Numerical Analysis on the Effect of Slot Width on the Design of Vertical Slot Fishways

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Abstract. An accurately designed fishway plays an important role in dimensioning migration issues of fish and assists in allowing fish to meet their life cycle’s essential necessities. ANSYS FLUENT was used to study the effect of changing slot width on the velocity, turbulence kinetic energy, and head difference ($\Delta h$) in water level inside the fishway. The turbulence model was used to predict the local zone turbulence inside the fishway. Using a previously designed model suggested by Zhang in 2017, this study investigated the influence of the change of the slot width for five values, 0.2, 0.25,0.3,0.4, and 0.5 m. The velocity value obtained for 0.2 m slot width ($b_o$), which represented 10% from pool width (B), was 1.57 m/s. While, for a slot width of 0.5 m which represented 25% from pool width, the velocity value was 1.59 m/s with high turbulence regions inside the pools due to the increase in the velocity of the flow. The best flow velocity obtained was 1.23 m/s. This value was obtained when using a 0.3 m value for the slot width. The turbulence kinetic energy for this value of the slot width was 0.08 m$^2$/s$^2$. Therefore, the value of 0.3 m of the slot width was considered as the optimum value for the examined vertical slot fishway design. The optimum ratio of the slot width to the pool width ($b_o/B$) was 15%.

Keywords: Vertical slot fishway, slot width, velocity

1. Introduction
Fish migration is one of the main and crucial aspects of their life. It includes two primary cycles namely a downstream journey, which is performed by fish at the early stages, and an upstream journey, which is normally carried out by fully grown fish. However, since the beginning of the construction of dams and other artificial obstructions by humans along the rivers and around other water bodies, the migration of fish has been affected cruelly [1]. Man-made obstacles have made the fish migration to be delayed for weeks [2]. In fact, fish populations in rivers are decreasing due to the construction of artificial barriers, such as dams and barriers [3]. For instance, structures like dams can cut off the migration path of fish and, eventually, influences the growth and breeding of the fish [[4]]. Furthermore, fish migration can be slowed down or even blocked if no suitable solution was presented. Therefore, the invention of fishways was the needed solution to such a problem.

Fishways, or as also known as fish ladders or fish passes [5], are hydraulic structures that are typically erected over or around the barriers created on water bodies, such as dams. The main purpose of designing and constructing such structures is to create safe and appropriate transportation means for the fish during their upstream migration. The design of fishways involves adaptive management and continued innovation [6]. However, the fishways are still restricted at the small section of the dam or weir giving them less importance [7].

The vertical slot fishway (VSF) is considered among the most common types of fishways. This type typically consists of a sloped rectangular channel separated into several small basins, commonly known as pools [8], by baffles. These baffles are installed along the channel length at evenly spaced
distances. The baffles have a vertical opening called slots that are designed to let the fish swim through passing upstream along the channel. The design of this type of fishway is aimed to create almost the same water velocities at the slots of the fishway in a way that makes it convenient for fish to burst their way through the vertical slots upstream to proceed with their journey. The effectiveness of a fishway design is governed by the watercourse, the targeted fish, and the fishway itself [9]. For instance, the understanding of the swimming ability for the targeted fish controls the water velocities’ specifications in the designed fishway [10]. While the design of the fishway itself plays a fundamental role in its effectiveness. Undeniably, the optimization of vertical slot fishway design plays an essential role in ensuring a suitable passage for fish through artificial obstacles. Therefore, many studies were done to achieve this goal.

Rajaratnam et al. conducted an experimental study on the vertical slot fishways hydraulics [11]. In their experimental study, seven designs, including some ordinary designs, were examined. The results presented by this study were used to developing a theoretical indication of the uniform and non-uniform flow states. In 1992, Rajaratnam et al. carried out another experimental investigation on vertical slot fishways [12]. The study dealt with the design of 18 vertical slot fishways. Additionally, the results for 11 more designs were added in this investigation. The study claims that the width and the length of respectively eight times the pool width, 8b0, and 10b0 that are commonly used for the pools are acceptable for designs.

