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Effect of submerged vanes in front of circular reservoir intake on sediment flushing cone

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Reservoir sedimentation is a long-term process with various risks, such as reduction of storage capacity, hydropower generation and flood control functions throughout a reservoir's lifespan. For reservoirs facing loss of function with severe deposition, sediment flushing is an approach to preserving long-term storage. Here, submerged vanes combined with pressure flushing operations are proposed to facilitate scouring of such deposition. Experiments with various submerged vane heights, inclination angles on the flow direction, spacing, and divergent and convergent arrangements were conducted to investigate the scour cone volume and removal efficiency. Results showed that two divergent submerged vanes at an angle of 20° on the flow direction and optimum vane spacing ratios removed the deposited sediment significantly. In the presence of the submerged vanes, final sediment flushing volume and efficiency increased by a factor of 48 compared to the reference test. Using the experimental results, three equations were proposed to estimate the scour cone dimensions (length, width and depth). Additionally, a non-dimensional equation was developed for estimating the scour cone volume, using a polynomial correlation with vane spacing. The results of this study recommend the best installation of submerged vanes for releasing deposited sediments in the region near the bottom outlets of reservoirs.

Notation

C_u	uniformity coefficient
D_o	diameter of bottom outlet
d_{50}	median grain size
d_c	depth of sediment flushing cone
E	flushing efficiency index
Fr	Froude number
G_s	sediment specific gravity
g	gravitational acceleration
H	height of submerged vanes
H_s	sediment level
H_{sv}	height of submerged vanes above sediment bed
H_w	water head
L	length of submerged vanes
L_c	length of sediment flushing cone
L_{hr}	minimum distance of submerged vanes from each other
L_v	distance of submerged vanes from bottom outlet
Re	Reynolds number
u_o	flow velocity at the bottom outlet
V_c	volume of sediment flushing cone
W_c	width of sediment flushing cone
θ	inclination angle of submerged vanes on the flow direction
μ	fluid viscosity
ρ_s	sediment density
ρ_w	fluid density
σ	gradation of the sediment mixture

1. Introduction

Reservoir sedimentation is a major problem that occurs when a reservoir behind a dam is filled with sediment carried by the incoming river. The rate of sedimentation in a reservoir depends on numerous factors, including the catchment and reservoir characteristics and climate (Dreyer, 2018). All over the world, the average global sedimentation rate of reservoirs is about 0.8% of the original storage capacity per year, but this figure is much higher in some regions, such as Asia (Annandale *et al.*, 2016; White, 2001). Sedimentation not only reduces the storage capacity of a reservoir but also influences water supply, efficiency of hydropower schemes, flood control, navigation, recreation, energy production and the environment (Das *et al.*, 2020; Petkovsek and Roca, 2014). Sediment accumulation also leads to the clogging of outlet structures. This problem threatens dam safety and the sustainability of reservoirs because the intakes and outlets are not designed for the passage of sediment. Therefore, efficiency decreases and maintenance costs increase (Schleiss *et al.*, 2016).

Several sediment strategies have been applied all over the world to control and manage reservoir sedimentation (Kantoush *et al.*, 2010, 2011). These strategies can be categorised into three groups: (*a*) reduce sediment yield, for instance through watershed management and upstream check dams; (*b*) minimise deposition, for example by drawdown sluicing, density current venting and sediment bypass; and (*c*) sediment removal from reservoirs, using procedures such as hydraulic flushing and dredging (Mooris, 2020; Schleiss *et al.*, 2016). Hydraulic flushing is an effective method for evacuating reservoir sedimentation by scouring out deposited sediments from reservoirs with the opening of bottom outlets (Esmaeili *et al.*, 2017; Kantoush and Sumi, 2010). Generally, depending on the level of water in a reservoir during the flushing process, flushing can be classified as either free-flow or pressure flushing. In pressure flushing, the water level is sustained in the reservoir, and deposited sediment can be scoured out very rapidly in the vicinity of the sluice gate opening. In this method a cavity or hollow in the form of a cone or funnel will develop after a time in front of the bottom outlet (Emamgholizadeh *et al.*, 2006).

It should be mentioned that pressure flushing can never ensure the reservoir capacity, since its effect is only close to the low-level outlet in front of the dam. In principle, the purpose of pressure flushing is to maintain the functionality of bottom outlets, which are safety release structures that eventually free the intakes from sediments if they are located close to the outlets. Over the whole reservoir, Müller *et al.* (2014) and Schleiss *et al.* (2016) proposed the approach of whirling up fine sediments with introduced turbulence using pumped-storage operation, air bubble and water jets.

Many researchers have investigated the process of hydraulic pressure flushing. Typically, in such research, the behaviour of pressure flushing and the effects of hydraulic parameters on pressure-flushing performance are investigated (Fang and Cao, 1996; Fathi-Moghadam *et al.*, 2010; Kamble *et al.*, 2017; Powell and Khan, 2012; Shahmirzadi *et al.*, 2009; Talebbeydokhti and Naghshineh, 2004). Previous research indicates that the dimensions of flushing cones depend on the water depth in the reservoir, the discharge and diameter of the bottom outlet, and the mechanical properties of the sediments. Results show that the depth of the scour and its length will be increased by the sediment's height and reduced by the sediment's diameter.

Pressure flushing without combination with an auxiliary structure will have limited impacts on the scouring cone dimensions and volume. Different researchers have proposed and used techniques to increase flushing efficiency. Ahadpour Dodaran *et al.* (2012) studied the impact of vibrator plates in sedimentary layers and their location on the volume and dimensions of flushing cones. They found that the position of the vibrator plates toward the dam axis and their frequency rate were the main factors affecting the dimensions of flushing cones. Jalili and Hosseinzadeh Dalir (2012), using a semi-cylindrical structure with a gap in it, reported that increasing the diameter of the semi-cylindrical structure increased the amount of discharged sediment. Althaus *et al.* (2015) also investigated the application of jets in flushing and found that flushing efficiency increased between 1.5 and 2 times compared to the reference test without jets. The results obtained by Madadi *et al.* (2016) revealed that the semi-confined piles group structure increased the amount of flushed sediments by a factor of 3.5 compared to the reference tests without piles. In another study by Madadi *et al.* (2017), the authors improved the efficiency of the sediment-flushing operation by using a semi-cylindrical structure. Mohammad *et al.* (2018) demonstrated that an increase in internal outlet offset from 20 to 80 mm increased the scour cone volume 1.8 times compared to the reference test without structure. They also found that a greater amount of sediment was scoured when the sediment height increased or the sediment size decreased. Dreyer (2018) indicated that a flat, rectangular outlet shape showed the best performance because it created the longest, widest and deepest flushing cones in most scenarios. The effects of submerged vanes (SVs) on pressure-flushing performance have been explored by Abdolahpour *et al.* (2015) and Mahtabi *et al.* (2018). The authors showed that pressure-flushing efficiency increases with the use of SVs. Abdolahpour *et al.* (2015) concluded that the best flushing performance is achieved when the ratio of the distance of SVs from the outlet to the outlet diameter is 0.3. Mahtabi *et al.* (2018) found a similar increase in sediment-flushing performance by decreasing the row number of vanes in a parallel arrangement. They also obtained an increase of 11.33 times in pressure-flushing efficiency compared to the reference test.

As mentioned above, several techniques have been employed to increase the performance of sediment pressure flushing in reservoirs. The present study represents the first comprehensive investigation into using SVs with new arrangements and different characteristics to increase the performance of hydraulic pressure flushing and sediment removal efficiency in reservoirs.

The SV technique is a method of sediment control and river and alluvial duct management. It is an effective method for protecting riverbanks against erosion, avoiding sediment entry into the water intake or diversion structures, deepening the sedimentary bed and stabilising the river crossing (Odgaard, 2009). In general, SVs are structures that can be used to intensify the sediment discharging by creating eddy currents and increasing turbulence (Odgaard, 2017). They are installed at a low angle of attack flow in channel beds. By establishing vanes, secondary currents are produced on both sides, which, by extending in a downstream direction, create a bigger rotational flow. The formation of secondary currents is due to vertical pressure gradients on both sides of the vanes. The side of a SV that is directly exposed to the upstream approaching flow is called the high-pressure side. On this side, along the SV height, the pressure decreases from bottom to top; on the opposite side, which is called the low-pressure side, the pressure increases from bottom to top. As a result of the reverse distribution of pressure on both sides of the vane, there will be a secondary stream from the high-pressure side to the low-pressure side; this means that, on the high-pressure side, there is an upward velocity component and, on the low-pressure side, the velocity component is downward. These vertical components of velocity form vortices behind the end edge of the vane. Vortices twist a little lower than the upper edge of the vane and create larger vortices, which, while rotating on the vertical vane perpendicular to the flow, are extended downstream with the mainstream. This rotational stream causes changes in bed shear stress, the transverse distribution of sediments and the sedimentary bed topography (Odgaard, 2009) (see Figure 1).

