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Investigating pressure changes at the bottom of the stilling basin after the stepped spillway using a numerical model

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Abstract

Stepped spillways are hydraulic components of dams used to dissipate energy downstream of the dams. Numerous studies have been conducted to understand the hydraulics of flow on stepped spillways, primarily in laboratory settings. The flow passing over stepped spillways can be categorized into two types of flow regimes: Nappe Flow and non-Nappe Flow. In this research, the FLOW-3D software was utilized to model the Cardan configuration of the downstream basin of the stepped overflow based on laboratory data. In this investigation, we compared the distribution profile of maximum, minimum, and average pressures in three areas: the center, right, and left, with the laboratory data in the numerical model using graphical methods and statistical indicators. The results revealed that 08% of the pressures obtained from the model closely matched the laboratory data with an error rate of only 5.1%.

Keywords: Pressure fluctuations; Stilling basin; Flow 3D Model; Stepped spillway

1. Introduction

The flow of currents resulting from floods can present various hazards downstream of dams (1). One effective solution for mitigating flood energy is the implementation of structures like stilling basins. Stilling basins, which are designed to dissipate the excess energy from dam overflow, experience more pronounced pressure fluctuations (2,3). In such structures, the average pressure is an inadequate representation of the pressure dynamics because momentary pressure fluctuations can pose significant risks to the integrity of the structure (4–6).

When a hydraulic jump occurs in stilling basins, various forces act on the bottom slab of the stilling basin, including hydrostatic and hydrodynamic forces (7–9). These forces consist of the weight of the water on the slab, the lifting force on the subslab, and hydrodynamic forces caused by pressure fluctuations during the hydraulic jump. Due to the two-phase nature of hydraulic jumps, flow fluctuations, and high turbulence, it is not possible to obtain pressure values using conventional methods. These pressures are non-linear and vary depending on the magnitude of fluctuations and turbulence at each point (10). Therefore, it is necessary to investigate and interpret the fluctuating characteristics of pressure. There have been limited studies, based on analytical and numerical relationships, that review changes in static and dynamic pressure in the basin after stepped spillways are implemented, and some relationships are presented in this context. Utilizing FLOW3D models, complex geometric conditions can be accurately simulated. By establishing different flow scenarios and measuring and recording dynamic and momentary pressure distribution, inferences can be made regarding the pressure distribution in the basin after dam overflow events (11,12).

1.1. The effect of pressure on the bottom of the stilling basin

The phenomenon of pressure fluctuations in hydraulic structures has been the focus of a large number of engineers and scientists in recent decades. This focus on hydraulics coincides with the rapid advancement of applied hydraulic science and the construction of thousands of hydraulic structures, both large and small, worldwide. There is a growing need to

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understand and measure the pressure field exerted by water on the components of these structures. This need has pushed the capabilities of many instruments to their limits (13,14).

Magionesi et al. showed in hydropower structures such as stilling basins, which are responsible for dissipating excess energy at the dam outlet through the mixing of water and air, pressure fluctuations have a more pronounced effect, especially during the hydraulic jump process (15). Fluctuations in pressure along the floor and walls of the stilling basin can lead to damage, as the turbulent flow interacts with the basin, forming vortices. This high-speed flow condition near the floor and walls can also trigger cavitation due to pressure fluctuations, potentially causing significant damage to the structure. The generation of dynamic pressures on the basin structure is a result of the disturbance and fluctuations in the high-speed flow, which propagate from the upper side of the overflow to the downstream side of the stilling basin (16,17).

The pressure field around the attachments of the stilling basin consists of both average pressure and pressure fluctuations. Stilling basins, along with their appendages, such as the blocks at the base of rapids and the middle blocks, are located in areas where intense turbulence is generated during the formation of hydraulic jumps. Their primary purpose is to dissipate the excess energy from the outflow of hydraulic structures. As a result, they are subjected to severe and unpredictable pressure fluctuations that can lead to surface wear or complete destruction.

