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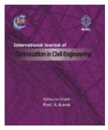

NUMERICAL STUDY ON DIFFERENT TYPES OF WEIRS TO DETERMINE THEIR OPTIMALITY BASED ON THE HYDRAULIC AND STRUCTURAL CRITERIA

T. Bakhshpoori[*,†,1] and M. Heydari[2]
[1]*Faculty of Technology and Engineering, East of Guilan, University of Guilan, Rudsar, Iran*
[2]*Department of Civil Engineering, Rahman Institute for Higher Education, Ramsar, Iran*

ABSTRACT

In this research, different types of weirs have been numerically investigated to determine the optimal design based on two hydraulic and structural criteria. FLOW 3D and ABAQUS software were utilized for the hydraulic and structural analysis, respectively. The accuracy of the numerical models was verified with the available experimental and numerical results. In the hydraulic investigation, 18 models of different types of weirs including rectangular (6 models), square, triangular (3 models), circular, ogee (3 models), and labyrinth (4 models) weirs were examined. In the structural study of weirs, there are 13 models, including rectangular, square, triangular (3 models), circular, ogee (3 models), and labyrinth (4 models) weirs were analyzed. The results of hydraulic analyzes showed that the dimensions of the rectangular weir significantly affect the output velocity. In triangular weirs, the highest energy dissipation will occur with an apex angle of 45°, and with the increase of the apex angle in the ogee weir, more turbulence is observed in the downstream flow. In labyrinth weirs, by changing the shape of the weir from triangular to rectangular, the output velocity and also turbulence of the flow will be much less. According to the findings of the structural analyses, the increase of the apex angle in triangular weirs, the weir will be more critical, but the situation will be more suitable in ogee weirs. Additionally, the rectangular labyrinth weir performs the best structurally among the labyrinth weirs.

Keywords: Numerical study, Weir, Hydraulic analysis, Structural analysis, Optimal design.

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[*]Corresponding author: Faculty of Technology and Engineering, East of Guilan, University of Guilan, Rudsar, Iran
[†]E-mail address: tbakhshpoori@guilan.ac.ir (T. Gholizadeh)

1. INTRODUCTION

Weirs are considered to be the main and important structures of dams, and it is expected that they will be able to be promptly operational for the use and discharge of floods and protection of the dam and the related establishments [1]. About 23% of dam failures are caused by inadequate weir discharge capacity, which leads to breaches in the lateral cross-section, high pore water pressure, and finally can lead to erosion, seepage problems, and even failure [2]. The ideal design of the weir should be given special consideration due to the significant expense of weir development, which is usually about 20 and 80% of the complete expense of dam development in small and large dams [3-5]. Several weirs have been constructed to direct floodwater downstream from the reservoir. In this research, to determine the optimal design of weirs based on the parameters affecting it, different types of weirs including rectangular, square, triangular, circular, ogee, and labyrinth have been modeled using numerical methods and their hydraulic and structural behavior has been evaluated. The focus of this paper is two-fold:

• From the hydraulic standpoint, the optimal design is the design with the lowest output velocity from the weir and flow disturbance downstream, and thus the occurrence of the lowest rate of erosion and sedimentation downstream of the dam. In the first phase, hydraulic analyzes have been done to determine the optimal design of weirs based on the above criteria.

• In the second phase, the weirs' optimal design has been achieved through structural analysis. The lowest stress level in the weir structure is a criterion for optimal design in structural analyses.

The results of previous researchers must be reviewed to reach the aims set out in this paper. In the following, the most important research related to the topic of this article will be reviewed.

2830 laboratory tests on the labyrinth side weirs were conducted by Emiroglu et al. [6]. They concluded that the discharge coefficient of the labyrinth side weir is up to 4 times higher than the rectangular side weir. Yildiz et al. [7] concluded that the discharge is not significantly affected by the weir height in triangular sectioned weir. Ibrahim and Shaikhli [8] reported the discharge coefficient of a triangular weir is higher than the discharge coefficient of a rectangular weir. The result of Ghaderi et al.'s research [9] showed that due to the collision of nappes in the upstream apexes, trapezoidal–triangular labyrinth weirs approximately dissipate the maximum amount of energy. Abbaspuor et al. [10] investigated hydraulic passing flow through a triangular labyrinth weir. They concluded that, by increasing the angle of the weir, the crossflow interference with the lateral fall blades reduced and created less flow vortex. Kumar et al. [11] used a triangular plan for a labyrinth weir to experimentally investigate the discharge coefficient. They discovered that by decreasing the apex weir angle, the length of the interference zone increased, while the weir discharge coefficient decreased significantly. The findings of Ghaderi et al.'s research [12] demonstrated as the apex angle increases in the triangular plan form weir, leads to less disturbance and vortex flow. Seo et al. [13] looked into how weir shapes affected weir discharge and reported that the discharge of the labyrinth weir had an increase of approximately 71% in comparison with the linear ogee weir.

The following limitations are revealed by a review of previous studies. 1) Most of the research has investigated one or two cases of weirs related to a specific project or several factors affecting weir performance. 2) Checking the performance of weirs is generally limited to their hydraulic behavior and checking the structural behavior of weirs has been limited. In this research, different types of weirs including rectangular, square, triangular, circular, ogee, and labyrinth have been numerically investigated to determine the optimal design based on two hydraulic and structural criteria. For the hydraulic and structural analyses, respectively, FLOW 3D and ABAQUS were used. The accuracy of the numerical models was verified with the available experimental and numerical results. Then, the output velocity, flow turbulence, and stress level in all types of weirs were investigated and compared.

2. METHODOLOGY

In this research, studies will be conducted in two parts. In the first part, hydraulic studies and flow analysis will be done by FLOW 3D software, and in the second part, structural studies will be done using ABAQUS software to investigate the structural behavior of weirs.

To begin with, in FLOW 3D software, 18 models of different types of weirs were modeled and analyzed, including rectangular (6 models), square, triangular (3 models), circular, ogee (3 models), and labyrinth (4 models) weirs. One of the most crucial aspects of the numerical models produced by the FLOW 3D software is the utilization of Cartesian meshing, the combination of the VOF (Volume of Fluid) method and the FAVOR (Fractional Area-Volume Obstacle Representation) method for the detection of rigid boundaries. The way these models are meshed is one important aspect. An accurate and reasonable solution time should be guaranteed when determining the number of cells in a suitable grid. Consequently, the sensitivity analysis of the results to the number of cells was carried out for each kind of weir. For example, the number of 20,000 cells led to good results in all types of ogee weirs.

In the next step, in ABAQUS software, 13 weirs models including rectangular, square, triangular (3 models), circular, ogee (3 models), and labyrinth (4 models) were modeled and analyzed. The free technique was utilized to mesh the models. There is no predetermined pattern used in this meshing method, But the quality of the meshing can be improved by selecting the appropriate mesh size. In the analysis performed in ABAQUS software, the force caused by the fluid is applied as static pressure on the weir structure.

