Arabian Journal of Geosciences (2021) 14: 90
https://doi.org/10.1007/s12517-020-06378-4

ORIGINAL PAPER

3D flow simulation to improve the design and operation of the dam bottom outlets

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Received: 27 July 2020 / Accepted: 16 December 2020 / Published online: 15 January 2021

Abstract
The most widely used method of flushing of reservoirs is to remove the deposited sediment through the bottom outlets. The size and shape of gates affect the outflow volume of water, the volume of removed sediments, and flushing efficiency. The purpose of this study is to investigate the effect of the area, number and shape of the bottom outlet gates on the velocity, concentration, and volume of the removed sediments and the dimensions of the flushing cone. Four different shapes with the same area were used for this purpose. Moreover, to study the effect of area and number of gates on flushing efficiency, circular gates with two different diameters were used. In this research, various pressure flushing modes were simulated using the Flow-3D model. Calibration and evaluation of this model were performed based on experimental findings. Results showed the parameters of the Flow-3D measures such as length, width, maximum depth, and flushing cone size with an average error of 3%, which is in good agreement with experimental results. As the area of the outlet gates increases, flushing is less risky in viewpoints of the operation process. Furthermore, the gate with a horizontal-rectangular section has an optimal shape with the highest flushing efficiency.

Keywords Computer model · Scouring · Flushing · Bottom outlet · Flow-3D · Sedimentation

Introduction

Dams are built to control devastating flood flows, water storage for downstream use, and energy production. Nowadays, sedimentation in dam reservoirs is the main problem of the exploitation of dams (Huan et al. 2018), as the sediments accumulate in the reservoir, so the dam slowly loses its ability to store water. Therefore, it is important to minimize reservoir volume losses due to sedimentation for water resource planners. Sedimentation is the most important factor in reducing the useful life of dams, and many reservoirs have become unusable due to filling up with sediment. Currently, most sediment management activities focus on erosion control. Although these activities are necessary, they alone cannot be sufficient to keep the balance of sedimentation and the long-term maintenance of the reservoir's storage capacity. In fact, among methods of sediment management, a method that includes all the strategies to maintain the sediment balance in the reservoir is efficient and can be acceptable (Morris 1995). One of the most effective ways to reduce the amount of sediment over time is to remove sediments. Hydraulic flushing is a technique for disposal of sediments deposited in the dam, which is done by opening the bottom outlet gates of the dam. This method is used in different dams in the world. There are many altitudes on the effectiveness of the flushing method in the disposal of sediments deposited in reservoirs. Some researchers state that in large reservoirs, the effect of this method is not clear (Hemphil 1931). Other researchers believe that the flushing method is the only suitable method for reservoirs with an additional amount of water entering the reservoir (according to Brandt 2000). In general, use of the sedimentation method has been proposed as a suitable and economical way to retrieve the capacity of dams' reservoirs. A strategy for controlling flow behavior in the process of

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flushing is the use of a 3D hydrodynamic model (Khosronejad et al. 2008), which solves the Reynolds-averaged Navier-Stokes equations by finite volume method (Török et al. 2017; Esmaeili et al. 2017; Xie 2011). Results of Atkinson (1996) investigation show that the use of hydraulic flushing in some dams has been very effective in restoring lost volume. Holly and Cunge (1975) and Dawdy and Vanoni (1986) have studied the work done on numerical simulation in sediment hydraulics and, by applying simplistic assumptions, have analyzed the governing equations for sedimentation and erosion. Epely-Chauvin et al. (2014) validated the Flow-3D model by comparing laboratory measurements and numerical results. Their research revealed that sediment simulation in Flow-3D is in good agreement with laboratory results. Lyn (1987) presents nonlinear solutions for sedimentation and erosion, which show better agreement with laboratory data than linear solutions. The time required for the complete formation of the flushing cone and its geometric shape stability depends on the type of sediment, the reservoir water level, the height of the accumulated upper sedimentation, and the discharge of the gates. This may take a few hours to several days. As an illustration, experiments conducted on the Gebi, reservoir model in Switzerland showed that the sedimentation hole is in equilibrium after 2 to 3 h (Morris and Fan 1998). In a study by Yucel and Graf (1973), the phenomenon of sedimentation in a hydraulic model in a permanent one-dimensional flow was studied using bed loading formulas, and changes in bed profiles and free flow of water were analyzed. Fang and Cao (1996) investigated the effect of the bottom outlet on cleaning and preventing the entry of sediment coarse grains into turbine unit of power plants. The result shows that in a pressure flushing, a flushing cone forms in front of the bottom outlet. Petkovšek et al. (2020) emphasized that the size of the bottom outlet is an important factor in flushing performance. White and Bettess (1984) did some researches to obtain the expansion of the flushing cone during the pressure hydraulic sediment flushing. They stated that in this method, the length of the flushing cone depends on the depth of the reservoir water and the discharge outlet of the dam. Scheuerlein et al. (2004) believe that considering the three-dimensional flow pattern toward downstream outlets and the involvement of multiple parameters in the sedimentation phenomenon, the study of the mathematical behavior of the sedimentation process is complex. Therefore, using a physical model was suggested to study the flushing phenomenon. The purpose of their experiments was to study changes in the rate of flushing in terms of changing the height of water in the reservoir. Lai and Shen (1996) studied the phenomenon of flushing using a physical model of the reservoir. The result of this study showed that when flushing is under pressure and flow is in steady state (inlet flow to the model is equal to the outlet discharge of the gate), a stable flushing cone is formed near the sluice gate. Dehghani et al. (2010) investigated the quantitative and qualitative flushing cone diffusion during pressure flushing and different hydraulic conditions. The results showed that the cross-sectional area of the bottom outlet is an important parameter in the hydraulic flushing phenomenon. As the diameter of the bottom outlet increases, the dimensions of the flushing cone also increase (Meshkati et al. 2009).