Usually, SVs have been used for preventing river bank erosion, to deepen channels for navigation, to exclude sediment from water intakes and to stabilise river crossings (Maatooq and Adhab, 2017; Odgaard, 2017; Odgaard and Kennedy, 1983; Seyed Mirzaei *et al.*, 2016; Sharma and Ahmad, 2019; Tan *et al.*, 2005).

In this study, SVs were proposed with the purpose of increasing the reservoir flushing efficiency. The aim of this study was to investigate the impact of different arrangements and geometric parameters of vanes on flow characteristics behind the bottom outlet and the sediment evacuation rate. Eventually, the final volume of the flushing cone and flushing efficiency were calculated and an equation for estimating the reservoir sediment evacuation volume was proposed.

2. Materials and methods

2.1 The physical model

In this study, a physical model of a dam with a low-level outlet and water conduit was constructed in the Hydraulic and Water Structures Research Laboratory of the Water Engineering Department of Shahid Bahonar University of Kerman, Iran, and all the tests were carried out on this model (Figure 2).

The physical model occupies an area 7.5 m × 3.5 m in its entirety and is 1.8 m high. The physical model was not based on any specific existing reservoirs, but was rather a representation of the general problem of deposited sediment behind any dam wall (Dreyer, 2018). This experimental study was designed and tested to provide an insight into the scour cone formation associated with the installation of different arrangements of vanes.

The physical model consists of five main parts: (*a*) an input section that includes a centrifuge pump, a water transfer

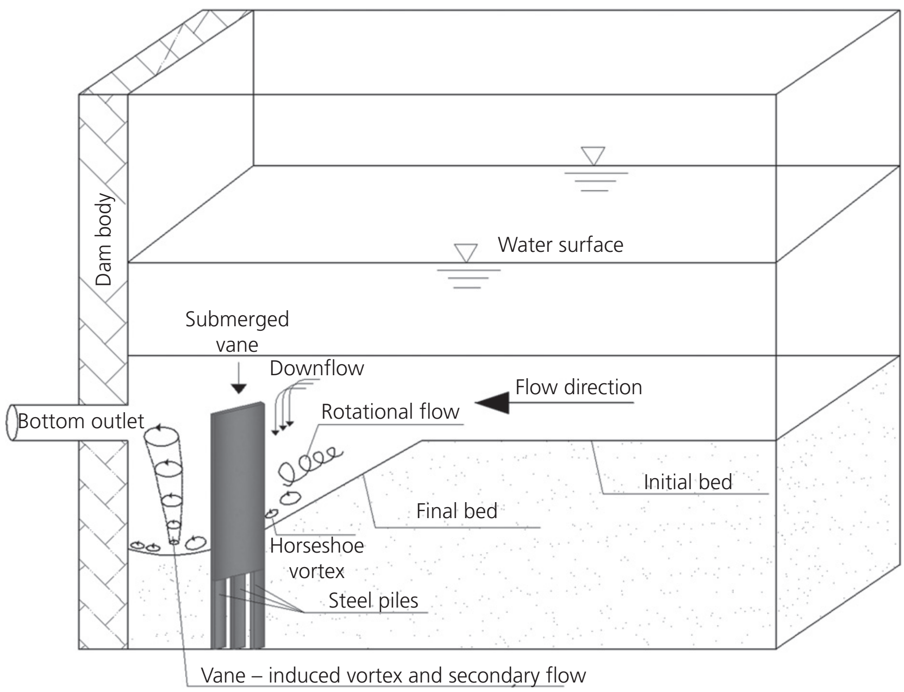

Figure 1. Hydraulic behaviour and induced downstream vortex of SV in reservoir

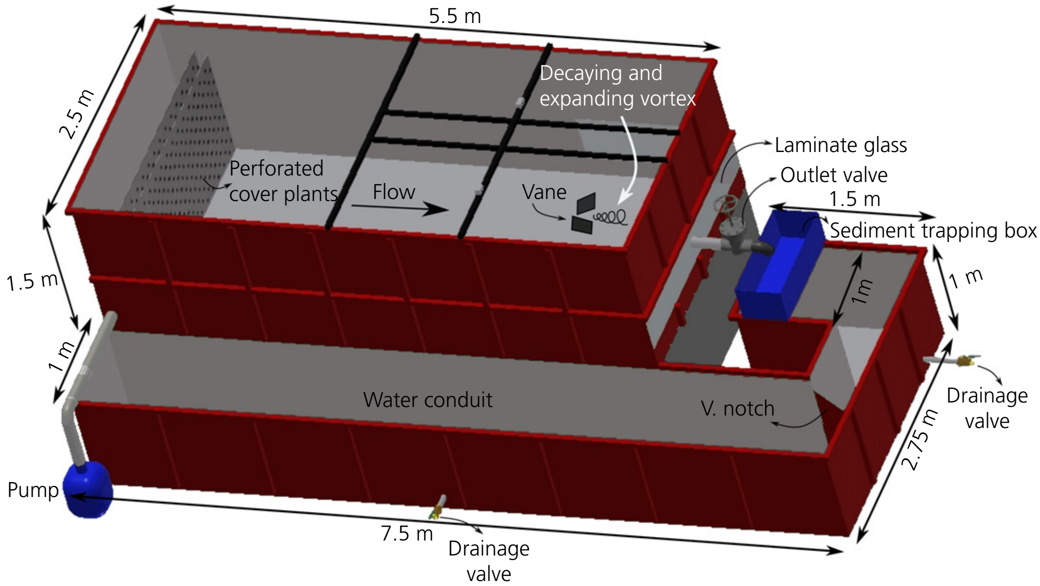

Figure 2. Three-dimensional representation of the physical model with a schematic diagram showing SVs and induced vortex

pipe and perforated cover plates for dissipating the inlet flow, which are placed 50 cm from the beginning of the reservoir; (*b*) the main reservoir; (*c*) an output section that includes an outlet pipe and sediment trapping box with dimensions of 1.1 m long, 0.45 m wide and 0.35 m in high; (*d*) a V-notch weir for measuring outlet discharge; and (*e*) a water conduit.

It should be noted that, on the front side of the reservoir, a laminate glass was used for better observation of flow and sediment behaviour during the tests. An outlet pipe with an inner diameter of 10 cm was in the middle of this glass, at a distance of 40 cm from the bottom of the reservoir. There was a valve on the outlet pipe for setting output flow.

2.2 Sediment characteristics

In this study, non-cohesive silica was used as sediment material and standard test methods ASTM C128-15 (ASTM, 2015) and ASTM C136/C136M-14 (ASTM, 2014) for the sieve analysis of fine and coarse aggregates were used. The median grain size (d_{50}) and specific gravity of the sediment were determined to be 0.73 mm and 2.625 t/m^3, respectively.

By analysing the sediment size distribution, the uniformity coefficient (C_u) and gradation of the sediment mixture (σ) were calculated as 2.45 and 1.49, respectively. These results indicate a quasi-uniform size distribution because C_u and σ are less than 4 and 1.5, respectively (Shafai Bejestan, 2009; Fathi-Moghadam *et al.*, 2010).

It should be noted that sediments in rivers and reservoirs often contain fine-grained and cohesive materials. However, since there are many problems in modelling cohesive sediments, such as the existence of several variables and changing sediment behaviour in relation to small changes in the amount and type of cohesive sediment, most studies, especially those on erosion, have been carried out with non-cohesive sediments. Therefore, in this study, the effect of the vanes on non-cohesive sediments only was investigated, and the results do not show the absolute values for other sediment conditions.