The purpose of hydraulic (structural) modeling and analysis is to investigate the effect of weir geometry on changing its hydraulic (structural) behavior; Therefore, it is necessary to consider suitable values for other parameters. In this study, the length of the tank behind and in front of the weir, the height and length of the entire structure, and the water level upstream and downstream are assumed to be 10, 20, 17, 20, 15, and 2 meters, respectively.

3. VALIDATION

In this section, numerical models are validated to ensure the obtained results and their accuracy. A model based on Fig. 1 was considered to verify the accuracy of the modeling and analysis performed in FLOW 3D software. This model has been investigated experimentally and numerically by Bagheri and Heidarpour [14] and Ghotbi et al. [15] respectively. Fig. 2 shows the comparison between the velocity distribution along the weir obtained from the experimental study conducted by Bagheri and Heidarpour [14] and the numerical study conducted by Ghotbi et al. [15] with the numerical modeling results conducted in the present study. According to Fig. 2, the results of the numerical analysis performed in the current study are in acceptable agreement with the previous results. To check the accuracy of the model more closely, the normalized velocity values obtained from the results of the present numerical model with previous results are shown in Table 1. According to this table, the results of the current research differ by an average of 8% with the numerical study conducted by Ghotbi et al. [15] and by 15% with the experimental results conducted by Bagheri and Heidarpour [14]. Therefore, it can be concluded that the results of the numerical model made in FLOW 3D software have acceptable accuracy.

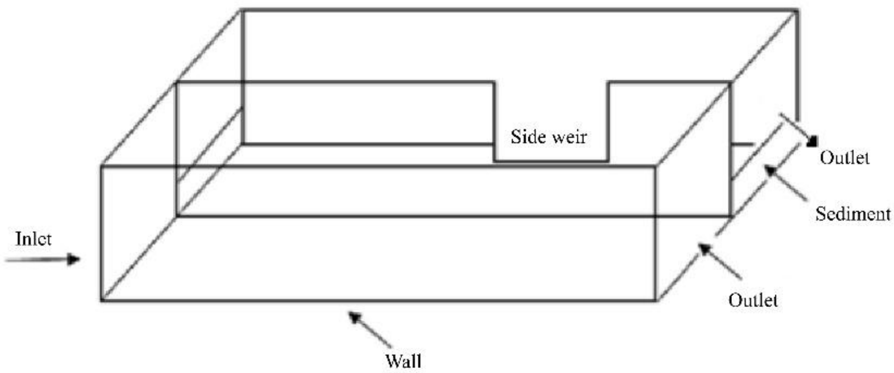

Figure 1: Scheme for computational domain and boundary conditions [15].

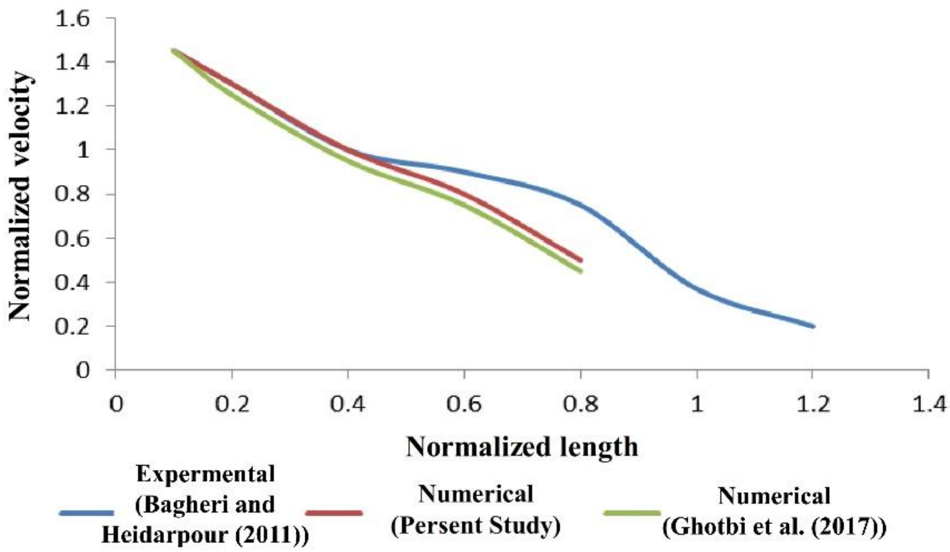

Figure 2: Comparison of the normalized velocity in the present study with the available data.

Table 1: Comparison of the normalized velocity values obtained from the present study with references [14] and [15].

x/L	A: Ux/U (Persent study)	B: Ux/U [15]	C: Ux/U [14]	Error (A/B)	Error(A/C)
0.799072	0.437778	0.510095	0.754163	0.858228	0.580482
0.730858	0.546693	0.61901	0.81788	0.883173	0.668427
0.623666	0.719137	0.782414	0.899928	0.919126	0.799105
0.477494	0.864714	0.92799	0.964149	0.931814	0.896868
0.370302	0.991959	1.03716	1.03716	0.956418	0.956418
0.256613	1.15541	1.21868	1.21868	0.948083	0.948083
0.159165	1.31875	1.38202	1.38202	0.954219	0.954219
0.107193	1.4366	1.44561	1.44561	0.993767	0.993767
Mean				0.930604	0.849671

After ensuring the accuracy of the hydraulic analysis, further verification of modeling and structural analysis was carried out. In this regard, a model according to the research done by Akoz et al. [16] has been considered. Fig. 3 shows the schematic model of the experimental model of Akoz et al. [16]. In Fig. 4, the results of the flow height distribution along the weir can be seen. The obtained results show a difference of about 8% between the results presented in reference [18] and the present modeling, which can be reduced based on the change in mesh size; But the obtained value is within the acceptable range.

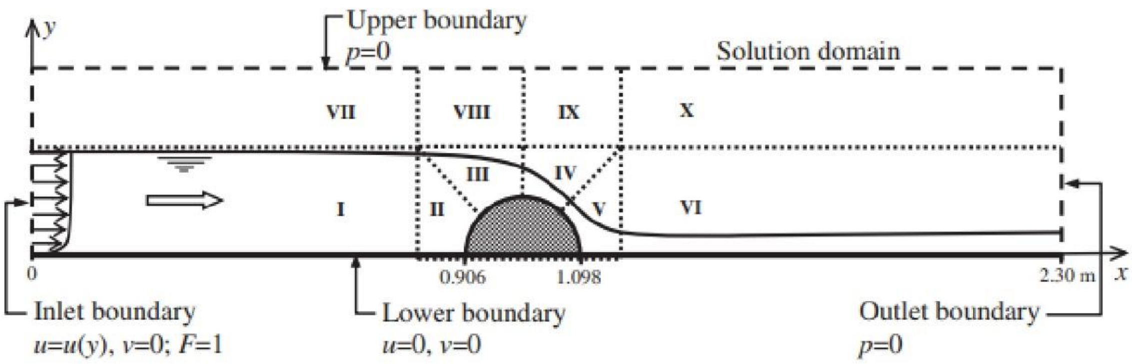

Figure 3: Geometry and boundary conditions of the solution domain with 10 subdomains employed in the computations [16].

