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Sediment flushing upstream of large orifices: An experimental study

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ABSTRACT

Due to the constricting and localization of flow by orifices, these hydraulic structures are commonly used in dams and water impoundment reservoirs to flush deposited sediments. They are also one of the most important flow measurement structures. In this study, the flow characteristics at upstream of a large circular orifice located at the wall of a water reservoir, in the case that the sediments were accumulated behind it, was investigated. The experiments were performed at the hydraulic laboratory of Shahid Bahonar university of Kerman, in a model of rectangular reservoir. The experiments were performed in two parts. First, the flow behavior during the scour development at upstream of the orifice and the extent of sediment erosion due to the orifice flow was investigated. Next, a semi-confined structure was located at the upstream of orifice to increase the sediment removal efficiency. The effect of the geometrical characteristics of structure on the dimensions of scour hole was determined. It was observed that the interactions of water, sediment and structure generated strong vortices upstream of the orifice, which caused the lifting and sweeping away of a large amount of sediment from the reservoir and let to formation of a semi-cone hole upstream of the orifice.

1. Introduction

Orifices are hydraulic structures that are used for different purposes. In dams, they are used to flush deposited sediments from the reservoir. They are also one of the main flow measurement structures. Streeter et al. [24] defined the orifice as an opening through which the fluid flows. Generally, the orifice flow condition is established when the head above the center of orifice become 2–2.2 times of the orifice diameter [10]. If the head is less than 5 times the diameter of the orifice, the orifice is categorized as a large orifice (Goyal, 2015).

They are commonly used as one of the most appropriate measures to remove the accumulated sediments from the reservoirs. The practice of removing the deposited sediments in the reservoir by the orifice accelerated flow is called flushing operation. During the flushing operation, high flow velocities are localized at the orifice, causing removal of sediments through it [1].

Previous field and laboratory studies showed that sediment flushing by orifices has very low efficiency [6,17]. Flushing efficiency (E) implies the ratio of volume of flushed sediment ($\forall_C$) to the volume of water used ($\forall_w$) during the flushing operation [21]. It can be calculated by Eq. (1).

$$E = \frac{\forall_C}{\forall_w} \tag{1}$$

On the other hand, one of the main disadvantages of the orifice structure is the probability of blockage by the submerged debris and deposited sediments. This problem frequently occurs at the dam orifices (low-level outlets) due to the accumulation of sediments, and influences the hydraulic behavior of orifices. When the orifice structure is used as bottom outlet of dams, it is desirable to prepare such conditions that increase the strength of orifice flow to remove more sediments from the reservoir (improve the flushing efficiency). In this research, to increase the strength of orifice flow, a semi-confined piles group structure was designed and placed at the upstream of the orifice. This structure can protect the orifice from the blockage problem, as well. It is anticipated that such a structure causes a complex flow condition at upstream of the orifice. To the author's knowledge, the interaction of structure, sediment and flow upstream of large orifices as well as the measurement of spatial and temporal variations of their upstream sedimentary bed have not been completely studied, up to now. The initial purpose of this research was to observe the behavior of flow and the variations of sedimentary bed geometry due to the erosion at upstream of a large orifice during the flushing operation. Next, the effect of geometrical characteristics of semi-confined piles group structure on the dimensions of scour hole was investigated. Henceforth, the 'flushing cone' is used as the 'scour hole' throughout the paper.

Review of the literature concerning orifices indicates that most of the available studies dealt with the discharge characteristics of orifices and the downstream effects of orifice flow. Chanson et al. [3]

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Nomenclature

d_{50}	median size of the sediment particles (m);
d_{hole}	maximum depth of flushing cone (m);
$D_{orifice}$	diameter of orifice (m);
D_{pile}	pile diameter (m);
E	flushing efficiency (dimensionless);
g	acceleration due to gravity (m s^{-2});
G_s	specific gravity of sediment (dimensionless);
H	flow head above the center of orifice (m);
I	the distance between two adjacent piles (m);
R	the distance of each pile from the orifice (m);
Re	orifice Reynolds number (dimensionless);
R_{hole}	radius of flushing cone (m);
V	the outflow velocity (m s^{-1});
W_c	maximum width of flushing cone (m);
x,y,z	coordinate system points (m);
ρ_s	mass density of the sediment (kg m^{-3});
ρ	mass density of the fluid (kg m^{-3});
μ	dynamic viscosity of the fluid (kg m^{-1} s^{-1});
σ_g	geometric standard deviation of sediment (dimensionless);
$\forall_C$	volume of flushing cone (m^3);
$\forall_w$	volume of water (m^3).

investigated the unsteady flow patterns, the discharge capacity and the velocity field in a rectangular orifice flow, discharging vertically. They found that the discharge coefficient of the vertical orifice flow is very close to that of horizontal orifice flow. They also reported that the unsteady velocity field is consistent with potential flow calculations and good agreement was existed between their experimental data and ideal-fluid flow theory. Shammaa et al. [23] studied the effect of size and shape of orifice on the flow behavior and the velocity field upstream of a finite-size orifice. They found that in the near field zones, the iso-velocity surfaces appear to be semi-ellipsoidal, while, in the far field zones they become hemispheres. Emamgholizadeh et al. [7] documented that the effective variables on the volume of the flushing cone upstream of the orifices are the physical properties of fluid and sediment and the condition of outflowing water. Bryant et al. [2] performed an experimental study to investigate the flow patterns upstream of an ideal orifice, multiple orifices, and an orifice near the flow surface. They developed a new potential flow solution for flow behind orifices and reported that there is good agreement between the results of their proposed solution and measured data. Hussain et al. [10] performed analytical and experimental study to estimate the discharge coefficient of sharp-crested circular orifices. Powell and Khan [19,20] investigated the sediment transport, the extent and the shape of the scour hole upstream of unbounded orifices under steady flow conditions for different sediment sizes and heads on the orifice. They found that the maximum scour depth increases with the head on the orifice and decreases as the sediment size increases. In addition, they measured longitudinal and vertical components of orifice flow velocity and reported that the maximum velocity occur below the centerline of the orifice. They used a three-dimensional flow model to simulate the flow behavior upstream of the orifice under fixed bed and mobile bed conditions and reported that the model could accurately predict the velocity field in both cases. Sun and Liu [25] studied the characteristics of vortices near the orifices, gates and intakes structures. Based on collected experimental data and a theoretical analysis, they proposed a mathematical model capable of describing the main hydraulic characteristics of vortex. The results of proposed model was compared with the experimental data and other vortex models and good agreement was found.

Role of vortices on scour phenomenon was also investigated by Raudkivi [22] and Melville [13]. Raudkivi [22] claimed that wake vortices have a vertical axes with vertical flow direction at the center. Melville [13] reported that when the flow collides with the upstream face of a structure (here, pile), a stagnation pressure is created, which, causes establishment of downflow in front of pile. The downflow

