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Numerical investigations of stilling basin efficiency downstream radial gates – A case study of New Assuit Barrage, Egypt

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Abstract: Radial gates are more common than vertical sluice gates for a number of reasons. They are simpler to use, cause less flow disturbance, require less lifting force, and deliver better discharge. Radial gates are commonly used in new barrages, such as the New Assuit Barrage. Prior researchers used physical investigations to study the efficiency of stilling basin downstream radial gates, but physical studies cost a lot of money and time, so numerical solutions should be investigated. The current study aimed to explore numerically the influence of stilling basin shape and baffle block arrangement on the stability of bed protection, near-bed velocity, energy dissipation, and hydraulic jump characteristics downstream of radial gates. Different 12 discharges were investigated, and their results were compared with previous physical results to verify the performance of the numerical results. The results obtained from the numerical model from all trials are almost identical to the physical model results. Five different alternative designs were carried out numerically to enhance the design of the New Assuit Barrage (NAB) spillway stilling basin. Results showed that alternatives 4 (changing the geometry of the basin by removing the end step and concrete slab) and 5 (as alternative 4 in addition to adding rounded baffle blocks presented in two rows arranged in a staggered way) gave good velocity distribution with low turbulence, low values of near-bed velocities, and stability of bed protection. Also, it is more economical because of the lower cost of concrete and excavation.

Keywords: Flow-3D, New Assuit Barrage, riprap stability, stilling basin, verification

INTRODUCTION

Alternative barrage designs have been recommended, involving broad-span vents, bottom-dropped aprons, and numerous contracted flow fields to minimise the scour downstream of the aprons. Ministry of Water Resources and Irrigation (MWRI) replaced the current barrages with new designs depending on radial gates, requiring a hydraulic model study to determine the feasibility of building the new barrages such as the New Assuit Barrage (NAB). The New Assuit Barrage now takes the place of the old one. The NAB will have three major components: four sets of lightbulb turbines at a hydroelectric power plant, eight 17-metre-wide radial gates on the spillway, as well as a 160-metre-long, 17-metre-wide double chamber navigation lock. There will be a change in flow throughout construction via elements of the current barrage system in two or three stages. The design of the new barrage gave excessive scour downstream of the apron and low energy dissipation in the submerged hydraulic jump. The best solution to minimise the scour is to use an efficient stilling basin. Constructing controlling hydraulic structures including barrages, dams, and weirs, involves using stilling basins. They are energy dissipaters offered by downstream (D.S.) to protect and stabilise the riverbed, riprap is a substance that has been put to the D.S. of the stilling basin. It is described as a defensive covering made up of a haphazardly arranged mound of stones. The present study focused on numerical studying different alternative designs of the stilling basin of NAB under the submerged flow condition.

Many researchers showed that the stable bed protection stone's mean diameter can be determined using various equations. Isbash (1935) established a formula for stone movement, also some of the formulas connected the steady average protection material size to the average bed velocity (Mavis and Laushey, 1948; Peterka, 1958; Graf, 1971; Simons and Senturk, 1976; Saleh, 1995; Chiew, 2004; Tabarestani and Zarrati, 2019). The complete protection against scour is too expensive. So, the maximum scour depth and the upstream slope of the scour hole have to be predicted to minimise the risk of failure. Many academics have investigated the phenomenon of local scours. Several studies, which include those by Dey and Barbhuiya (2005), Zhang *et al.* (2009), Sheppard, Melville and Demir (2013), Helal (2014), Basiouny *et al.* (2018a), Elkiki (2018), Alhealy and Hayawi (2019), Abdelhaleem *et al.* (2023), Abdelhaleem and Ibrahim (2023).

Römisch (1995) developed the stability coefficient (B') to check the riprap's stability, keeping in mind that the riprap's stability downstream a stilling basin is affected by both turbulence intensity and flow velocity:

$$B' = \frac{V_b(1 + 3SDV)}{\sqrt{D_{50} \cdot g \cdot \Delta'}} \tag{1}$$

where: B' = stability coefficient (1.25–1.30), V_b = bottom velocity, D_{50} = mean size of riprap particles, Δ' = specific gravity of the submerged riprap, SDV = velocity variations' standard deviation, g = gravitational acceleration (9.81 m·s^{-2}).