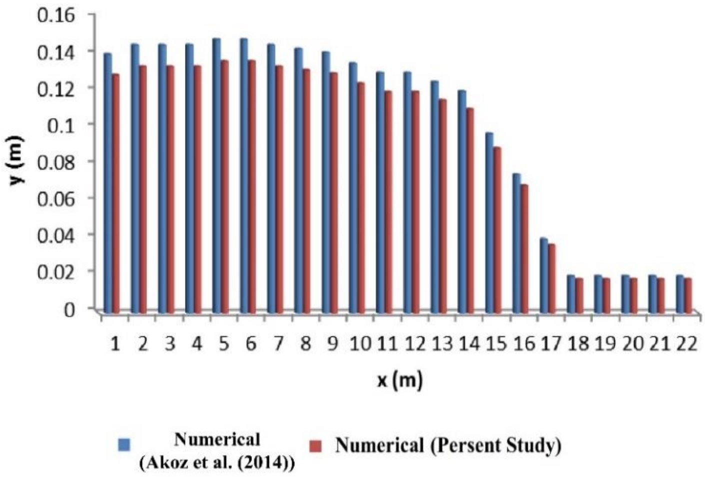

Figure 4: Comparing the results of the analysis done by Akoz et al. [16] and the results of the present study.

4. RESULTS AND DISCUSSION

In the previous section, the accuracy of the numerical modeling was confirmed by comparing it to the available experimental and numerical results. Therefore, studies related to this research can now be conducted and their findings analyzed. In the following, the most important results of hydraulic and structural analyzes will be presented and discussed.

4.1. Hydraulic analysis

4.1.1. Rectangular weirs

Five rectangular weirs will be considered in this section. Different ratios of the weir's outlet length to height are the primary variable in the parametric study; which are considered according to Table 2. Hydraulic flow studies were performed based on the use of the Computational Fluid Dynamics (CFD) method on 5 models. The specifications of these models are shown in Table 2 and the results of their analysis are shown in Fig. 5.

Table 2: The length and height values of the outlet of the rectangular weir opening in different models.

Model number	The length of the outlet of the overflow opening (m)	The height of the outlet of the overflow opening (m)
1	10	7
2	14	7
3	10	4
4	14	10
5	8	10

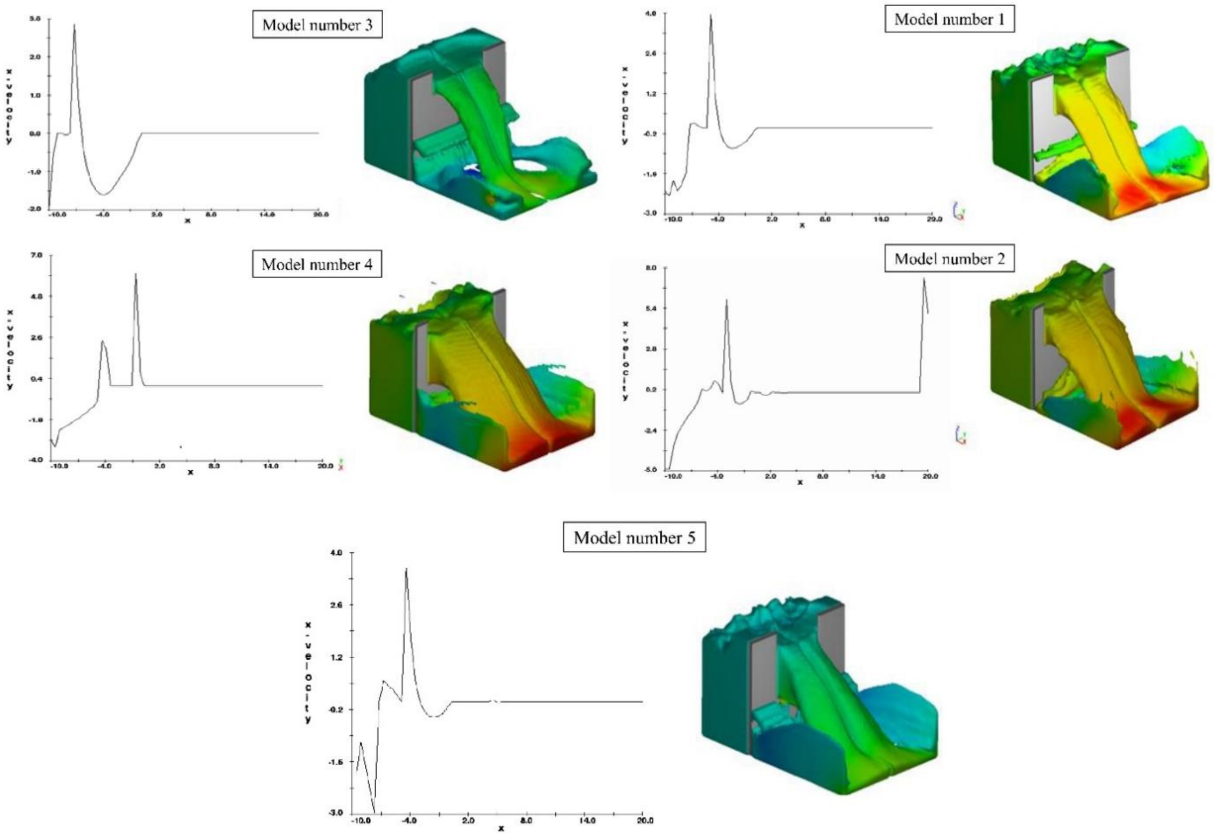

Figure 5: Flow distribution in all types of rectangular weirs

The maximum output velocity in various cases is depicted in Fig. 6. According to this figure, the output velocity is significantly influenced by the weir's dimensions so the maximum velocity occurred in model number 2 (7.8 m/s) and the minimum velocity in model number 3 (2.8 m/s). As a result, a weir with a height of 4 meters and a length of 10 meters will be the most effective design for a rectangular weir. The rate of erosion and sedimentation downstream will be significantly lower in this optimal design than in other models due to the increase in energy dissipation and reduction in output velocity. As shown in Fig. 6, with the increase in the length of the weir, the outlet velocity also increases. For instance, in the case where the height is 7 meters, increasing the length from 10 to 14 meters will lead to a 195% increase in the outlet velocity. Also, in models No. 5 and 4, by increasing the length of the weir from 8 to 14 in the case that the height is 10 meters, the outlet velocity has increased from 3.5 m/s to 6.3 m/s (180% increase).