In a research conducted by Sawadogo et al. (2019), an experimental model was developed to simulate flushing cone physically. The depth, width, and height of the scour hole were measured. Then, the physical model results were used to validate a three-dimensional numerical model. The geometric features of the flushing cone upstream of the bottom outlet were analyzed and compared in both models. The results showed that the experimental model and the numerical model are in good agreement. The need to increase the useful life of dams and maintain their storage capacity for controlling and optimizing the use of limited water resources is one of the most important issues in dam engineering. In addition, the necessity of sustainable management of the reservoir requires integrated sediment management, taking into account all aspects of the rules and strategies that are appropriate to the conditions prevailing in the studied area. In order to solve the problem of sedimentation of reservoirs, various methods can be used which are briefly: watershed management and soil conservation, passing density current, hydraulic flushing, using the bypass systems, and disposal of reservoir sediments by mechanical devices such as dripping and siphoning. Applying these methods requires a complete understanding of the capabilities and limitations of these methods.

Previously, the most effective way to analyze the flushing process was to model the dam and bottom outlets in laboratory scale. This method is expensive and time-consuming, and sometimes, it is unsuccessful to design and change the specifications of the flushing process correctly. In these conditions, the use of numerical models has been proposed as an alternative solution, especially when some robust experimental results could help in calibration process. Flushing is necessary to maintain the operating capacity of reservoirs. Simulating of dam bottom outlets with numerical and physical models and combining their results will increase the flushing efficiency in existing and new dams. It should be mentioned that based on the literature, no research has been done so far to simulate the performance of bottom outlets in three-dimensional mode (especially with different sections). The purposes of this study are to verify Flow-3D software to simulate flushing of reservoirs using laboratory results and use it to design optimal gates for dam's bottom outlets. For this purpose, the results of the laboratory modeling of Dehghani et al. (2010) have been used. Finally, the output of both models (laboratory and simulated numerical model) is compared with each other. In addition, the effect of the number, dimensions, and shape of bottom outlets on the amount of eroded sediment also has been investigated with a constant volume of used water.

Table 1 Results of measurements in sedimentation experiments using the gate 3 with a diameter of 5.08 cm (Dehghani et al. 2010)

Test number	Height of water (cm)	Discharge outlet from drain (L/s)	Sediment height (cm)	Flushing cone width (cm)	Flushing cone length (cm)	Flushing cone volume (cm^3)
Gate 1-3	36	0.16	16	24	24.2	6028
Gate 2-3	36	0.3	16	25.4	25.4	6977
Gate 3-3	36	0.8	16	27.2	27.2	8062
Gate 4-3	36	1.4	16	29.3	29.3	9436
Gate 5-3	36	3	16	31.4	31.4	11219
Gate 6-3	66	0.3	16	23.8	23.8	6235
Gate 7-3	66	0.8	16	25.9	26.5	7219
Gate 8-3	66	1.4	16	27.6	27.8	8447
Gate 9-3	66	3	16	30.6	30.4	10700
Gate 10-3	66	5	16	32.8	32.8	12723
Gate 11-3	96	0.3	16	22.2	22.2	6571
Gate 12-3	96	0.8	16	24.2	24.5	6723
Gate 13-3	96	1.4	16	26.4	26.4	7830
Gate 14-3	96	3	16	29.4	29.4	9946
Gate 15-3	96	5	16	31.4	31.4	11735

Research materials

In this study, Flow-3D software was used to investigate the effect of shape, dimensions, and the number of the bottom outlet on flushing operations.

Flow-3D model

The Flow-3D model is an ideal model for simulating fluids with complex geometry (Movahedi et al. 2018). This program applies to unsteady three-dimensional streams that have a free surface. The software uses a finite volume method in regular rectangular grids. Flow-3D uses single and double precision methods to solve equations. The software uses five turbulence models, such as RNG (K-ε) models. In the Flow-3D model, two numerical techniques are used for geometric simulation, (i) the volume of fluid (VOF) method: to show free surface behavior and (ii) fractional area-volume obstacle representation (FAVOR): to simulate the rigid surfaces and some components, such as geometric boundaries. The use of Flow-3D software and the RNG turbulence model (K-ε) was recommended for modeling of sedimentation by Brethour and Burnham (2010).

Table 2 Specifications of bottom outlet gates

Gate	Shape	Dimensions (cm)	Total area (cm^2)
Gate 1	Circle	D = 5.08	20.25
Gate 2	Square	V = 4.5, H = 4.5	20.25
Gate 3	Vertical rectangle	V = 3.5, H = 5.9	20.25
Gate 4	Horizontal rectangle	V = 5.9, H = 3.5	20.25
Gate 5	Circle	D = 2.54	5.06
Two-Gate 6	Two circles	D = 3.59	20.25

Scouring modeling in Flow-3D software

Sediment scour model in Flow-3D software is used to simulate sediment transport, erosion, and deposition and change the sedimentation status due to fluid flow. The scour model uses two fields of suspended sediment concentration and bed sediment. Moving and raising suspended sediments with fluid is due to local pressure gradient changes. These suspended sediments may be caused by the inflow of suspended particles or by the erosion of the bed. Also, bed load is not easily displaced because they are confined by adjacent particles. Bed sediments move only when they are eroded and become suspended loads at the interface between the fluid and the bed. The suspended load can be converted to bed load if the sedimentation rate is higher than the bed erosion rate. The part of the volume of control that is occupied by solid particles of sediment and fluid is defined in accordance with Equation (1), with symbols of f_s (solid volume fraction) and f_L (liquid volume fraction), respectively.