For the shallow state system, a mathematical formulation of the optimal design problem for a vertical slot fishway design was studied by Alvarez-V’azquez et al. [13] using a mathematical formulation. Ten standard pools with a slope of 5% were the case of this study. Numerical results obtained by this study were used to determine the optimum geometry of the tested pools.

Tarrade et al. carried out a study to illustrate and characterize the turbulent flow for several configurations of vertical slot fishways [14]. The study matrix included three main variables, discharge (Q), pool width (B), and pool slope on inclination (I). It was shown from the results of this experimental study that, depending on the length to width (L/W) ratio of the pool, there are two topological models that the flow pattern always follows.

Chorda et al. have conducted a simulation on the mean velocity and turbulence level fields for the two-dimensional flow patterns that take place in vertical slot fishways [15]. The obtained numerical results of this study were compared to velocity measurements that were examined at the Laboratoire d’Etudes Aerodynamiques of University of Poitiers, France. The study had given great consideration to the calculated turbulent kinetic energy and the rate at which energy is been dissipated.

Wang et al. conducted an experimental study of flow characteristics on a scale model of vertical slot fishways [16]. Various novel results were obtained from this study, specifically the effect of shape factor (B/b), the ratio of the pool width (B) to the slot width (b), and slope on flow topology. However, only on the value of the shape ratio (L/b), the ratio of the pool length (L) to the slot width (b), was considered in this investigation. Many observations were perceived by this study such as the effect of slope on turbulent kinetic energy and low-velocity zone volume.

Marques et al. carried out a study in 2011 in which a mathematical model for the fish passage decision structure is offered [17]. The results of the undertaken case study of their investigation reported a 52% reduction in the total cost, compared to a base situation similar to real operations. However, it was declared by the author that the used model is still under development and more future improvements are required.

Li et al. introduced a numerical study using ANSYS FLUENT to investigate the flow patterns inside the fishway channel [18]. Different cases were examined. For instance, when the ratio P/B (the length ratio between the short baffle and the width of the pool) = 0.1 was used, it was found that the was near the wall with no curve formed between one slot and the other. This type of flow pattern was referred to as Flow Pattern One (FP1). On the other hand, when the ratio P/B = 0.25 was used, the main flow was in the center of the pool. The flow in this case entered the center of the pool as a curved jet. Then, it spread to the center of the pool before reaching the next slot of the fishway. This type of flow was referred to as Flow Pattern Two (FB2). The third case studied was to use P/B = 0.5. The flow jet in
this case showed a curved pattern along the opposite side of the wall. The flow pattern in this case was referred to as Flow Pattern Three (FB3).

Sanagiotto et al. studied simulation of vertical slot fishway by using ANSYS CFX with k-ε turbulence model. This study aims to validate the numerical simulation with the experimental results [19]. Results that were analyzed are velocity, pressure, and turbulence. The results showed good agreement of validation of the numerical simulation and experimental results.

In 2020, Zhou et al. performed an investigation on the fishway design using a three-dimensional mathematical model for a natural fishway [20]. Three aspects were the target of this investigation, namely the flow velocity, the flow pattern of the tank room, and the turbulent kinetic energy. Regardless of the number of observations obtained by this investigation, more investigating, especially on flow velocity, energy dissipation, and even lower pool length to slot width ratios, are still required.

One of the main aspects that are to be investigated to optimize the vertical slot fishway design is the slot width. It controls many design parameters such as the discharge, velocity, pattern, turbulence, and the head difference of the flow.

2. The aim of this study
This study aims to optimize vertical fishway design. The improvement that would be obtained by optimizing the fishway design will assist in easing the migration process of fish through water barriers and dams constructed on water bodies. This is to be achieved through:

- Performing a numerical study on the vertical slot fishway model and analyze the results using ANSYS FLUENT. Then, verify the results obtained from the created model to check the results and compare them with the field results from previous studies.
- Investigating the influence of varying the slot width on the flow velocity and turbulence.