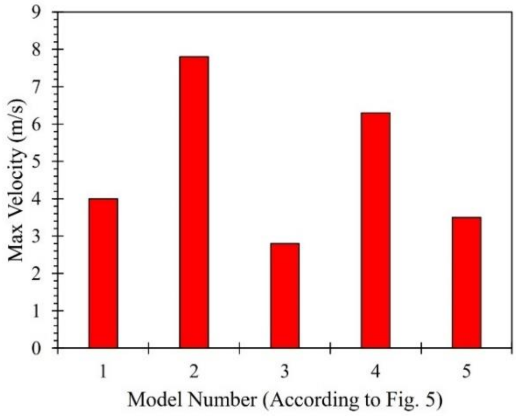

Figure 6: Comparison of the maximum velocity in all types of rectangular weirs.

4.1.2. Square, triangular, and circular weirs

In this section, a comparison has been made between common executive weirs with different forms. For this purpose, a square weir with dimensions of 4 meters (length and height), a rectangular weir with dimensions of 8 and 4 meters (length and height), 3 triangular weirs with different apex angles (30, 45, and 60 degrees) and a circular weir with a radius of 2 meters are considered. Fig. 7 shows the flow velocity distribution for weirs. Also, the maximum output velocity values are presented in Fig. 8.

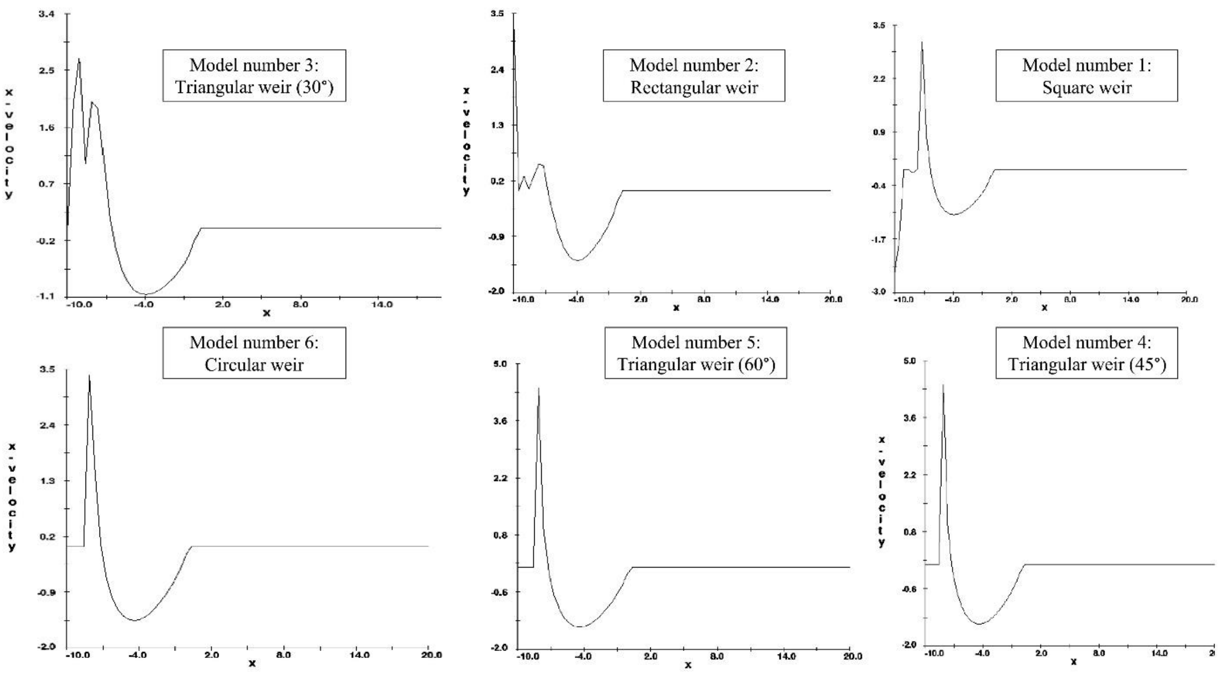

Figure 7: Flow velocity distribution for square, rectangular, triangular and circular weirs.

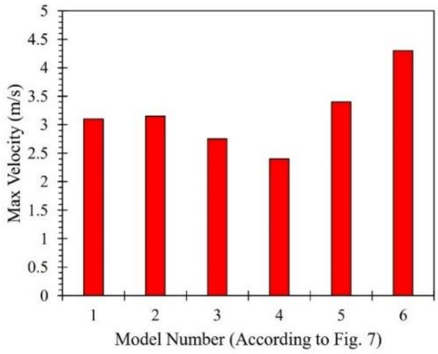

Figure 8: Comparison of the maximum velocity in square, rectangular, triangular and circular weirs.

The comparison of the maximum output velocity in two types of square weir (model no. 1) and rectangular (model no. 2) shows that the maximum output velocity in the square weir is about 2% lower than the rectangular weir; Therefore, there has been no significant reduction in energy dissipation. Among the 3 triangular weirs with different apex angles, the highest energy dissipation occurred at 45 degrees; Because the output velocity, in this case, is 13% and 30% lower than the 30° and 60°, respectively. The maximum output velocity among the 6 models occurred in the circular overflow; Therefore, it is expected that the rate of erosion and sedimentation downstream of the dam in the case of circular overflow is significantly higher than in other models. The most optimal design among models 1 to 6 is related to the triangular overflow with an apex angle of 45 degrees; Because the highest dissipation of energy has occurred in this state. This has led to the lowest output velocity occurring in this case.

4.1.3. Ogee weirs

The purpose of this section is to evaluate the behavior of the ogee weir and the influence of the slope angle in this type of weir. A view of 3 ogee weirs with 30, 45, and 60-degree angles is shown in Fig. 9. Figs 10 shows the velocity distribution in ogee weirs. Also, to better compare the results obtained from the modeling of ogee weirs with three angles of 30, 45, and 60 degrees, a bar diagram is presented according to Fig 11.

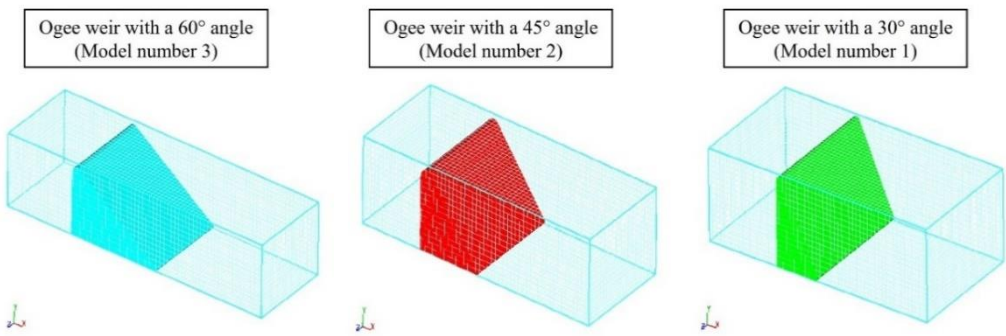

Figure 9: Types of ogee weirs.