$$f_s + f_L = 1 \tag{1}$$

The suspended load increases the fluid's real viscosity. This increase continues as long as the solid volume fraction (f_s) reaches the cohesive solid fraction (f_{sCO}). After reaching this amount, increasing the suspended load does not increase the viscosity, but it causes the particles to act

Table 3 Comparison of the results of numerical modeling of pressure flushing with experimental result of Dehghani et al. (2010)

Parameter	Numerical modeling results with Flow-3D	Experimental results	Error (%)
Flushing cone length (cm)	37	31.4	0.85
Flushing cone width (cm)	33	31.4	0.95
Maximum flushing cone height (cm)	20.7	19.8	0.96
Flushing cone volume (cm^3)	10,477	11,735	1.12

like solid. In this case, the average fluid viscosity is calculated from Equation (2).

$$\mu^* = \mu_f \left[1 - \frac{Min\,(f_s, f_{sCO})}{f_{sCR}}\right]^{-1.55} \tag{2}$$

where μ_f is fluid viscosity and f_{sCR} (critical solid fraction) is the critical component of the sediment particles, and by default, its value is set to 0.67. μ^* is increased viscosity due to suspended sediments in the fluid that its maximum for the critical component of the sediment is 18 μ_f. If the volume fraction of the sediment is greater than or equal to f_{sCR}, the density of the dense sediment is equal to $f_{sCR} \times \rho_S$, which is part of the initial condition of the model.

According to Equation (3), the apparent density ($\overline{\rho}$) assumed as a linear function of the volume of sediments:

$$\overline{\rho} = \rho_L + f_s(\rho_s - \rho_L) \tag{3}$$

where ρ_L and ρ_S are the apparent density of the fluid and sediment.

The shear stress bed is active and causes erosion and displacement of the sediment at the bed surface. This erosion is a function of the shear stress of the fluid in the surface, the critical shear stress, and the density of the fluid and sediment. By following Equation (4), the critical Shields parameter shows the minimum shear stress required to lift the sediment particles from the joint surface of the fluid and the active bed.

$$\theta_{crit} = \frac{\tau_{crit}}{g(\rho_L - \rho_s)d} \tag{4}$$

In which θ_{crit} is the critical Shields parameter and τ_{crit} is the shear stress flow at the threshold of motion of the sediment particles. This model is developed to estimate and predict the amount of sediment flow that has eroded from the common bed. For this purpose, the shear rate parameter $\sqrt{(\tau/\rho)}$ is defined for measuring the flow separator power. Therefore, the rate of lifted sediments from the bed (u_{lift}) is shown by Equation (5).

$$u_{lift} = \alpha n_s \sqrt{\frac{\tau - \tau_{crit}}{\overline{\rho}}} \tag{5}$$

where n_s is the normal vector of the bed surface, α is the dimensionless parameter that shows the probability that the sediment particles will separate from the bed, which is usually

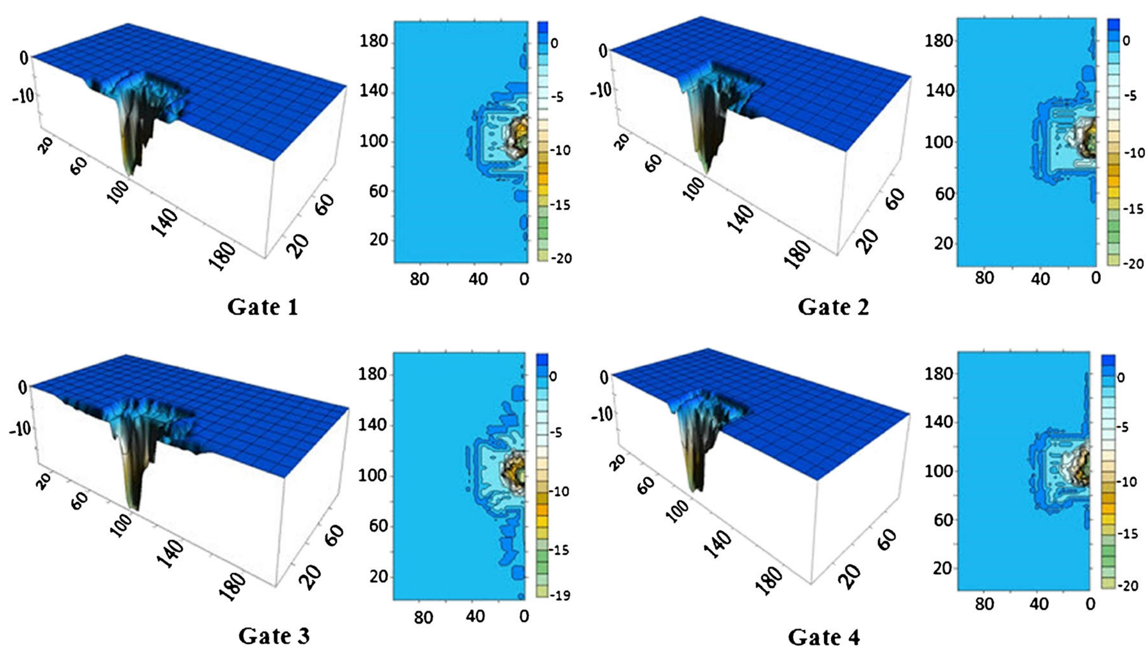

Fig. 1 A three-dimensional and two-dimensional (plan) of scouring cone of one to four gates (axis units are in centimeters)