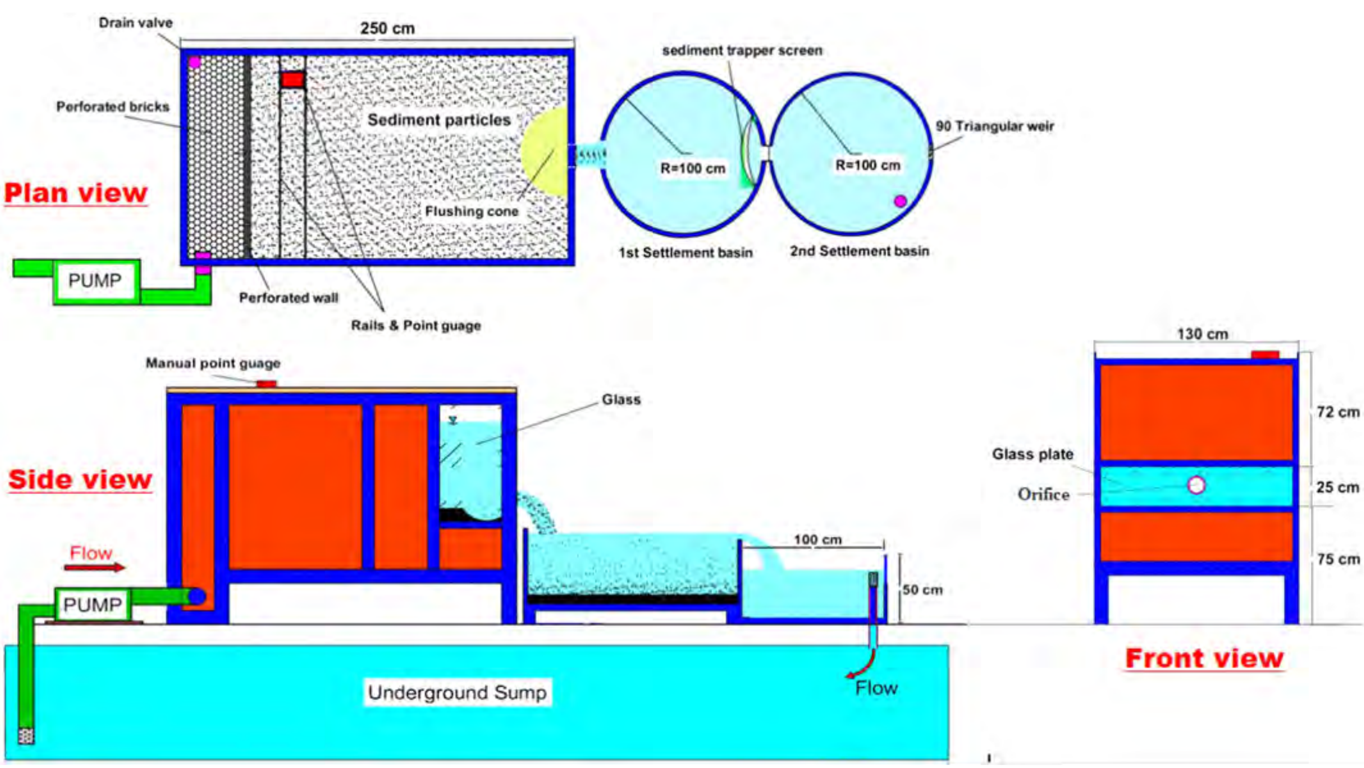

Fig. 1. Schematic representation of the water supply system and model of reservoir.

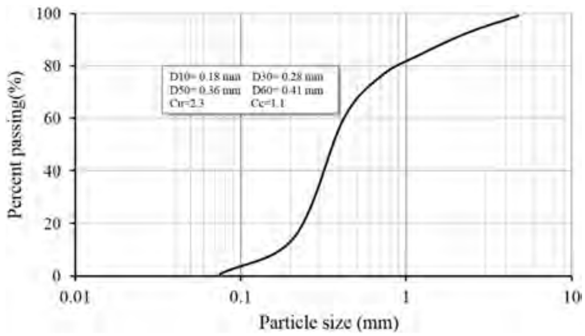

Fig. 2. Particle size distribution curve of bed sediment.

accelerates downward with a spiraling motion and pushes the bed sediment, causes the formation of horseshoe vortex. Simultaneously, the separation of flow at the sides of each pile creates the wake vortices with an opposite rotation direction compared to the horseshoe vortex. Melville and Hadfield [15] reported that a substantial scour occurs downstream of piles because of deflecting the streamlines and creating a wake region behind them. Other important factor in scour phenomenon is the time [14,12]. In this way, the temporal variations of flushing cone should be considered especially for design and operation of hydropower dams. It depends on the condition of flow, geometry of structure and sediment properties [7,16].

2. Materials and methods

The experiments were conducted at the Hydraulic Laboratory of Department of Water Engineering at Shahid Bahonar University of Kerman on a model of rectangular reservoir with a large circular orifice with 9.5 cm diameter. Considering the laboratory space and the pump capacity, the whole size of reservoir was selected large enough to facilitate the observing of sediment flushing process while the scale effects remain negligible. The width of reservoir was long enough that the reservoir side walls have no effect on the flushing phenomenon. The length of reservoir was long enough to ensure that the approaching flow is smooth. In this way, the length, width and height of the reservoir was 2.5 m, 1.3 m and 1.5 m, respectively. A part of right and front walls of the reservoir was made of glass to observe the flow condition near the orifice during flushing operation. (Fig. 1) shows the schematic view of the model. The flow was supplied from an underground sump by a centrifugal pump located adjacent to the reservoir. There were two butterfly valves in the reservoir circulating system, one regulating the inflow and other regulating the outflow. Multiple measures including perforated bricks and vertical screens were used at the inlet section of reservoir across the entire cross-section of the reservoir to prevent the formation of large-scale disturbances and to reduce the turbulence and vortices caused by pump fluctuations. Non-cohesive sediments with d_{50}=0.36 mm and σ_g = 2.24 were used in this study. (Fig. 2) represents the particle size ditribution curve of bed sediment. Before starting of each run, the sediment thickness in the reservoir was 40 cm, set with the bottom edge of the orifice. PVC cylindrical piles with different diameters (D_{pile}) and different spacing (I), according to (Table 1), were implemented in the reservoir at different distances (R) from the orifice (Fig. 3). The geometrical dimensions of flushing cone were measured using a point gauge mounted on the railways above the reservoir. Dye injection technique was used together with *Canon Powershot IS 170 SX* camera to visualize the flushing features during the experiments by taking photos and recording videos.

2.1. Test procedure

The purpose of this research was to study the mechanism of sediment scouring upstream of a large circular orifice during the flushing operation. To increase the orifice flow power, a new structure, as shown in (Fig. 2), composed of a series of submerged semi-confined cylindrical piles was placed around the orifice. (Fig. 4) shows the side and plan view of piles implementation layout. The reason for choosing semicircular layout arised from the results of conducting the reference test, where, the final shape of flushing cone was semicircular. In this study, the reference test was the test without implementation of piles around the orifice. In total, 203 experiments were performed to measure the flushing cone dimensions. All tests were performed under constant head condition (H=*45* cm, from the center of the orifice to the water surface) at the reservoir, but for two different orifice outflow discharges (14.5 L/s and 10 L/s).

The tests procedure was such a way that, initially the pump was started and discharged the flow to the reservoir. After that, the orifice was opened so that the inflow to reservoir was equal to the outflow. Any variation in scour due to differences in the opening of the orifice was negligible for each run. The tests were run for 6 h (up to reaching to the equilibrium condition). The flushing cone was assessed as having reached equilibrium when the centerline bed profile did not change more than 2 mm within a 2-h period. Then the pump was turned off and the orifice was closed gradually. After that, the water in the reservoir was drained completely and then the geometrical dimensions of flushing cone were measured. Cross sections were taken at various $Z/D_{orifice}$ distances by means of a point gauge limnimeter. The coordinate system was set with the origin at the invert of the orifice as previously showed in (Fig. 4). As can be seen, the z positive location was measured upstream of the orifice and the x positive location was measured laterally across the orifice.

2.2. Dimensional analysis

Considering the effective variables on flushing process reported by Emamgholizadeh et al. [7] and the geometrical properties of proposed structure in the present study, it is concluded that the main variables that affect the volume of flushing cone ($\forall_C$) are fluid density (ρ), fluid viscosity (μ), the median size of sediment (d_{50}), the sediment density (ρ_s), the total head above the center of the orifice(H), the orifice outflow discharge (Q), the diameter of orifice ($D_{orifice}$), the acceleration due to gravity (g), pile diameter (D_{pile}), the distance between two adjacent piles (I), and the distance of each pile from the origin of the orifice (R). Eq. (2) shows these terms in functional form.

$$f(\ \forall_C\ ,\ \rho,\ \mu,\ d_{50},\ \rho_s,\ H,\ Q,\ D_{orifice},\ g,\ D_{pile},\ I,\ R) = 0 \tag{2}$$

By selecting H, g, and ρ as the repeating variables, the resulting terms of the dimensional analysis are obtained as Eq. (2).

$$f\left(\frac{\forall_C}{D_{orifice}^3},\ \frac{d_{50}}{D_{orifice}},\ \frac{H}{D_{orifice}},\ \frac{Q}{\sqrt{gD_{orifice}^5}},\ \frac{D_{pile}}{D_{orifice}},\ \frac{I}{D_{orifice}},\ \frac{R}{D_{orifice}},\ Gs,\ Re\right) = 0 \tag{3}$$

Where, $\mathrm{Re} = \frac{\rho V D_{orifice}}{\mu}$ is the orifice *Reynolds number* and $G_s = \frac{\rho_s}{\rho}$ is the *specific gravity* of sediment. For the purpose of this study some of the terms in Eq. (3) may be dropped. For all tests, the sediments used were sand with the same specific gravity, so the relative density term (G_s) can be neglected. In addition, the effect of Re was considered negligible under a fully turbulent flow from the orifice. Since the value of $D_{orifice}$, H and d_{50} was constant in all tests of this study, the value of $\frac{H}{D_{orifice}}$ and $\frac{d_{50}}{D_{orifice}}$ remained constant, as well. Regarding the above explanations, Eq. (3) can be simplified as Eq. (4):

$$\frac{\forall_C}{D_{orifice}^3} = f_1\left(\frac{Q}{\sqrt{gD_{orifice}^5}},\ \frac{D_{pile}}{D_{orifice}},\ \frac{I}{D_{orifice}},\ \frac{R}{D_{orifice}}\right) \tag{4}$$

According to Eq. (3), the piles diameter and spacing and their

Table 1
Experiments carried out in the present research.

