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Experimental and numerical analysis of weir structures in open channel flows

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ABSTRACT

Weirs are important water structures used to hold water in dams and canals and to safely transfer water from upstream to downstream. Due to these features, these structures, which have been used for years, have many different designs. In this study, a rectangular labyrinth weir and an inclined-bed rectangular weir were studied experimentally and numerically. The weir geometries used in the experiment were produced in a 3D printer and transferred to the numerical simulation with the same dimensions. The discharge and discharge coefficients corresponding to five different upstream heights obtained from the experiment and numerical simulation were obtained and the data were compared. Comparison of numerical and experimental results showed a good agreement. Where the difference between the tests is maximum was calculated at H_0/P = 0.1 m where the water load is the lowest.

1. Introduction

Weirs are hydraulically important structures that are built in different types and shapes, used to drain excess water that passes through a canal or in the dam reservoir. While determining the weir types in open channels, issues such as the maximum flow and velocity of the flow expected to pass through the channel should be considered. In structures with limited cross-section such as open channels, designs that increase the spillway capacity come to the fore. One of the most common and effective methods used to increase the amount of water taken from the channels is to increase the water contact surface of the weirs. Different types of designs determined to increase the performance of the weirs are determined in the light of the data obtained from experimental, theoretical and numerical studies. It has been shown by the studies in the literature that the performance of the labyrinth style weirs is much higher than the weirs designed in the classical style (straight) and are widely used in practice. Some studies in the literature can be given as follows.

Aydin and Ulu (2017) numerically examined the effects of antivortex to reduce flow turbulence over labyrinth side weirs. Anderson and Tullis (2012) compared the efficiency of Piano Key weirs (PKW) with rectangular labyrinth weirs in a laboratory setting. The results showed that the performance of Piano Key type weirs is more efficient than rectangular labyrinth weir. Sadeghian et al. (2019) investigated the advantages of inclined-bed application for triangular labyrinth side weirs. In the study, more than 160 experimental laboratory tests were performed and different hydraulic and geometry variables were used. Le et al. (2021) compared the discharge capacity of piano key and rectangular labyrinth weirs using a three-dimensional numerical model validated by available experimental data. Balzner et al. (2017) investigated piano key and labyrinth weirs on different geometries under free and submerged flow conditions and compared the findings. Aydin et al. (2019a), worked on the determination of water surface profiles in high-head spillways using computational fluid dynamics method. Khanh (2017), describes the initial procedure for laboratory research on

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Piano Keyweirs (PKW) in 2004. Also, the study gives some information about existing and projected dams with PKW. Aydın et al. (2019b) conducted a detailed analysis study on trapezoidal labyrinth weirs using computational fluid dynamics (CFD) method. Kabiri-Samani (2013) carried out experimental and analytical tests on rectangular labyrinth weir. The results showed that this type of weir can be five times more productive than a conventional weir. Aydın and Işik (2015) examined hydraulic structures using a CFD software in their study and stated the advantages and disadvantages of using such programs in hydraulic structures. In addition to these, Schleiss (2011), Azimi and Hakim (2019), Anderson and Tullis (2013), Crookston and Tullis, (2012) and Ghanbari and Heidarnejad (2020) have comprehensive studies in literature.

Labyrinth weirs are currently used as a water intake structure in open channels and surface flowing spillways. These weirs, which have different types of designs and sizes, have high weir capacity at low nappe loads. They increase the capacity of reservoirs and channels and minimize nappe loads. In this study, a rectangular labyrinth weir and an inclined-bed rectangular weir type that inspired from piano-key weirs were studied using experimental and computational fluid dynamics (CFD) methods. Inclined-bed rectangular weirs have not been studied as widely in the literature as other weir types. For this content, the study contributed to the literature in this context. The three-dimensional models prepared in the CAD environment were printed on a three-dimensional printer and used in the experiments and transferred to the numerical analysis program in accordance with the 1/1 scale and the analyses were carried out. The data obtained from the experiments were analysed in the numerical analysis program and comparisons were made. As a method in the study, an open channel laboratory set and a developed CFD numerical analysis program were used.

2. Material and method

Two methods were used in the study. The first is laboratory work and the other is FLOW-3D, a computational fluid dynamics software. The length of the open channel setup used in the experiments is 4.0 m and the width is 0.40 m. The experiments were carried out without slope. The pump with a power of 2200 W produces a flow of 1300 l/min. The amount of water entering the channel was measured with a flowmeter. Discharge over sharp crested rectangular labyrinth weirs can be expressed as:

$$Q = \frac{2}{3} * C_d * L * \sqrt{2g} * H_0^{3/2} \tag{1}$$

Here, Q is flow discharge over weir; C_d is discharge coefficient, L is total length of the crest; g is the gravitational acceleration and H_0 is total upstream head.