2.3 SV characteristics

The SVs used in this research were made of galvanised plates with dimensions of 15, 50 and 0.2 cm for length, height and thickness, respectively. The total height of the plates was determined with the aim of making the vanes stable and preventing them from collapsing. Odgaard (2009) proposed the ratio of $H/L = 0.3$ for determining the length of vanes for sediment management in rivers. In this study, SVs were used for scouring deposited sediments in reservoirs. Long vanes act as an obstruction against the bottom outlet and reduce the efficiency of vanes and flushing performance. Also, increasing the length of SVs does not have a remarkable effect on the distribution of shear stress in the sediment bed (Seyed Mirzaei *et al.*, 2016). The length of the plates was determined according to the recommendation of Mahtabi *et al.* (2018), who used plates 7.5 cm high and 25 cm long for sediment removal in a reservoir.

The experiments were carried out for two SVs in each test, four minimum distances of vanes (L_{hr}: $0.5D_o$, D_o, $1.5D_o$ and $2D_o$), three distances of vanes from the outlet (L_v: $0.3D_o$, $0.5D_o$ and D_o), two vane heights above the sediment bed (H_{sv}: D_o and $2D_o$) and two arrangements of divergent and convergent of vanes in two inclinations at angles (θ) of 20° and 70° on the flow direction. It should be mentioned that, for generalising the results of this study to real-size reservoirs, all the

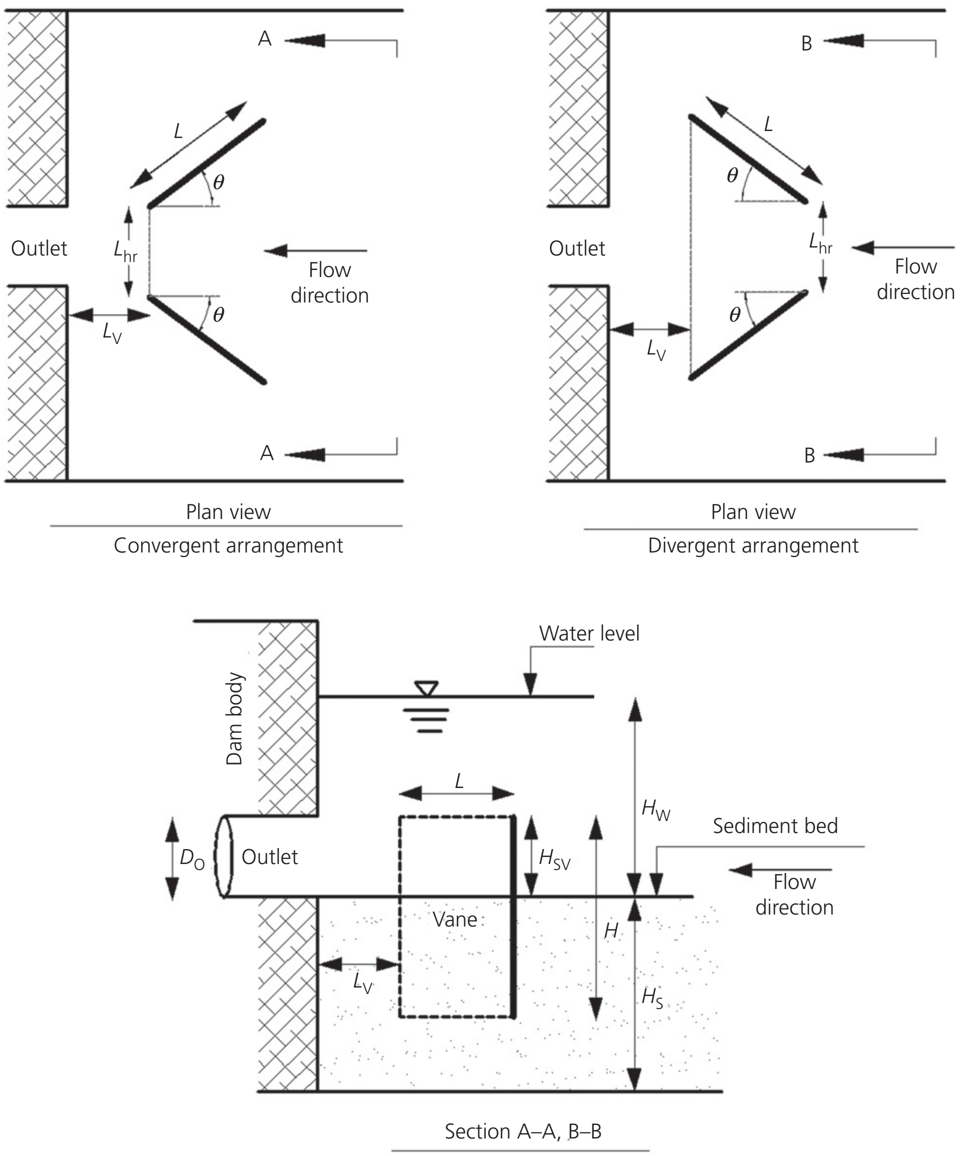

Figure 3. Vane design parameters

parameters were dimensionless by the diameter of the bottom outlet (D_o). The vanes' height above the sediment bed was determined based on recommendations by Odgaard and Kennedy (1983), who suggested $0.2 < H_{sv}/H_w < 0.5$, where H_{sv}/H_w was equal to 0.2 and 0.4 in the present study. The optimal inclination angle of vanes to the flow was determined as 20° by Odgaard (2009) and applied in this study; additionally, the angle perpendicular to the axis of flow (70°) was used for more investigation. These angles were used for both convergent and divergent arrangements (see Figure 3).

2.4 Dimensional analysis

The effective variables of dimensional analysis in this study are related to the hydraulic and sediment characteristics and geometric dimensions of vanes and outlets. The volume of sediment flushing cones (V_c) depends mainly on variables such as fluid viscosity (μ), total water head (H_w), sediment level (H_s), median size of sediment particles (d_{50}), sediment density (ρ_s), fluid density (ρ_w), acceleration due to gravity ($\boldsymbol{g}$), diameter of the bottom outlet (D_o), flow velocity at the bottom outlet (u_o), height of the SVs above the sediment bed (H_{sv}), length of the SVs (L), minimum distance of the SVs from each other (L_{hr}), distance of the SVs from the outlet (L_v) and angle of the SVs on the flow direction (θ) as follows:

$$V_c = f(H_w, H_s, d_{50}, \rho_w, \rho_s, \mu, g, D_o, u_o, H_{SV}, L, L_{hr}, L_v, \theta) \quad (1)$$

According to the Buckingham π theorem and by substituting ρ_s/ρ_w as the sediment specific gravity, $u_o/\sqrt{\boldsymbol{g}D_o}$ as the Froude

Table 1. Constant values in dimensional analysis

H_w/D_o	H_s/D_o	d_{50}/D_o	L/D_o	Froude number (bottom outlet) (Fr)	Reynolds number (bottom outlet) (Re)	G_s
5	4	0.0073	1.5	4	159523	2.625 t/m^3

number (Fr) and $\rho_w u_o D_o/\mu$ as the Reynolds number (Re) in Equation 1

2. $$\frac{V_c}{D_o^3}=f_1\left(\frac{H_w}{D_o},\ \frac{H_s}{D_o},\ \frac{d_{50}}{D_o},\ G_s,\ \text{Fr},\ \text{Re},\ \frac{H_{sv}}{D_o},\ \frac{L}{D_o},\ \frac{L_{hr}}{D_o},\ \frac{L_v}{D_o},\ \theta\right)$$

In all experiments, the sediment's specific gravity (G_s) and the Froude number (Fr) were constant because the same sediment material was used, and a single hydraulic condition. The Reynolds number (Re) was considered negligible under a fully turbulent flow from the bottom outlet. Also, in this experimental study, H_w/D_o, H_s/D_o, d_{50}/D_o and L/D_o remained constant. The constant values in Equation 2 are shown in Table 1.

Regarding the above explanations, Equation 2 can be simplified as follows:

3. $$\frac{V_c}{D_o^3}=f_2\left(\frac{H_{sv}}{D_o},\ \frac{L_{hr}}{D_o},\ \frac{L_v}{D_o},\theta\right)$$

Therefore, the effect of dimensionless variation of H_{sv}/D_o, $L_{hr}/D_o, L_v/D_o$ and θ on pressure-flushing performance is investigated in this research, according to Equation 3.

It is noticeable that the scale-length factor was selected in the dimensional analysis as an iterative parameter. The scale-length factor should preferably not be one of the experimental variables and one of the study objective parameters. Also the dimensionless parameters created should be theoretically meaningful. The diameter of the bottom outlet (D_o) has all these features. Moreover, in pressure flushing, the bottom outlet is completely open, and it is not possible to set the flow discharge with this outlet. Therefore, the size of D_o is a suitable parameter for expressing the flow's cross-sectional area, and the value of this parameter is constant in any dam. Furthermore, all of the geometric parameters of the flushing cone are dependent on D_o and the dimensionless proportions created are the right expressions for the behaviour of this phenomenon. Thus, in this study, D_o was selected as the most appropriate parameter for the scale-length factor in the dimensional analysis.