For a number of reasons, radial gates are more common than vertical sluice gates. They are simpler to use, cause less flow disturbance, require less lifting force, and deliver better discharge (Sehgal, 1996). According to the depth of the tailwater and the dimension of the gate opening, the flow via radial gates is either classed as free-flowing or submerged. Plenty of research on free and submerged radial gates may be found, such as Buyalski (1983), Clemmens, Strelkoff and Replogle (2003), Bijankhan, Kouchakzadeh and Bayat (2011), Clemmens and Wahl (2012), Bijankhan, Ferro and Kouchakzadeh (2013), Ali, Abdelhaleem and Elsayed (2015), Abdelhaleem (2017), Basiouny *et al.* (2018b), Ibraheem *et al.* (2018).

Several investigations on submerged hydraulic jump were recorded. Rao and Rajaratnam (1963) used physical models to study the submerged hydraulic jump in rectangle-shaped channels. Rao and Rajaratnam (1963) characterised the submerged jump as an example of a turbulent vertical wall. McCorquodale and Khalifa (1980) studied the submerged radial gate hydraulic jump empirically and hypothetically. Long, Steffler and Rajaratnam (1991), Ma and Prinos (1999), and Ma, Hou and Prinos (2001) numerically explained the submerged hydraulic jump. Vallé and Pasternack (2006) studied natural hydraulic jumps in a mountain river with bedrock step-pools, both submerged and unsubmerged. Ali and Mohamed (2010) examined the effects of the various features of the stilling basin end sill on the length of the submerged jump, the energy dissipation by the jump, and the depth and length of the scour holes downstream of the basin. Ali *et al.* (2010) studied the velocity profile and velocity decay along the stilling basin's bed in relation to several end sill conditions. Prior research focused on methods and approaches for studying the efficiency of stilling basin downstream radial gates empirically. The majority of these empirical tests are frequently conducted on huge and important barrages so it costs much, but numerical studies are efficient and with minimum cost. Jalal and Hassan (2020a) clarified that Flow-3D is a computational fluid dynamics (CFD) software with particular modules for hydraulic engineering applications; numerical techniques are utilised to solve fluid motion equations for transient and three-dimensional solutions in order to get multi-scale multi-physics flow issues. Flow-3D by Flow Science (2014) as a combination of physical and numerical options, allows users to apply it to a wide variety of fluid flows and heat transfer phenomena, and it is frequently used to solve various hydraulic difficulties. To solve the governing equations of fluid flow, Flow-3D solves a variant of the regularly used Reynolds-averaged Navier–Stokes equations. Richardson and Panchang (1998) clarified that to show the geometrical data and follow the free surface, the software had algorithms. Many researchers have proposed using Flow-3D to simulate different hydraulic phenomena (Vasquez and Walsh, 2009; Basiouny *et al.*, 2018b; Daneshfaraz *et al.*, 2019; Hassan and Jalal, 2020b; Namadian and Asadi, 2022).

Mohamed *et al.* (2016) studied the stability of the protection layer downstream of major hydraulic structures using Flow-3D. Ibrahim (2015) investigated physically at Hydraulics Research Institute (HRI) the efficiency of stilling basin downstream radial gates and proposed some basin shapes to get the best efficiency, but due to the high cost and time requirements of physical studies, this study aims to enhance the efficiency of stilling basins by numerically testing alternative designs using Flow-3D and studying its effect on submerged jump characteristics, energy dissipation and riprap stability.

MATERIALS AND METHODS

CALIBRATION OF NUMERICAL MODEL

Verification of Flow-3D using physical model

Flow-3D computational fluid dynamics (CFD) package was offered by Flow Science Inc. In this study, volume of fluid (VOF) and fractional area volume obstacle representation (FAVOR) methods of Flow-3D were employed to identify the position of the free surface and the obstructions, respectively. Because numerical model calibration and validation are critical, they are included as a component of the investigation activities in the majority of CFD models. In essence, it is a continuous endeavour to validate with published or experimental evidence that is still required. This is critical for ensuring modelling accuracy and providing a high level of confidence in its use. The tests used to verify the results of Flow-3D were conducted at the Hydraulic Research Institute (HRI) (Ibrahim, 2015). The tests investigated physically the effectiveness of downstream stilling basin in radial gate structures. The tests were conducted using a 1.0-metre-wide, 26.0-metre-long and 1.20-metre-deep flume. A sluiceway bay exists within 11.6 m downstream of the flume intake. The sluiceway bay is made up of two half-piers that are 9.5 cm thick each and placed symmetrically on both wall sides, along with a gated sill. The radial gate of 57 cm radius is rested on a sill with a length of 0.49 m, width of 0.81 m and height of 0.23 m. Then comes an inclination apron with varying slopes. The horizontal apron extends from the inclination apron's endpoint to the downstream side. It consisted of a series of trials with 9 geometric variables and 12 hydraulic variables. In this study, we chose 3 groups with different geometric shapes (A, B and I) and all 12 hydraulic variables to verify Flow-3D results with them. The first two groups (A and B): A) had no element roughness, only a sharp end step at a distance of 14.6 m from the flume inlet, B) had rounded baffle blocks with 0.04 m diameter and 0.02 m height presented in two rows arranged in a staggered way at a distance of 14.68 m from the beginning of flume and 0.3 m from the end step, the end step height for both series was 0.071 m. The third group is named group I. In this group, the element roughness had a width of 0.092 m, and a height of 0.071 m, and was arranged in 7 rows. The existing step height was 0.071 m with a 0.01 m radius of rounded edge at a distance of 0.14 m from the step. Figure 1 shows the geometric shapes of these test series.