Another method used in the study is the FLOW-3D software program, which is a CFD program. Like other CFD software, FLOW-3D is known for numerically solving a number of basic fluid equations to determine fluid motion. The basic equations of fluid motion are modelled using finite elements or volumes with the help of programs such as FLOW-3D. CFD method solves the theoretical and semi-empirical dynamical equations of compressible and incompressible fluids by using various numerical methods and computational tools. Momentum and continuity equations used in the FLOW-3D given as follows:

Momentum equation:

$$\begin{aligned}
\frac{\partial u}{\partial t} + \frac{1}{V_F}\left[uA_x\frac{\partial u}{\partial x} + vA_y\frac{\partial u}{\partial y} + wA_z\frac{\partial u}{\partial z}\right] &= -\frac{1}{\rho}\frac{\partial p}{\partial x} + G_x + f_x \\
\frac{\partial v}{\partial t} + \frac{1}{V_F}\left[uA_x\frac{\partial v}{\partial x} + vA_y\frac{\partial v}{\partial y} + wA_z\frac{\partial v}{\partial z}\right] &= -\frac{1}{\rho}\frac{\partial p}{\partial y} + G_y + f_y \\
\frac{\partial w}{\partial t} + \frac{1}{V_F}\left[uA_x\frac{\partial w}{\partial x} + vA_y\frac{\partial w}{\partial y} + wA_z\frac{\partial w}{\partial z}\right] &= -\frac{1}{\rho}\frac{\partial p}{\partial z} + G_z + f_z
\end{aligned} \tag{2}$$

Continuity equation:

$$\frac{\partial}{\partial x}(uA_x) + \frac{\partial}{\partial y}(vA_y) + \frac{\partial}{\partial z}(wA_z) = 0 \tag{3}$$

here, t is time, ρ is the fluid density, V_f is the volume fraction, (u, v, w) are velocity components, (A_x, A_y, A_z) are fractional areas open to flow in Cartesian coordinates. (G_x, G_y, G_z) are mass accelerations, (f_x, f_y, f_z) are viscous accelerations (Flow Science, 2019).

2.1. Rectangular labyrinth weir model

The prepared rectangular labyrinth weir with sharp edges is 0.10 m in height (P), 0.40 m in length, and 0.69 m in weir (crest) length (Fig. 1). The drawings prepared in the CAD environment were produced in two parts on a 3D printer due to the capacity of the printer, and then the parts were glued together. It has been determined that 10% fullness rate for the produced parts will have the desired strength and rigidity. The production process of this piece took twenty-five hours.

2.2. Inclined-bed rectangular weir model

The prepared inclined-bed rectangular weir is 0.10 m high (P), 0.40 m long and 0.99 m in weir (crest) length. Similar to the rectangular model, the drawings prepared in the CAD environment were produced in two parts in the printer due to the printer's capacity, and then the parts were glued together (Fig. 2). It has been determined that 10% fullness rate for the produced parts will have the desired strength and rigidity as well. The production process of this piece took fifty hours. Figure 3 shows some images from the experimental setup.

