate.

2.2 Components of laboratory model

The model of the bottom outlet channel of the Narmashir dam included a repair valve, a metal cover with a rectangular cross-section, a conduit inlet, a gate groove, a middle conduit, an emergency valve, an emergency valve chamber, its grooves, a service valve, aerator between two valves and also downstream channel service gate, This model was made of a transparent sheet (Plexiglas) in metal parts according to the drawings provided by the design consulting engineer (in detail) with a ratio of 1:15. A cylindrical tank with a height of about 18 m which was fed by two pumps with a capacity of 100 l/s was used to supply the required water height and required flow rate. Fig. 1 illustrates a schema of this tank, in which energy-retaining grilles were used to calm the flow and prevent turbulence of the water entering the tank (Hosseini et al., 2010).

Fig. 1. A view of the supply tank of head (Hosseini et al.)

To accurately study the flow pattern and drops due to the design and exit jet from the gate, and to investigate the flow between the two gates and the effect and amount of aeration, the piezometers were installed at critical points. A number of 13 piezometers were installed on the gate to measure the pressures on the valve. All piezometers were connected to strong interface hoses and guided out through open spaces inside the valve. The pressure of the above points was determined by connecting piezometers to vertical manometers. There was a stilling basin at the exit section of the outlet channel. The floor level of the basin was 1345.5 m. The length of the stilling basin on the axis and at the above level was 30 m and its width was 20 m. The floor of the basin was a circular curve with a radius of 32.05 m. The inner slope of the walls of the stilling basin was selected in a ratio of 1 horizontal to 4 vertical. Thus, the height of the basin wall to floor level was equal to 16 m. The final part of the stilling basin had a common structure with a bottom outlet channel. The outlet width of this part of the basin that ends in the river was 25 m. Measurement of pressure at different points of the conduit and gate, as well as the measurement of flow rate and air velocity in the aerators were on the agenda. All experiments were performed at three levels of the dam reservoir. The experiments were performed at the maximum level at an elevation of 670 cm, the normal water load level at 636 cm, and the minimum level at an elevation of 327 cm. Initially, after recording the water height in the model tank, flow, pressure, and air velocity measurements were performed for six service gate openings, including 10, 20, 40, 50, 60, and 80%, and a fixed emergency valve. Finally, a series of experiments were performed on the maximum head for simultaneous operations. The overflow was measured using a point gage installed next to the channel. The measured error rate was less than 2.6% due to changes in the water surface in the overflow and fluctuations in the water surface profile. The water effective height in the tank was adjusted by inlet pumps and an outlet discharge valve in the tank. All experiments were performed based on three different tank heads. The measurement accuracy of the model was ±0.5 mm (6 mm in the actual sample) based on the reading of the middle wire of the camera with reference to a special ruler calibrated in millimeters. Thus, the level of different parts of the model was reflected up to two digits. The flow rate in the model was measured by a sharp-edged rectangular overflow. The discharge measurement error depends on three parameters, including (i) the channel construction error and the sharp-edged overflow and its installation, (ii) the bar scale reading error (reading the water blade height in the overflow), and (iii) model leakage error before the flow reaches the measuring point. A bar scale with a reading accuracy of ±1 mm was used in the model to read the height of the water blade on the overflow.

2.3 Numerical model

In the present research, the Flow-3D business code has been used to solve the basic equations governing fluidity and the equation of continuity and momentum in a 3-D method. The physical model was first drawn using SOLIDWORKS software, then loaded into the software (as shown in Fig.2), and meshed.

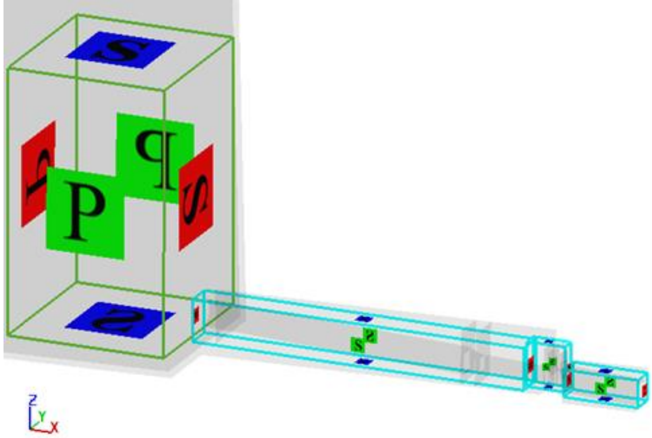

Fig 2. A display of the number and location of meshed blocks and their boundary conditions

Fig. 3 shows the part of the model that is filled with water (Azimian, 1998).