3. Methodology
The methodology followed to achieve the set objectives for the present work can be explained in two main steps. The first step is to create a full-scale model of a vertical slot fishway using Computational Fluid Dynamics (CFD) simulations in the ANSYS environment. The geometry and basic specification of the created model were taken from an experimental model from a study done by Zhang et al. [21]. Then, a verification check is performed on the created model and the results were compared with the experimental ones from Zhang’s experimental model to verify the reliability of the numerical model.

The second step is to change the slot width of the numerical model for five different values to study the influence of varying the slot width on both the velocity of the flow and the kinetic turbulence energy. Figure 1 shows the geometry of one pool of the fishway.

![Figure 1. The geometry of one pool of the fishway.](image)

3.1. Theoretical Basis
The governing equations used in the presented work are the Reynolds averaged Navier-Stokes (RANS) (Momentum equation) and the Continuity Equation. Both of these equations were involved in the simulation process of the model of fishway design used in this study [22].

Momentum Equation:

\[
\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla \rho g + \frac{\partial}{\partial x_i} \left[ \left( \mu + \mu_t \right) \frac{\partial u_i}{\partial x_i} \right] \quad (1)
\]
Where, \( \rho \): The Density of the fluid. \( u \): The velocity time series, which can be divided into an average component and a time-varying component. \( \mu \): The dynamic viscosity of the fluid. 
\( \mu_t \): The turbulent viscosity of the fluid.
Continuity equation [23]:
\[
\frac{\partial}{\partial x_i} (\rho u_i) = 0
\]
(2)
Where, \( (u_i) \) is the velocity in the x-direction.

3.2. Slots Width Layout
The width of the vertical slot was the targeted parameter that is to be studied to optimize the vertical slot fishway design. The same dimensions for the verification model were used for the newly tested model. However, the vertical slot width was changed and its influence on the flow velocity, the maximum velocity, and turbulence inside the pools was examined. The main aim of studying the slot width varying is to assist in selecting the optimum slot width that can be used for the vertical slot fishway design. This can help reduce the number of pools needed for a specific fishway. The fewer the number of pools the less the cost of the construction of the fishway. A total of five vertical slot widths were examined. These width values are 0.2, 0.25, 0.3, 0.4, and 0.5 m. The geometry for the fishway pool with these four values of slot width is shown in figures 2.a, 2.b, 2.c, 2.d, and 2.e respectively.

![Figure 2. Fishway pool with slot width of: (a) 0.2 m. (b) 0.25 m. (c) 0.3 m. (d) 0.4 m. (e) 0.5 m.](image)
4. Meshing Process
For the case study, the type of mesh used for the model is the tetrahedral mesh. Within its structure, this type consists of numerous triangular elements. It perfectly fills all the spaces in the domain with a constant element size approximately as displayed for demonstration purposes in figure 3. It also provides better distribution for the elements that are close to the slot and other complicated regions in the model. Details of the tetrahedral mesh for one pool are shown in table 1.

![Figure 3. Tetrahedral mesh for one pool of the fishway.](image)

| Table 1. Details of mesh for the model using a tetrahedral mesh. |
|---------------------------------------------------------------|
| Element size | 55 mm (max size = 80 mm) |
| Number of elements | 3310374 |
| Number of nodes | 632359 |
| Notes | Medium smoothing |

5. Results and discussions
5.1. Verification of the model
A comparison was performed between the velocity values of the experimental model and the numerical model at distances (X values) that are stepped at 0.3 meters along the model. These values are also plotted and compared as shown in figure 4. It can be seen that the numerical model can be considered as a great match for the experimental model.