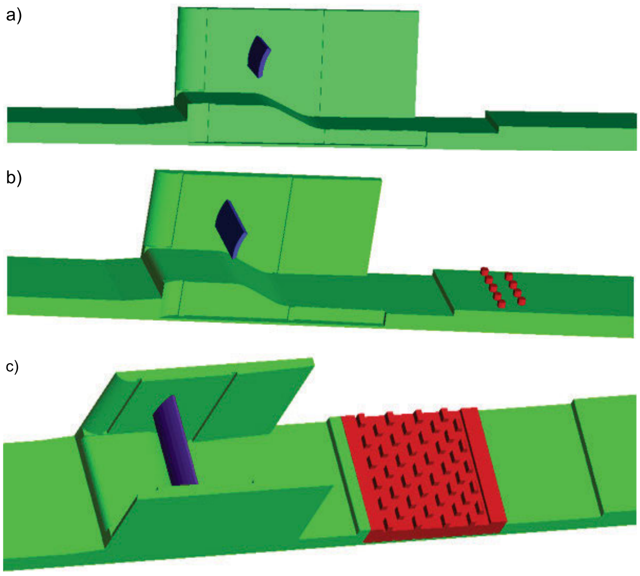

Fig. 1. Geometric shape of: a) group A, b) group B, c) group I; source: own elaboration made in Flow-3D by Flow Science (2014)

Hydraulic variables

Groups (A, B and I) were tested in series with 12 different hydraulic variables to verify the performance of the numerical results of hydraulic jump characteristics, flow velocities and riprap stability downstream radial gates in a wide range of discharges as follows in Table 1.

Measured results to be verified

Verification in this study is performed by comparing Flow-3D results with collected experimental results from HRI, comparison is in terms of velocity distribution. The velocity is measured at seven cross sections (1, 2, 3, 4, 5, 7, and 9) with unequal distances for A and B groups. For test (I), the velocity is measured at the

Table 1. Hydraulic variables used to test groups (A, B and I)

Test No.	Flow discharge, Q ($m^3 \cdot s^{-1}$)	Upstream water depth, Hu (m)	Down stream water depth, Y_T (m)	Gate opening, w (m)
1	0.24740	0.438	0.51	0.267
2	0.17937	0.438	0.47	0.182
3	0.13610	0.438	0.43	0.131
4	0.09900	0.438	0.39	0.091
5	0.07420	0.438	0.35	0.063
6	0.04950	0.438	0.32	0.042
7	0.14220	0.438	0.47	0.153
8	0.09280	0.438	0.44	0.093
9	0.04950	0.438	0.39	0.047
10	0.13610	0.400	0.41	0.135
11	0.09900	0.400	0.37	0.095
12	0.07420	0.400	0.33	0.067

Source: own elaboration.

nine cross sections with unequal distances. Cross sections 1, 2, and 3 are located on the apron downstream of the slope. Cross sections 4, 5, 6, 7, 8, and 9 are located on the slab downstream of the sill, the location of sections is clarified in Figure 2 by Ibrahim (2015). To describe the vertical velocity profile, velocity values are taken at five levels in the vertical direction along the water depth at calculated distances from the surface of 20%, 40%, 60%, 80% and 90% of total water depth.

Energy dissipation. Stilling basin shape affects energy dissipated from the jump as a result of that energy at the start of the jump (E_1) and at the end of the basin (E_2) are measured and expressed in terms of relative energy to get the best shape of the basin that dissipates the energy efficiently.

$$E_L = E_1 - E_2 \tag{2}$$

where: E_L = energy loss in the submerged jump, E_1 = energy at the beginning of the submerged jump, E_2 = energy at the end of the basin, E_L/E_1 = relative energy loses.