Model	D (m)	I (m)	R (m)	Q (L/s)	H (m)	Model	D (m)	I (m)	R (m)	Q (L/s)	H (m)
Reference1	–	–	–	14.5	0.45	D_3 I_3 R_4	0.032	0.048	0.050	10	0.45
Reference2	–	–	–	10	0.45	D_3 I_4 R_1	0.032	0.064	0.020	10	0.45
D_1 I_1 R_1[a]	0.020	0.016	0.020	14.5	0.45	D_3 I_3 R_1	0.032	0.048	0.020	14.5	0.45
D_1 I_1 R_2	0.020	0.016	0.030	14.5	0.45	D_3 I_3 R_2	0.032	0.048	0.030	14.5	0.45
D_1 I_1 R_3	0.020	0.016	0.040	14.5	0.45	D_3 I_3 R_3	0.032	0.048	0.040	14.5	0.45
D_1 I_1 R_4	0.020	0.016	0.050	14.5	0.45	D_3 I_3 R_4	0.032	0.048	0.050	14.5	0.45
D_1 I_2 R_1	0.020	0.032	0.020	14.5	0.45	D_3 I_4 R_1	0.032	0.064	0.020	14.5	0.45
D_1 I_2 R_2	0.020	0.032	0.030	14.5	0.45	D_3 I_4 R_2	0.032	0.064	0.030	14.5	0.45
D_1 I_2 R_3	0.020	0.032	0.040	14.5	0.45	D_3 I_4 R_3	0.032	0.064	0.040	14.5	0.45
D_1 I_2 R_4	0.020	0.032	0.050	14.5	0.45	D_3 I_4 R_4	0.032	0.064	0.050	14.5	0.45
D_1 I_3 R_1	0.020	0.048	0.020	14.5	0.45	D_3 I_5 R_1	0.032	0.096	0.020	14.5	0.45
D_1 I_3 R_2	0.020	0.048	0.030	14.5	0.45	D_3 I_5 R_2	0.032	0.096	0.030	14.5	0.45
D_1 I_3 R_3	0.020	0.048	0.040	14.5	0.45	D_3 I_5 R_3	0.032	0.096	0.040	14.5	0.45
D_1 I_3 R_4	0.020	0.048	0.050	14.5	0.45	D_3 I_5 R_4	0.032	0.096	0.050	14.5	0.45
D_1 I_4 R_1	0.020	0.064	0.020	14.5	0.45	D_4 I_1 R_1	0.040	0.016	0.020	14.5	0.45
D_1 I_4 R_2	0.020	0.064	0.030	14.5	0.45	D_4 I_1 R_2	0.040	0.016	0.030	14.5	0.45
D_1 I_4 R_3	0.020	0.064	0.040	14.5	0.45	D_4 I_1 R_3	0.040	0.016	0.040	14.5	0.45
D_1 I_4 R_4	0.020	0.064	0.050	14.5	0.45	D_4 I_1 R_4	0.040	0.016	0.050	14.5	0.45
D_1 I_5 R_1	0.020	0.096	0.020	14.5	0.45	D_4 I_2 R_1	0.040	0.032	0.020	14.5	0.45
D_1 I_5 R_2	0.020	0.096	0.030	14.5	0.45	D_4 I_2 R_2	0.040	0.032	0.030	14.5	0.45
D_1 I_5 R_3	0.020	0.096	0.040	14.5	0.45	D_4 I_2 R_3	0.040	0.032	0.040	14.5	0.45
D_1 I_5 R_4	0.020	0.096	0.050	14.5	0.45	D_4 I_2 R_4	0.040	0.032	0.050	14.5	0.45
D_2 I_1 R_1	0.025	0.016	0.020	14.5	0.45	D_4 I_3 R_1	0.040	0.048	0.020	14.5	0.45
D_2 I_1 R_2	0.025	0.016	0.030	14.5	0.45	D_4 I_3 R_2	0.040	0.048	0.030	14.5	0.45
D_2 I_1 R_3	0.025	0.016	0.040	14.5	0.45	D_4 I_3 R_3	0.040	0.048	0.040	14.5	0.45
D_2 I_1 R_4	0.025	0.016	0.050	14.5	0.45	D_4 I_3 R_4	0.040	0.048	0.050	14.5	0.45
D_2 I_2 R_1	0.025	0.032	0.020	14.5	0.45	D_4 I_4 R_1	0.040	0.064	0.020	14.5	0.45
D_2 I_2 R_2	0.025	0.032	0.030	14.5	0.45	D_4 I_4 R_2	0.040	0.064	0.030	14.5	0.45
D_2 I_2 R_3	0.025	0.032	0.040	14.5	0.45	D_4 I_4 R_3	0.040	0.064	0.040	14.5	0.45
D_2 I_2 R_4	0.025	0.032	0.050	14.5	0.45	D_4 I_4 R_4	0.040	0.064	0.050	14.5	0.45
D_2 I_3 R_1	0.025	0.048	0.020	14.5	0.45	D_4 I_5 R_1	0.040	0.096	0.020	14.5	0.45
D_2 I_3 R_2	0.025	0.048	0.030	14.5	0.45	D_4 I_5 R_2	0.040	0.096	0.030	14.5	0.45
D_2 I_3 R_3	0.025	0.048	0.040	14.5	0.45	D_4 I_5 R_3	0.040	0.096	0.040	14.5	0.45
D_2 I_3 R_4	0.025	0.048	0.050	14.5	0.45	D_4 I_5 R_4	0.040	0.096	0.050	14.5	0.45
D_2 I_4 R_1	0.025	0.064	0.020	14.5	0.45	D_5 I_1 R_1	0.050	0.016	0.020	14.5	0.45
D_2 I_4 R_2	0.025	0.064	0.030	14.5	0.45	D_5 I_1 R_2	0.050	0.016	0.030	14.5	0.45
D_2 I_4 R_3	0.025	0.064	0.040	14.5	0.45	D_5 I_1 R_3	0.050	0.016	0.040	14.5	0.45
D_2 I_4 R_4	0.025	0.064	0.050	14.5	0.45	D_5 I_1 R_4	0.050	0.016	0.050	14.5	0.45
D_2 I_5 R_1	0.025	0.096	0.020	14.5	0.45	D_5 I_2 R_1	0.050	0.032	0.020	14.5	0.45
D_2 I_5 R_2	0.025	0.096	0.030	14.5	0.45	D_5 I_2 R_2	0.050	0.032	0.030	14.5	0.45
D_2 I_5 R_3	0.025	0.096	0.040	14.5	0.45	D_5 I_2 R_3	0.050	0.032	0.040	14.5	0.45
D_2 I_5 R_4	0.025	0.096	0.050	14.5	0.45	D_5 I_2 R_4	0.050	0.032	0.050	14.5	0.45
D3 I_1 R_1	0.032	0.016	0.020	14.5	0.45	D_5 I_3 R_1	0.050	0.048	0.020	14.5	0.45
D3 I_1 R_2	0.032	0.016	0.030	14.5	0.45	D_5 I_3 R_2	0.050	0.048	0.030	14.5	0.45
D3 I_1 R_3	0.032	0.016	0.040	14.5	0.45	D_5 I_3 R_3	0.050	0.048	0.040	14.5	0.45
D3 I_1 R_4	0.032	0.016	0.050	14.5	0.45	D_5 I_3 R_4	0.050	0.048	0.050	14.5	0.45
D3 I_2 R_1	0.032	0.032	0.020	14.5	0.45	D_5 I_4 R_1	0.050	0.064	0.020	14.5	0.45
D3 I_2 R_2	0.032	0.032	0.030	14.5	0.45	D_5 I_4 R_2	0.050	0.064	0.030	14.5	0.45
D3 I_2 R_3	0.032	0.032	0.040	14.5	0.45	D_5 I_4 R_3	0.050	0.064	0.040	14.5	0.45
D3 I_2 R_4	0.032	0.032	0.050	14.5	0.45	D_5 I_4 R_4	0.050	0.064	0.050	14.5	0.45
D_5 I_5 R_4	0.050	0.096	0.050	14.5	0.45	D_5 I_5 R_1	0.050	0.096	0.020	14.5	0.45
D_1 I_1 R_2	0.020	0.016	0.030	10	0.45	D_5 I_5 R_2	0.050	0.096	0.030	14.5	0.45
D_1 I_1 R_3	0.020	0.016	0.040	10	0.45	D_5 I_5 R_3	0.050	0.096	0.040	14.5	0.45
D_1 I_1 R_4	0.020	0.016	0.050	10	0.45	D_3 I_4 R_2	0.032	0.064	0.030	10	0.45
D_1 I_2 R_1	0.020	0.032	0.020	10	0.45	D_3 I_4 R_3	0.032	0.064	0.040	10	0.45
D_1 I_2 R_2	0.020	0.032	0.030	10	0.45	D_3 I_4 R_4	0.032	0.064	0.050	10	0.45
D_1 I_2 R_3	0.020	0.032	0.040	10	0.45	D_3 I_5 R_1	0.032	0.096	0.020	10	0.45
D_1 I_2 R_4	0.020	0.032	0.050	10	0.45	D_3 I_5 R_2	0.032	0.096	0.030	10	0.45
D_1 I_3 R_1	0.020	0.048	0.020	10	0.45	D_3 I_5 R_3	0.032	0.096	0.040	10	0.45
D_1 I_3 R_2	0.020	0.048	0.030	10	0.45	D_3 I_5 R_4	0.032	0.096	0.050	10	0.45
D_1 I_3 R_3	0.020	0.048	0.040	10	0.45	D_4 I_1 R_1	0.040	0.016	0.020	10	0.45
D_1 I_3 R_4	0.020	0.048	0.050	10	0.45	D_4 I_1 R_2	0.040	0.016	0.030	10	0.45
D_1 I_4 R_1	0.020	0.064	0.020	10	0.45	D_4 I_1 R_3	0.040	0.016	0.040	10	0.45
D_1 I_4 R_2	0.020	0.064	0.030	10	0.45	D_4 I_1 R_4	0.040	0.016	0.050	10	0.45
D_1 I_4 R_3	0.020	0.064	0.040	10	0.45	D_4 I_2 R_1	0.040	0.032	0.020	10	0.45
D_1 I_4 R_4	0.020	0.064	0.050	10	0.45	D_4 I_2 R_2	0.040	0.032	0.030	10	0.45
D_1 I_5 R_1	0.020	0.096	0.020	10	0.45	D_4 I_2 R_3	0.040	0.032	0.040	10	0.45
D_1 I_5 R_2	0.020	0.096	0.030	10	0.45	D_4 I_2 R_4	0.040	0.032	0.050	10	0.45
D_1 I_5 R_3	0.020	0.096	0.040	10	0.45	D_4 I_3 R_1	0.040	0.048	0.020	10	0.45
D_1 I_5 R_4	0.020	0.096	0.050	10	0.45	D_4 I_3 R_2	0.040	0.048	0.030	10	0.45
D_2 I_1 R_1	0.025	0.016	0.020	10	0.45	D_4 I_3 R_3	0.040	0.048	0.040	10	0.45
D_2 I_1 R_2	0.025	0.016	0.030	10	0.45	D_4 I_3 R_4	0.040	0.048	0.050	10	0.45
D_2 I_1 R_3	0.025	0.016	0.040	10	0.45	D_4 I_4 R_1	0.040	0.064	0.020	10	0.45
D_2 I_1 R_4	0.025	0.016	0.050	10	0.45	D_4 I_4 R_2	0.040	0.064	0.030	10	0.45