The verification of the results was conducted using the root-mean-square error (RMSE). This method is, basically, a measure that uses the differences between two sets of different values; the predicted values obtained by the numerical (virtual) model and the values obtained from the experimental (actual) model. This process is done to verify for the numerical model and its done using equation 3 shown below [[24]]:

\[
RMSE = \sqrt{\frac{\sum_{i=1}^{n}(v_{\text{experimental}} - v_{\text{numerica}})^2}{n}}
\]  

(3)

An ideal value for RMSE is 0. For this presented study, the RMSE obtained for the above-mentioned comparison was a small value (0.159). This indicates that the numerical model can be considered as an acceptable model for the experimental one.
It can be observed from figure 4 that there is an obvious fluctuation in the velocity values recorded along the fishway channel. The main reason for this is that the flow between every two slots will pass through a narrow cross-section at the slot which leads to an increase in the velocity. Then, the cross-section of the flow increases at the center of the pool which causes the velocity to be reduced gradually. This cycle of increasing and decreasing is repeated for each pool of the fishway. Another observation is the difference in values between the numerical and experimental models. This is due to the fact that the laboratory conditions of the experimental model can’t be ideal and give results as perfect as the results obtained from the numerical model. Another method of statistical verification was using correlation coefficient (r) and calculating the relative error [24]. The correlation coefficient was calculated and the value was 0.98. Figure 5 shows the statistical method of verification for the examined model between the simulated (numerical) values and the observed (experimental) values of velocity.

5.2. Results of slot width variation
The results of the velocity and the kinetic turbulence energy for the five cases of the slot width were determined at a water depth of 1.5 meters, which represents half the clear depth for the fishway channel, at a horizontal plane (xz). The results, for each case, are presented below at the same depth and plane in contour figures for both the velocity and the kinetic turbulence energy to study the influence of varying the slot width on the flow inside the fishway.

5.2.1. Results for slot width 0.2 m (Slot width(bo)/Pool width(B) = 0.1). The velocity contour for the case of using a 0.2 m slot width is shown in figure 6 and for the kinetic turbulence, energy is shown in figure 7. It can be observed from these results that the maximum velocity was increased due to the increase of the flow at the slot due to the narrow slot opening. The maximum velocity value was 1.57
m/s. This value is approximately the same value for the burst speed of fish. Therefore, this slot is considered exhausting for fish. Besides, the maximum value of the turbulence kinetic energy was 0.1 m²/s² and resting areas for fish can be observed. Two vortexes were formed in this type of flow. The large one was formed between every two long baffles while the small one was formed between the short baffles.

5.2.2. Results for slot width 0.25 m (Slot width(bo)/Pool width(B) = 0.125). The results for the velocity and the turbulence kinetic energy for this case are shown in figures 8 and 9 respectively. The flow pattern of this case was similar to the one observed in the case of using a 0.2 m slot width. However, the maximum velocity value was decreased from 1.57 m/s to 1.43 m/s due to the increase of the slot width from 0.2 m to 0.25 m. On the other hand, the turbulence was increased and mostly concentrated with maximum values around and at the slots of 0.09 m²/s² due to the jet velocity. Also, it was noticed that the turbulence at the surface is four times the one at the bottom of the fishway channel.
5.2.3. Results for slot width 0.3 m (Slot width(bo)/Pool width(B) = 0.15). For the case where the slot width was 0.3 m, the flow inside the fishway channel was in form of a wave that moves through the slots along the channel with relatively high velocities. The velocities start to decrease when the flow reaches the midpoint of each pool and then increases as the flow arrives at the slots. The decrease of the velocity can be simply observed by comparing the maximum velocity calculated in this case (1.23 m/s) with the previous cases (1.57 and 1.47 m/s). Also, it can be observed that the turbulence for this case, which is 0.08 m²/s², was less than the previous cases and was well distributed inside the pools. Additionally, the turbulence was concentrated at slots and dissipated gradually inside the pools. Possible rest areas for fish can be seen inside the pools near the fishway walls across the slots. figures 10 and 11 show the velocity and turbulence kinetic energy for this case respectively.