1.2. Pressure in hydraulic structures

In hydraulic structures, the forces acting on the structure from the fluid side are two forms of hydrostatic forces and forces There is hydrodynamics. Hydrostatic forces are caused by the weight of the fluid and are usually easy to calculate. Forces Or hydrodynamic pressures enter the structure when the fluid has a velocity factor and the flow lines are at an angle with the body of the structure have Although in a constant flow, the characteristics of the fluid at a specific point are constant and independent of time the fact is that due to the random formation and removal of eddies in a completely turbulent flow, the characteristics of the fluid, including speed and the pressure at a point does not have a specific and constant value and changes constantly (18). Fiorot and colleagues showed one of the important issues in engineering Hydraulics is the study and evaluation of hydrodynamic pressures and momentary changes of these pressures on structures. About Static pressures are not a problem because the structures are designed in such a way that the warp resists against a constant stress but in the case of hydrodynamic fluctuations, the force applied to the structure is not a constant force but at every moment It has a variable value (19).

Many researchers, such as Kai et al. and Hua et al., have considered the study of pressure fluctuations in hydraulic structures characterized by non-hydrostatic pressure distributions, as well as in locations where vortices are present and where the flow impacts bends, blocks, and aqueducts, to be of significant importance (20,21). Consequently, there are certain areas where it is recommended, according to designers' opinions, to assess pressure fluctuations. These areas include stilling basins at the end of rapids, absorption basins downstream of dams, arched concrete structures, bends between rapids, throw cups, stepped spillways, and areas downstream of valves installed in drainage tunnels, particularly those situated beneath dams. Conducting studies to examine and monitor dynamic pressures is advised in these specific locations. Kamyab Moghaddam et al. conducted a series of experiments to analyze the static pressure in stepped chutes with inclined and horizontal steps. Their results demonstrated that the static pressure in the middle of the step is higher than the static pressure on the right and left sides of the steps at all discharge rates. Inspired by their work, a similar approach and location for the piezometers has been adopted in this research to study and examine pressure fluctuations in the stilling basin, the results compared to their work to confirm the accuracy of the model (22). Zienkiewicz and Moriguchi et al. showed different parts of the basin experience varying levels of pressure, with the maximum values typically occurring in the initial parts of the basin due to the direct impact of the water jet on the first blocks. To assess the dynamic pressure on these blocks, it is crucial to understand the conditions, functions, and governing equations of the flow across different sections of the stilling basin, as well as the parameters influencing flow and fluctuations, and the pressures they impose (23,24).

2. Research Methodology

The FLOW3D software is a versatile program that is compatible with complex flow conditions in both two-dimensional and three-dimensional modeling. This software is specialized in Computational Fluid Dynamics (CFD) and is provided by Flow Science. It utilizes the finite volume method for solving equations. FLOW3D is well-suited for handling complex problems. It offers five turbulence models, including the RNG (renormalized group) model, which has been tested through trial and error. The software also provides two numerical techniques for geometric simulations.

1-Volume of fluid method (VOF): In this method, it is used to show the behavior of the fluid in the free surface.

2- Obstacle volume subtraction method (FAVOR): This method is employed for geometric simulations involving solid surfaces and volumes, such as borders.

In this article, the tested model is the hydraulic model of the stilling basin at Barvan Dam. Prior to modeling, it is essential to investigate the software's accuracy in modeling and calculating flow parameters. To achieve this, the appropriate mesh dimensions were selected using a method that involves dimension selection and ensuring the independence of the results from the network size.

Pressure and velocity distribution functions for five flow rates 0.31,0.28,0.19,0.15,0.13 and with the number of meshes in three directions X, Y, Z equal to 0.2,0.5 and 1 meter that in total 2775000 the calculation cell is calculated.

3. Pressure distribution on the bottom of the stilling basin

Pressure distribution in 9 piezometers and for five flow rates 0.13, 0.15, 0.19, 0.28, 0.31 cubic meter per second was calculated. in the table 1 the place of pressure collection is presented for three sections of center, left and right of stilling basin.

Table 1 The location of pressures on the bottom of the stilling basin in the software

		X	Y	Z
	Right	8.96	0.16	1.12
piezometer9	Center	8.96	0.85	1.12
	Left	8.96	1.28	1.12
	Right	9.56	0.16	1.11
piezometer10	Center	9.56	0.85	1.11
	Left	9.56	1.28	1.11
	Right	9.9	0.16	1.1
piezometer11	Center	9.9	0.85	1.1
	Left	9.9	1.28	1.1

4. Comparison of the results obtained from the numerical model and the laboratory model

The average values of the pressures taken from the laboratory model in the piezometers along with its similar value in the data model are presented in tables (2) to (6).