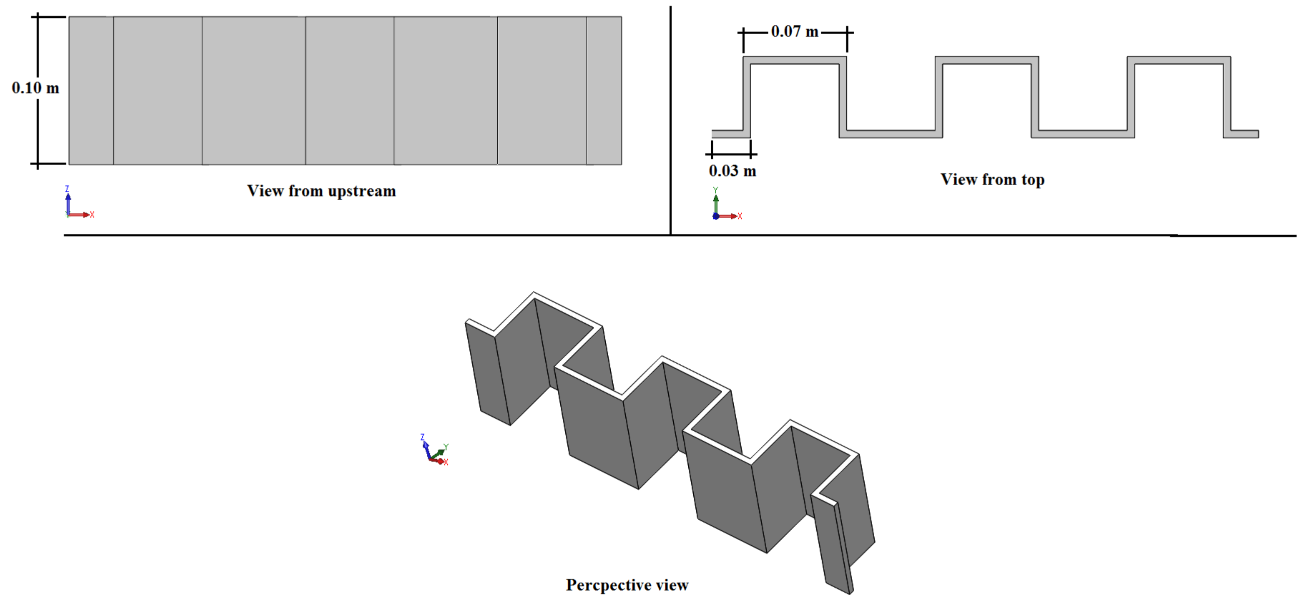


Figure 1. Rectangular labyrinth weir.

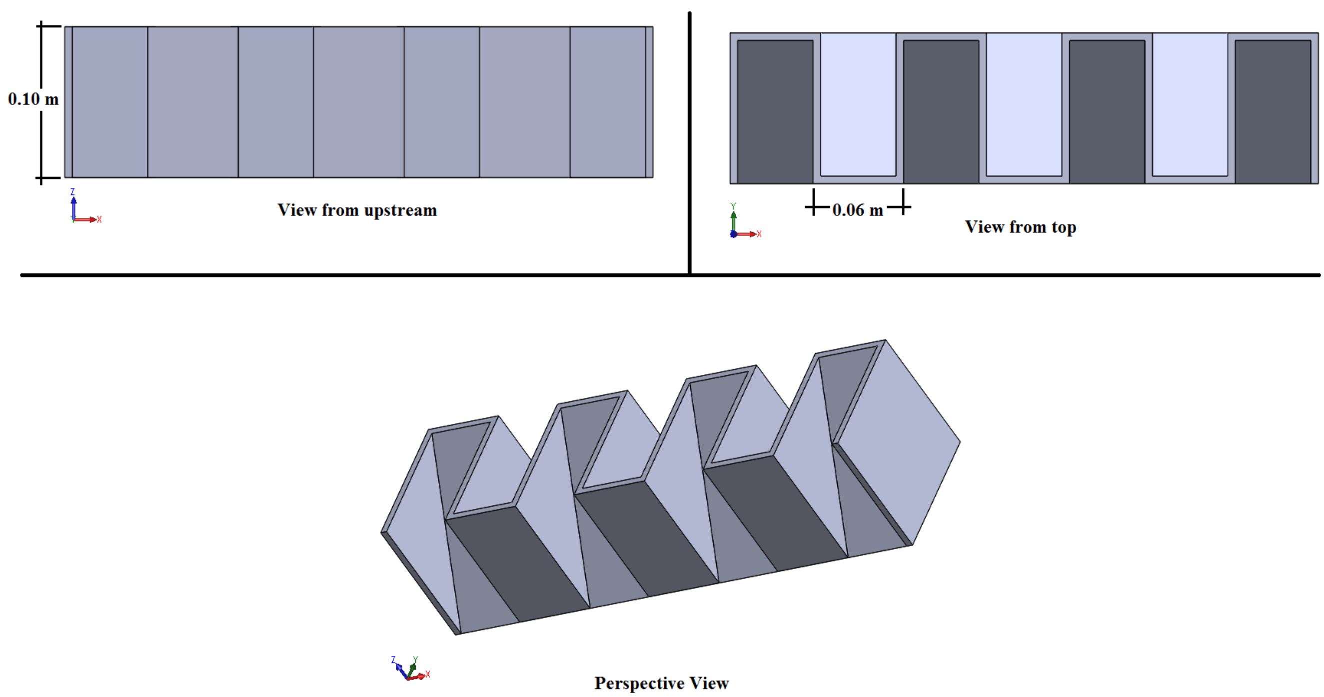
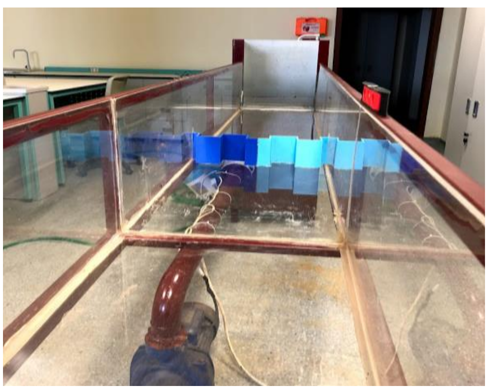
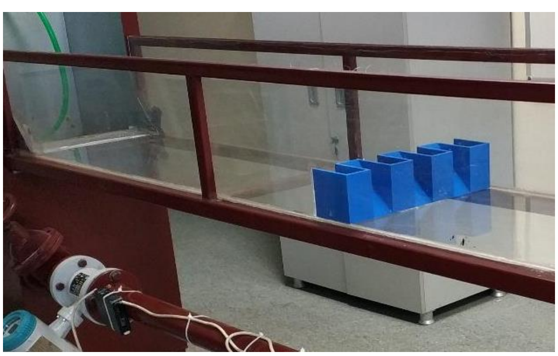


Figure 2. Inclined-bed rectangular weir.