The friction angle of the sediments has been neglected, since only one grain size distribution and exclusively non-cohesive material were tested. Given that the effects of geometric parameters in vane installation were to be investigated in this study, in all experiments, the discharge, sediment height and water height were kept constant (12.5 l/s, 40 cm and 50 cm, respectively), and a single hydraulic condition was tested; also, sediments were levelled below the bottom outlet.

The flow discharge of the bottom outlet is a considerable parameter in the flushing process. Previous studies have revealed the effect of discharge on sediment flushing. As the discharge increases, the dimensions of the flushing cones expand significantly (Emamgholizadeh *et al.*, 2006; Fathi-Moghadam *et al.*, 2010; Shahmirzadi *et al.*, 2009). An increase in discharge increases the passing flow through the bottom outlet, leading to higher velocities over the bed, which extends further upstream, causing sediment scouring farther from the bottom outlet. Additionally, previous studies have shown that, with an increase in sediment level and a decrease in water level, there is a corresponding increase in scour dimensions (Dreyer, 2018; Fathi-Moghadam *et al.*, 2010).

It should be noted that, in dimensional analysis, the effect of time is not considered. The temporary amount of discharged sediment and the changes in the sediment flushing cone are completely unsustainable. Initially, the rate of scoured sediments and changes in the flushing cone are high, decreasing over time until they reach a stable state. The aim of this study was to obtain the dimensions of the final sediment flushing cone; thus, time changes were not investigated.

2.5 Experimental set-up and test procedure

First, sediment was poured into the reservoir layer by layer until it arrived at the desired level below the outlet, after which it was completely smoothed by a prismatic straightener. The experiments were carried out in two series: non-structural tests (reference tests) and structural tests (using SVs). According to the designed scenarios shown in Table 2, SVs were placed in the sediment, and the sediment surface was smoothed again. Then, the centrifugal pump was turned on, and the discharge was set with a volumetric meter. When water arrived at the desired level, the outlet valve opened and the test started. During all experiments, the water level was controlled with the point gauges on both sides of the reservoir. At the beginning of each test, the maximum amount of sediment was evacuated from the bottom outlet, after which the intensity of the evacuation gradually decreased. After reaching dynamic equilibrium conditions, the centrifugal pump was turned off and the output valve was closed; water was drained with a drain valve located at the bottom of the reservoir. Then, the SVs were removed from the sediment very slowly. The temporal variations of the flushing cone were established by a 12 h test and

Table 2. Experimental characteristics

Arrangement	θ: deg	Arrangement ID	Number of experiments	H_{sv}: cm	L_{hr}: cm	L_v: cm
Convergent	20	C20°	24	10, 20	5, 10, 15, 20	3, 5, 10
	70	C70°	24	10, 20	5, 10, 15, 20	3, 5, 10
Divergent	20	D20°	24	10, 20	5, 10, 15, 20	3, 5, 10
	70	D70°	24	10, 20	5, 10, 15, 20	3, 5, 10

Note: C20°, convergent arrangement of submerged vanes with angle of attack 20° with the flow; C70°, convergent arrangement of submerged vanes with angle of attack 70° with the flow; D20°, divergent arrangement of submerged vanes with angle of attack 20° with the flow; D70°, divergent arrangement of submerged vanes with angle of attack 70° with the flow

the equilibrium time was determined. It was observed that, after 3 h, more than 96% of the flushing cone was formed and, after about 6 h, the variation rate in the flushing cone was decreased and the final shape of the cone was formed.

To analyse the experiments and measure the sediment flushing cone topography, a photo scanning technique (PST) with an advanced Canon IXUS 190 with remote control ability was used. For more accuracy, the sediment flushing cone dimensions, including maximum length (L_c), maximum width (W_c) and maximum depth (d_c), were measured with a point gauge. At the end of each test, the evacuated sediment was gathered in a trapping box and weighed after drying.

3. Results and discussion

The results of this study are presented as follows. First, the general observations are reported. Next, the effects of employing the different arrangements of SVs on the flushing operation and the geometry of the flushing cones are discussed. Then, the best arrangement of SVs with their geometric characteristics is suggested. Finally, the flushing efficiency is calculated, and relations are proposed for predicting the dimensions and volume of flushing cones. The reference test in this paper is called the RT, and the tests' IDs are shown as the arrangement IDs with three subscripts, H_{sv}, L_{hr} and L_v.

3.1 Analysis of the RT

In pressure flushing, the sediment is drawn toward the bottom outlet radially across the bed surface. The sediments lift from the bed and become suspended in flow, and two counter-rotating vortices begin to form, one rotating clockwise and the other counterclockwise below the bottom outlet. Then, suspended sediments due to the vortices move into the main flow. Over time, the vortices grow and sediments rotate in a spiral shape, become entrained in the vortex, and are evacuated vertically through the bottom outlet. During the scouring process, parallel ridges that are dependent on the vortex are established. The centre ridge often starts relatively straight, and the sediment is always moving towards the ridge, rather than in the direction of the primary flow field. The depth of the scour cone depends on the strength of the vortices. The lateral and longitudinal extent of the scour cone is determined by the interaction of vortex-induced erosion at the base of the slope and sediment trying to maintain a stable angle (Powell and Khan, 2012).

After the beginning of the scouring process, constant flow is established in the reservoir, and a stable flushing cone is formed behind the bottom outlet. The sediment flushing cone formation in the RT confirms the results of previous studies, such as those of Fang and Cao (1996) and Scheuerlein *et al.* (2004). The observations of the present study showed that, in the RT, in the first seconds, the sediments were evacuated at high densities. After 10–15 min, the sediment discharge decreased, and a relatively small scour cone formed in front of the outlet. This can be ascribed to vertical vortices that form behind the bottom outlet and move around inside the cone (Dreyer, 2018). In fact, the main reason for sediment evacuation through the bottom outlet was flow shear stress due to accelerated outflow (Madadi *et al.*, 2017).

3.2 Analysis of experiments in the presence of SVs

In the presence of SVs in the flow direction, the flow before reaching the bottom outlet encounters the vanes. This leads to the creation of a constricted flow and high velocity, which picks up deposited sediments. As the flow reaches the leading edge of a vane, a high-velocity field and an acceleration flow are formed around it. This leads to separation flow induced by negative pressure gradients. As a result of these pressure gradients, a counter-circulation develops across the vane. Vertical pressure gradients begin to form on both sides of the SVs, and the flow passes from the high-pressure side to the low-pressure side. The pressure decreases from bottom to top on the upstream (high-pressure) face, while on the downstream (low-pressure) face, pressure increases from bottom to top. As fluid flows through the vane, these pressure regimes trigger the formation of vertical vortices that reinforce the secondary circulation that is occurring (Odgaard, 2009). The passing flows over the SVs plunge down toward the bed and lift the sediments. The flow downstream of a vane is so turbulent that a pair of clockwise and counterclockwise vortices is formed. The secondary currents generated by the vanes distribute the flow and enhance the circulation. The circulating flows interact with one another and with secondary current changes to the rotational flow; thus, the sediments rotate with severe vortices. Because of the high velocity of water in the outflow and the shear stress