Table 2 The pressure recorded in the laboratory model during the 0.13 discharge

Q		**0.13**					
Data		**model**			**lab**		
Velocity		**V=1.9**			**V=1.68**		
Location		**center**	**Right**	**Left**	**center**	**Right**	**Left**
piezometer9	max	3.39	3.12	3.22	3.6	3.66	3.57
	min	0.41	2.22	1.13	2.43	2.57	2.32
	Average	2.35	2.79	2.76	2.88	2.99	2.92
piezometer10	max	3.59	3.5	3.72	3.79	3.77	3.52
	min	1.16	2.54	2.1	3.04	3.02	2.86
	Average	2.73	3.11	3.12	3.44	3.37	3.19

piezometer11	max	3.73	3.57	3.53	3.83	3.89	3.73
	min	0.96	2.57	1.89	3.32	3.32	3.1
	Average	2.84	3.16	3.14	3.59	3.59	3.39

Table 3 The pressure recorded in the laboratory model during the 0.15 discharge

Q		**0.15**					
Data		**model**			**lab**		
Velocity		V=1.7			V=1.48		
Location		center	Right	Left	center	Right	Left
piezometer9	max	3.23	3.53	3.15	4.47	4.31	4.57
	min	1.01	0.88	1.31	2.08	2.2	1.46
	Average	2.88	2.83	2.68	3.14	3.18	3.13
piezometer10	max	3.74	3.75	3.46	4.18	4.16	3.79
	min	2.25	0.9	1.59	3.16	3.25	3.11
	Average	3.3	3.18	3.02	3.74	3.67	3.49
piezometer11	max	4.05	3.73	3.61	4.11	4.2	3.97
	min	2.18	1.93	1.76	3.74	3.34	3.56
	Average	3.38	3.26	3.04	3.93	3.95	3.75

Table 4 The pressure recorded in the laboratory model during the 0.19 discharge

Q		**0.19**					
Data		**model**			**lab**		
Velocity		**V=2.1**			**V=1.88**		
Location		**center**	**Right**	**Left**	**center**	**Right**	**Left**
piezometer9	max	3.97	4.13	6.04	5.7	6.29	6.93
	min	0.84	2.82	1.46	1.92	1.9	1.63
	Average	3.35	3.63	3.33	3.56	3.8	3.94
piezometer10	max	4.92	4.3	4.44	5.05	4.73	4.55
	min	2.04	3.33	2.38	3.62	4.34	4.05
	Average	3.96	4.09	3.76	4.48	4.53	4.34
piezometer11	max	5.14	4.43	4.81	4.8	4.9	4.8
	min	2.46	3.38	2.43	4.45	4.48	4.32
	Average	4.14	4.16	3.9	4.65	4.68	4.49

Table 5 The pressure recorded in the laboratory model during the 0.28 discharge

Q		**0.28**					
Data		**model**			**lab**		
Velocity		**V=2.8**			**V=2.58**		
Location		center	Right	Left	center	Right	Left
piezometer9	max	4.91	5.16	4.78	8.22	8.55	9.02
	min	0.78	1.42	0.6	1.11	1.03	1.81
	Average	4.14	4.24	3.8	3.56	3.02	3.25
piezometer10	max	5.35	5.43	5.19	6.31	6.52	5.83
	min	0.72	1.27	3.22	2.26	2.1	2.31
	Average	4.58	4.87	4.72	4.19	4.2	4.09
piezometer11	max	5.59	5.47	5.35	7.97	7.4	6.73
	min	4.26	3.63	2.74	4.74	4.96	4.82
	Average	5.28	5.11	4.84	5.98	5.56	5.42

Table 6 The pressure recorded in the laboratory model during the 0.31 discharge

Q		**0.31**					
Data		model			lab		
Velocity		V=3.04			V=2.82		
Location		center	Right	Left	center	Right	Left
piezometer9	max	5.69	5.94	4.69	6.11	7.03	8.06
	min	1.31	1.52	1.28	0.94	1.64	2.51
	Average	3.4	3.54	3.33	3.23	2.1	2.38
piezometer10	max	5.68	5.9	5.38	6.93	6.81	7.5
	min	1	0.78	1.83	1.76	6.08	1.06
	Average	4.18	4.33	4.27	3.89	0.9	3.78
piezometer11	max	6.48	5.5	5.38	8.46	3.79	7.51
	min	3.08	4.2	3.08	4.76	7.27	4.85
	Average	4.95	4.88	4.61	6.17	4.96	5.62

4.1. Validation of the model

Modeling is a type of prediction, and this prediction will be useful when the accuracy of the model is confirmed. Accuracy of the model can be examined from two aspects.

