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Numerical investigation of flow behavior over arced trapezoidal piano key weirs

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ABSTRACT: Weir is one of the most common artificial hydraulic structures that are used to measure flow in canals, divert flow, store water, change the flow regime in canals, and control floods during rainfall. One of the most important advantages of piano key weirs compared to linear weirs is the improvement of flow transfer capacity by increasing the length of the crest and as a result, increasing the length of the water passage in a fixed width of the construction without increasing the upstream water load. The purpose of this research is to numerically model the flow and investigate the effect of simultaneous changes in the number of cycles and the angle of the weir on the flow coefficient by trying to keep the total length of the weir crest and other geometric parameters constant for all models. After the investigations, it was found that increasing the weir angle of the piano key at a fixed length for all models increases the discharge coefficient, while increasing the number of cycles at a fixed length for all models due to the reduction of the inlet key water tank area, increasing the contraction of the current streamlines and then intensifying the local submergence in the outlet key, the current permeability coefficient will decrease significantly. Among all the weirs modeled in this research, the ATPK135-2 is known as the best model and was able to increase the discharge coefficient by 47% compared to the linear state (without curvature).

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1- Introduction

The intensity of flow in weirs is directly proportional to the length of their crest. Unlike conventional linear weirs, non-linear weirs can increase the flow discharge capacity without increasing the width of the weir without increasing the upstream total head. Meanwhile, a new form of non-linear weirs is PKWs. PKW has a high discharge capacity and for this reason, it can be used as economic structures with high efficiency. Recently, various types of weirs have been developed in the same way and used in various dam construction projects. In general, PKW[1] can be divided into 4 types A, B, C, and D, and it should be noted that type A is also the subject of this research.

The hydraulic performance of free weirs for a fixed head has a direct relationship with the length of the weir and the discharge coefficient (C_d) of them is calculated using equation (1):

$$C_d = Q/(\frac{2}{3}L\sqrt{2g}H^{1.5}) \quad (1)$$

where L= total length of weir crest, H = flow head on the weir, and Q = weir discharge.

Andersen and Tullis investigated the equal height PKWs, labyrinth, and labyrinth with inclined keys with the same rectangular plan. His results showed that in the design of a spillway with restrictions on the width of the channel and the width of the spillway if a longer length can be created with the limitations of the construction space, even if the curves of the discharge coefficient (C_d) for that geometry are lower than the spillway, the increase in the flow rate in the constant head is quite remarkable. But in general, the curve of discharge coefficient in relation to ⍰⍰/⍰ (the ratio of the flow height from the weir to the energy level line to the crest of the weir) of the trapezoidal labyrinth weirs with larger angles is higher than PKWs[1].

Chartaghi, Nazari, and Shoushtari (2019) conducted a laboratory and numerical study of a series with arced- in plan. The comparison of the results obtained for arced trapezoidal piano key weirs (ATPKW[2]) and linear rectangular piano key weirs (LRPKW[3]) showed that, in lower H/P ratios (flow height on the weir to crest height) the LRPKWs showed better performance however increasing the H/P ratio gradually but

1 Piano key weir

2 Arced Trapezoidal Piano Key Weirs
3 Linear Rectangular Piano Key Weirs

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continuously improves the hydraulic performance of ATPKW models. Reducing the arc angle in the ATPKW models initially reduced the hydraulic performance of these models but later strengthened it significantly [2].

Munish Kumar et al. (2020) in their laboratory research compared the increased discharge efficiency with TPKW[1] with RPKW[2] and concluded that both have the same L/W ratio. The benefit from the synergistic discharge of TPKWs compared to RPKWs was between 2 and 15%. The effect of weir height in increasing the discharge capacity of both types of piano key weirs was positively observed due to the limitation of early immersion of outlet keys with low weirs. In the current research, the effect of weir height observed with TPKWs was slightly stronger than RPKWs in influencing hydraulic performance [3].

In the present research, an attempt has been made to investigate the combined effects of changing the overflow angle and the number of cycles, considering the reduction of the multifaceted effects of other geometric parameters with the help of numerical modeling. For this purpose, in the first step, numerical modeling was done by using the laboratory results of one of Anderson's models [1], and validation of the numerical model was performed by examining two turbulence models RNG[3] and LES[4]. Then in the second step after validation of the numerical model and selection of the best turbulence model, the influence of changes in the geometrical parameters of the weir angle and the number of cycles was also investigated and in the last step, by analyzing the obtained results, the effect of the combined changes of the weir angle and the number of cycles on the weirs coefficient was determined and then the optimal weir with better efficiency was introduced

2- Materials and methods

2- 1- Validation of the numerical model for simulating the flow on the PKW

In this part, the analysis of the results of setting the numerical model and its comparison with the results of the corresponding laboratory model conducted by Anderson have been discussed. In the present study, a laboratory model, which will be mentioned later, is considered as the adjusted basic model. For this purpose, numerical model validation using laboratory data is provided.

2- 2- Boundary conditions

In order to achieve acceptable results, appropriate boundary conditions should be selected, corresponding to the actual laboratory conditions. The numerical model has three non-uniform grid blocks with the number of grids along (x, y, z). The optimal grid for each block is determined according to the sensitivity of that block's location and also with the help of the GCI[5] algorithm [4].