(continued on next page)

Table 1 *(continued)*

Model	D (m)	I (m)	R (m)	Q (L/s)	H (m)	Model	D (m)	I (m)	R (m)	Q (L/s)	H (m)
D_2 I_2 R_1	0.025	0.032	0.020	10	0.45	D_4 I_4 R_3	0.040	0.064	0.040	10	0.45
D_2 I_2 R_2	0.025	0.032	0.030	10	0.45	D_4 I_4 R_4	0.040	0.064	0.050	10	0.45
D_2 I_2 R_3	0.025	0.032	0.040	10	0.45	D_4 I_5 R_1	0.040	0.096	0.020	10	0.45
D_2 I_2 R_4	0.025	0.032	0.050	10	0.45	D_4 I_5 R_2	0.040	0.096	0.030	10	0.45
D_2 I_3 R_1	0.025	0.048	0.020	10	0.45	D_4 I_5 R_3	0.040	0.096	0.040	10	0.45
D_2 I_3 R_2	0.025	0.048	0.030	10	0.45	D_4 I_5 R_4	0.040	0.096	0.050	10	0.45
D_2 I_3 R_3	0.025	0.048	0.040	10	0.45	D_5 I_1 R_1	0.050	0.016	0.020	10	0.45
D_2 I_3 R_4	0.025	0.048	0.050	10	0.45	D_5 I_1 R_2	0.050	0.016	0.030	10	0.45
D_2 I_4 R_1	0.025	0.064	0.020	10	0.45	D_5 I_1 R_3	0.050	0.016	0.040	10	0.45
D_2 I_4 R_2	0.025	0.064	0.030	10	0.45	D_5 I_1 R_4	0.050	0.016	0.050	10	0.45
D_2 I_4 R_3	0.025	0.064	0.040	10	0.45	D_5 I_2 R_1	0.050	0.032	0.020	10	0.45
D_2 I_4 R_4	0.025	0.064	0.050	10	0.45	D_5 I_2 R_2	0.050	0.032	0.030	10	0.45
D_2 I_5 R_1	0.025	0.096	0.020	10	0.45	D_5 I_2 R_3	0.050	0.032	0.040	10	0.45
D_2 I_5 R_2	0.025	0.096	0.030	10	0.45	D_5 I_2 R_4	0.050	0.032	0.050	10	0.45
D_2 I_5 R_3	0.025	0.096	0.040	10	0.45	D_5 I_3 R_1	0.050	0.048	0.020	10	0.45
D_2 I_5 R_4	0.025	0.096	0.050	10	0.45	D_5 I_3 R_2	0.050	0.048	0.030	10	0.45
D_3 I_1 R_1	0.032	0.016	0.020	10	0.45	D_5 I_3 R_3	0.050	0.048	0.040	10	0.45
D_3 I_1 R_2	0.032	0.016	0.030	10	0.45	D_5 I_3 R_4	0.050	0.048	0.050	10	0.45
D_3 I_1 R_3	0.032	0.016	0.040	10	0.45	D_5 I_4 R_1	0.050	0.064	0.020	10	0.45
D_3 I_1 R_4	0.032	0.016	0.050	10	0.45	D_5 I_4 R_2	0.050	0.064	0.030	10	0.45
D_3 I_2 R_1	0.032	0.032	0.020	10	0.45	D_5 I_4 R_3	0.050	0.064	0.040	10	0.45
D_3 I_2 R_2	0.032	0.032	0.030	10	0.45	D_5 I_4 R_4	0.050	0.064	0.050	10	0.45
D_3 I_2 R_3	0.032	0.032	0.040	10	0.45	D_5 I_5 R_1	0.050	0.096	0.020	10	0.45
D_3 I_2 R_4	0.032	0.032	0.050	10	0.45	D_5 I_5 R_2	0.050	0.096	0.030	10	0.45
D_3 I_3 R_1	0.032	0.048	0.020	10	0.45	D_5 I_5 R_3	0.050	0.096	0.040	10	0.45
D_3 I_3 R_2	0.032	0.048	0.030	10	0.45	D_5 I_5 R_4	0.050	0.096	0.050	10	0.45
D_3 I_3 R_3	0.032	0.048	0.040	10	0.45						

[a] D_1=0.020, D_2=0.025, D_3=0.032, D_4=0.040, D_5=0.050, I_1=0.016, I_2=0.032, I_3=0.048, I_4=0.064, I_5=0.096, R_1=0.200, R_2=0.300, R_3=0.400, R_4=0.500 m.

distance from the orifice are three effective parameters on the volume of flushing cone. As said, one of the purposes of this research was to investigate the effect of $D_{orifice}$, I and R on the extent of flushing cone. The flushing cone geometric characteristics investigated were: (1) the maximum scour depth (2) the maximum radius of flushing cone, (3) the amount of evacuated sediments through flushing operation.