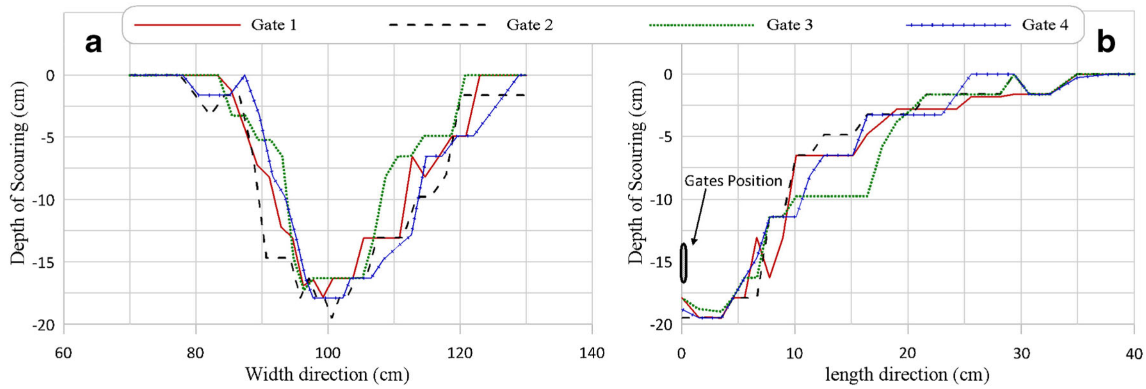

Fig. 2 Scouring cone near the gates with different shapes: **a** cross section, **b** longitudinal profile

equal to or less than 1. The angle of the natural deposition of sediments in this model is obtained from Equation (Dehghani et al. 2010), where *n* is the normal vector of the surface and *g* is the gravity vector (Dehghani et al. 2010)

$$\theta = \frac{n}{|g|} \quad (6)$$

In Flow-3D, effective critical shear stress at the sloping surface in bed scouring is estimated by the effect of the internal friction angle of the sediments by Equation (7) (Brethour 2003).

$$\tau_{crit} = \tau_{crit0}\sqrt{1 - \frac{sin^2\theta}{sin^2\varnothing}} \quad (7)$$

In static flow, the internal friction angle of the sediment particles determines the minimum level at which the walls of the scour hole can remain stable. The high internal friction angle of the sediments indicates the steady slope of the wall in steep slopes (such as clay). At the lower angles, the wall would drop and move forward (like sand). The scour model in Flow-3D software offers a direct and easy approach to modeling and erosion and sedimentation in 3D streams. The simulations show that the depth of the scour hole is in good agreement with the experimental results. However, the following constraints exist for the scour model: the coarse particles of the sediment cannot be simulated correctly, because the prevailing hypotheses for the sedimentation in the model are being violated. Such a model typically requires the modeling of the bed load in which the sediment particles on the bed of dense sediments are rolled or slipped until they are suspended during the flow (Brethour 2003).

Methods

Calibration of 3D model of pressurized flushing

To calibrate and evaluate the model, information and experimental data of Dehghani et al. (2010) were used. This setup could be summarized as follows:

- Water supply system consists of an underground tank and a pump to recirculate the steady flow. The system is also supported by an adjusting valve, a digital flow-meter, and an 11-m flume. Main reservoir is hexahedral with dimensions of 3 m (length), 2 m (wide), 1.5 m (height).
- Bottom outlet of main reservoir is a 1-inch-diameter gate valve. Sediments in the system include silica particles with a median diameter (d_s) 1 mm and geometric standard deviation (σ) of 1.25. Sediments deposited at the end of main

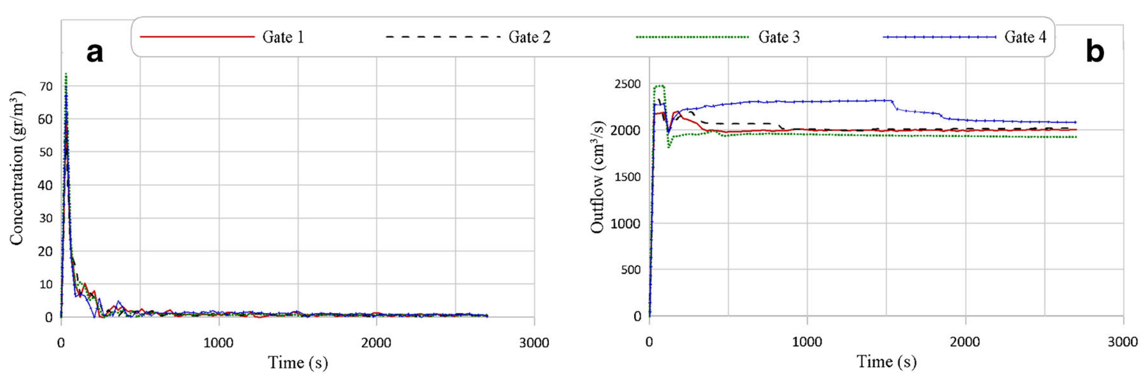

Fig. 3 Fluctuations in concentration and volume of output sediment from the gates over time: **a** sediment concentration, **b** outflow variation