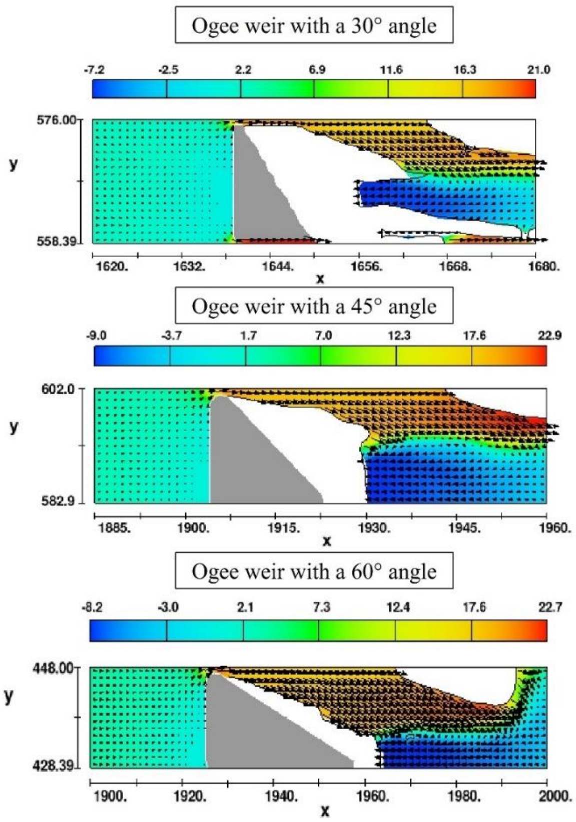

Figure 10: Flow distribution in all types of ogee weirs.

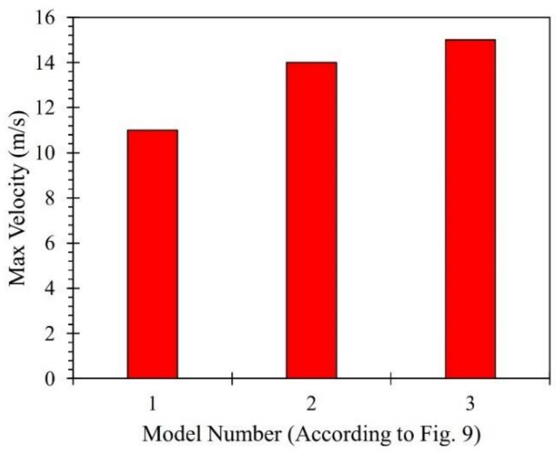

Figure 11: Comparison of the maximum velocity in all types of ogee weirs.

The velocity distribution diagrams show that the downstream flow experiences more turbulence the higher the slope angle of the ogee weir. As a result of this issue, the weir's output velocity will also increase as the angle increases, Therefore, the reason for the increase in output velocity in models 1 to 3 can be justified in Fig 11. For example, by increasing the slope angle from 30 to 60 degrees, the output velocity of the weir has changed from 11 to 15 m/s (a 36% increase in the output velocity).

4.1.4. Labyrinth weirs

In this part, the labyrinth weirs' behavior has been evaluated. For this purpose, rectangular, triangular, curved-tip triangular, and semicircular labyrinth weirs (Fig 12) were modeled and analyzed. The results of the flow distribution (Fig 13) showed that by changing the shape of the labyrinth weir from triangular to rectangular, the output velocity and the turbulence of the flow will be much less. A comparison of flow turbulence and output velocity in curved-tip triangular and semicircular labyrinth weirs shows the performance of semicircular labyrinth weirs is slightly better than that of curved-tip triangular. A bar graph is shown in Fig 14 to make it easier to compare the results of modeling labyrinth weirs. As it is clear in Fig 14, the rectangle is the optimal design for labyrinth weirs because the outlet velocity is 75%, 67%, and 66% lower than triangular, curved-tip triangular, and semicircular labyrinth weirs, respectively.

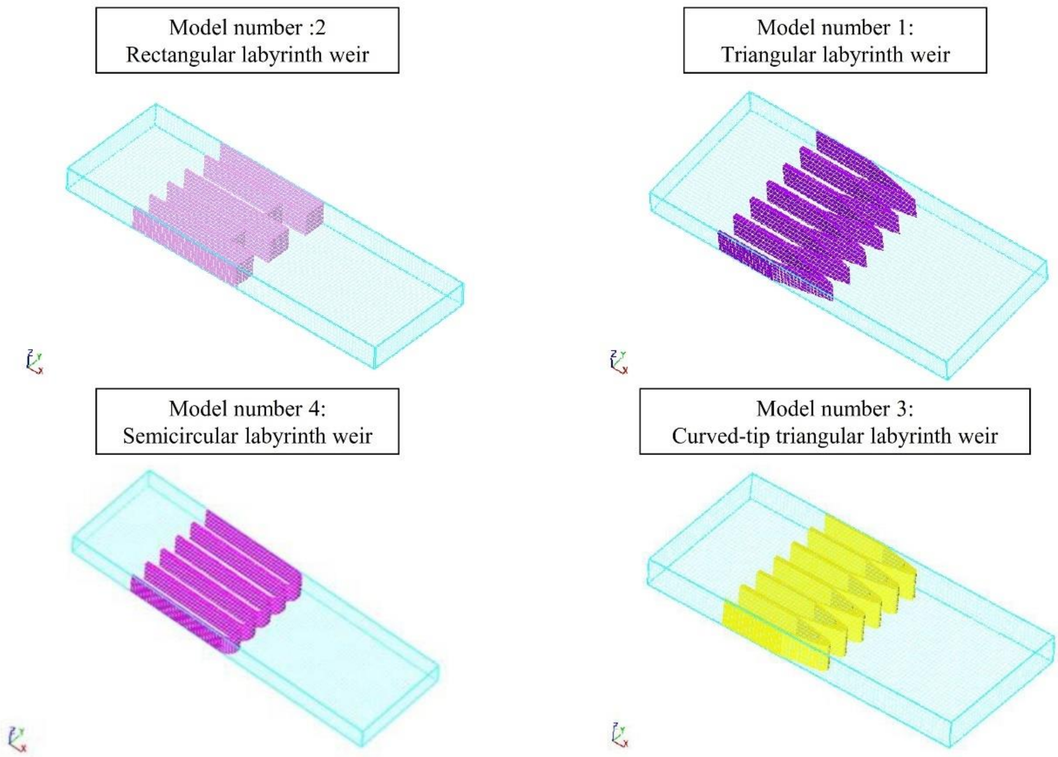

Figure 12: Types of labyrinth weirs.

