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Three-dimensional Numerical Investigation of Flow through Screens as Energy Dissipators

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Energy Dissipators 2

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Abstract	16
Screens, perforated units to dissipate energy in hydraulic structures, are investigated	17
numerically in this study. These units are part of a physical setup exposed to supercritical	18
flows, normally created by sluice gates. The interaction of perforated screens and	19
supercritical flows are local complexes with three-dimensional flows, which can be analyzed	20
by the application of RANS-based flow equations. The most important controlling parameters	21
include supercritical Froude number between 2-10 and screen porosity of 40% and 50%.	22
Numerical water surface profiles and energy dissipation are validated by the author's	23
experimental data. This paper derives a set of equations in terms of depth ratio of the	24
hydraulic jump through the perforated screens and assesses the effect of baffles on energy	25
dissipation. This study seeks a proof-of-concept for the application of the RANS-based	26
technique for further application of the result to real hydraulic structures in due course.	27
Keywords: Screen, hydraulic jump, energy dissipation, supercritical flow, baffles	28

1. Introduction 29

The energy dissipator structures are installed in order to control flow velocity and dissipate 30
extra energy in the downstream of hydraulic structures. The rate of energy dissipation has the 31
direct relation with flow turbulence. Therefore, in order to achieve a considerable amount of 32
energy dissipation, more turbulence in the relatively small region is favorable. The theoretical 33
and experimental studies show that there are different structures for energy dissipation, such 34
as a stilling basin and baffled outlet (Hager and Sinniger 1985); a flip bucket and ski-jump 35
(Chaudhry 1996; Kökpınar et al. 2016) or impact-type dissipators that include drops and a 36
plunge pool (Rajaratnam and Chamani 1995; Chanson 1999; Carvalho and Leandro 2011; 37
Zare and Doering 2012). 38

Recently, the screens are proposed as energy dissipators in the downstream of hydraulic 39
structures (Rajaratnam and Hurtig 2000; Çakır 2003; Bozkuş 2004; Balkış et al. 2004; 40
Bozkuş et al. 2005; Bozkuş et al. 2006; Bozlus et al. 2007; Aslankara 2007; Bozkuş and 41
Aslankara 2008; Sadeghfam et al. 2014). Screens are porous planes, which are placed 42
vertically in the flow a specified distance from the supercritical flow generator. The studies 43
that used screens as energy dissipators are summarized in Table 1. In this table, flume 44
dimension, the range of supercritical Froude numbers (Fr_A), and screen porosity and 45
arrangement are specified. 46

The studies summarized in Table 1 report that screens with 40% and 50% porosities dissipate 47
energy more successfully than hydraulic jump. Screen thickness, inclination, and multiple 48
arrangements were identified as insignificant parameters. Also, a double arrangement 49
dissipated more energy than a single arrangement. 50

Notably, the research in Table 1 is experimental, as the authors investigated flow through 51
screens using numerical modeling. The most important advantage of using numerical 52

modeling is to reduce costs of experimental setup construction and instrumentation. Recently, 53
different types of energy dissipation structures have been investigated numerically. 54
Researchers have used different numerical methods, such as Finite Volume Method – FVM 55
(Carvalho et al. 2008; Wanzheng 2015); and Finite Element Method – FEM (He and Zhao 56
2009; Jianhua et al 2010). 57

The turbulence models for treating and simulating turbulence effects in hydraulic flows are 58
categorized into four groups by Rodi (2017) as: (i) empirical relations; (ii) the Reynolds- 59
averaged Navier-Stokes (RANS) based statistical turbulence models; (3) direct numerical 60
simulations (DNS); and (4) large-eddy simulations (LES). The empirical relations are still 61
useful for solving simple problems and for providing first estimates. By advent of computer, 62
turbulence models in connection with RANS equations became a powerful tool which copes 63
successfully with situations with complex irregular boundaries and the interaction of different 64
flow regimes. Among the RANS-based turbulence models, the $k-\varepsilon$ (RNG) version performs 65
better than the others in hydraulics (Rodi 2017) except in sediment transport applications 66
(Lyn 2008). 67