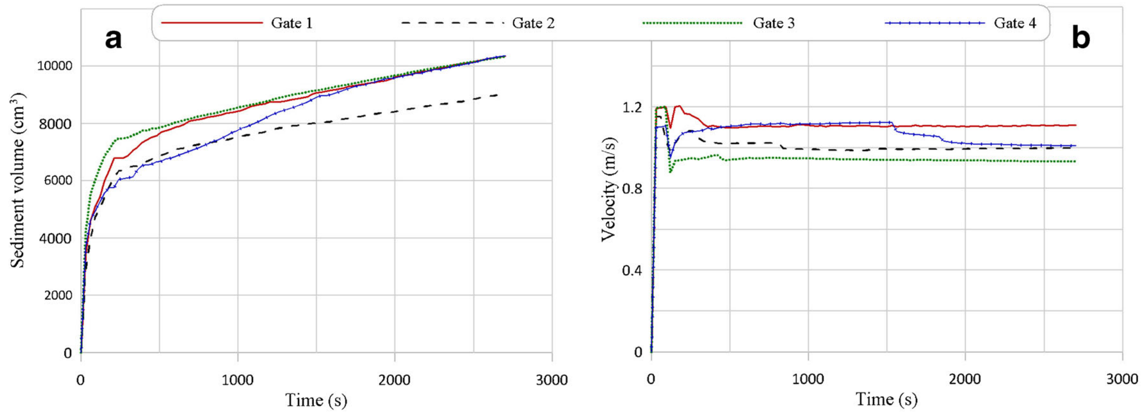

Fig. 4 The variations of the outflow velocity and sediment from the gates over time: **a** volume of the output sediment, **b** variation in average velocity

reservoir, so that the top layer of the sediment deposits was flattened at a certain level over the bottom outlet.

– Settling basin reservoir is the region that the water and sediment were mixed and sediments were settled. The basin is a rectangular flume of 3.6 m long, 1 m wide, and 76 cm height.

The width and length of the scour cones formed in the laboratory setup were 24.3 and 24.7 cm, respectively. Also, the geometry of the cone formed in the Flow-3D software was similar to that of the experimental model. In this research, due to the wide range of factors affecting the scouring phenomenon, especially in three dimensions, and due to the importance of this phenomenon in the design of the bottom outlet gates of dams and given that the operation of three-dimensional models is very timely, to save time, a 24-core computer server was used. A sample of the experimental results is presented in Table 1.

At the calibration stage, different types of sediment transport models used in Flow-3D were selected and sediment transport model parameters, such as Shields parameter and turbulence model, were investigated. For this purpose by changing the above parameters, the results such as scouring profile as well as the amount of sediment removal (volume of removed sediment versus time and total volume of removed sediment) were compared with the experimental values. On the other hand, calibration was carried out completely on the basis of matching the results of numerical model with experimental data. Results of the best adaptation were reported in the paper (Table 3). The error reported in Table 3 shows the appropriate accuracy and acceptable selection

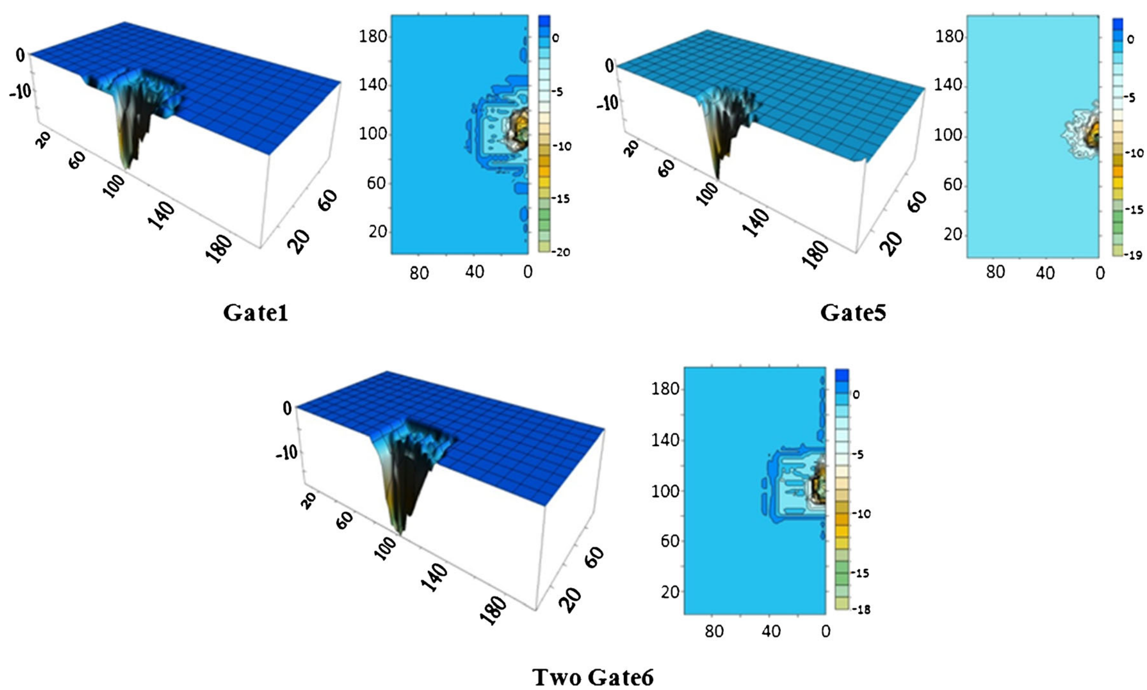

Fig. 5 A three-dimensional and two-dimensional (plan) scouring cone with different area and number of gates (unit axis is centimeters)