1-The structure of the model: that is, the model is considered in terms of physical parameters, meshing and numerical model. consider the best structure for it. The structure of the stepped spillways model in the previous chapter with trial and error and considering different modes of meshing were optimized.

2-Accuracy of observations used in model fitting: For this purpose, the outputs of the model should be compared to a series of observations that here is the data obtained from the laboratory model, compared.

Validation of the model is possible in different ways, which in this research are two methods of graphical comparison and indices statistics have been used to validate the model.

4.2. Graphical comparison of data

For this type of comparison, graphical comparison of simulated and observed time series can be done sorted series of simulated and observed data, scatter plot of simulated data vs. data used observations and residual diagrams.

The scatter plot of simulated data against observational data is the selected method for graphical comparison in this research. This comparison was conducted for the maximum, minimum, and average data, and it was also performed for the entire dataset. The results are presented in diagrams (1) through (4).

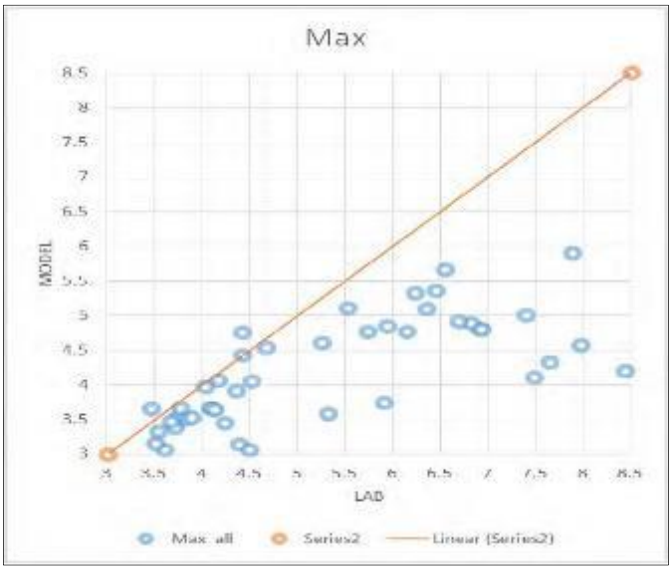

Figure 1 Distribution of maximum pressures

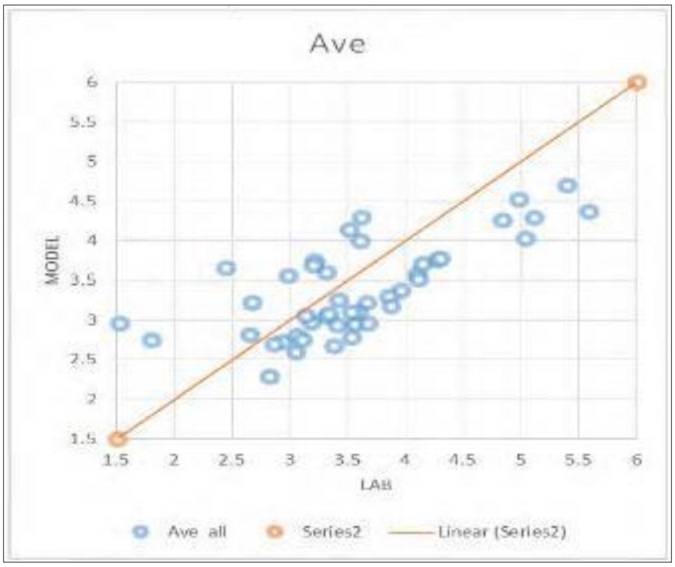

Figure 2 Distribution of average pressures

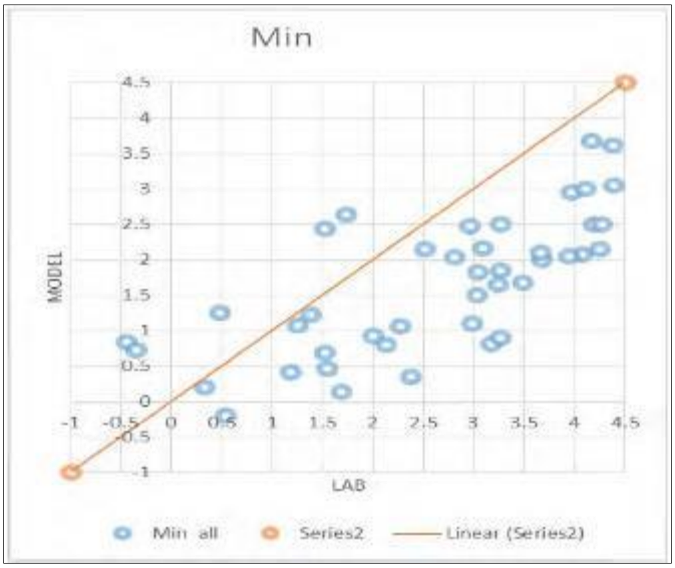

Figure 3 Distribution of minimum pressures

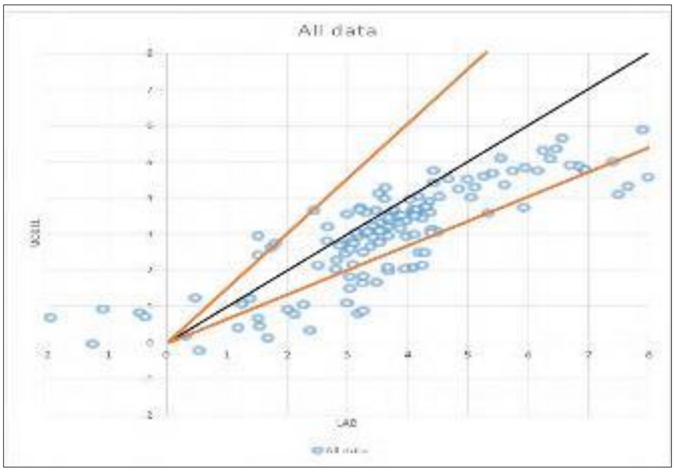

Figure 4 Distribution of total pressures

4.2.1. Analysis of comparative data charts

As seen in the distribution charts, in the maximum data, considering 15% error, 72% the pressures taken from the model are consistent with the laboratory pressures. In the minimum diagram, this matching percentage is equal to 60 and also in average pressures, the acceptable number is 92%.

In the comparison of the goodness of fit for all the data as seen in the graph number four, the matching percentage is equal to 80%.

4.2.2. Comparison of statistical errors (quantitative performance measures)