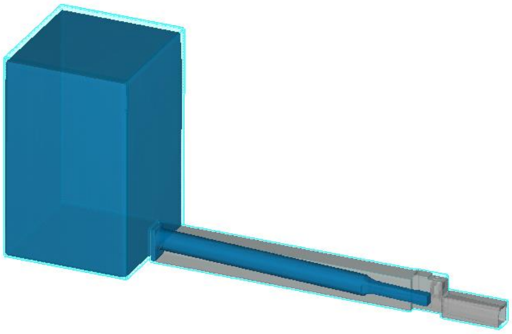

Fig. 3. The initial location of the fluid before starting the analysis

3. Results

3.1 Study of Froude number

Figs. 4 and 5 show the Froude number of flow at different heads and for different operations of gates at different openings.

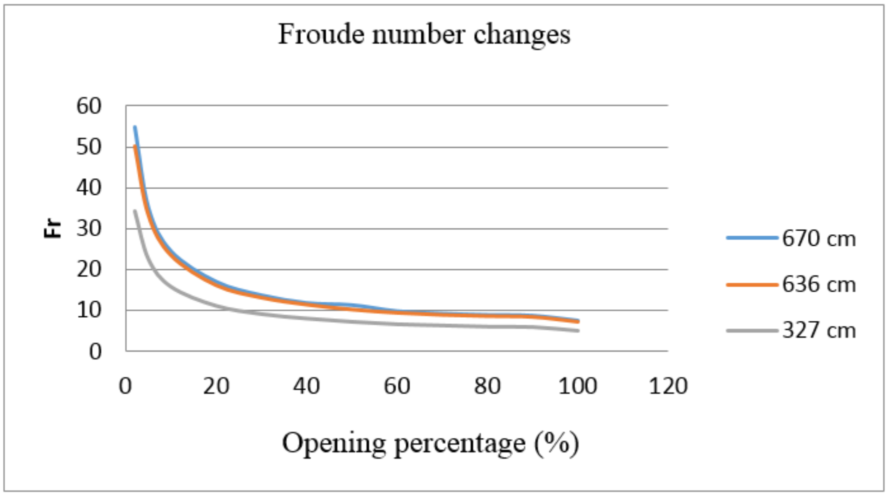

Fig. 4. The change of Froude number for different heads

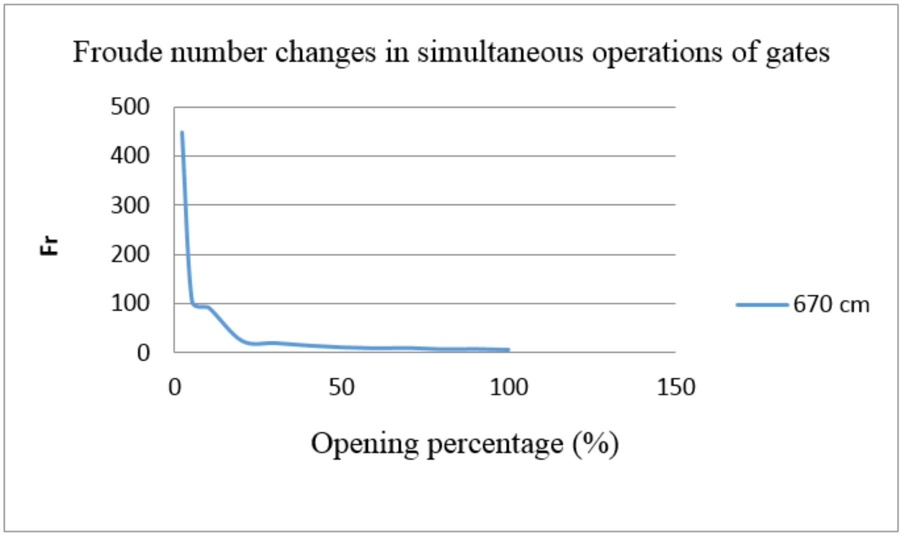

Fig. 5. The change of Froude number for related heads

As shown in Fig.5, the changes of the Froude number at different heads were similar. In the initial openings, the rate of change was high and the intensity of the changes increased with increasing of the tank head. As the opening increased, its value decreased and from the opening above 50%, it went to a linear state whose slope was almost equal at different heads.

3.2 A comparison between experimental and numerical results

Table 1. A comparison of Froude number between experimental and numerical results

Opening percentage (%)	Experimental	Numerical	Error (mm)

80	8.9	10	12.36
60	9.89	11.5	16.5
30	13.79	16.5	19.65

Table 2. A comparison of Froude number between experimental and numerical results

Emergency	Service	Experimental	Numerical	Error (mm)
78	80	8.04	7.51	6.55
57	60	10	10.74	7.4
29	30	20.57	23	11.8

Figs. 6 and 7 show the changes of Froude number in the longitudinal direction of the conduit for 60% opening.