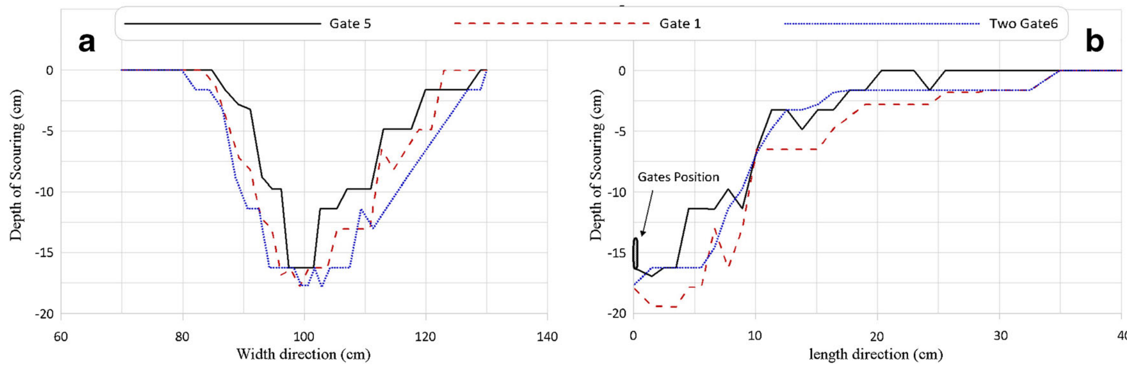

Fig. 6 Scouring cone near the gates with different shapes and sizes: **a** cross section, **b** longitudinal profile

of calibration parameters. In the calibration process, k-ε turbulence model was selected as the appropriate model.

Flow-3D software determines and selects the optimum time step during the simulation. The user can declare the minimum and maximum desired time step as limiting to the model. Here, the time step was selected as 0.001, as the time step in the calibration process. Finally, the model continues with the optimal time step

3D modeling of sedimentation for the design of bottom outlet gates

As the flow passes through the bottom outlet gates, the sediment of the tank is washed and the sediment operation is simulated appropriately. By changing the shape of the gates from the circle to the square, vertical rectangle, and horizontal rectangle, the effect of the shape of the gates on the amount of eroded sediment volume (with a constant volume of water usage) was investigated. Four gates with the same area (20.25 cm^2) were investigated for the effect of the shape of the gate on the efficiency of the pressure flushing as presented in Table 2. In addition, to examine the effect of the area parameter, gate 1 and gate 5 were compared. To evaluate the effect of the number of gates on the efficiency of pressure flushing, gate 1 was compared with two circular gates with a diameter of 3.59 cm (two-gate 6). Flushing efficiency is the most important parameter in the evaluation of the effect of the shape and area of gates in flushing. This parameter shows the relationship between the amount of water used and the amount of washed sediment. The higher efficiency shows that the maximum amount of sediment can be drained from the tank with constant water usage.

Results and discussions

Calibration and evaluation three-dimensional Flow-3D model in pressure flushing

The Flow-3D model was calibrated for the same conditions as Dehghani et al. (2010) for a gate with a diameter of 5.08 cm and a 96 cm water head. Accordingly, sediment concentration approaches zero at 40 s after starting the experiment, but the modeling was done for 2700 s (45 min). In Table 3, the Flow-3D modeling results are compared with the experimental conditions. According to Table 3, the results of the Flow-3D model in the simulation of pressure flushing are appropriately matched with the experimental results.

Evaluation of the effect of gate shape on the efficiency of pressure flushing

The duration of the modeling in Flow-3D was 2700 s (equal to the experiment time). In all gates, 37 to 41 s after the start of sediment evacuation, the concentration of the outflow sediment decreased sharply, followed by a slowdown trend (Fig.

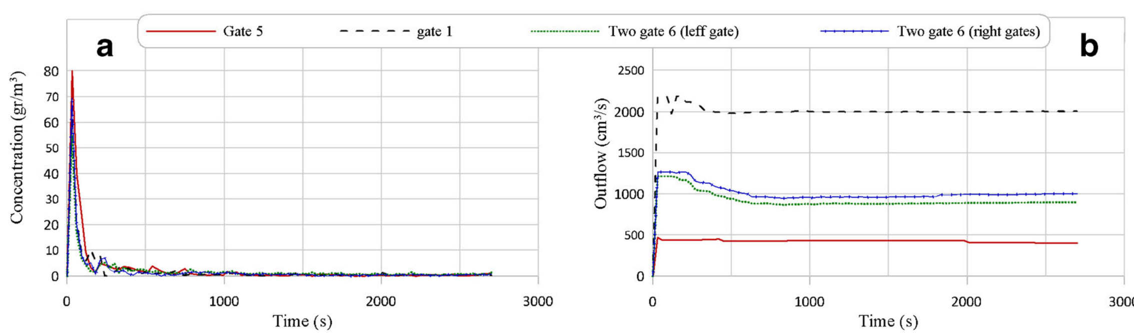

Fig. 7 Fluctuations in concentration and volume of output sediment from the gates over time: **a** sediment concentration, **b** outflow variation

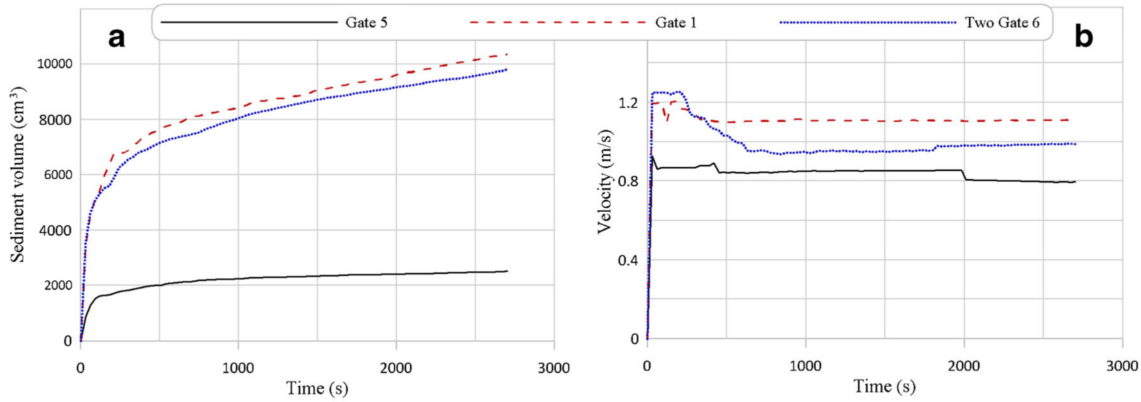

Fig. 8 The variations of the outflow velocity and sediment from the gates over time: **a** volume of the output sediment, **b** variation in average velocity