Statistical errors allow when a large amount of data is available, an analysis of how the data is distributed and goodness of fit between observation data and model data.

In this research, four indices RMSE, ME, MAE, NSE were used to compare the pressures measured in the laboratory and the pressures obtained in the FLOW3D numerical model. The equations used for each of the statistical indicators are as follows:

$$RMSE = \sqrt{\frac{1}{n}\sum(\mathrm{P}_{Lab} - \mathrm{P}_{m})^2}$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|\mathrm{P}_{Lab} - \mathrm{P}_{m}|$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}(\mathrm{P}_{Lab} - \mathrm{P}_{m})$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}(\mathrm{P}_{Lab} - \mathrm{P}_{m})^2}{\sum_{i=1}^{n}(\mathrm{P}_{Lab} - \overline{\mathrm{P}_{Lan}})^2}$$

Pm is the pressure value obtained from the model and where Plab is the pressure value measured in the laboratory, ~Plab the average value of laboratory.

Table number seven presents the value of these errors for the maximum, minimum, average and total pressures, as can be seen in the analysis of statistical parameters, average pressures have a more acceptable error than other data.

It should be noted that the closer the value of NSE is to one, the more valid it will be, while the value of NST is more than 0.2 acceptable.

Table 7 Statistical errors for the results of the model

	RMSE	**ME**	**MAE**	**NSE**
Max	1.54	1.1	1.13	0.09
Min	1.44	0.82	1.3	0.32
Ave	0.67	0.24	0.6	0.54
Total	1.28	0.72	1.01	0.22

5. Conclusion

In this research, the results presented show a high correlation between the pressures measured in the model and the laboratory data. When considering the use of the FLOW3D model for modeling pressure fluctuations, it is important to note that this software exhibits weaknesses in capturing random phenomena, such as hydraulic jumps, which result in significant variations between maximum and minimum pressures. However, the average pressure values align well with the laboratory data.

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