3. Experimental results

The first set of experiments was conducted without placing the proposed structure upstream of the orifice. The primary mechanism of sediment transport during the first seconds of this set of experiments was the excess flow shear stresses, generated by the accelerated outflowing water from the orifice, which scoured the sediment and created a flushing cone upstream of the orifice. After about 3 min, due to increasing the depth of flushing cone, the velocities and shear stresses in the flushing cone decreased. After this initial stage, two counter-rotating vortices begun to form below the invert of the orifice (Fig. 5). These vortices caused lifting the sediments from the flushing cone into the outflowing water and afterward became the dominant mechanism for removing the sediments from the flushing cone. Then, the vortices were mixed together and produced a stronger drifting vortex. Sediment particles begun to roll down the sides of the flushing cone, then was fed into the central drifting vortex and sucked vertically out of the cone and through the orifice. At the end of each experiment, a series of ridges and troughs formed within the flushing cone. Formation of these ridges and troughs proves the existence of vortices [18].

The observations revealed that the amount of flushed sediments was largely dependent on the strength of these vortices. Therefore, by increasing the strength of these vortices, it is possible to remove more sediments from the reservoir. Accordingly, in this experimental study a structure composed of semi-confined piles was connected to the orifice to increase the strength of the vortices and flow turbulence. In addition, by using the proposed structure in dams, the risk of orifice blockage due to submerged debris decreases.

One of the main representative characteristics of scour hole at upstream of the orifices is the final shape of the scour hole. The scour hole cross-sectional data may be used for the future calibration, assessment and development of numerical models, as well. (Fig. 6) shows the transverse cross-section of flushing cone for three different distances of $Z/D_{orifice}$=0.53, $Z/D_{orifice}$=1 and $Z/D_{orifice}$=1.53 from the orifice. From the figure, the dimensions of flushing cone decreased by increasing the distance from orifice. In other word, the cone cross-sectional area at distance $Z/D_{orifice}$=0.53 was 9.22 times the cross-sectional area at $Z/D_{orifice}$=1.53.

Also, the experiments showed that, the side slope of flushing cones was approximately equal to the submerged angle of repose of the sediment, 26°. This is consistent with the observations of Emamgholizadeh and Fathi-moghadam [6]. In this regard, Fang and Cao [9] reported that, for granular sediments, the slope of flushing cone may be estimated by the submerged angle of repose.

3.1. Effect of proposed structure on the flushing process

The mechanism of flushing operation in the presence of proposed structure was influenced by two factors: 1) encountering the flow with piles (local scour) 2) constricting the flow due to using confining plate and vertical piles.

During each experiment of this research, there was a strong interaction between the size of the pile, the distance between two adjacent piles, the size of the flushing cone and the strengths of down flow, horseshoe and wake vortices (Fig. 7). The wake vortices interacted with the horseshoe vortex at the flushing cone, increased its strength and caused it to oscillate laterally and vertically. In addition, the wake vortices caused an erosion process that sucked up the material from the flushing cone and swept them away from the base of the cone. Dye injection showed that the flow field, approaching the piles, varies three dimensionally with complex recirculation zones and secondary flows. In this case, the flow had to pass through the gap between piles, led to establishing a constricted flow with higher velocity, turbulence and tractive forces which swept away the bed material and developed the flushing cone at a faster rate compared to the reference test. By this processes, the flushing cone were deepened due to the conflicting

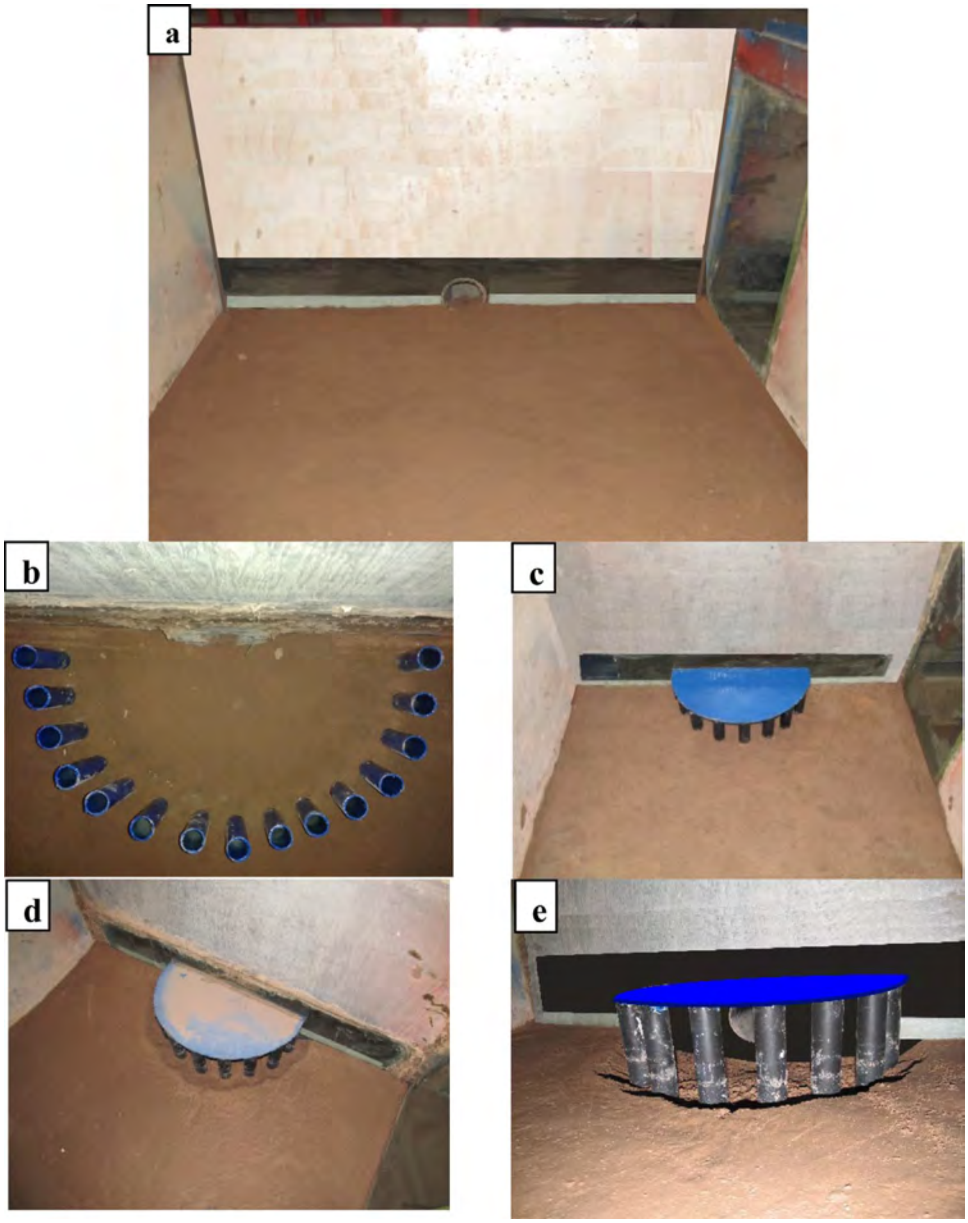

Fig. 3. Preparing the sedimentary bed upstream of orifice (a) and procedure for embedding the proposed structure in the reservoir: before (b, c) and after the test (d, e).