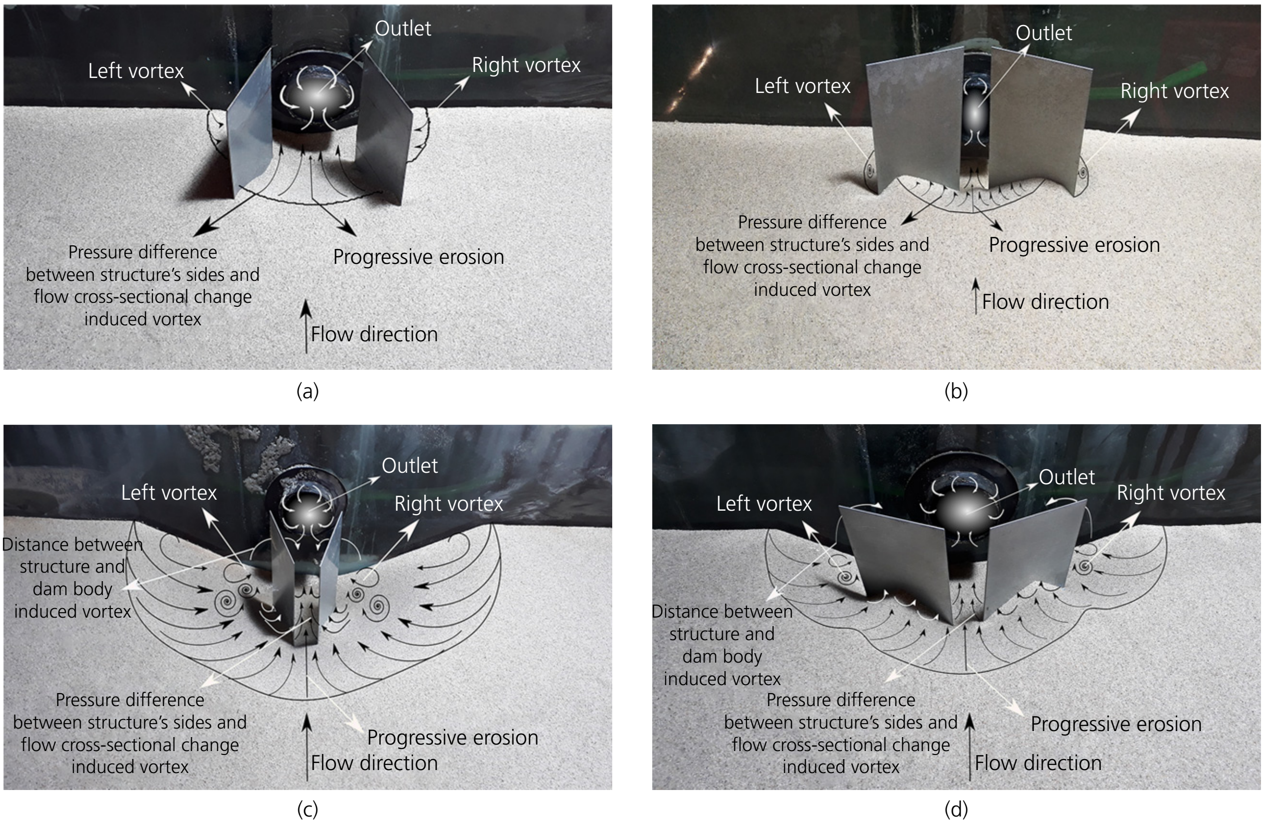

Figure 4. Sediment flushing cones and flow patterns in tests: (a) C20°$_{20,15,3}$; (b) C70°$_{20,5,3}$; (c) D20°$_{10,5,3}$ and (d) D70°$_{10,5,3}$

due to rotational flow, the sediments collect in front of the bottom outlet and are evacuated.

The scouring process generated by the presence of SVs consists of three stages. (*a*) The axial flow passing through the vanes causes the evacuation of the deposited sediments, first by progressive erosion and next by retrogressive erosion. (*b*) Lateral vortices are created by the pressure difference between the vanes' sides and flow cross-sectional change, through which sediments are evacuated from the bottom outlet, and the flushing cone expands to both sides of the vanes. (*c*) The distance between the vanes and the dam body induces a vortex that leads to an intensity of rotational flow and sediment discharging (Figure 4).

It was observed that, in all experiments, the final dimensions of the flushing cone and the final volume of the evacuated sediments increased, and scouring with high intensity began from the first seconds and continued until the end.

After analysing two inclination angles of vanes in a convergent arrangement, it was determined that $\theta = 20°$ had slightly better flushing performance than $\theta = 70°$ (Figures 4(a) and 4(b)). Reduction of the vanes' angle with the flow reinforces the shear stress produced by progressive and retrogressive erosions. Also, the transverse section is reduced and the vanes do not obstruct the bottom outlet. Thus, more sediments are scoured and the flushing performance increases.

In a divergent arrangement of SVs, because of contraction and expansion in the cross-section of the flow, a high pressure difference on both sides of the SVs is created. This leads to piping erosion and an increase in turbulence, finally reinforcing the rotational flow and sediment discharging. In these series of experiments, θ was shown to have a significant influence on the final bed form. As may be seen in Figures 4(c) and 4(d), in a 20° angle of attack, the maximum value of vortices was generated and the flushing performance was better than in a 70° angle of attack. In D70°, the vanes acted as a barrier in front of the flow because the transverse area was more affected by the SVs. Therefore, less sediment was transferred downstream, and the sediment flushing performance decreased compared to D20°. In the angle of attack of 20° with the flow, constriction and a gradual opening of the SVs in front of the bottom outlet enhanced the shear stresses created by the outflow. Thus, the secondary current increased, flow separation occurred over around a third or more of the vane length, producing a persistent scour cone near the upstream end of each vane, and the sediments below the bottom outlet discharged strongly. In this arrangement, progressive and retrogressive erosions were more

Table 3. Analysis of flushing cone dimensions in the best and the worst tests of each arrangement compared to the R.T

Arrangement	Arrangement ID	Test ID	L_c/D_o	W_c/D_o	d_c/D_o	Increasing rate of L_c compared to RT: %	Increasing rate of W_c compared to RT: %	Increasing rate of d_c compared to RT: %
Reference test	RT	RT	0.98	2.4	0.45	—	—	—
Convergent	C20°	C20°$_{10,5,10}$	1.6	2.5	0.5	63	4	11
		C20°$_{20,15,3}$	2.4	3.6	0.8	145	50	78
	C70°	C70°$_{10,20,10}$	1.6	2.5	0.5	63	4	11
		C70°$_{20,5,3}$	2	4	0.8	104	66	77
Divergent	D20°	D20°$_{10,20,10}$	2	2.9	0.6	104	21	33
		D20°$_{10,5,3}$	4.05	7.65	2.2	313	219	389
	D70°	D70°$_{20,20,10}$	1.7	3.6	0.55	73	50	22
		D70°$_{10,5,3}$	3.15	6.4	1.15	221	167	155

Note: C20°$_{20,15,3}$, C20° test with three subscripts, H_{sv}, L_{hr} and L_v, respectively; C70°$_{20,5,3}$, C70° test with three subscripts, H_{sv}, L_{hr} and L_v, respectively; D20°$_{10,5,3}$, D20° test with three subscripts, H_{sv}, L_{hr} and L_v, respectively; D70°$_{10,5,3}$, D70° test with three subscripts, H_{sv}, L_{hr} and L_v, respectively

effective than side vortices; hence, the width of the cone increased less compared to the other dimensions.

To gain a better understanding of the effect of vanes on flushing cone dimensions, analysis of the best and the worst tests of each arrangement was conducted and compared with the RT (Table 3). This table shows that divergent experiments had better flushing performance than convergent experiments. In test D20°$_{10,5,3}$, which was the best test of divergent arrangements, the length, width and depth of the flushing cone increased by 68.75%, 112.5% and 175%, respectively, compared to test C20°$_{20,15,3}$, which was the best test of the convergent arrangement.

As shown in Table 3, test D20°$_{10,5,3}$ had the best flushing performance across 96 experiments. Continued analyses were conducted with the results of this test.

Regarding the slope angles of the flushing cone, it should be noted that the scour cone geometry depends strongly on the friction angle of the sediments (Fathi-Moghadam *et al.*, 2010). After analysing the flushing cone, it was determined that the side slope angle of the scour cone was approximately close to the submerged friction angle of the sediments, 29°. This is consistent with the results of other studies of non-cohesive sediments (Fathi-Moghadam *et al.*, 2010; Madadi *et al.*, 2017).

3.3 Effect of SVs' characteristics on flushing performance

3.3.1 Distances of SVs from the bottom outlet (L_v)

When the trailing edges of vanes come close to the inlet flow jet and bottom outlet, the vane-induced vortex has the tendency to develop the vortices laterally across the flow direction. The interaction between these two types of flow causes significant differences in the flow pattern. These differences intensify piping erosion, create secondary flow and dissipate downstream rapidly. In this way, the dynamic pressure and a horseshoe vortex increase, and a vertical vortex is created in the pressure side of the vanes. Finally, sediment with rotational movements transfers from the sides of the vanes, and flushing performance increases.