5.2.4. Results for slot width 0.4 m (Slot width(bo)/Pool width(B) = 0.2). In this case, where the slot width was 0.4 m, the flow pattern was similar to the one in the case of 0.3 m slot width. However, the flow was more disturbed. Also, an increase in the velocity was also observed especially at the slots where the maximum velocity value reaches 1.41 m/s. This increase in the velocity causes high turbulence inside the pools which can make it difficult for fish to swim through. The velocity and turbulence kinetic energy simulation results are shown in figures 12 and 13 respectively.
5.2.5. Results for slot width 0.5 m (Slot width (bo)/Pool width (B) = 0.25). The velocity contour for the case of using a 0.5 m slot width is shown in figure 14 and for the kinetic turbulence, energy is shown in figure 15. The flow in this case moving directly through slots from one to another due to the increase in slot width. Increasing the slot width caused more water volumes to be transferred through the slots and less to collide with the baffles. As a result, the turbulence values were higher when compared to the previous cases due to the high velocity of water at the slots and around them. This could cause fish to consume most of their energy to pass through the slots for each pool.

For all the investigated cases of slot width design, the slope of the fishway channel used in this simulation was 2.5% with a discharge of 0.75 m³/s at the entrance. The results of the maximum velocity values for each case of varying the slot width in each pool are shown in table 2. These results are also plotted as shown in figure 16. It can be observed from these results that among the five cases examined for the slot width of the fishway design, the model with a slot width of 0.3 m resulted in the lower values of maximum velocities. Any increase or decrease in the slot width would result in a critical flow with high values of velocity and high turbulence inside the pools. Consequently, the maximum turbulence shall be concentrated at the slots which causes high disturbance in the flow distribution inside the fishway channel. Therefore, the optimum slot width for this design is 0.3 m.

Table 2. Maximum velocity for each case of varying the slot width in each pool

| Pool Number | bo = 0.2 m | bo = 0.25 m | bo = 0.3 m | bo = 0.4 m | bo = 0.5 m |
|-------------|------------|-------------|------------|------------|------------|
| Maximum Velocity (m/s) | | | | | |
This confirms what was presented by Rajratnam et al. that the dimensions of the pools of vertical slot fishways, length, and width, are designed concerning the width of the slot [12]. The length of the pool should be about ten times the width of the slot while the width of the pool should be about eight times the width of the slot. These dimensions control the values of velocity and the flow pattern. For instance, in a specific vertical slot fishway design, if the slot width selected to be 0.5 m, the pool dimensions would be 5 m in length and 4 m in width. Such design causes the fish with relatively small sizes to spend more time inside each pool to pass to the next one. This could make the fish lose their energy before reaching their destination. Therefore, the slot width is a crucial feature that must be determined following the targeted fish's dimensions.

As for the energy dissipation, it was noticed from the results that when the flow enters the pools through the slots a jet flow forms, and the energy is dissipated due to the collision of the flow with the baffles of each pool. This leads to some of the moving water volumes to form whirls while the rest of the water volumes are transferred to the next slot. As a result, the values of the head difference of water surface elevation were different. These values are shown in table 3.

**Table 3.** Values of the head difference of water surface elevation in the pools

| Pool Number | b_o = 0.2 m | b_o = 0.25 m | b_o = 0.3 m | b_o = 0.4 m | b_o = 0.5 m |
|-------------|-------------|-------------|-------------|-------------|-------------|
| 1           | 0.2         | 0.16        | 0.15        | 0.14        | 0.15        |
6. Conclusions
The verification of a previously designed model by Zhang was performed and the results of verification were satisfyingly matching. The following conclusions were drawn from the results:
1. ANSYS FLUENT was an effective tool to simulate the flow inside the pools of the fishway.
2. The results showed a great match with the experimental results from Zhang model. The error ratio was less than 5%.
3. The results of the change of the slot width highly affect the important parameters of the fishway design. Any increase or decrease of the slot width as a ratio of the pool width (b_o/B) affects the velocity of the flow. When the slot width of 0.2 m which slot represented 10% of pool width, the flow velocity was about 1.57 m/s while when the slot width was 0.5 m which represented 25% of pool width the flow velocity was 1.59 m/s. The best value for the velocity of the flow, which is 1.23 m/s, was obtained when the slot width was 0.3 m (i.e. b_o/B = 0.15).

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