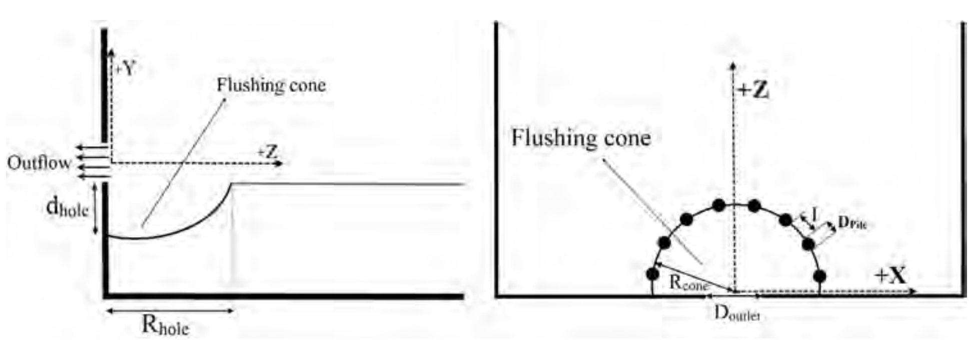

Fig. 4. Schematic representation of orifice and scour hole: side view (left) and top view (right).

velocity fields at the intersection of the wake vortex streams from adjacent piles. In all tests of this study, it was observed that the maximum scour depth occurred at the center of the flushing cone due to the additive effect of central drifting vortex scour and wake vortex scour (Fig. 7).

3.2. Effect of pile diameter

In the proposed structure, circular piles with five different relative diameters ($D_{pile}/D_{orifice}$) of 0.21 (D_1=0.020 m), 0.26 (D_2=0.025 m), 0.35 (D_3=0.032 m), 0.42 (D_4=0.040 m), and 0.53 (D_5=0.050 m) were used. In this section, the results of tests $D_1I_2R_2$, $D_2I_2R_2$, $D_3I_2R_2$, $D_4I_2R_2$,

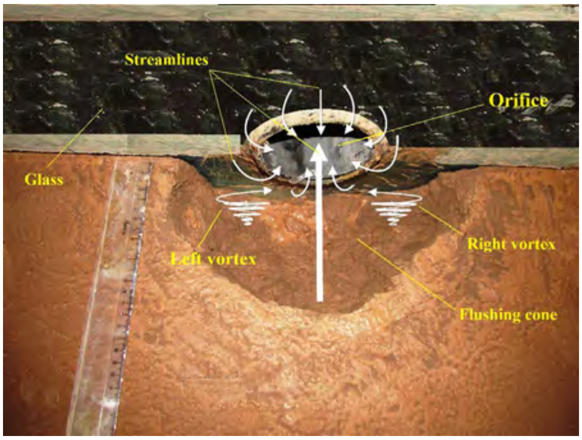

Fig. 5. Typical flow patterns upstream of the orifice.

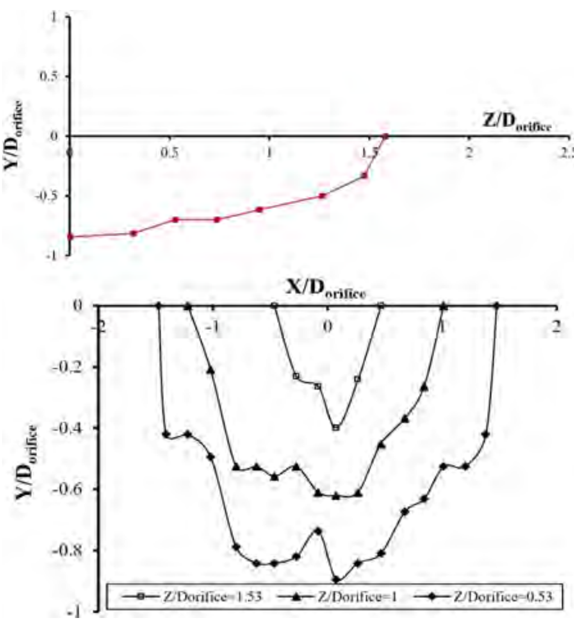

Fig. 6. Longitudinal profile (top) and cross-sections (below) of flushing cone.

and $D_5I_2R_2$ are reported and discussed (I_2=0.032 m, R_2=0.300 m). The results are consistent for all other combinations of I and R. For all other setups, The effect of pile diameter on the dimensions of flushing cone is demonstrated in (Fig. 8a, b). By implementing the piles, the relative flushing depth increased, so that, for the outflow discharge rate of 14.5 L/s, the value of $d_{hole}/D_{orifice}$ increased from 0.83 (in the reference test) to 0.95 for the test with $D_{pile}/I = 1$. By further increasing of the pile diameter, the depth of flushing cone decreased, so that, the minimum flushing depth was observed at $D_{pile}/I = 1.56$ equal to $d_{hole}/D_{orifice} = 0.68$ (Fig. 8a). In other word, among the tested pile diameters, the pile with $D_{pile}/I = 1$ has the most efficiency on the sediment removal. In this case, in addition to the central drifting vortex in front of the orifice, both the shear stresses and pile-induced vortices had significant role in formation, widening and deepening of flushing cone. For the thinner piles, (i.e. $D_{pile}/I < 1$) the pile-induced vortices were not strong enough to lift and sweep the sediments, therefore, little scour was observed upstream of the orifice. For the piles with larger diameters ($D_{pile}/I > 1$), no horseshoe vortex formed and the shear stresses was the only responsible for formation of the flushing cone. This is consistent with the observations of Carstens and Sharma [4]. In fact, larger piles acted as an obstacle, reduced the flow velocity and turbulence and imposed an attenuating effect on the strength of central vortex. Therefore, for $D_{pile}/I > 1$, the maximum depth of flushing cone decreased. In addition, for the piles with larger diameters, the pile-induced wake vortices had not sufficient opportunity to be strong enough because of the short distance between piles and the orifice. In other word, before strengthening the wake vortices, the flow reached to the orifice.

In the other hand, for the outflow discharge of 14.5 L/s, the relative radius of flushing cone(R_{hole}/I) reached from 1.58 in the reference test to 3.6 for the test with $D_{pile}/I = 1.56$, indicating 128% increment in the relative radius of flushing cone (Fig. 8b). By increasing the pile diameter, the scoured region increased compared to the reference test. Similar trend was observed for the outflow discharge of 10 L/s.

3.3. Effect of pile spacing

For the piles with the most scouring effect (i.e. $D_{pile}/I = 1$), the distance between the piles (I) was changed to investigate the effect of I on the dimensions of flushing cone. To this purpose, the piles were implemented in five different relative distances from each other, $I/D_{orifice} = 0.17,\ 0.34,\ 0.51,\ 0.67 \text{and}\ 1.01$. The results from tests $D_3I_1R_2$, $D_3I_2R_2$, $D_3I_3R_2$, $D_3I_4R_2$, and $D_3I_5R_2$ are discussed here. For all other setups, the results are consistent. (Fig. 9a, b) shows the effect of $I/D_{orifice}$ on the characteristics of flushing cone. By increasing the piles spacing, the maximum depth of flushing cone was firstly increased and then decreased. In the case of reference test, the value of $d_{hole}/D_{orifice}$ for the outflow discharge of 14.5 L/s was obtained 0.83, while, for $I/D_{orifice} = 0.17$, the value of relative depth reached to 1.3, indicating 56% increment in relative flushing depth. By increasing the pile spacing, the depth of flushing cone reached to 0.7, which was lower than the flushing depth at the reference test. In the case of $I/D_{orifice} > 0.17$, the scour depth between the piles as well as the maximum depth of flushing cone decreased because the effect of accelerated jet flow was weakened and the shear stresses were reduced in the flushing cone. In fact, by increasing the distance, the interference of the flow from each pile was significantly weakened and the strength of wake vortex decreased, rapidly. In addition, the collision between the flow jets and the central drifting vortex was alleviated and the turbulence decreased. This was consistent with the results of Elliott and Baker [5], and Kim et al. [11] who reported that if the pile spacing become large, the flow interference triggered by adjacent piles will be negligible. For $I/D_{orifice} = 0.17$, not only the erosion capacity of jet-flow became stronger, but also due to the interactions between flow and piles, the flow turbulence increased, resulted in more amount of scour upstream of orifice. In addition, the horse-shoe vortex became compressed and the collision between separated streamlines with each other and with the central drifting vortex increased.

From (Fig. 9b), the effect of piles relative spacing on the relative radius of flushing cone was approximately constant. In this case, the maximum relative radius of flushing cone was observed at $I/D_{orifice} = 0.17$, which was 3.37 for the outflow discharge of 14.5 L/s, indicating 113% increment in comparison with the reference test.