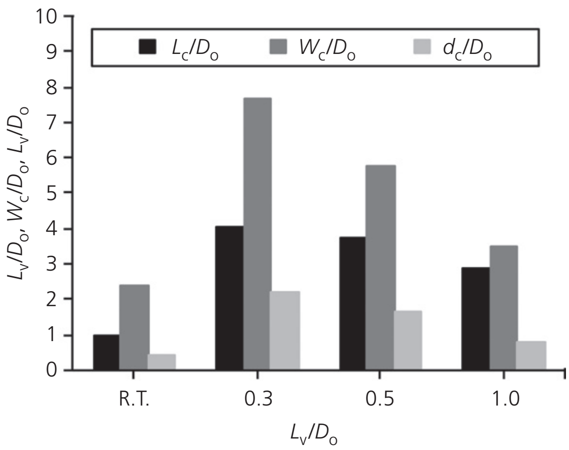

Figure 5. Variations of sediment flushing cone dimensions and distance of SVs from outlet compared to RT

By analysing three different L_v options, it was observed that a reduction of L_v caused better flushing performance. This means that, by decreasing L_v, scouring will occur in a very limited area. This is consistent with the observations of Abdolahpour *et al.* (2015) and Mahtabi *et al.* (2018). As shown in Figure 5, by reducing L_v/D_o from 1 to 0.3, the length, width and depth of the flushing cones increased 40%, 119% and 159%, respectively.

3.3.2 Minimum distances of SVs (L_{hr})

The minimum spacing of vanes is an essential component in generating circulation and enhancing the turbulence near the bottom outlet. According to Odgaard and Wang (1991), each vane acts as an individual vortex structure and generates vortices downstream. When the vanes are installed close to each other, vortices interact and the effectiveness of the vanes increases.

To investigate the effect of minimum distance of SVs on the dimensions of the flushing cones, four different L_{hr} values were used. Figure 6 shows the effect of L_{hr}/D_o on these dimensions; reducing L_{hr} is seen to increase the dimensions of the sediment flushing cones. It can be concluded that the first sudden contraction and the next expansion of outflowing water through the bottom outlet increase the strength of the axial flow. So, the flow turbulence and the intensity of vortices increase and flushing performance is reinforced. In fact, when L_{hr} is small, the vanes interact with each other. These interactions develop interaction between the centrifugal force, the lateral pressure gradient and circulation, and consequently increase the strength of the vortices. Analysis of the data revealed that the length, width and depth of the flushing cones increased by 50%, 91% and 193%, respectively, when L_{hr}/D_o was reduced from 2 to 0.5.

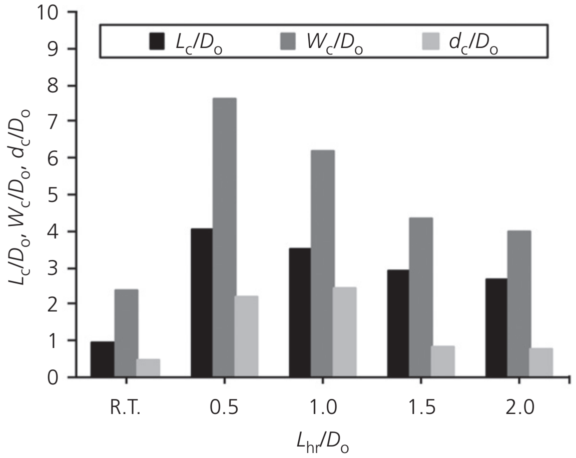

Figure 6. Variations of sediment flushing cone dimensions and minimum distance of SVs compared to RT

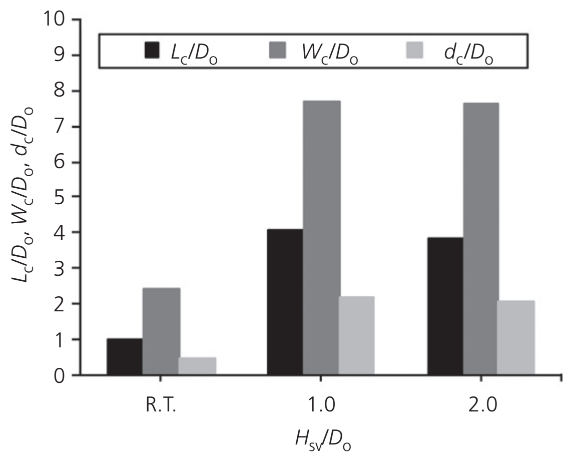

Figure 7. Variations of sediment flushing cone dimensions and height of SVs above sediment bed compared to RT

3.3.3 SVs' height above the sediment bed (H_{sv})

Vane height is a significant parameter, which is correlated with the generation of vortices. In this research, the height of the vanes above the sediment bed was assumed to be two values of D_o (10 cm) and $2D_o$ (20 cm). It can be seen in Figure 7 that the dimensions of the flushing cone in $H_{sv}/D_o = 1$ are slightly more than $H_{sv}/D_o = 2$. The reason for this increase is the downflow and the flow separation at the upstream edge of the flushing cone. Horseshoe vortices develop as a result. In fact, when the vane's height is increased, the obstacles in front of the entry flow increase and transverse vortices are reduced. Therefore, less sediment is transferred downstream. This finding is consistent with the results of Seyed Mirzaei *et al.* (2016), who reported that the secondary flow strength has an inverse relation with the height of the vanes. Additionally, as the vanes' height increases, they divert less flow to downstream, and the lesser extent of the flow forms less powerful secondary currents. Generally, at greater relative heights of SVs, the circulation has lower intensity and reduces the transverse velocity and transverse area of flushing (Sharma and Ahmad, 2019). It can be determined from Figure 7 that the length, width and depth of the flushing cones in $H_{sv}/D_o = 1$ increased by 5%, 1% and 7%, respectively, compared to $H_{sv}/D_o = 2$. It can be observed that the difference in flushing performance between these two H_{sv} values is insignificant, and the effect of this parameter is less than that of the other parameters.

3.4 Non-linear correlation between SVs' characteristics and flushing cone dimensions

Using the scour measurements, the non-dimensional equations are derived by linear regression for the scour depth, length and width. Equations 4–6 represent the relationships between the flushing cone dimensions and SV characteristics, consisting of the relative height of the SVs above the sediment bed for $1 \leq H_{sv}/D_o \leq 2$, the relative distance of the SVs from the outlet for $0.3 \leq L_v/D_o \leq 1$, the relative minimum distance of the SVs from each other for $0.5 \leq L_{hr}/D_o \leq 2$ and the relative angle of the SVs in the flow direction for $20° \leq \theta \leq 70°$.

4. $$\frac{L_c}{D_o} = 1.161\left(\frac{H_{sv}}{D_o}\right)^{-0.072}\left(\frac{L_v}{D_o}\right)^{-0.237}\left(\frac{L_{hr}}{D_o}\right)^{-0.253}(\sin\theta)^{-0.716}$$
$$R^2 = 0.882$$

5. $$\frac{W_c}{D_o} = 3.278\left(\frac{H_{sv}}{D_o}\right)^{-0.086}\left(\frac{L_v}{D_o}\right)^{-0.442}\left(\frac{L_{hr}}{D_o}\right)^{-0.394}(\sin\theta)^{-0.082}$$
$$R^2 = 0.931$$

6. $$\frac{d_c}{D_o} = 0.545\left(\frac{H_{sv}}{D_o}\right)^{-0.087}\left(\frac{L_v}{D_o}\right)^{-0.534}\left(\frac{L_{hr}}{D_o}\right)^{-0.682}(\sin\theta)^{-0.374}$$
$$R^2 = 0.908$$

3.5 Analysis of longitudinal and transverse sections of flushing cones

Scouring cones in pressure flushing are formed with a funnel shape, with the centre of the bottom outlet and its radius constantly increasing toward the upstream of the reservoir. The scour growth rate is very high in the early moments of the scouring process and then decreases until the equilibrium condition is reached. In this way, the transverse expansion of the flushing cone near the bottom outlet and the longitudinal expansion of the flushing cone toward the upstream of the bottom outlet are greater than in other regions. By installing vanes at the upstream of the outlet, lateral flows, due to a high pressure difference in both sides of the vanes, begin to form piping erosion, and the flushing cone extends laterally (transversely) with high intensity. Also, the flushing cone extends longitudinally because of the constricted axial flow passing through the vanes. The results show that installing the vanes at the flow direction causes the maximum longitudinal velocity to move farther toward the upstream of the reservoir.