The usage of RANS-based models is limited for the problems which turbulent transport by 68
large-scale structures plays a dominant role or turbulence exhibits strong anisotropy (Rodi 69
2017). The DNS model is superior in these situations, but it increases considerably the 70
computing effort which is unsuitable for practical problems. LES and the advanced version 71
by Sotiropoulos (2015) resolve only the scales larger than the mesh size of a grid that can be 72
afforded. Also, the sophisticated DNS and LES methods such as the hybrid LES/RANS 73
version could cope with the calculation of very complex reallife, multiphysics problems 74
while extracts all details of the turbulent motion. 75

In this study, the flow through screens (with porosities of 40% and 50%) is investigated numerically via FVM, Volume of Fluid (VOF), $k-\varepsilon$ (RNG) turbulence model by using the Flow-3D software. The supercritical Froude number varied in the range of 2-10 which created by sluice gate with a constant opening. The numerical water surface profiles are validated by authors experimental data. Also, the effect of baffles on energy dissipation and hydraulic jump features is simulated at upstream of screens. The main purpose of this study is to identify the behavior of flow through screen and baffles in more detail by numerical simulation which was not considered in the former experimental studies.

2. Governing Equations

Three-dimensional numerical simulations of flow through screens is carried out by Flow-3D software. This software solves Reynolds Averaged Navier-Stokes (RANS) equations by FVM in the meshed flow domain. RANS equations are time-averaged equations of motion for fluid flow. The following equations describe continuity and momentum equations in the Cartesian coordinates.

$$\frac{\partial U_i}{\partial x_i} = 0 \quad (1)$$

$$\rho \frac{\partial U_i}{\partial t} + \rho U_j \frac{\partial U_i}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left(\mu \frac{\partial U_i}{\partial x_j} - \overline{\rho u'_i u'_j} \right) + \rho g_i \quad (2)$$

where U_i and u'_i are averaged velocity and fluctuating velocity in the x_i direction respectively. Instantaneous velocity defines as $u_i = U_i + u'_i$. For the three perpendicular directions ($i=1,2,3$), $x_i = (x, y, z)$, $U_i = (U, V, W)$, $u'_i = (u', v', w')$. ρ and μ represent density and dynamic viscosity respectively. Also, P and g_i are kinematic pressure and gravitational acceleration respectively.

A turbulence model is needed for additional modeling of nonlinear Reynolds stress term. For this purpose, the $k-\varepsilon$ (RNG)¹ turbulence model is used in this study to simulate mean flow characteristics for turbulent flow conditions. Although there are more accurate turbulence models (e.g., DNS, LES, and hybrid models), the $k-\varepsilon$ (RNG) could cope successfully with a large number of meshes. It has been utilized successfully in the similar numerical studies which simulated hydraulic jump in the stilling basin (for instance, Carvalho et al. 2008; Babaali et al. 2005).

The $k-\varepsilon$ (RNG) model is a two equation model, and the first equation (Eq. 3) determines the energy in the turbulence and is called turbulent kinetic energy (k). The second equation (Eq. 4) is the turbulent dissipation (ε), which determines the rate of dissipation of the turbulent kinetic energy. These equations are as follows,

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + P_k - \rho \varepsilon \quad (3)$$

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial(\rho \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{1\varepsilon} \frac{\varepsilon}{k} P_k - C_{2\varepsilon}^* \rho \frac{\varepsilon^2}{k} \quad (4)$$

where in the above equation:

$$C_{2\varepsilon}^* = C_{2\varepsilon} + \frac{C_\mu \eta^3 (1 - \eta/\eta_0)}{1 + \beta \eta^3} \quad (5)$$

$$\eta = \frac{Sk}{\varepsilon} \quad (6)$$

$$S = \sqrt{2 S_{ij} S_{ij}} \quad (7)$$

$$S_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \quad (8)$$

¹ Re-Normalization Group

In the $k-\varepsilon$ (RNG) turbulence model, $C_{\mu}=0.0845$; $C_{1\varepsilon}=1.42$; $C_{2\varepsilon}=1.68$; $\sigma_k=0.7194$; $\sigma_\varepsilon=0.7194$; $\eta_0=4.38$; and $\beta=0.012$. These adjustable constants have been arrived by data fitting a wide range of turbulent flow (Yakhot et al. 1992).