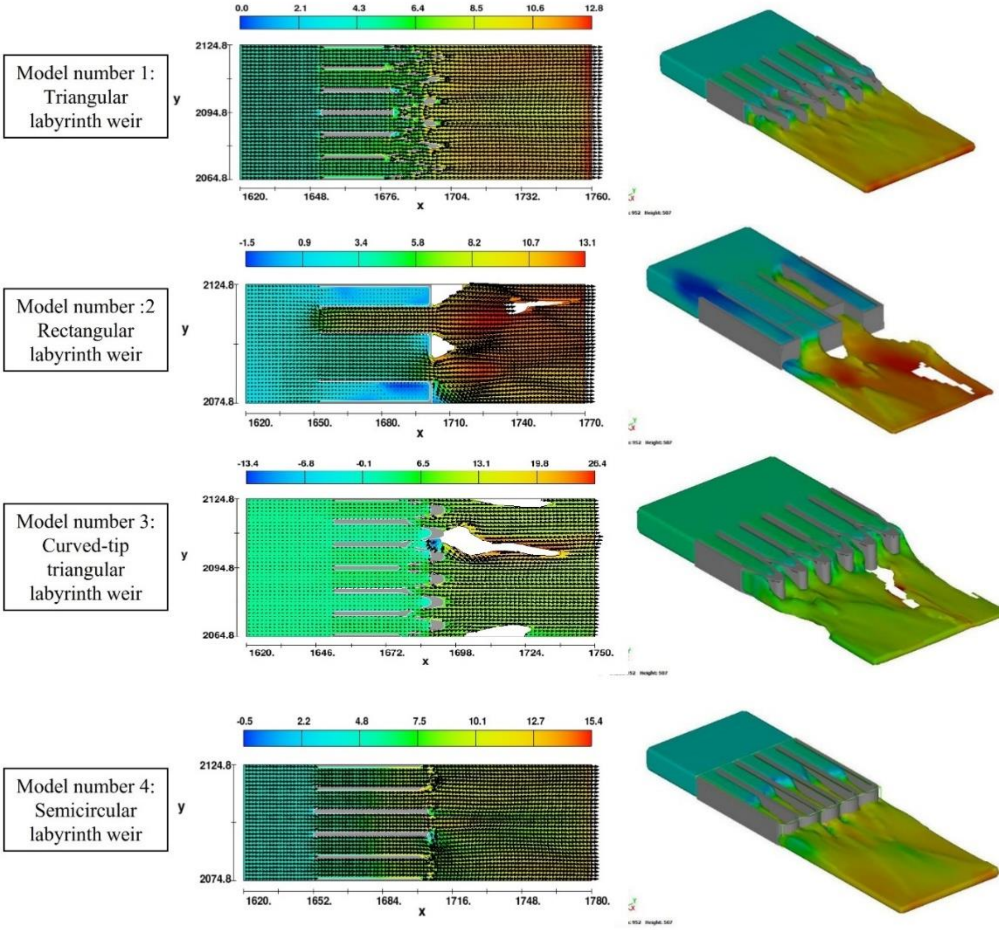

Figure 13: 2D and 3D flow distribution in all types of labyrinth weirs.

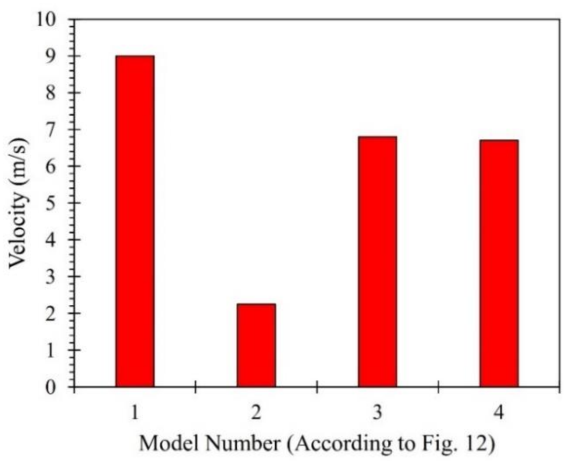

Figure 14: Comparison of the maximum velocity in all types of labyrinth weirs.

4.2. Structural analysis

In this section, structural analyses have been done on 13 types of weirs including rectangular, square, triangular (3 models), circular, ogee (3 models), and labyrinth (4 models) weirs using ABAQUS software. From a structural standpoint, the best design is one that exerts less stress against the fluid's hydrostatic pressure. The weir is less stressed the larger the weir area. According to this principle, the square weir has a better structural performance than the rectangular weir; Because there is a larger area against the hydrostatic pressure caused by the fluid in the square weir. According to Fig 15, the maximum stress in the square weir is 8% less than in the rectangular weir. In the circular weir, the stress distribution is not uniform compared to the square and rectangular cases, and there has been a local increase in the stresses in the weir, However, the maximum stress in the circular weir is higher than the square weir and less than the rectangular weir.

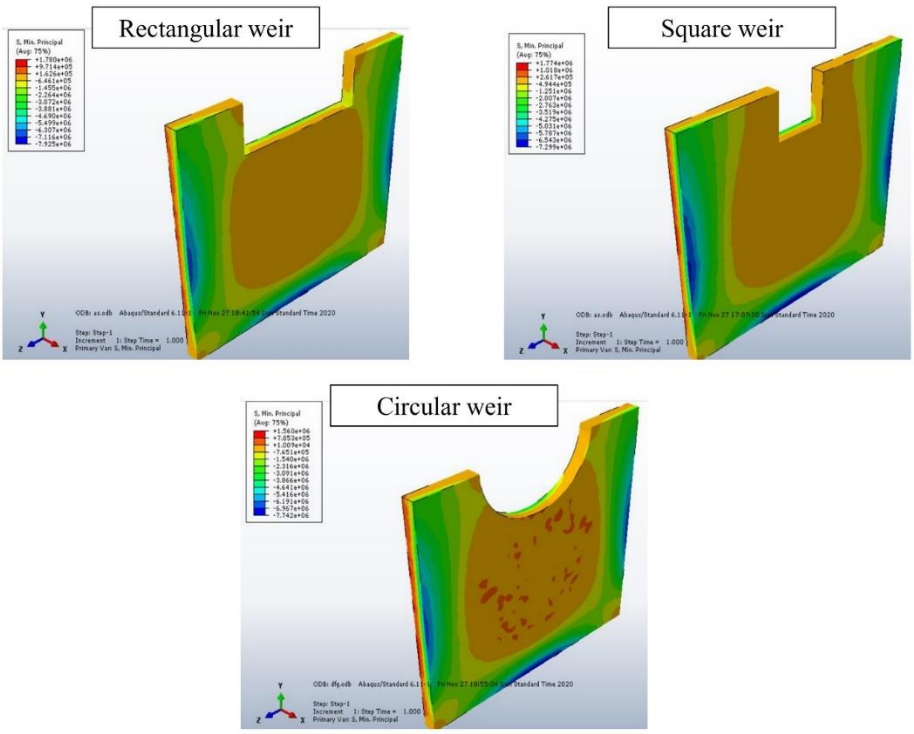

Figure 15: Stress distribution in rectangular, square, and circular weirs.