In order to specify the dimensions of cones, the longitudinal and transverse sections of cones are shown in the following figures. Figure 8(a) shows the longitudinal profile of flushing cones in the RT and test D20°$_{10,5,3}$. In this figure, the *Y*-axis corresponds to the sediment level under the bottom outlet, which is positive to the upstream of the reservoir, and the *Z*-axis is perpendicular to the bottom outlet direction, which is positive upward. Figure 8(a) shows a significant increase in the length and depth of flushing cones compared to the RT. Also, Figure 8(b) shows the cross-section of cones at two relative distances of 0.8 and 3. *X* is the transverse axis corresponding to the sediment level. As can be seen, there are many differences in cone width in both tests, as the RT is not effective on the transverse section when the relative distance is more than 0.98.

3.6 Analysis of sediment flushing cone volume and sediment removal efficiency

When incoming flow to the bottom outlet is constricted by SVs, a flow jet forms with stronger erosional forces and shear stresses and the flushing cone volume increases (Madadi *et al.*, 2017). After measuring the dimensions of the sediment flushing cones, a PST was used to obtain the topographies of the sediment flushing cones in order to calculate the volume of the scouring cones. At the end of each test, photographs were recorded with the given horizontal and vertical spacing above the reservoir on camera rails, using an advanced Canon IXUS 190 with remote control facility. The photos were then analysed, and the output of *x*, *y*, *z* points was imported to Arc

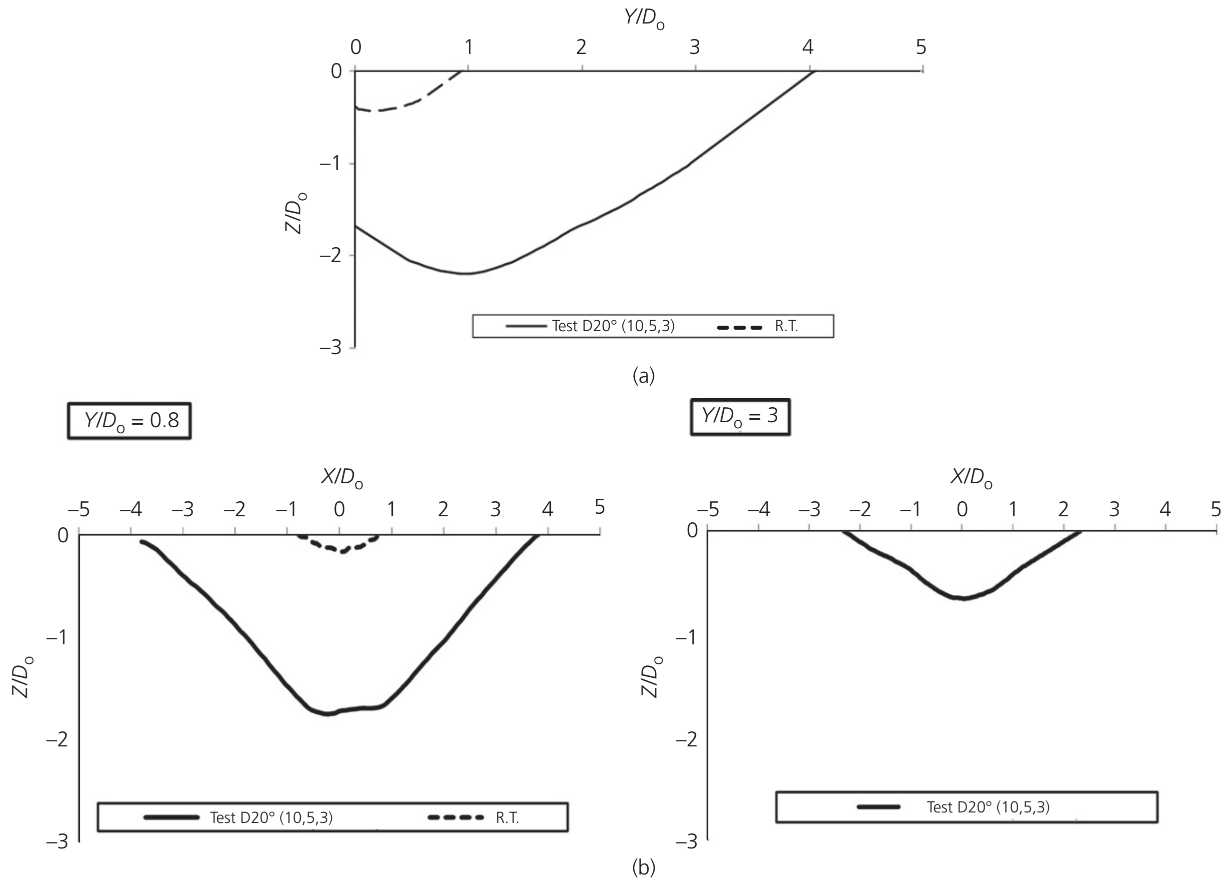

Figure 8. (a) Longitudinal and (b) transverse profiles of flushing cone in RT and test D20°$_{10,5,3}$

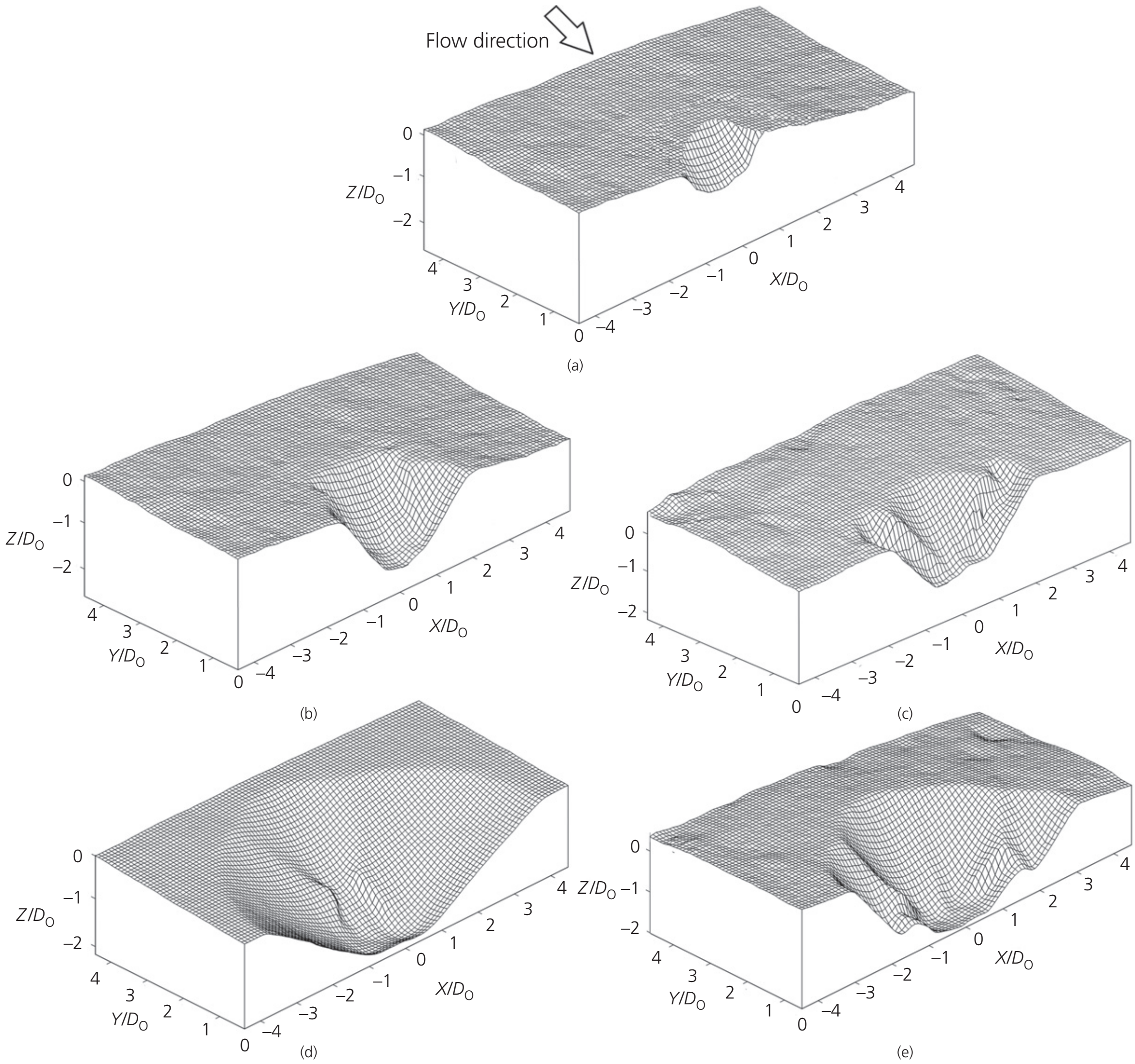

Figure 9. Three-dimensional schematic representation of sediment flushing cones in: (a) RT; (b) test C20°$_{20,15,3}$; (c) test C70°$_{20,5,3}$; (d) test D20°$_{10,5,3}$; (e) test D70°$_{10,5,3}$