The Flow-3D software uses the volume of fluid (VOF) for free surface modelling. This method is described as follows,

$$\frac{\partial F}{\partial t} + \frac{1}{V_f} \left(\frac{\partial}{\partial x} (FuA_x) + \frac{\partial}{\partial y} (FvA_y) + \frac{\partial}{\partial z} (FwA_z) \right) = 0 \quad (9)$$

where F is the fraction function, and when a cell is empty with no fluid inside, $F=0$. Also, when the cell is full, $F=1$.

3. Model Specifications - Flow domain Geometry, Meshes, and Discretization Schemes

The flow domain is constituted from 8 components including the following: the (i) **inlet boundary** and the (ii) **sluice gate**, a supercritical flow generator located downstream from the inlet boundary; the (iii) **reservoir** – the distance between the inlet boundary and sluice gate (iv) **baffles**, if present, as a checkered barrier located between the sluice gate and (v) **screen, which** acts as an energy dissipator structure located downstream before the (vi) **outlet boundary**; the (vii) **bottom and side** – governs by non-slip condition; and the (viii) **top boundary**. The supercritical flow, which is generated below the sluice gate, passes through the baffles and the screen in order to dissipate energy and then leaves the flow domain (see Figure 1(a)-(b)).

The flow domain length, height, and width are 2.25, 0.6, and 0.3 meters respectively. The sluice gate is located at a distance of 0.5 m from the inlet boundary, and the gate opening is fixed at 2.5 cm. Screens are fixed at a distance of 1.25 m from the sluice gate with porosities of 40% and 50%. Baffles are constituted from 8 blocks in the three non-aligned rows with

cross-section dimensions of $5 \times 5 \text{ cm}^2$ and a height of 10 cm. Baffles are located 25 cm from the screens. See Figure 1(b) for more details. Notably, four different cases have been simulated including the following: **Case 1** – flow simulation through a 40% screen without baffles; **Case 2** – flow simulation through a 50% screen without baffles; **Case 3** – flow simulation through a 40% screen with baffles; and **Case 4** – flow simulation through a 50% screen with baffles.

The flow domain is discretized by cubic meshes with the number of 4,200,000. Notably, in order to decrease the effect of mesh number on the final solution, the number of meshes is considered the same in the four above-mentioned cases. The transversal dimension of meshes is uniform (0.33 cm) along the flow domain width. However, the mesh size varies (0.33 cm to 0.83 cm) in the longitudinal and vertical directions with regard to flow parameter gradient. As an example, the velocity and pressure gradient is high in the vicinity of sluice gate and screen, so the mesh size is fine in that region. Notably, the mesh number and size are identified based on the RMSE and MAPE between calculated and experimental water surface profile and also simulation runtime which is presented as an example for 40% screen and $Fr_A=3.6$ in Table 2. Figure 1a depicts the flow domain and mesh in Case 4 as an example.

The boundary conditions of different components of flow domain are illustrated in Fig. 1a as follows: the outlet (EFGH) is outlet boundary condition in terms of zero relative pressure; the top (ABFE) is pressure outlet boundary condition in terms of zero relative pressure; the sidewalls (AEHD and BFGC), bottom (DCGH), screen, sluice gate, and baffles are wall boundary condition which has zero velocity relative to the boundary (no-slip condition); the inlet (ABCD) is specified pressure based on upstream total head behind the sluice gate with a hydrostatic pressure distribution. In defining inlet boundary condition, the flow rate and corresponding Froude numbers below the sluice gate ($Fr_A = v / \sqrt{g \times Cc \times \text{gate opening}}$) vary in the ranges of 2.5-9.6 and 4.3-17 Liter/s respectively, where v , g , and Cc represent, mean

velocity, gravitational acceleration and coefficient of contraction of sluice gate respectively (Cc=0.61 was recommended by Henderson (1966) for practical purposes). Also, the water depth behind the sluice gate varies in the range of 12 to 40 cm. The initial condition is illustrated in Figure 1(c). In order to decrease simulation time, the water is patched in the reservoir. Some characteristics of simulation runs including Fr_A , flow rate and water depth behind the gate are listed in Table 3.

As mentioned earlier, Flow3D software discretizes the governing equations by FVM. In this study, the discretization of convection terms is performed by the second-order UPWIND differencing method. The SIMPLE method is applied for a simultaneous solution for the pressure velocity coupled equations. Also, unsteady simulations with a time step of 0.001 s were continued until a steady state in the water surface profile was reached (after a simulation time of 20s).