From a structural standpoint, the condition of triangular weirs becomes more critical as the apex angle increases; because a larger apex angle provides less area against hydrostatic pressure. According to Fig 16, with the increase of the apex angle from 30 to 60 degrees, the maximum stress in the weir has increased by 76%.

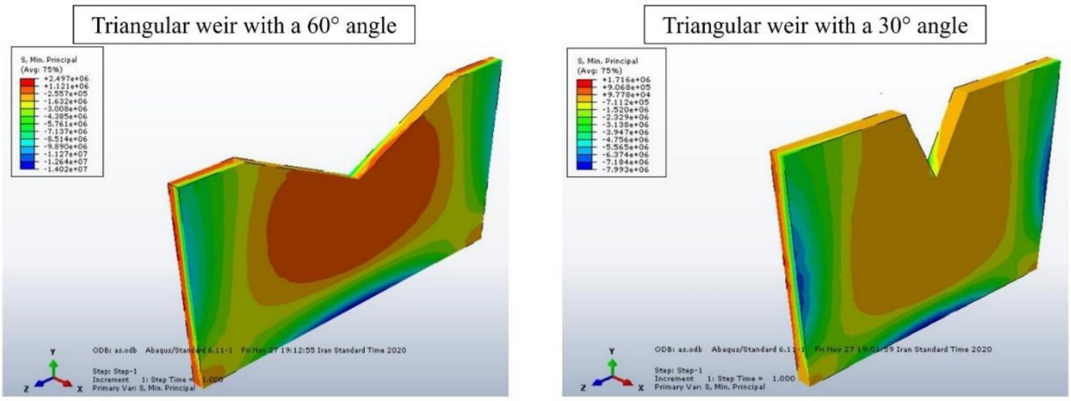

Figure 16: Stress distribution in triangular weirs.

Due to the least amount of stress, rectangular is better than triangular (The maximum stress in the rectangular labyrinth weir is 72% less than the maximum stress in the triangular labyrinth weir), curved-tip triangular (The maximum stress in the rectangular labyrinth weir is 90% less than the maximum stress in the curved-tip triangular labyrinth weir), and semicircular (The maximum stress in the rectangular labyrinth weir is 13% less than the maximum stress in the semicircular labyrinth weir) for labyrinth weirs. This issue can be concluded from Fig 17.

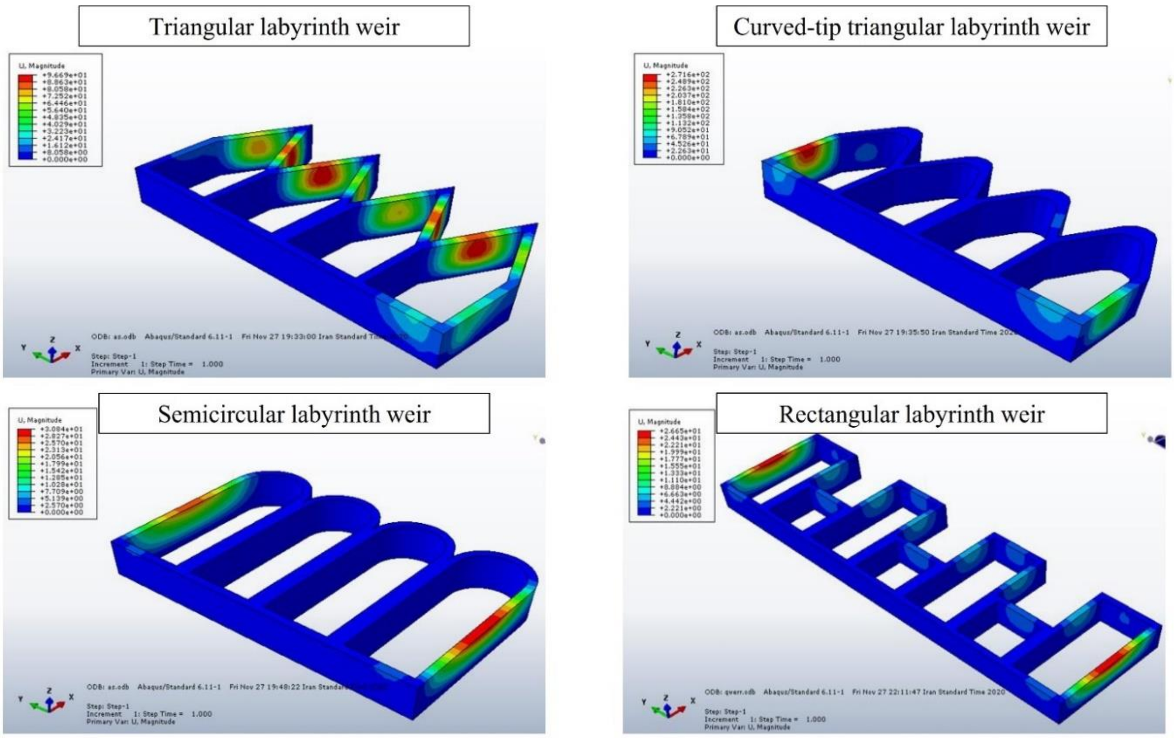

Figure 17: Stress distribution in labyrinth weirs.

In ogee weirs, with the increase of the angle, the distribution of stress on the weir becomes more balanced, so the weir with a greater angle has better conditions. For example, according to Fig 18, increasing the angle of the weir from 30 to 45 degrees has led to a reduction of the maximum stress by 79%.