3.4. Effect of piles distance from the orifice

As said, the top view of the piles position was semicircular shape with a radius of R. The results from tests $D_3I_1R_1$, $D_3I_1R_2$, $D_3I_1R_3$, $D_3I_1R_4$, and $D_3I_1R_5$ are discussed here. These tests (tests with D_3I_1) showed the most scour depth among the experiments. To investigate the effect of pile distance from the orifice, more piles were added as R was increased, keeping I the same. (Fig. 10a, b) show the effect of R on the characteristics of flushing cone. As shown, for Q=14.5 L/s and Q=10 L/s at $R/D_{orifice} = 3.16$, the relative flushing depth was obtained 0.96 and 0.72, which increased 15% and 13%, respectively, compared to the reference test. In the high values of R, the relative depth of flushing cone decreased. As can be seen, at $R/D_{orifice} = 5.26$, the relative flushing depth was close to the reference test for both outflow discharges.

In addition, for the outflow discharge of 14.5 L/s, the value of

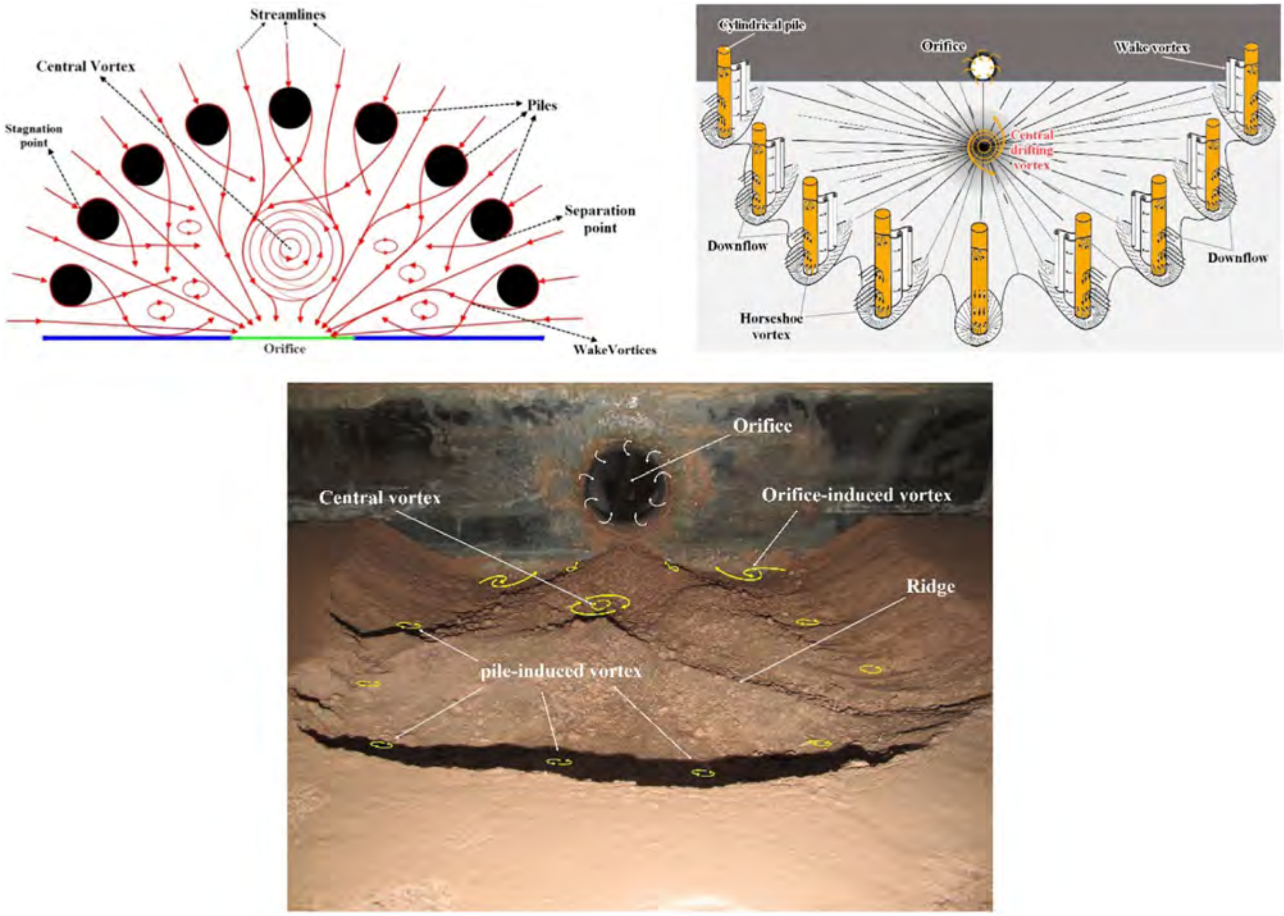

Fig. 7. Schematic representation of the interaction of flow and piles and the generated vortices (top) and ridges formed after flushing operation (below).

$R_{hole}/D_{orifice}$ for the reference test was 1.58, while, for the test with $R/D_{orifice}$ = 5.26, it was 5.32. Also, for outflow discharge of 10 L/s, the value of $R_{hole}/D_{orifice}$ for the reference test was 1.18, while, for the test with $R/D_{orifice}$ = 5.26, it was 4. In other word, the value of relative radius of flushing cone at the test $D_3I_1R_4$ was 3.37 and 3.39 times of that of the reference test, respectively for outflow discharges of 14.5 and 10 L/s. It was observed that more the $R/D_{orifice}$, more the $R_{hole}/D_{orifice}$. From the analysis it was found that, as the R increased, a wider area of the bed surface exposed to the shear stresses and a larger amount of sediment was scoured from the bed. In larger values of R, the inception point of scouring occurred close to the orifice and developed retrogressively to the upstream. In this case, the main factor for sediment removal was the extending of constricted flow region. In smaller values of R, the scouring process begun from the upstream face of piles and extended progressively toward the orifice by mixing with horseshoe vortex, wake vortices and central drifting vortex. For $R/D_{orifice} > 3.16$, the piles had inverse effect on the depth of flushing cone but caused a wider area of reservoir to scour.

3.5. Temporal variation of flushing cone

(Fig. 11) shows how the flushing cone developed over time upstream of the orifice. As can be seen by opening the orifice valve, the scour was initially occurred close to the orifice and thereafter extended symmetrically toward the upstream with a half-cone shape. The scour rate was very high at the early stage of the scouring process, then decreased with time. By embedding the proposed structure, the rate of temporal development of flushing cone increased significantly. In this way, the scouring process initiated at the flanks of each pile, then, propagated at the sides of piles. The final shape of flushing cone was semi-circular, similar to the reference test, but with a diameter of about twice that. After 6 h, the equilibrium condition was reached, and the walls of flushing cone became stable. At about 240 min after the commencement of the test, the variations rate of flushing cone were decreased and then the final shape of flushing cone was formed after 6 h, so that, no further development occurred, thereafter.

3.6. Flushing efficiency

To calculate the volume of flushing cone in this study, the x,y,z points of flushing cone were measured and then, imported to SURFER-10 software. (Fig. 12a, b) shows a sample of contour map and 3D wireframe map of flushing cone in the test $D_2I_4R_3$, obtained by SURFER-10. For the reference test of this study, the flushing efficiency was obtained 0.00094 for the first 1000 s of the test, while, for the test $D_3I_1R_4$ (test with the greatest effect), the flushing efficiency reached to 0.00324, indicating a remarkable effect of semi-confined pile structure on improvement of flushing efficiency. Emamgholizadeh and Fathi-moghadam [6] reported flushing efficiency of 0.00343 for their experimental conditions. By surveying some reservoirs over the world, Morris and Fan [17] reported the range of 0.00017–0.043 for flushing efficiency. The wide range of flushing efficiencies in different works is due to the differences in flow condition, sediment properties, geometry of bottom outlet, and time duration of flushing operation. These factors can heavily influence the flushing efficiency.