3a). The three-dimensional and two-dimensional scouring cone plan for all four gates is shown in Fig. 1. The height of the sediment surface is zero.

Figure 2 a shows the position of the maximum depth of flushing cone immediately after the gate. Figure 2 b shows the longitudinal profile of the scouring cone along with the flow for all four gates immediately after the gate. In Fig. 3a, variations in the sediment concentration of the gates are shown.

Figure 3 b shows the variations in gates outflow versus time for different gate shapes. Figure 4 a shows the variation in the volume of the outlet sediment and Fig. 4b shows the variations in the average velocity of the gates versus the time.

Effect of area and number of bottom outlets on the efficiency of pressure flushing

In this section, the effect of the area and the number of gates on the pressure flushing are considered. The three-dimensional and two-dimensional plan of scouring cone for all four gates is shown in Fig. 5. Figure 6 a shows the position of the maximum scour depth relative to the position of the gates, and Fig. 6b shows the longitudinal profile of the scouring cone along the flow path for all three gates.

Figure 7 a shows the changes in the sediment concentration of the outlet gates. Figure 7 b shows the variations in the outlet flow from the gate relative to the time for the different areas and the number of gates. Figure 8 a shows the variation in the volume of outlet sediment and Fig. 8b shows the variations in the average velocity of the gates versus time.

Table 4 reviews the 3D flushing simulation results for different types of gates. The specifications of the scouring cone and the performance and efficiency of the flushing process are comparable. According to Fig. 9, if the shape of the gate is a horizontal rectangle, the volume of the scour cone will be maximized. The maximum length scour cone occue in two gate 6 and the maximum width and depth of the scour cone occur in the vertical rectangle gate.

As shown in Fig. 10a, the minimum amount of flushed sediment was due to a circular gate with a diameter of 2.54 cm, due to the smaller area of the gate than the other gates. However, even though the horizontal rectangle gate has the same area in comparison with other gates and whereby the gate center is located in all the gates at the same depth; it has the largest amount of removed sediment. The reason is that the shape of the gate increases the average velocity of the transferred flow, compared with other gates. Figure 10 b shows the

Table 4 Results of 3D flushing simulation with Flow-3D for different types of gates

3D simulation	Gate 1	Gate 2	Gate 3	Gate 4	Gate 5	Two-gate 6
Flushing cone length (cm)	37	33	37.3	40.2	26.4	42
Flushing cone width (cm)	33	32	33.4	33	21.09	27.5
Maximum depth of flushing cone (cm)	20.7	20.69	20.71	20.2	18.15	19.09
Area of vertical projection of flushing cone (cm^2)	1221	1056	1246	1327	557	1155
Flushing cone surface (cm^2)	20,058	19,857	19,899	19,942	19,673	19,837
Sedimentation surface (cm^2)	8	0	0	0	11	0
Scoured sediment volume (cm^3)	10,477	10,118	9805	10,763	5245	9804
Sedimentation volume (cm^2)	0.2	0	0	0	2.63	0
Flushing time (s)	40	42	34	33	68	41
Water consumption volume (L)	200	210	170	165	95.2	205
Flushing efficiency (%)	5.24	4.82	5.77	6.52	5.51	4.43