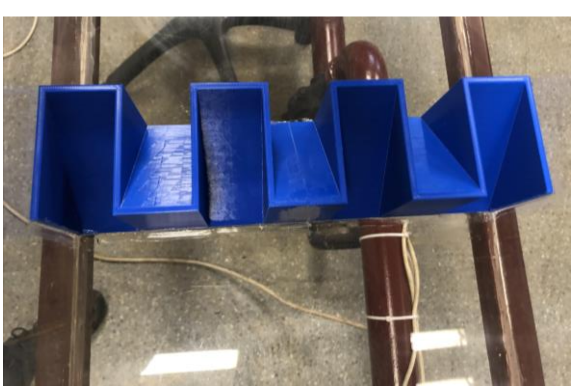
a)



b)



c)



d)

Figure 3. a-b) Views from upstream and downstream of rectangular labyrinth weir, c-d) Views from inclined-bed weir.

2.3. Numerical Model

The numerical model geometry was prepared in three dimensions according to its original dimensions as used in the experiment. In numerical model solutions, the quality of the solution network is very important in terms of receiving the data correctly and properly. On the other hand, the frequency of the mesh to be used for the model can significantly increase the processing time. An excessively high-resolution mesh structure may unnecessarily extend the solution time and cause an increase in numerical errors. In addition, the insufficient resolution of the solution mesh will cause the geometry to be not fully and accurately perceived by the CFD program. Therefore, it is useful to determine an optimum mesh size for the best numerical mesh structure (Figure 4-5). In the study, RNG (Renormalized Group) turbulent model is used. This model, which is similar to the k-epsilon turbulence model, is widely used in open channels.

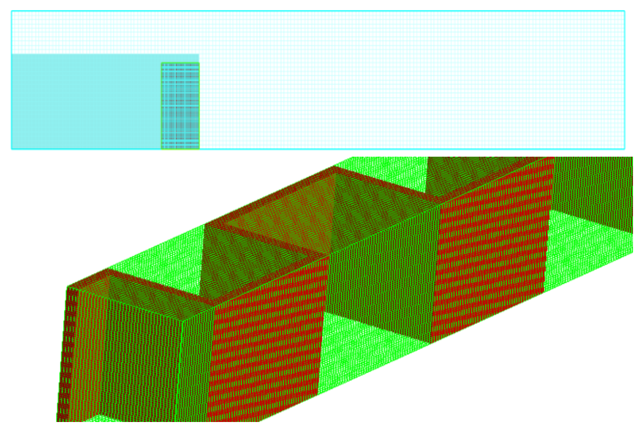


Figure 4. Rectangular labyrinth weir mesh structure.

FLOW-3D CFD software allows to create structured mesh. In the numerical model of the rectangular labyrinth situation, two different sizes of mesh blocks are used. The first net block is a 0.005 m net block that includes the weir. The second net block is 0.0015 m in size to cover the entire weir structure. The total number of mesh structure used is calculated as 1,225,424.

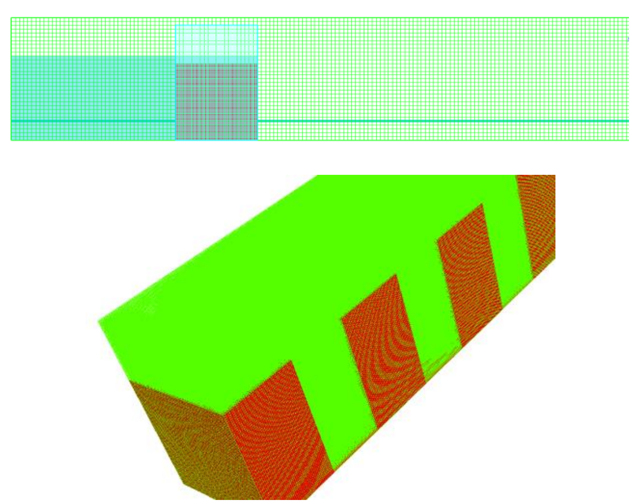


Figure 5. Inclined-bed rectangular weir mesh structure.

Similarly, in the numerical model of the inclined-bed situation, two different sizes of mesh blocks are used. The first mesh block is a 0.005 m mesh block that includes the weir. The second net block is 0.0015 m in size, including the entire weir structure and 0.05 m above the weir. The total number of mesh structure used in this model is given as 2,416,490.

