Sediment Sluicing from the Reservoirs with High Efficiency

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Sediment sluicing and flushing from the reservoirs is one of the necessary operations to save the useful life of the reservoirs. Many reservoirs in the world are faced with intense sedimentation, which causes the closure of the bottom sluice gates, and in the following increase of the sedimentation rate, which cause a deep decrease in the useful volume of the reservoir. According to many reports, Partial Flushing is one of the most effective ways of removing the deposited sediment from large reservoirs. This method has its advantages and disadvantages. For instance, this method does not need to deplete the reservoir completely. Hence, in the arid area, it's the only way that can be done to get rid of sediment, however, on the other side, this method erodes a teeny tiny amount of the accumulated sediment around the sluice gate (flushing cone), and it's not able to get the dam out of the sedimentation crisis by itself. In this study, by utilizing a numerical and physical model and with cognition of vortex flow around the sluice gate, the vortices around the sluice gate are enhanced by using a specific structure, which causes an increase in partial flushing efficiency. The results declared that by applying a half cylinder structure, the efficiency of partial flushing face with sharp increase up to 15 times. Therefore, the proposed method can be applied in all dams which encounter acute sedimentation to sluice a tremendous amount of sediment out of the reservoir, in a short time, with losing a small amount of water, and consequently, there will be a possibility to run the partial flushing repeatedly with a short interval.

Keywords: Reservoir, Partial flushing, bottom outlet, vortices flow, semi cylinder structure

Introduction

The life expectancy of reservoirs is usually limited by sediment accumulation and reducing useful storage capacity (Golze 1977). According to international reports, approximately 1% of the total storage capacity in the world's reservoirs is lost annually due to sedimentation. Sediments can also block intakes in reservoirs and damage tunnels and turbines. However, once a dam has reached the end of its useful life due to sedimentation, it's not possible to simply replace the dam since the sediment will still be in place. Therefore, the methods that increase the useful life of the reservoirs due to reducing sediment accumulation are vital for designing new dams and managing existing dams.

A sediment balance exists in the most rivers and sediment inflow to any reach is approximately equal to the outflow sediment. However, after a dam is built, slower flow velocities in the reservoir cause the deposition of a portion of the incoming sediment load. Hydraulic flushing is one of the most effective techniques used for scouring deposited sediments out from the reservoirs by use of low-level outlets in a dam. Flushing can be classified as pressurized flushing (partial drawdown) and free-flow flushing (fully drawdown). Under the pressure flushing, water is released through the bottom outlets, while the water level in the reservoir is kept high. Free flow flushing means that the reservoir is completely drained, and the sediment removal is accomplished through the creation of channel networks in the reservoir (Fig 1). In this study, partial drawdown flushing is evaluated.

Fig 1. Channel networks in the reservoir in fully drawdown flushing (Hajhosaini 2008)

Partial drawdown flushing, scour sediments in the vicinity of the sluice-gate opening within a very short period, and a funnel-shaped crater called "flushing cone" will be formed (Fig 2). Once the flushing cone has been formed and there is no sediment moving into the cone, the flowing water is clear through the opening, meaning that the formation of the flushing cone is fairly stable, and no sediment will be removed. In this study development of the flushing cone is investigated when the water level is kept high.

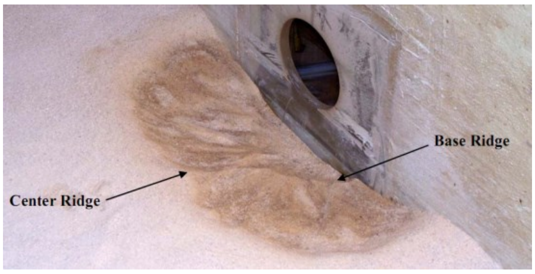


Fig 2. View of Flushing Cone (Powell 2007)

In most flushing studies, experiments focused on the unpressurized flow conditions, because this method has been more effective in many studies in the world. But the followings reasons are the restrictions of this method:

1. Only small reservoirs can perform fully drawdown flushing because they can recharge quickly (Reservoirs

with a storage capacity less than 30% of the mean annual runoff), but this process is not feasible for large reservoirs.

2. This may be a concern for the downstream river reach, since plus of high sediment concentration with low water outflow, may cause damage the environment and sediment may accumulate rather than being transported further downstream (Janssen 1999). Therefore, Downstream impacts can act as a constraint in the planning and operation of fully drawdown flushing.

3. Operational considerations, such as water and power demands, can inhibit the ability to fully flushing.

4. Critical region of deposited sediment in the reservoir is around the gates that bring about the blockage or improper functioning of the gates. However, Erosion of deposited sediments in fully drawdown flushing is limited to a narrow flushing channel that extended to the upstream of the reservoir.