4. Result and Discussion

4.1 Water Surface Profile

In order to validate water surface profiles of numerical results, cases 1 and 2 were investigated experimentally by a flume 0.3 m wide, 0.5 m deep, and 5 m long at Maragheh University. The flow depths were measured by point gauge through calculating the average number of 3 depths in the middle and 3 cm from the channel walls. The details of the experimental setup were the same as Figure 1. The configuration of this study components (Cases 1 and 2) are same as Rajaratnam and Hurtig (2000) and Sadeghfam et al. (2014). Figure 2 compares experimental and corresponding numerical flow behavior through the screen. According to Figure 2, submerged hydraulic jump has been generated except in Case 2 - $Fr_A=6.8$ in both the experimental and the numerical runs.

Figures 3 and 4 compare the experimental and numerical water surface profiles for cases 1 and 2 respectively. The horizontal and vertical axes are represented by dimensionless parameters of y/y_0 and normalized horizontal direction (x/x_s) respectively, where x , x_s , y and y_0 are, respectively, longitudinal dimension, the location of screen (1.25 m from sluice gate), vertical dimension and the depth of water behind the sluice gate. The high values of R^2 and low values of RMSE (mm) indicate that numerical water surface and type of hydraulic jump (free or submerged) agree with experimental results.

Figure 5 depicts the characteristics of the hydraulic jump that occurs between the sluice gate and the screen on semi-logarithmic scale. Figure 5a shows the depth ratio of the hydraulic jump (y_2/y_1) versus supercritical Froude number (Fr_A) for the entire investigated runs, where y_1 and y_2 are initial and final depths of the hydraulic jump respectively. According to this figure, the depth ratio of hydraulic jump increases as Fr_A increase, since higher Fr_A results in stronger jump and the higher final depth of hydraulic jump with respect to initial depth. Notably, the initial depth of submerged hydraulic jump is assumed to be the submerged depth of the sluice gate. According to this figure, the depth ratio of jump varies between 1-2, except in Case 2 where the free hydraulic jump is observed. Since free hydraulic jump has lower initial depth and consequently higher depth ratio of hydraulic jump with respect to submerged hydraulic jump, the data related to Case 2 locates above data related to Cases 1, 3 and 4. The linear equations (Eqs. 10 and 11) were fitted to the result of the depth ratio of the submerged and free hydraulic jump through the screen based on the curve-fitting technique. These equations describe the depth ratio of the hydraulic jump as a function of Froude number of supercritical flow and could be considered as a guide in design frameworks in the studied range of Fr_A .

$$\frac{y_2}{y_1} = 0.081 \times Fr_A + 0.93 \quad (\text{for submerged hydraulic jump in } 4.5 < Fr_A < 9) \quad (10)$$

$$\frac{y_2}{y_1} = 0.27 \times Fr_A + 2.55 \quad (\text{for free hydraulic jump in } 4.5 < Fr_A < 10) \quad (11) \quad 209$$

Figures 5b and 5c depict the variation of dimensionless parameters of length (L/X_0) and location (X/X_0) of hydraulic jump through a screen, where L , X , and X_0 are hydraulic jump length, hydraulic jump location and distance between the sluice gate and the screen respectively. According to Fig. 5b and 5c, the length and location of hydraulic jump increase asymptotically by increasing Fr_A (Except in Case 2), because screen confines the length and the location of hydraulic jump to the distance between sluice gate and screen. For the Fr_A greater than 5, the type of hydraulic jump change from submerged to free. Therefore the length of jump decreases (Fig. 5b) and location of jump increases to screen location (Fig. 5c, $X/X_0 = 1$).

4.2. Energy Dissipation through Screen

Energy dissipation through a screen is computed based on a specific energy equation ($E = y + \frac{v^2}{2g}$) where flow depth (y) and mean velocity (v) are obtained from numerical simulations. Figure 6 depicts the variation of “screen performance” ($(E - E_0)/E_0$) along the normalized horizontal direction (x/x_s) for different supercritical Froude numbers (Fr_A), where E_0 and E are the specific energy behind the sluice gate and each section respectively. According to this figure, screen performance increases along the horizontal direction. Also, the higher Froude number results in the higher turbulences and, consequently the higher screen performance. Meanwhile, the different variations of screen performance arise from type and location of hydraulic jump and intensity of flow turbulence. The relatively abrupt change in gradient of screen performance between the gate and the screen indicate energy dissipation through a hydraulic jump. Further explanations of tacit knowledge in Fig. 6 are illustrated in Figs. 7, 8 and 9.