2.4. Model Boundary Conditions

As in the channel design where the weir is located, the water inlet (*specified pressure*) is given from the channel entrance point (Figure 6). Since the upstream side of the weir is open to the atmosphere, it was evaluated as the *Specified Pressure*. The lower part of the sluice was defined as a *Wall*, and the remaining areas were left as *Symmetry*.

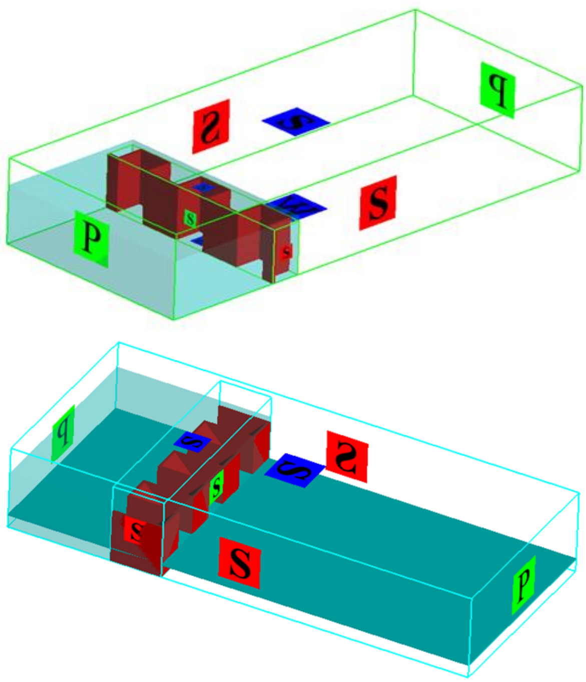


Figure 6. Model boundary conditions. (P: Specified Pressure; S: Symmetry; W: Wall)

In order to see the precision of the applied mesh resolution on the numerical model geometry, the images in the shapes were obtained by using the 'FAVOR' feature in FLOW-3D (Figure 7-8).

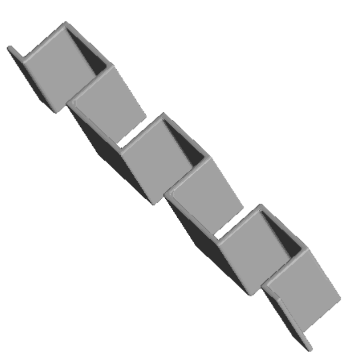


Figure 7. Designed rectangular labyrinth model 'FAVOR' image.

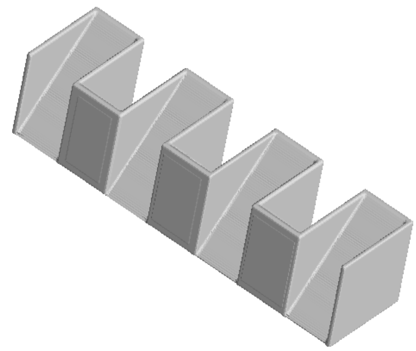


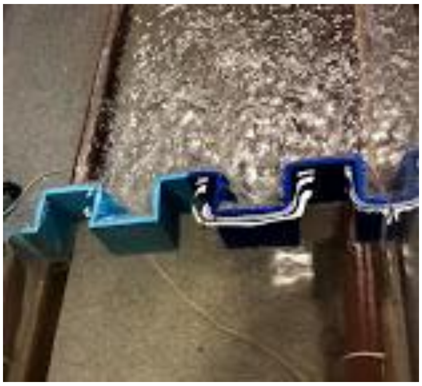
Figure 8. Designed inclined-bed rectangular model 'FAVOR' image.

3. Results

The weir types produced were tested in the laboratory using an open channel test set. Calculations in the experiments were made by measuring the discharges corresponding to five different upstream water levels of H = 0.11 m, H = 0.12 m, H = 0.13 m, H = 0.14 m and H = 0.15 m. In both cases, the difference in discharge in the test and CFD analyses was maximum at low nappe loads. The reason for this was thought to be due to insufficient mesh resolution compared to nappe load, and it was predicted that the results would be the same when the mesh quality was increased. Since the spillway capacity of a weir is important in terms of transferring maximum discharges, this difference at low nappe loads does not have a great effect. In the experiments, it was observed that the weir was operating with maximum efficiency at minimum nappe loads for both weirs, but as the nappe load increased, it was observed that the weir eyes were insufficient and the discharge capacity decreased.