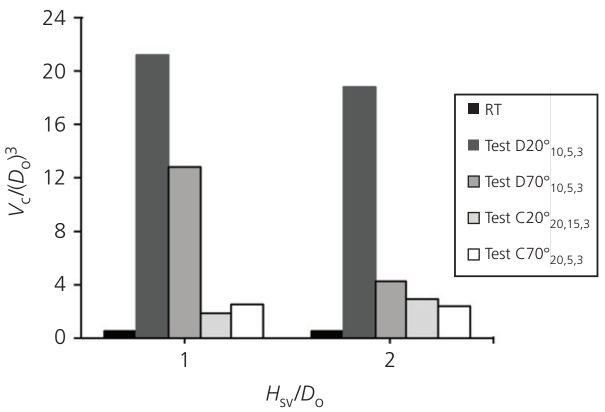

Figure 10. Variations of dimensionless sediment flushing cone volume and dimensionless height of SV above sediment bed

GIS software as a dense-point cloud, allowing the volumes of the flushing cones to be calculated, based on the sediment surface before and after in each test. Also, for comparison of the flushing cone volume in different arrangements of SVs, the bed topographies were drawn by importing x, y, z to Surfer-16 software (Figure 9).

It should be noted that the PST was investigated and calibrated on a cube with known dimensions and volume. The data accuracy at a distance of 50 cm was determined to be 0.35%, which equates to an error of approximately 1.75 mm.

Figure 10 offers better understanding of the flushing cone volume in these experiments. It was determined that the maximum flushing cone volume was in test D20°$_{10,5,3}$, with an increase of 48 times compared to the RT.

Based on the experimental results of this study, a non-linear correlation of SV characteristics for the estimation of flushing cone volume with the same constraints as for Equations 4–6 was obtained as Equation 7.

7. $$\frac{V_\text{c}}{D_\text{o}^3} = 1.283\left(\frac{H_\text{sv}}{D_\text{o}}\right)^{-0.026}\left(\frac{L_\text{v}}{D_\text{o}}\right)^{-1.089}\left(\frac{L_\text{hr}}{D_\text{o}}\right)^{-1.314}(\sin\theta)^{-0.695}$$
$$R^2 = 0.945$$

As no method is provided to estimate the dimensions of the flushing cone and the volume of flushed sediments, Equations 4–7 are statistical analyses based on experimental data for predicting the sediment cone dimensions and volume (including the diameter of the bottom outlet and the geometric characteristics of the SVs).

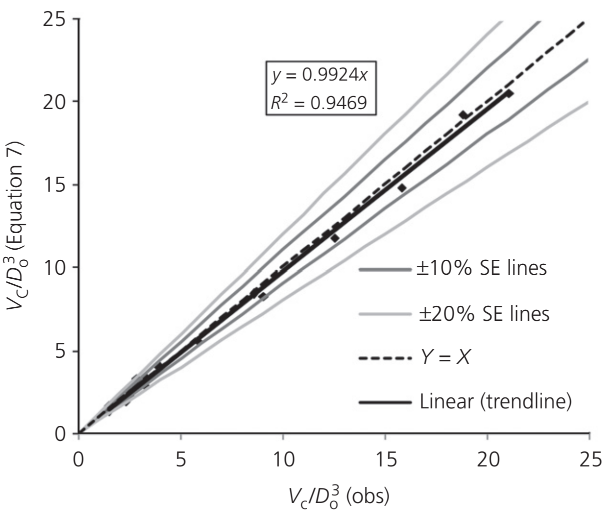

Figure 11. Observed and calculated dimensionless flushing cone volume

As this study aimed to investigate the effects of different arrangements and geometric parameters of vanes on sediment flushing performance, and only a single hydraulic condition was tested (the hydraulic parameters were determined in Section 2.4), the results of these equations can be used for relative comparison only and not for estimating the effective volume for other hydraulic conditions.

Figure 11 represents the observed values of the dimensionless volume of the flushing cones with the values calculated by Equation 7. As shown, there is good agreement between the observed and the calculated values.

Flushing efficiency (E) is an index that describes the effectiveness of hydraulic flushing. The following formula was suggested by Qian (1982) for this index:

8. $$E = \frac{V_\text{c}}{V_\text{w}}$$

where E is the sediment-flushing efficiency; V_c is the volume of flushed sediment; and V_w is the volume of water used during the flushing operation. Previous studies indicated that a pressure-flushing operation has very low efficiency (Madadi *et al.*, 2017). In the present study, the flushing efficiency in the RT was obtained as 0.000064, whereas, when using the SVs in test D20°$_{10,5,3}$ (test D20° with $L_\text{hr}/D_\text{o} = 0.5$, $L_\text{v}/D_\text{o} = 0.3$ and $H_\text{sv}/D_\text{o} = 1$), the flushing efficiency reached 0.0031. This indicates that the flushing efficiency increased 48 times compared to the RT.

Figure 12. The development pattern of flushing cone with time in (a) non-structural and (b) structural test

In order to clarify the definition of flushing efficiency, the required time for the flushing operation was investigated during the scouring process. Figure 12 shows the development pattern of the flushing cone over time in non-structural and structural tests. As can be seen, the use of vanes reduces the duration of the scouring process. The full extension of the flushing cones in the RT was complete 180 min after the commencement of the test, whereas the same amount of extension occurred in 30 s in the structural test. This indicates that the scouring process in the structural test expanded faster than in the RT, and the rate of temporal development of flushing cones increased significantly.

4. Conclusions

In this study, the final dimensions of sediment flushing cones and sediment removal efficiency in a RT and structural experiments were investigated. In the structural tests, the SVs in two arrangements of convergence and divergence and different characteristics were used, and their effects on flushing operations were investigated. The results showed that when SVs were employed, the final dimensions and volume of the flushing cone increased significantly. It was found that the divergent arrangement experiments were more effective than the convergent arrangement. Additionally, in the divergent arrangement, the angle of 20° on flow direction performed better than the angle of 70°. Furthermore, the results indicated that, in the divergent arrangement with an angle of 20° on flow direction, by reducing L_{hr}/D_o from 2 to 0.5, L_v/D_o from 1 to 0.3 and H_{sv}/D_o from 2 to 1, the length, width and depth of the final flushing cones increased by 102.5%, 164% and 267%, respectively. In addition, the quantity of final flushed sediments was calculated, and it was concluded that the sediment-flushing efficiency increased 48 times compared to the RT. This designed structure, in which the deposited sediments in the region closer to the bottom outlet of the reservoirs are scoured out, can help to keep the intakes free from sediments. Although deposited sediments in the region near the bottom outlets of reservoirs are mainly silts and clays with some cohesive properties, this study focused on non-cohesive and coarse sediments, simply because of the complexities and uncertainties involved in modelling cohesive sediment.

The use of structural methods to improve the flushing performance of reservoirs has weaknesses, such as problems in carrying out the installation of these structures, which increases the cost of dam construction. Of course, it is not possible to use SVs for all reservoirs. The dimensions of the sediment discharging outlet, the number of outlets, the reservoir width on the floor, the conditions of the reservoir bed and the profile and rate of sediment deposition in the vicinity of the reservoir wall should be considered. Also, the vanes must be positioned before the operation of the reservoir. The location of the bottom outlet should be such that the vane's height does not rise too much from the floor. To estimate the height of the vanes, modelling is essential. Additionally, relatively accurate forecasting of the sediment deposition profile in the reservoir is required.

The other issue is the risk that the vanes become blocked by floating debris. According to the catchment conditions, it is possible for floating debris to enter the reservoir. Usually, a containment boom is used to prevent such debris from entering the reservoir and blocking the bottom outlet. Further recommendations are to (*a*) regularly monitor the reservoir bathymetry before and after pressure flushing to ensure that there is no buried floating debris within the installed vanes, and (*b*) design the facilities in the right places to evacuate floating objects.

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