Hydraulic jump characteristics. The hydraulic jump characteristics are determined during each test series including the conjugate depth (Y_1), the backup water depth just downstream the gate (Y_3), and the length of the jump (L_{sj}). The distance from that point with zero velocity to the gate is measured; this distance represents the length of the submerged jump.

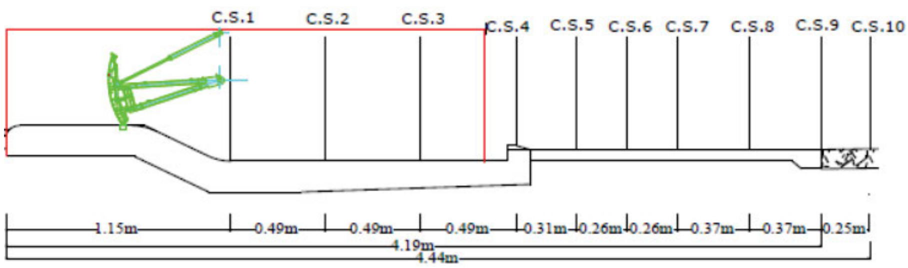

Fig. 2. Velocity sections to be investigated; source: own elaboration based on Ibrahim (2015)

Verification results and analysis

Velocity results. Velocity distribution sections for geometry (I) in hydraulic test No. 1. In Figure 3, the relation between certain depth/water depth (z/Z) and velocity at certain depth/average velocity (v/u) are described. Velocities obtained from the numerical model from all trials are nearly matched with the physical model results as shown in Figure 3. For example, geometric design (I) results showed that near-bed velocities decreased after baffle blocks and the lowest value was at the last section before riprap to guarantee its stability, which was also clarified by Flow-3D results.

Comparison between numerical and physical results. In Figure 4, there is a comparison of hydraulic jump characteristics values between the present study's numerical results and the physical results (Ibrahim, 2015). Figure 4 shows that the values of the present study are very close to the values of the physical results (Ibrahim, 2015).

The coefficient of contraction values (C_C) is directly proportional to discharge values, therefore Y_1 increases. Figure 4a showed that the present numerical results and the physical results (Ibrahim, 2015) gave near values of C_C.

The percentage of the relative energy losses (E_L/E_1) was estimated to evaluate the spillway stilling basin's design effectiveness. Figure 4b shows that the highest value of relative energy losses was at minimum discharge which gives the minimum C_C and the minimum value of relative energy losses that took place at the maximum discharge. The present study's numerical results and physical results (Ibrahim, 2015) clarified the same conclusion with nearly the same values.

Figure 4c shows that Y_3 values increase as discharge increases because Y_3 is directly proportional to the discharge. It is also affected by the shape of baffle blocks and their arrangement, and the values get higher without the blocks. The present study's numerical results and physical results (Ibrahim, 2015) reached the same outcome.

Figure 4d shows that there is a direct proportional relationship between L_{sj} and discharge so as the discharge increases the length of the submerged jump increase. The present study's numerical results and physical results (Ibrahim, 2015) came to a similar finding.

Figure 5a was picked carefully to assess the effect of Froude's number (Fr) on of relative energy losses E_L/E_1 for all test cases to check the design efficiency of the stilling basin. A direct proportional relationship was clearly noticed in physical and numerical values. The maximum and minimum proportion of relative energy losses was determined to be at test No. A-6 and test No. A-1, respectively. From Figure 5b, it is clearly noticed that as Fr increases the relative length of jump increases in both physical and numerical values. The maximum value of L_{sj}/Y_1 was found at test 6 for cases A and B which refer to the lowest discharge and the minimum value was found at test No. I-1 that refers to the highest discharge. From Figure 5c, a direct proportional relationship was noticed between Fr and Y_3/Y_1 for all tested runs. Both numerical and physical results showed