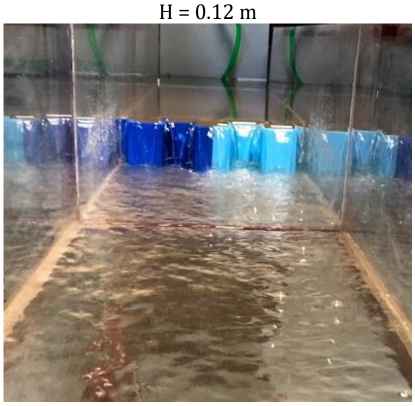
3.1. Rectangular labyrinth weir

For rectangular labyrinth weirs, five different flow rates were obtained for five different water heights in the experiments carried out in the laboratory. In CFD analyzes prepared according to the original situation, upstream water levels obtained from the laboratory were used for each design. In the experiments, discharges corresponding to dimensionless H_0/P=0.1-0.5 m were calculated (Figure 10-11). In both experiments and numerical solutions, it was waited until the flow become steady at the determined height and the data were taken. In CFD analyses, it was observed that stabilization of the flow in low nappe load conditions requires a longer solution time compared to high nappe loads.



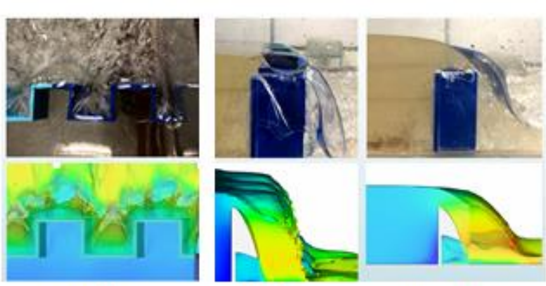
H = 0.11m

H = 0.12 m



H = 0.13 m

Figure 9. Some images from the moment of the experiment.



H=0.12 m H=0.13 m H=0.14 m

Figure 10. Comparison of flow conditions.

The situation where the difference between the tests is maximum was calculated at H_0/P = 0.1 m where the water load is the lowest. The reason for this difference at low nappe loads is thought to be due to insufficient mesh resolution compared to nappe load. It is predicted that better results can be obtained if a higher resolution mesh is used.

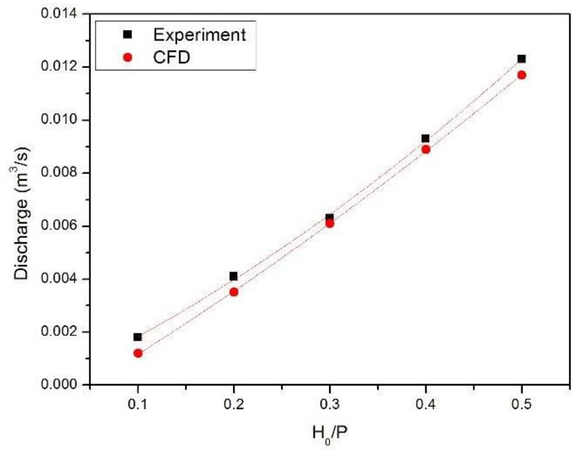


Figure 11. Comparison of rectangular labyrinth model experiment and CFD discharge.

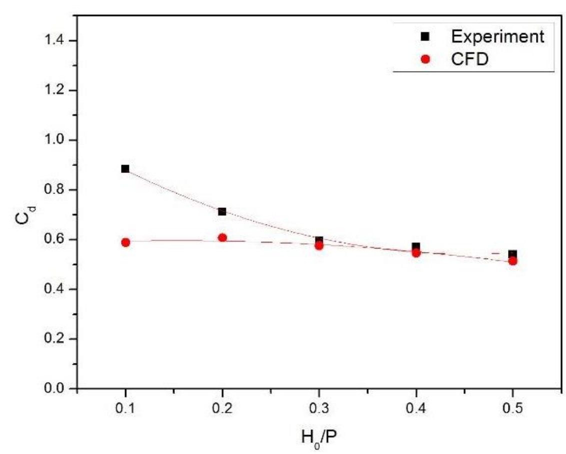
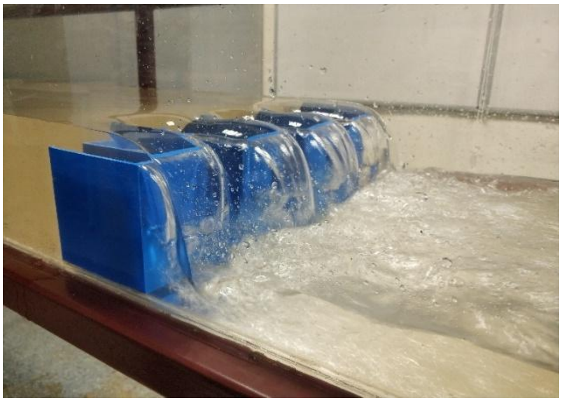


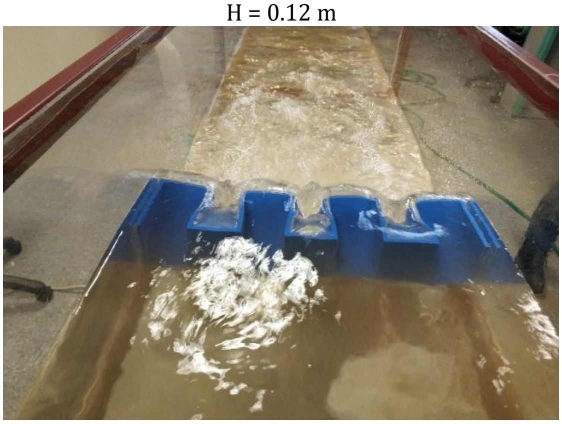
Figure 12. Experiment and CFD comparison of discharge coefficient of rectangular labyrinth model.