If the longitudinal losses are neglected due to the low frictional forces, the separated percentage of energy dissipation through hydraulic jump, screen, and baffles (if present) are illustrated in Figure 7 by using existing information in Figure 6. According to this figure, by increasing the Froude number, energy dissipation through hydraulic jump increases but the portion of screen and baffles from total energy dissipation decreases. By increasing the Froude number, hydraulic jump is strengthened and flow turbulence increases. Notably, hydraulic jump plays the most important role in energy dissipation. The highest value of energy dissipation through baffles is observed in Case 4 because the hydraulic jump occurred immediately upstream of the baffles and the baffles were located in a relatively turbulent flow. This event did not occur in Case 3 due to low porosity of screen regarding Case 4.

By averaging the contribution percentage in energy dissipation, the effect of Fr_A has been decreased in Fig. 8. Therefore it provides the comparison between different cases regardless Froude number. According to this figure and Fig. 7, since baffles decrease the contribution percentage of hydraulic jump in energy dissipation, they could be effective components in this system, especially when providing structural stability to a channel bed or screen. For instance, according to Fig.7, comparing cases 1 and 3 (for $Fr_A=9.4$ and 9.6) indicates that the existence of baffles decreases the contribution percentage of hydraulic jump from 85% to 75% in the energy dissipation process. Also, according to Fig.8 and by considering all Froude numbers in cases 1 and 3, the existence of baffles decrease the contribution percentage of hydraulic jump from 69% to 61%.

The parameter of final screen performance varies between 0-1 and indicates a fraction of the initial energy, which has been dissipated through screen, hydraulic jump and longitudinal losses. Final screen performance means:

$$\frac{E_0 - E_{vc}}{E_0} \quad (12)$$

where E_{vc} is specific energy in downstream of screen at *vena contracta*. 256

Figure 9 compares final screen performance of this study and the former experimental 257
research. In this figure, SS, DS and P, respectively stand for single screen, double screen and 258
screen porosity. According to this figure, the energy dissipation through the screen is more 259
than free hydraulic jump for the numerical study (present) and experimental (former) studies. 260
Also, energy dissipation through Cases 3 and 4 (screen and baffles) is a little more than 261
corresponding Cases 1 and 2 respectively, but it is not significant. 262

5. Conclusion 263

This paper analyzed numerically the behavior of flow through screens to study the water 264
surface profile and energy dissipation. The supercritical Froude number varied in the range of 265
2-10 and screens with porosities of 40% and 50%. Numerical water surface profiles and 266
energy dissipation were validated by author's experimental data. The result of numerical 267
studies facilitates assessment of flow parameters, often costly in former experimental studies 268
in this field. These parameters include screen performance along the flow direction, depth 269
ratio of hydraulic jump, separating the contribution of different components in energy 270
dissipation. The paper derived a set of equations in terms of depth ratio of hydraulic jump 271
through the perforated screen for submerged and free hydraulic jump. This paper also 272
assessed the effect of baffles on energy dissipation, and it was found that baffles had an 273
insignificant effect on energy dissipation but could decrease the contribution percentage of 274
hydraulic jump from total energy dissipation. Therefore, they could be useful when providing 275
stability to a channel bed or a screen confronted with some problems. Increasing the 276
supercritical Froude number resulted in increasing the contribution percentage of hydraulic 277
jump but decreasing contribution percentage of screen and baffles from total energy 278
dissipation. Therefore, in the high Froude numbers, the screen plays the role of a component 279

that imposes hydraulic jump, but in the low Froude numbers it contributes to the energy
dissipation process.

This study was within the remit of research for the proof-of-concept, and the results were
expected to develop in real case hydraulic structures in the near future. The Froude number
ranges covered Froude number USBR stilling basin type 4 and 5. The arrangement of baffle
blocks was considered similar to USBR stilling basins with a checkered pattern, in order to
create the higher turbulences and consequently the higher energy dissipation. Further research
could be contributed to different arrangements, location and heights of baffles, wider Froude
number ranges and different locations of screens.