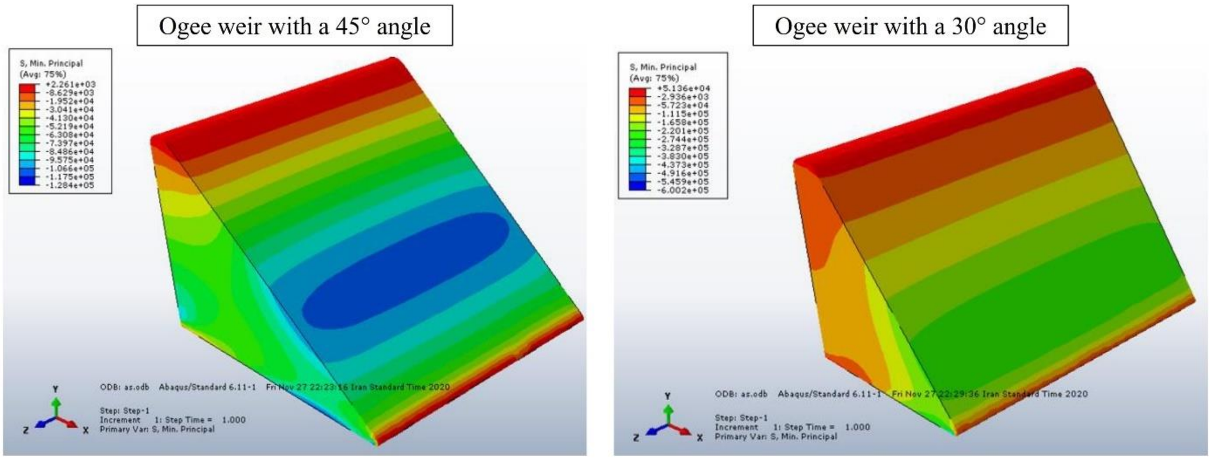

Figure 18: Stress distribution in ogee weirs.

5. CONCLUSIONS

In this paper, by performing numerical analysis with the FLOW 3D (for hydraulic analysis) and ABAQUS (for structural analysis) software, various types of weirs were examined to find the optimal design based on hydraulic (the lowest output velocity and the rate of erosion and sedimentation in the downstream) and structural (low stress in the weir) criteria. The following concluding observations can be made:

Based on the results obtained from the hydraulic analysis for the rectangular weir, it was determined that the dimensions of the weir significantly affect the output velocity. So, the minimum velocity occurred in model number 3 (weir with a length of 10 meters and a height of 4 meters). In this optimal plan, due to the increase in energy dissipation, and the minimization of the output velocity, the rate of erosion and sedimentation downstream will be significantly lower than in other cases.

In rectangular weirs, with the increase in the outlet length, the outlet velocity also increases.

Based on the results obtained from the hydraulic analysis for the triangular weir, it was determined that among the 3 triangular weirs with different apex angles, the highest energy dissipation occurred in the 45-degree case, Because the output velocity in this mode is 13% and 30% lower than the 30° and 60°, respectively.

The higher the slope angle in the ogee weir, the more turbulence is observed in the downstream flow. also, the output velocity of the weir increases with the increase of the angle.

Based on the results obtained from the hydraulic analysis for the labyrinth weirs, it was determined that by changing the shape of the weir from rectangular to triangular, the output velocity and also turbulence of the flow will be much less.

A square weir has a better structural performance than a rectangular weir because there is a larger area against the hydrostatic pressure caused by the fluid in the square weir.

The condition of a triangular weir will become more critical from a structural standpoint as the angle increases, whereas an ogee weir's condition will become more suitable from a structural standpoint as the angle increases.

Among the labyrinth weirs, the rectangular labyrinth weir has a better condition than the triangular, curved-tip triangular, and semicircular labyrinth weirs due to the least amount of stress.

REFERENCES

1. Ghanbari R., Heidarnejad M. Experimental and numerical analysis of flow hydraulics in triangular and rectangular piano key weirs, *Water Science*, 2020. **34**(1): 32-38.
2. Abhash A, Pandey KK. (). A review of Piano key Weir as a superior alternative for dam rehabilitation. *ISH J of Hyd Eng*, 2022. **28**(1): 541-51.
3. Hosseini K, Nodoushan EJ., Barati R, Shahheydari H. Optimal design of labyrinth spillways using meta-heuristic algorithms. *KSCE J of Civil Eng*, 2016. **20**: 468-77.
4. Ghare, A. D., Mhaisalkar, V. A., & Porey, P. D. (). An approach to optimal design of trapezoidal labyrinth weirs. *World Appl Sci J*, 2008. **3**(6): 934-38.
5. Haddad OB., Mirmomeni M, Marino MA. (). Optimal design of stepped spillways using the HBMO algorithm. *Civil Eng Env Sys*, 2010. **27**(1): 81-94.
6. Emiroglu ME., Kaya N, Agaccioglu H. Discharge capacity of labyrinth side weir located on a straight channel. *J Irr Drain Eng*, 2010. **136**(1): 37-46.
7. Yildiz A, Marti AI., Gogus M. Determination of hydraulic characteristics of flow over a triangular sectioned weir by using experimental and numerical modeling. *J of Comput App Mech*, 2021. **52**(2): 215-32.
8. Al Shaikhli HI., Kadhim KN. Development an equations for flow over weirs using MNLR And CFD simulation approaches. *Int J Civil Eng Tech*, 2018. **9**(3): 70-79.
9. Ghaderi A, Daneshfaraz R, Dasineh M, Di Francesco S. Energy dissipation and hydraulics of flow over trapezoidal–triangular labyrinth weirs. *Water*, 2020. **12**(7): 1992.
10. Abbaspuor B, Haghiabi AH., Maleki A, Poodeh HT. (). Experimental and numerical evaluation of discharge capacity of sharp-crested triangular plan form weirs. *Int J Eng Syst Model Sim*, 2017. **9**(2): 113-19.
11. Kumar S, Ahmad Z, Mansoor T. A new approach to improve the discharging capacity of sharp-crested triangular plan form weirs. *Flow Measurement and Instrumentation*, 2011. **22**(3): 175-80.
12. Haghiabi AH., Abbaspoor B, Maleki A, Torabi Pudeh H. Numerical Simulation of Flow Pattern on the Triangular Plan Form Weirs and Comparing to Linear weir Techniques Using Flow-3D. *Water Res Eng*, 2016. **9**(29): 125-37.
13. Seo IW., Do Kim Y, Park YS., Song CG. Spillway discharges by modification of weir shapes and overflow surroundings. *Env Earth Sci*, 2016. **75**: 1-13.
14. Bagheri, S., & Heidarpour, M. Characteristics of flow over rectangular sharp-crested

side weirs. *J of Irri Drain Eng*, 2012. **138**(6): 541-47.
15. Ghotbi S, Abdollahi A, Azhdari Moghadam M. Three-dimensional numerical modeling of score hole in rectangular side weir with finite volume method. *J Hyd Struct*, 2017. **3**(2): 22-31.
16. Akoz MS., Gumus V, Kirkgoz MS. Numerical simulation of flow over a semicylinder weir. *J Irri and Drain Eng*, 2014. **140**(6), 04014016.
17. Kaveh A, Shokohi F, Ahmadi B. Analysis and design of water distribution systems via colliding bodies optimization. *Int J Optim Civil Eng*, 2014. **4**(2): 165-85.
18. Kaveh A, Ahmadi B, Shokohi F, Bohlooli N. Simultaneous analysis, design and optimization of water distribution systems using supervised charged system search, *Int J Optim Civil Eng*, 2013. **3**(1): 3-55.