3.2. Inclined-bed rectangular weir

As in the rectangular labyrinth weir type, five different discharges were obtained in exchange for five water heights in these experiments. In CFD analyzes prepared according to the original situation, upstream water levels obtained from the laboratory were used for each design.

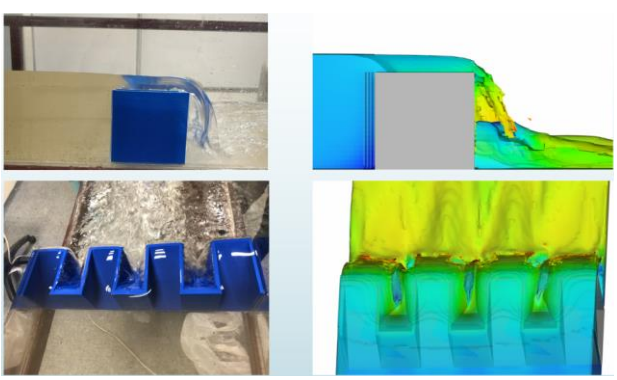


H = 0.12 m

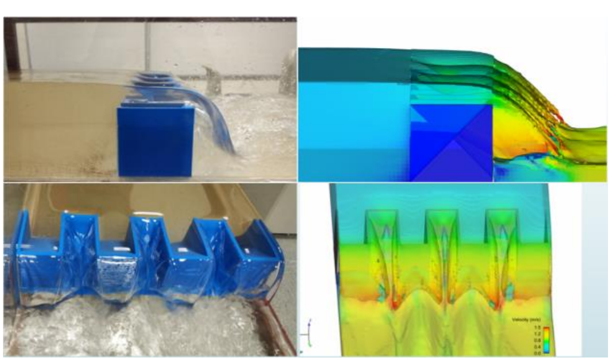


H =0.12 m

Figure 13. Images from the moment of the experiment.



H= 0.11 m



H= 0.13 m

Figure 14. Comparison of flow conditions.

It was observed that the discharges obtained from H_0/P = 0.4 m and H_0/P = 0.5 m water head were very close to each other (Figure 15-16). It is seen that the discharge continues to increase linearly at maximum nappe load. It has been understood from the experimental results that if the nap load continues to increase, the weir operates as a submerged flow.

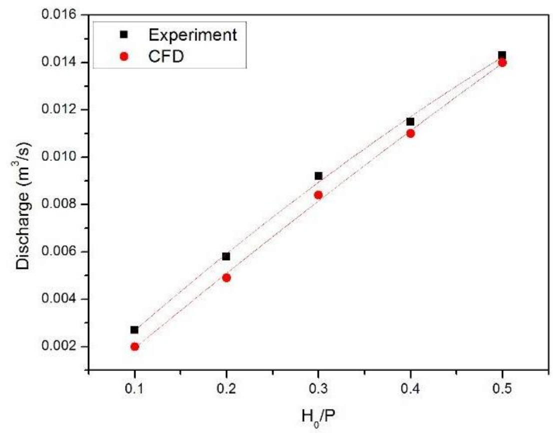


Figure 15. Comparison of inclined-bed rectangular model experiment and CFD discharge.

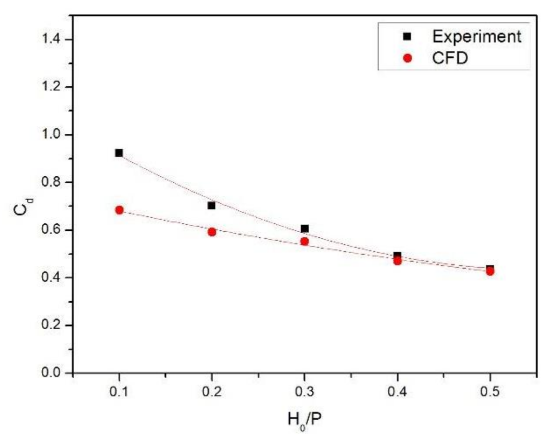


Figure 16. Experiment and CFD comparison of discharge coefficient of inclined-bed rectangular model.