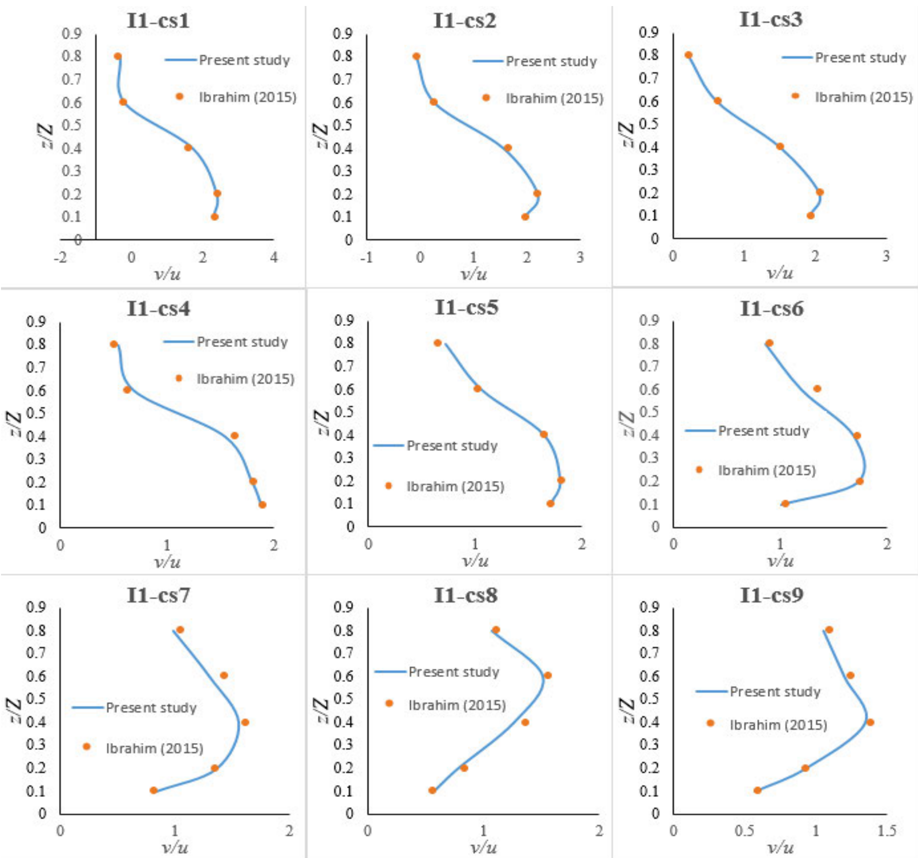

Fig. 3. Velocity distribution at selected sections for geometric design (I); I1-cs1–I1-cs9: I1 = usage of the hydraulic variables of test number one (1) on geometry (I) of basin, cs1–cs9 = chosen sections from one (1) to nine (9), location of sections is shown in Fig. 2, z/Z = certain depth/water depth, v/u = velocity at certain depth/average velocity; source: own elaboration based on present study and Ibrahim (2015)

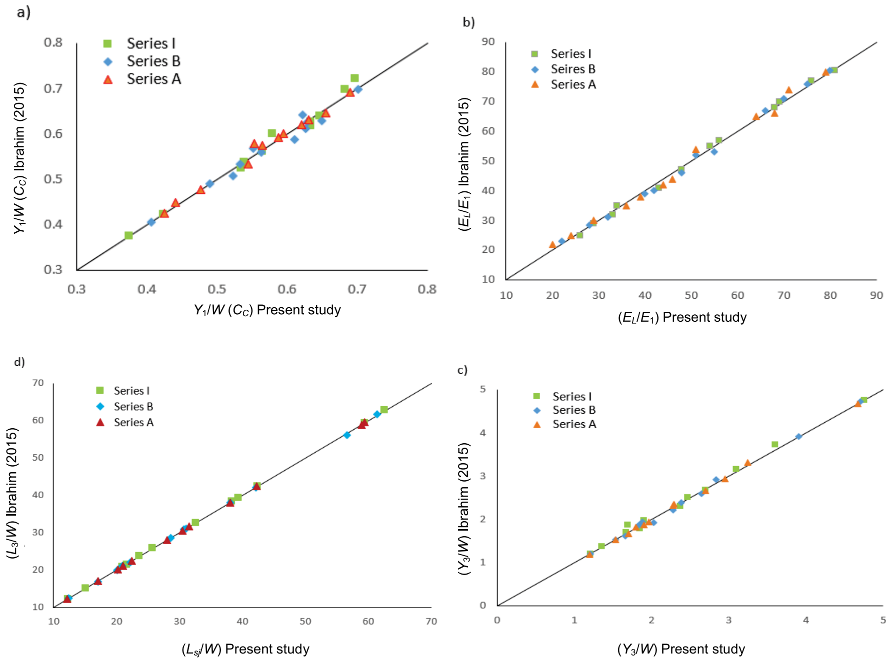

Fig. 4. Comparison between the present study and Ibrahim (2015) for: a) coefficient of contraction ($C_C = Y_1/W$), b) relative energy losses (E_L/E_1), c) relative backup water depth (Y_3/W), d) relative length of submerged jump (L_{sj}/W); E_L = energy losses during the jump, E_1 = energy at start of the jump, Y_1= water depth at vena contracta, W= gate opening, Y_3 = backup water depth, L_{sj} = length of submerged jump; source: own elaboration based on present study and Ibrahim (2015)