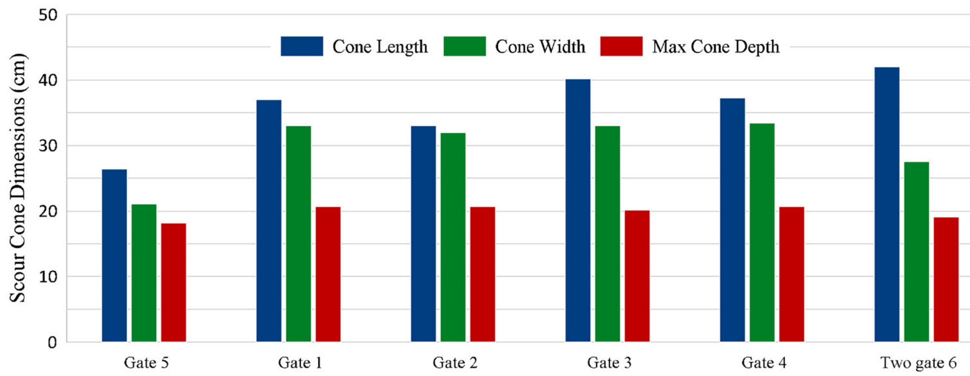

Fig. 9 Comparison of scouring cone dimensions for all types of gates

duration of flushing for different types of gates, as it is expected that a gate with a smaller area needs more time of flushing. The benefit of one gate is that in the shortest time, the maximum amount of sediment is washed and the least amount of water is used. As shown in Fig. 10b, the time required for gate 1 to flushing is approximately equal to two-gate 6. However, the gate 1 sedimentation efficiency is 18% higher than the efficiency of two-gate 6. Given that the area of the two gates is the same, it can be realized that a gate with a specific area has a higher efficiency than two gates with the same area. Also, the comparison of gate 1 and gate 5 shows that when the area of the gate increases four times (the gate with a diameter of 2.54 cm compared with the gate with a diameter of 5.08 cm), the time required for flushing is reduced by 70%. Therefore, when the time for flushing is important, it is better to use gate 1, which has a higher surface area and less efficiency. However, if time is not a limiting parameter, gate 5 is recommended with less area and more efficiency. However, in a constant area, the gate with a horizontal rectangle shape needs the least time for flushing removal. Figure 10 a also shows the amount of water used for flushing in a variety of gates, as it is expected that a smaller area gate (diameter of 2.54 cm) uses the least volume of water, and in the constant area, the minimum value is obtained in a horizontal rectangle gate. As shown in Fig. 10a, the maximum efficiency is related to a rectangular horizontal gate. This gate with a constant area over a period drains less water volume. However, due to its form, the flow rate is greater and the further volume of the sediments is depleted. The smaller area gate, although it removes less amount of the sediment, but has a suitable efficiency due to use of less water. However, the duration of the flushing increases, which may interfere with the operation of the reservoir. In operation, the flushing gate with a larger area than the gate with the lower area is preferred. Because if significant volumes of sediment accumulate in front of the gate, when flushing is changed from under pressure to free mode (river), accumulated sediment may collapse in front of the gate and the gate will generally be blocked. This has actually happened in dams like Latyan and Dez (in Iran). Therefore, the gate with a horizontal rectangular shape is optimal in terms of the removal of sediments in pressure flushing operations. Finally, the larger the area of the gate causes lowering the operational risk. However, in terms of sedimentation efficiency for each reservoir, the optimal area can be determined with regard to the volume of water and the shape of the topography and other effective parameters (such as rapid drainage of the reservoir during emergencies).

Conclusion

In this study, using the 3D-Flow model, the effect of the area, number, and shape of the bottom outlet on the dimensions (volume, length, and width) of the scour cone under the

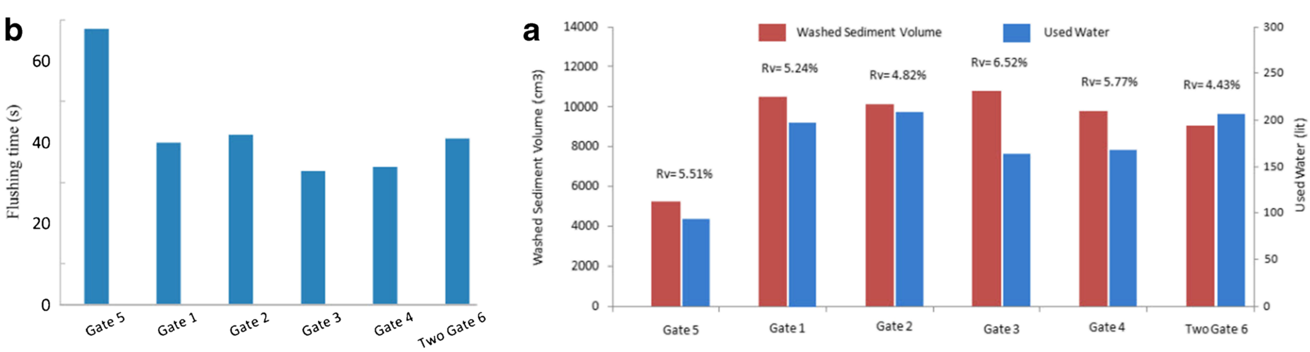

Fig. 10 Flushing efficiency for different gates: **a** the amount of washed sediment, the amount of used water, **b** flushing time

pressurized flushing were studied. To calibrate and evaluate the model, experimental data of Dehghani et al. (2010) were used. The calibration results showed that the Flow-3D model is a suitable and effective tool for testing pressure flushing on a laboratory scale, and the results of the model are in good agreement with the experimental results. Finally, it was revealed that the maximum length and maximum depth of the scour cone are obtained for the horizontal rectangular gate. According to the results of this study, it is possible to prioritize various outlets in terms of removed sediment, the time required for flushing, and the amount of water consumed for flushing (Table 4). However, the most effective parameter in the evaluation of the effect of the shape and area of the outlets is the flushing efficiency. This parameter indicates the relationship between the amounts of consumed water and the removed sediment. Higher efficiency shows that by using constant amount of water, more sediment could be removed from the reservoir. More efficiency belongs to bottom outlets with rectangular (horizontal) section. Considering the constant area, this outlet, in less time, discharges less volume of water. However, because of the greater flow velocity (due to the type of its orientation), it removes more deposited sediments. Although the outlet with less area removes less sediment, it uses less water and its flushing efficiency is significant. Relatively, time duration for flushing increases and it means inappropriate operation of the reservoir. Practically, the outlet with greater area is preferable than the one with smaller area. Because if a considerable volume of sediment is accumulated in front of the outlet, it will be collapsed when flushing is converted from pressurized form to free flow. It may completely block the bottom outlets. This issue has occurred in some cases of Iran (e.g., Latian Dam and Dez Dam). Therefore, in the pressurized flushing, bottom outlets with rectangular (horizontal) form are optimal from the point of sediment removal. The more the bottom outlet area, the less risk is in the flushing operation. According to the method used in this research and from the point of view of flushing efficiency, optimal area can be determined for each reservoir according to the volume of water, topography, and other design parameters. Meanwhile, the results of Sawadogo et al. (2019) are consistent with the results of present study and stated that numerical models are reliable in precisely predicting the development of scouring hole around the bottom outlet.

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