1 Trapezoidal Piano Key Weir
2 Rectangular piano key weir
3 Renormalization Group
4 Large Eddy Simulation
5 Grid Convergence Index

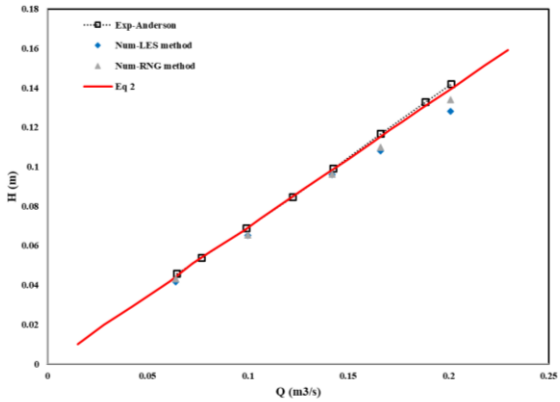

Fig. 1. Comparison of changes in water head relative to discharge in the weir.

2- 3- Choice of turbulence model

One of the most important steps in the numerical modeling of the flow is the selection of the appropriate turbulence model, and in most natural phenomena, the fluid flow is turbulent. Turbulent flow is a type of fluid flow, in which the fluid undergoes strong mixing processes. In this research, RNG and LES turbulence models have been used to model the flow for the same grid for both models.

3- Results and discussion

Figure 2 shows the streamlines in the lower and middle levels of ATPK45-2 and ATPK135-2 weirs. As can be seen, in the mentioned weirs after reaching the inlet key the lower flows are uniformly distributed on the side crests and the inlet key, of course, a better flow distribution can be seen for the ATPK135-2 weir. Regarding the flows approaching the side keys for the mentioned weirs, as can be seen, the flow passes through the entrance key with a proper distribution but some of the streamlines approaching the central key are drawn towards the side keys and change direction to the upper layers and then passes through the side crest of the weir side keys. In these areas, the flow velocity decreases and the flow recirculates. One of the reasons for this is the angular sides of the weir foundations and the distance created between the sloping surface and the place of flow transfer from the tank to the inlet key. The creation of the recirculation area in the inlet key reduces the effective width of the flow in the inlet key.

As can be seen in Figure 3, by increasing the angle of the weir or in other words by decreasing the radius of curvature with the overall length of the weir crest being constant, the amount of flow passing through the ATPKWs has increased and on the other hand with the increase in the number of cycles with the overall length of the weir crest being constant and the value of the flow passage coefficient has a downward trend which is the reason for the reduction of the area of the inlet water catchment. The above-mentioned points are directly

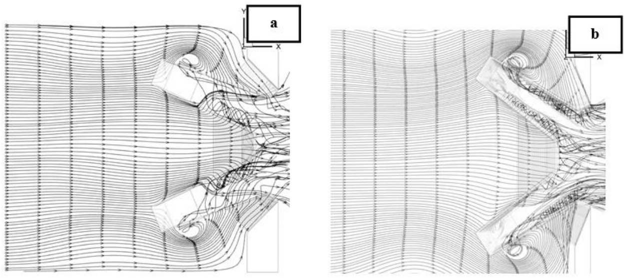

Fig. 2. Streamlines of the lower layer of the weir a) ATPK45-2 b) ATPK135-2.

related to the flow pattern passing through the weirs of the subject of the present research and regarding the investigation of their hydraulic performance. the general pattern as well as the streamlines are discussed on them.

4- Conclusions

•Among all the weirs modeled in this research, the ATPK135-2 is known as the best model and has been able to increase the discharge coefficient by 47% compared to the linear mode of the PK1.0 weir.

•In examining the effects of simultaneous changes in the weir angle and the number of cycles, one should pay attention to the economic efficiency of the design because in the present research it was found that increasing the total length of the weir, the number of cycles and the weir angle cannot necessarily lead to the achievement of a high discharge coefficient because in the sections it was mentioned before that the APK150-5 weir (reviewed by B.Noroozi) had a geometric advantage (the total length of the weir and the width of the building is larger) compared to the ATPK135-2 weir (the best model of this research) but it had a weaker hydraulic performance.

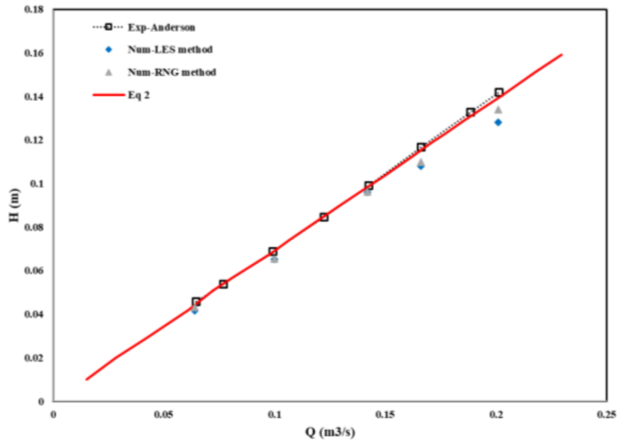

Fig. 3. Comparison of the discharge coefficient of ATP-KWs against the effect of increasing the cycle and weir angle for the same crest length of all weirs.

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