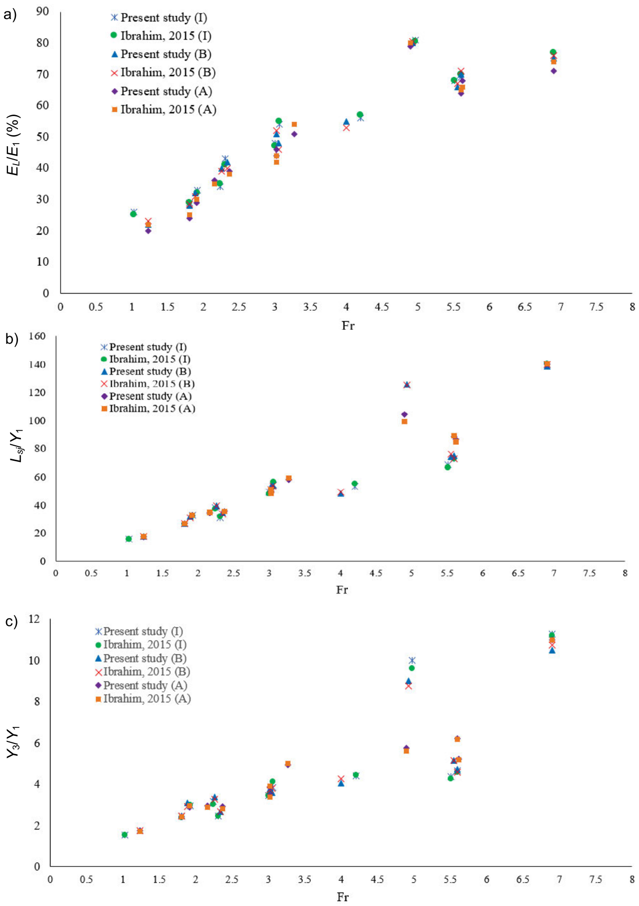

Fig. 5. Relationship between Froude's number (Fr) and: a) relative energy losses, b) relative length of jump, c) submergence ratio; E_L, E_1, Y_1, Y_3, L_{sj} as in Fig. 4; source: own elaboration based on present study and Ibrahim (2015)

that the maximum submergence ratio was observed for stilling basin type I at the test condition (test No. 9) which refers to the lowest discharge, while the minimum value of submergence ratio was found at case I (test No. 1) which refers to the highest discharge.

Results showed an average difference of around 5% in all values between the present study and physical measurements (Ibrahim, 2015).

NUMERICAL SETUP AND PROCEDURES

Alternative designs geometric variable

Five different alternative designs were carried out numerically to enhance the design of the New Assuit Barrage (NAB) spillway stilling basin. The geometrical changes in the five alternatives are described in Table 2.

All five alternative designs were compared in terms of near-bed velocity, energy dissipation, riprap stability and economic consideration. After comparing all results, it was found that alternative designs 4 and 5 were the best designs and in this study we will focus on their results.

Table 2 provides a detailed description of two alternative designs, namely alternative design 4 and alternative design 5. Alternative design 4 is represented in Figure 6a, while alternative design 5 is represented in Figure 6b.

Hydraulic variables

Alternative designs will be tested in 12 different flow conditions to clarify the comparison between the results of alternative designs and the original design results. In order to maintain consistency and accuracy throughout the testing process, the same hydraulic variables that are listed in Table 1 will be utilised.

Table 2. Alternative designs that could be used to enhance the basin efficiency

Alternative design	Description of the shape of basin
1	changed *h* from 0.23 m (original) to 0.16 m so that the step will be closed
2	changed *h* from 0.23 m to zero so that there will be no slope after sill
3	kept *h* as 0.23 m and removed the end step of the basin so that slope and *h* after sill will be the same
4	kept *h* as 0.23 m (original) and removed the end step of the basin in addition to removing the concrete slab which was at a distance from 14.38 to 15.81 m so that riprap will start at a distance of 14.38 m
5	same as design 4 with the addition of rounded baffle blocks with 0.04 m diameter and 0.02 m height presented in two rows arranged in a staggered way at a distance of 13.88 m

Explanations: *h* = height of slope after sill.
Source: own study.