3.3. Comparison of the weirs

Comparative CFD and experimental study discharge coefficients of weir structures with rectangular labyrinth and inclined-bed model are given in Figure 17-18. As can be seen from the graphs, the results of both cases show similar trends. In particular, it is seen that the data obtained from the experimental study are much closer. In addition to these, the comparison of numerical and experimental results also showed a good agreement. (Figure 19-20).

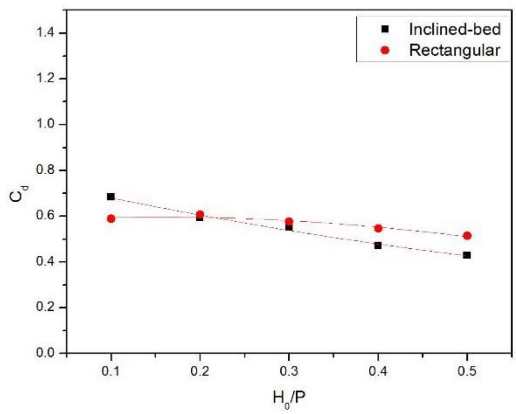


Figure 17. Comparison of rectangular labyrinth and inclined-bed model CFD discharge coefficients.

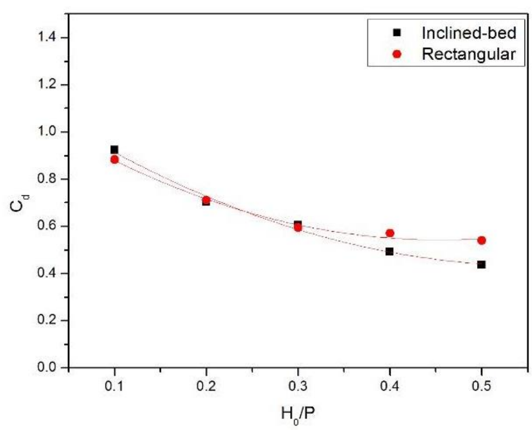


Figure 18. Comparison of rectangular labyrinth and inclined-bed model experiment discharge coefficients.

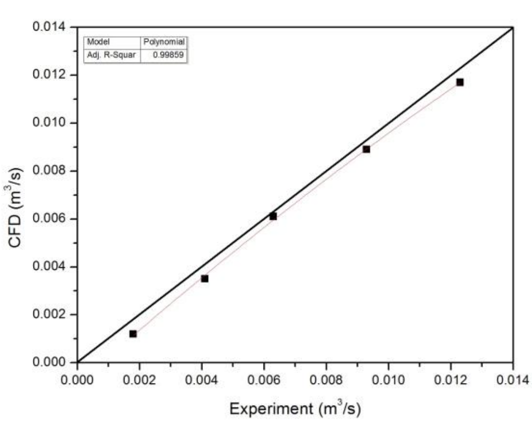


Figure 19. Comparison of rectangular labyrinth weir discharge

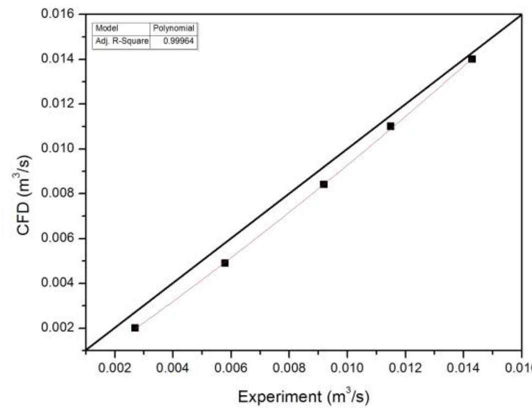


Figure 20. Comparison of inclined-bed rectangular weir discharge

4. Conclusions

In the study, a rectangular labyrinth and an inclined-bed rectangular weir prepared in the CAD environment were produced with the help of a three-dimensional printer. Experiments of the produced parts were carried out in the laboratory using an open channel test set. Calculations in the experiments were made by measuring the discharges corresponding to five different upstream water levels of H = 0.11 m, H = 0.12 m, H = 0.13 m, H = 0.14 m and H = 0.15 m. Prototype dimensions were prepared in 3D digital environment and analyses were made under nap loads determined by using single-phase, Reynolds Averaged Navier-Stokes (RANS) turbulent flow model with the help of FLOW-3D. Parallel to the literature, it has been observed here that more discharge is obtained with the increase of the crest length. In both cases, the difference in discharge in the experimental and numerical results analyses was maximum at low nappe load. The reason for this was thought to be due to insufficient mesh resolution compared to nappe load, and it was predicted that the results would be the same when the mesh quality was increased. Since the spillway capacity of a weir is important in terms of transferring maximum discharges, this difference at low discharges does not have a great effect. According to the experimental results, it was observed that the weir was operating with maximum efficiency at minimum nappe loads for both weirs, but as the nappe load increased, it was observed that the weir eyes were insufficient and the flow capacity decreased.

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