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Table 1. Experimental setup and details of former research

355

Researchers' Names	Flume dimensions (Length×Width×Height) (meter)	Froude number range	Objective key contributions
Rajaratnam and Hurtig (2000)	6×0.305×0.7	5-13	<ul style="list-style-type: none"> 40 and 50% porosities Single/Double arrangement
		4-7.2	<ul style="list-style-type: none"> Triangle arrangement
Çakır (2003) Bozkuş et al. (2004) Bozkuş et al. (2007)	7.5×0.29×0.7	5-18	<ul style="list-style-type: none"> 20, 40, 50, 60% porosities Single/Double with 2 and 4 cm gap Screen thickness (2, 4 cm and Double with 2 cm)
Balkış (2004) Bozkuş et al. (2005) Bozkuş et al. (2006)	7.5×0.29×0.7	5-24	<ul style="list-style-type: none"> 40% porosity Screen inclination 60, 75, and 90 degree regard to horizontal
Aslankara (2007) Bozkuş and Aslankara (2008)	6.3×0.45×0.43	5-22.5	<ul style="list-style-type: none"> 40% porosity Multiple screen (single, double, quadruple with different arrangement)
Sadeghfam et al. (2014)	5×0.3×0.45	2.5-8.5	<ul style="list-style-type: none"> 40% and 50 % porosities Single/Double with 1, 3, 5 cm gaps Focused on submerged hydraulic jump

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Table 2. Sensitivity of mesh number to experimental water surface profile for 40% screen and $Fr_A=3.6$

Number of meshes	RMSE (mm) Root Mean Square Error	MAPE (%) Mean Absolute Percentage Error
	$\sqrt{\frac{1}{n} \sum_1^n (X_{\text{exp}} - X_{\text{nmr}})^2}$ X_{exp} : Experimental value of X X_{nmr} : Numerical value of X n : Number of data	$100 \times \frac{1}{n} \sum_1^n \left \frac{X_{\text{exp}} - X_{\text{nmr}}}{X_{\text{exp}}} \right $ X_{exp} : Experimental value of X X_{nmr} : Numerical value of X n : Number of data
Coarser meshes	Solution was not converged.	
1700000	9.6	12.53
4200000	4.1	5.35
5900000	2.5	4.45
Finer meshes	Solution needed higher computational storage.	

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Table 3. Flow characteristics of simulation runs

Case 1				Case 2			
	Fr_A	Water depth behind the gate (cm)	Flow rate (Liter/s)		Fr_A	Water depth behind the gate (cm)	Flow rate (Liter/s)
	2.5	11.72	4.28		3	10.37	5.43
	3.6	14.94	6.35		4.5	14.87	8
	4.2	19.95	7.4		5.2	17.37	9.19
	5.6	26.44	9.94		5.4	19.88	
	6.6	29.98	11.66		5.8	22.40	10.21
	9	41.94	16.72		6.8	30.90	12.05
	9.6	47.03			8.7	35	15.39

Case 3	Fr_A	Water depth behind the gate (cm)	Flow rate (Liter/s)	Case 4	Fr_A	Water depth behind the gate (cm)	Flow rate (Liter/s)
	2.6	11.72	4.56		2.8	10.40	4.93
	3.2	14.93	5.63		3.4	14.93	6.1
	4.1	19.96	7.22		4.8	18.91	8.62
	4.8	26.42	8.51		5.5	22.40	9.81
	6.1	29.97	10.76		6.5	31.04	11.4
	8	34.96	14.03		8.3	35.00	14.6
	9.4	41.95	16.63				
Gate opening = 2.5 cm							

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Figure 1. Model specifications for Case 4: (a) Flow domain, components, meshes and boundary condition; (b) Plan and longitudinal view; (c) Initial condition

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Figure 2. Flow behavior and type of hydraulic jump through screen

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Figure 3. Comparison between numerical and experimental water surface profiles – Case 1

Figure 4. Comparison between numerical and experimental water surface profiles – Case 2

Figure 5. The characteristics of hydraulic jump through screen:
(a) depth ratio of hydraulic jump; (b) length of hydraulic jump; (c) location of hydraulic jump

Figure 6. Screen performance along horizontal direction for different cases

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Figure 7. Contribution percentage of different components in energy dissipation

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Figure 8. Averaged contribution percentage of different components in energy dissipation

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Figure 9. Screen performance comparison between current and former studies

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