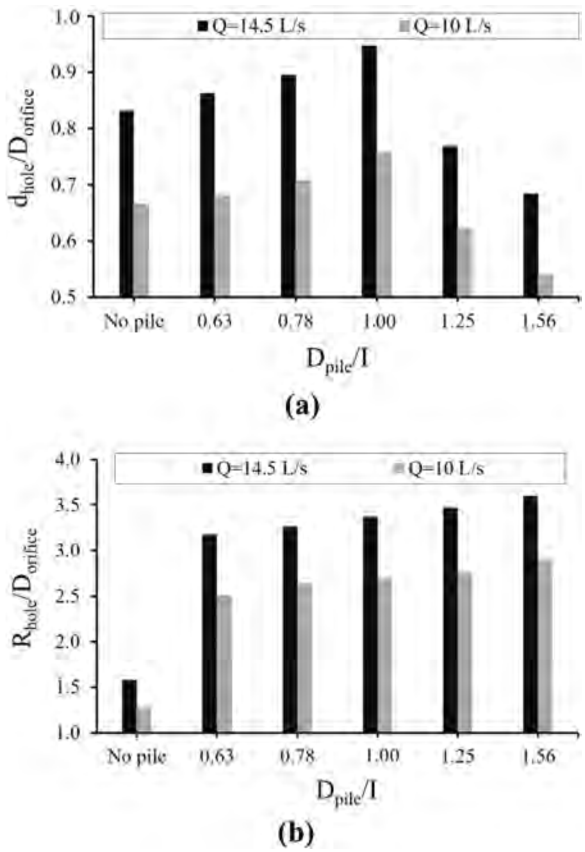

Fig. 8. Variations of flushing cone relative depth (b) and relative radius (a) vs. pile diameter.

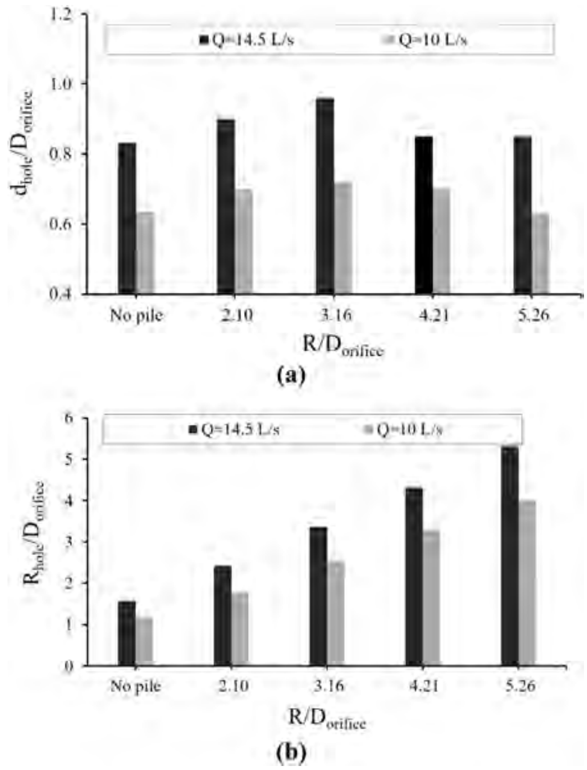

Fig. 10. Variations of flushing cone relative depth (a) and relative radius (b) vs. pile distance from the orifice.

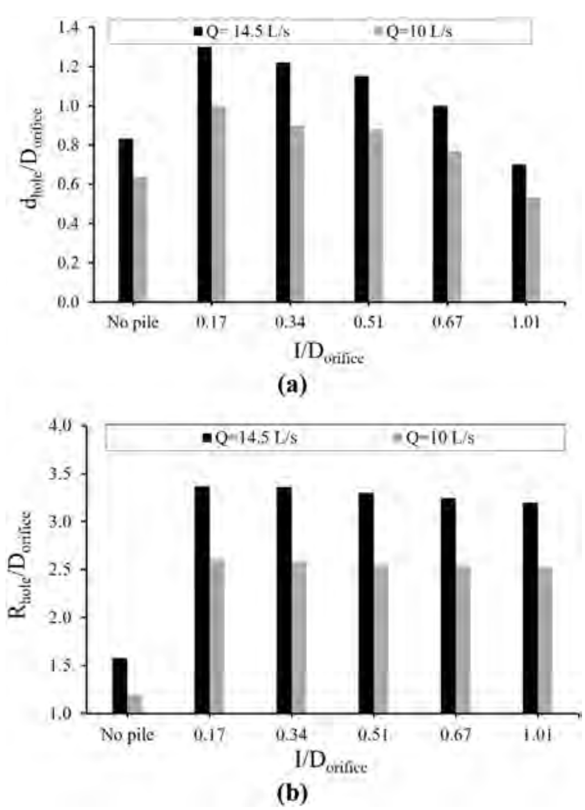

Fig. 9. Variations of flushing cone relative depth (a) and relative radius (b) vs. pile spacing.

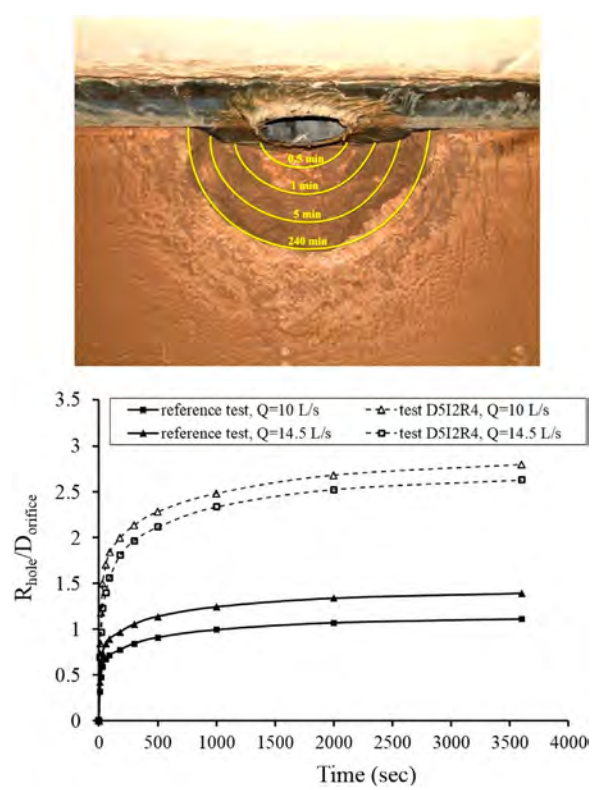

Fig. 11. Temporal variation of flushing cone in the reference test (top) and comparison it with the test $D_5I_2R_4$ (below).

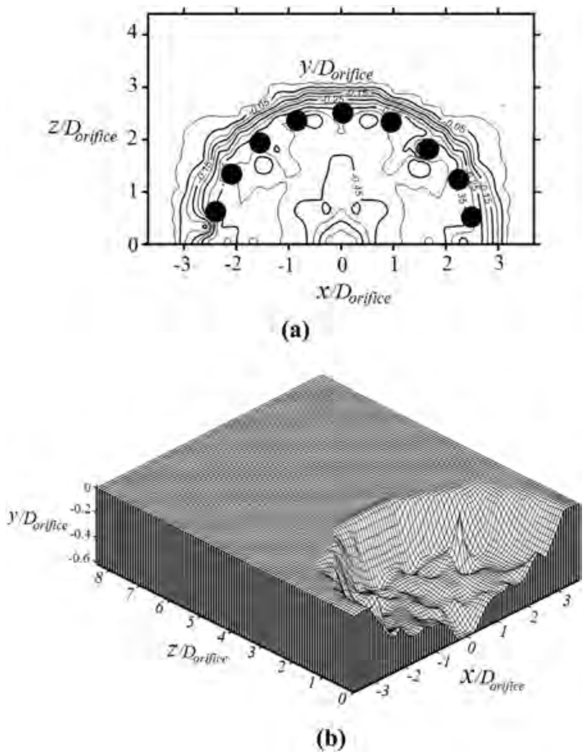

Fig. 12. Contour map (a) and 3D map (b) of flushing cone in the test $D_2I_4R_3$.

4. Conclusion

In this research the flow characteristics and sediment scour at the upstream of a large orifice, when the sediments are accumulated up to the invert of orifice, were investigated. Next, a semi-confined piles group structure was used to strengthen the power of orifice flow with the purpose of improving the sediment removal efficiency. The effect of geometrical properties of proposed structure on the dimensions of flushing cone was investigated. The results showed that by using the proposed structure, both the relative depth and the relative radius of flushing cone increased. In this way, piles diameter had a significant effect on the dimensions of scoured region. It was observed that by increasing the piles spacing, the maximum depth of flushing cone was firstly increased and then decreased. Furthermore, it was found that as the distance of piles from the orifice increased, a larger amount of sediment was scoured from the flushing cone. Then, the time development of flushing cone was followed with and without the structure. It was observed that in the presence of proposed structure, the rate of temporal development of flushing cone increased significantly. The observations indicated that, the amount of flushed sediments increased by up to 250% compared to the reference test.

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