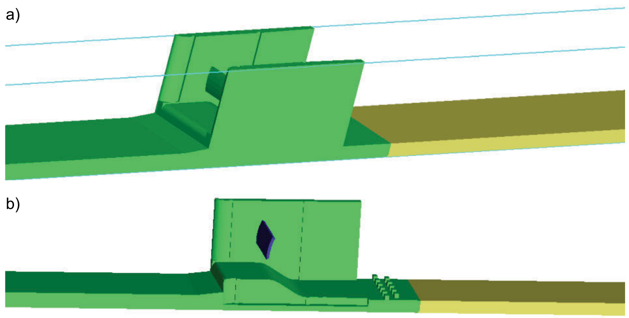

Fig. 6. Models of the alternative stilling basin designs: a) alternative design 4, b) alternative design 5; source: own study

RESULTS AND DISCUSSION

VELOCITY RESULTS

Figure 7 represents velocity distribution sections for alternative design 4 in test No. 1. The results of velocity measurements at all sections with different hydraulic characteristics showed that alternative design 4 has good velocity distribution with low turbulence and low values of near-bed velocity, it's not less than design A as the step and concrete slab have been removed but it will be also safe for riprap as shown in Table 3. Alternative design 4 is safe and more economical as lowers the cost of concrete and excavation.

For design 5, the results of velocity measurements at all sections with different hydraulic characteristics showed that design 5 reduced near-bed velocity more than design 4. The baffles made a reverse flow around it, increased the backup water and reduced the near-bed velocity. Therefore, it will cause less scour and more bed protection stability, as well as economical and lower cost of excavation.

RIPRAP STABILITY

In order to prevent scouring downstream of the stilling basin, riprap particles must be verified to be stable under the flow phenomena. The stability coefficient (Eq. 1) was formulated by Römisch (1995) was used to calculate stability coefficient for riprap protection layer.

The stability coefficient (B') should be less than 1.3 for the stability condition and if this coefficient exceeds 1.3 the riprap will be unstable. Table 3 shows the stability coefficient for the riprap protection layer. Results showed that B' is less than 1.25–1.3, so all of the cases are safe.

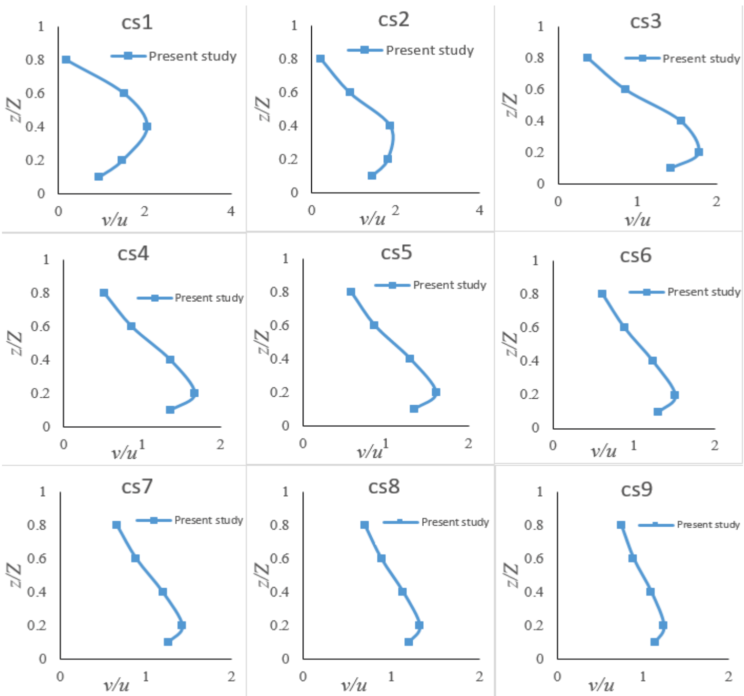

Fig. 7. Velocity profile for alternative design 4 – test No. 1; cs1–cs9 = chosen sections from 1 to 9, as in Fig. 2, *z*/*Z*, *v*/*u* as in Fig. 3; source: own study

Table 3. Stability coefficient for riprap protection layer

Alternative design	Test No.											
	1	2	3	4	5	6	7	8	9	10	11	12
4	1.01	0.70	0.54	0.45	0.29	0.20	0.32	0.19	0.17	0.57	0.48	0.24
5	0.84	0.62	0.47	0.35	0.27	0.19	0.29	0.18	0.15	0.50	0.38	0.20

Source: own study.