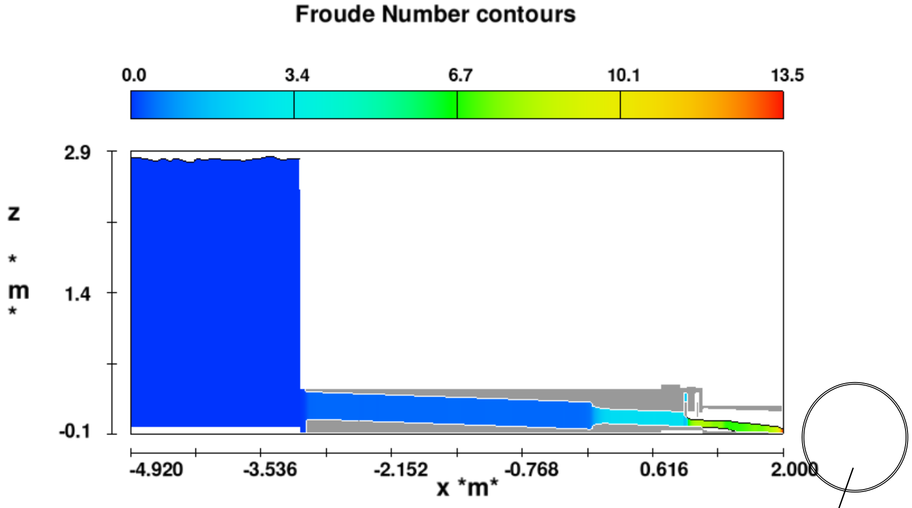

Fig. 6. The changes of Froude number in the longitudinal direction of the conduit for 60% opening.

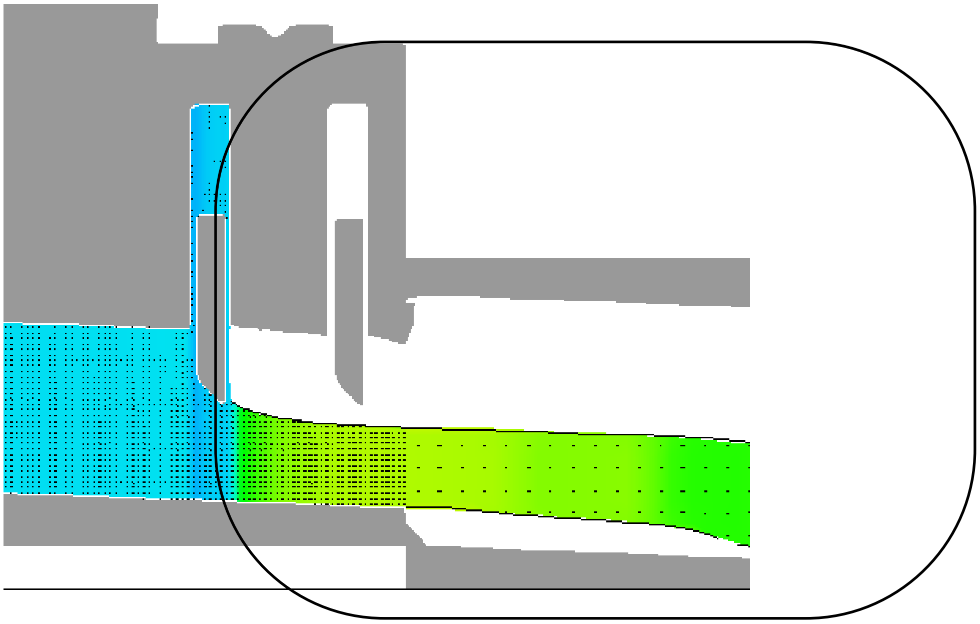

Fig. 7. The changes of Froude number in the range between two gates for the 60% opening

4. Conclusions

The purpose of the present study was to numerically and experimentally investigate the Froude number in the bottom outlet channel. In this research, the physical model of conduit and gates constructed in the laboratory of the Soil Conservation and Water Management Research Institute (SCWMRI) was applied, and the necessary tests were performed. Based on the obtained results, the change of Froude number at different heads was similar. The rate of change in the initial openings was high, and the intensity of the changes increased with the increase of the reservoir head. Then, the Froude number decreased with increasing opening, and after the 50% opening, it tended to be linear with almost identical slopes at different heads.

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