The percentage of the relative energy losses E_L/E_1 was estimated to evaluate the spillway stilling basin design's effectiveness. Figure 8a presents the relation between the percentage of relative energy losses E_L/E_1 and Fr in each test case. There was no doubt that the correlation was directly proportional. The maximum and minimum proportion of relative energy losses was determined to be at alternative design 5 (test No. 6) and alternative design 4 (test No. 1), respectively. Alternative designs (4 and 5) gave very good energy dissipation results with the near values of the original designs (A and B) so that the basin is efficient in energy dissipation. Also, with the lower cost of concrete and excavation, the alternative designs are efficient and more economical.

From Figure 8b, it is noticed that as the relative length of the jump increases, the Fr also increases. The maximum value of L_{sj}/Y_1 was found at alternative design 4 (test No. 6) which refers to the lowest discharge, and the minimum value was found also at alternative design 4 (test No. 1) which refers to the highest discharge. Alternative designs 4 and 5 gave very good relative length of submerged jump results with near values of the original designs (A and B). Also, with lower costs of concrete and excavation, the alternative designs are efficient and more economical.

From Figure 8c, a direct proportional relationship was noticed between Fr and submergence ratio for all tested runs. The maximum submergence ratio was found at alternative design 4 (test No. 6), which refers to the lowest discharge, while the minimum value of submergence ratio was found at alternative design 4 (test No. 1), which refers to the highest discharge. Alternative designs 4 and 5 gave very good submergence ratio results with near values of the original designs (A and B). Also, with lower costs of concrete and excavation, the alternative designs are efficient and more economical.

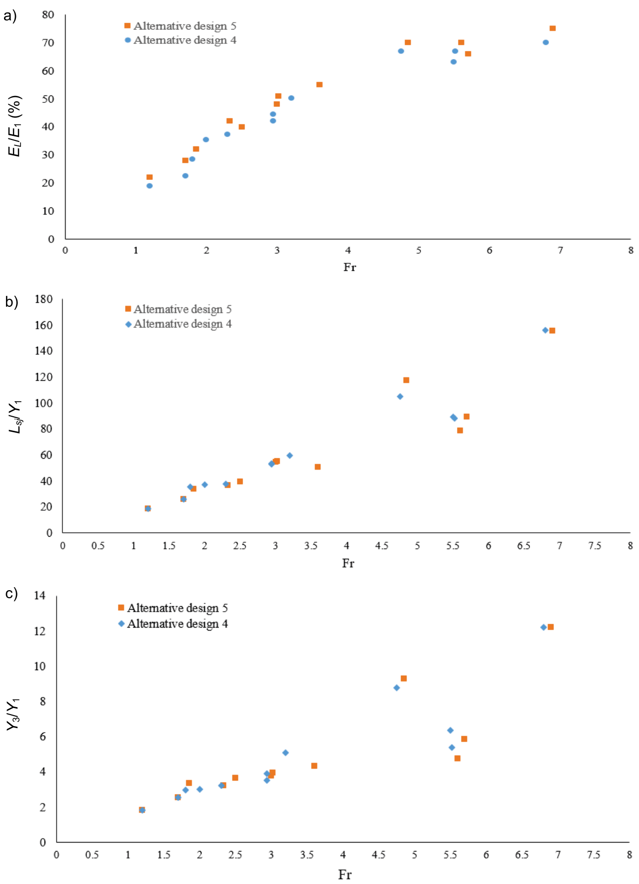

Fig. 8. Relationship between Froude's number (Fr) and: a) relative energy losses, b) relative length of jump, c) submergence ratio; E_L, E_1, Y_1, Y_3, L_{sj} as in Fig. 4; source: own study

CONCLUSIONS

Numerical models were carried out to study the effect of stilling basin design on velocity profile, bed protection stability and hydraulic jump characteristics. The velocity profile and the relation between hydraulic characteristics and the Froude's number were presented for each tested basin shape.

- The rate of error is equal to 5% for the velocity profile and submerged hydraulic jump characteristics, the correlation between the experimental and numerical work is well validated by this observation.
- The numerical simulation successfully reproduces the effect of the stilling basin design.
- These findings show that the suggested numerical model Flow-3D is a useful tool for simulation and prediction of the effect of stilling basin design on velocity profile and hydraulic jump characteristics.
- From the analysis of the results of all alternatives, the best two alternative designs were designs 4 and 5 as they gave the economic benefits in terms of lower cost of concrete and excavation and the hydraulic benefits as it is safe for riprap and will not cause scour after basin.
- Designs 4 and 5 give near values of Y_1 as well as the same discharge and same geometry before vena contracta, Y_3 nearly higher as we removed the step, shorter length of submerged jump and good relative energy losses.
- In further studies, it is recommended to try a rough bed as a corrugated bed and study its effect on the submerged jump and flow velocities.

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