The aim of this study is to increase efficiency in pressurized flushing and consequently increasing in sediment erosion in the flushing cone and to achieve these goals, must first a thorough understanding of flow mechanism during the flushing cone will be found. According to many studies on the flow mechanism around the reservoir bottom outlet, such as studies Rajaratnam, and Humphries (1982), White and Bettess (1984), Janssen (1999), and Powell (2007 and 2015), at the beginning of the partial flushing 2 vortex (Fig.3) with different orientations are created under the bottom outlet, which these vortices help sediments to get up and get out from the bottom outlet. It is known that there exists a radial flow with high velocity upstream of a bottom outlet. The flow field in this area varies rapidly and has the capacity to transport bed sediments. The flow field in this region may be similar to the intersection point of a channel and river or river with river. In fact, close to the outlet when a flow with high velocity, forced to change its direction, the radial flow transforms to a vortex flow. This situation also arises in the lateral intakes. In order to develop vortices, the flow acceleration near the gate must be enhanced and directed towards the gate. This can be easily done by artificially lowering water inlet (i.e., increasing head of the water) and reducing water inlet opening.

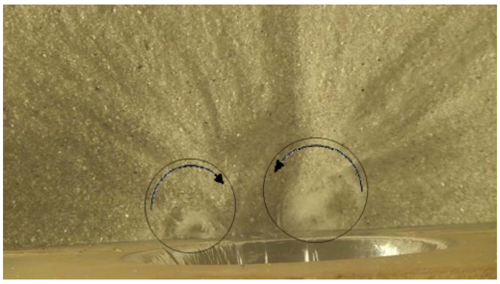


Fig 3. The Vortices around the bottom outlet (Powell 2007).

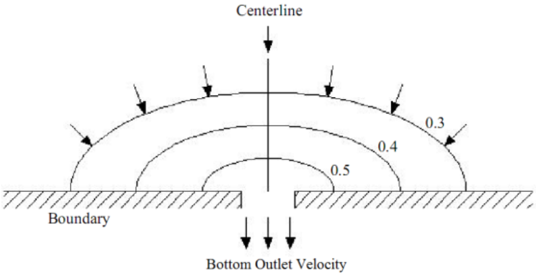


Fig 4. Contour speed line around the bottom outlet (Powell 2007)

These vortices have a short lifetime and at a short time after start of the flushing will be disappeared and consequently, outlet water will be cleared, and the created flushing cone reaches a steady state (until it reaches to free flushing condition).

According to a study conducted by Powell (2007 and 2015), by moving away from the bottom outlet, flow velocity around the bottom outlet, rapidly decline. Based on Powell's study, by moving away from the sluiceway up to the amount of 1D (Diameter of the bottom outlet) the velocity rate reaches about 10 percent of the velocity around the bottom outlet (Fig. 4).

Rajaratnam and Humphries (1982) measured velocities and pressure distributions upstream of sluice gates. They observed a drop in the pressure at the bed just upstream of the gate due to the acceleration of flow under the gate. They showed that the pressure reduction just upstream of the gate was approximately 40% of the hydrostatic pressure and became negligible after approximately 5 times the gate opening.

Salehineyshabouri and et.al (2008) used a 3D numerical modeling to study the effects of sluicegate opening height on sediment removal efficiency. Their results indicated that as the opening of the gate decreases removal of sediment from the reservoir increases.

According to obtained information about the nature of eddy flows around the bottom outlet, the idea of giving direction to the bottom outlet flow path was developed in order to increase sediment suction. To achieve this goal and reduce executive costs at first a 3D numerical model (Flow 3D) was used. With using this numerical model, a large number of structures could help to extend the vortices built and tested, and at the end the best and optimal model was chosen to carry out at the physical model.

Materials & Methods

To find the best structure which is able to extend the vortices around the bottom outlet, initially a three-dimensional numerical model (FLOW 3D) was used. It is the product of Flow Science Company. This three-dimensional model is capable to model multiphase flows (liquid and solid) and can easily model the relation between hydraulic structures and multiphase fluids.

One of the most important features of this model is achieving results (very close to reality) in a short time.

The basic motion equations in this model are the finite difference method, the non-linear Navier-Stokes equations are solved in this model. The fixed rectangular mesh (Eulerian method) is used in FLOW 3D and using the FAVOR method can be overcome combinations of mesh problems.

The strength of this model is its ability to accurately solve the three-dimensional equations in the contacts between flow, sediment and structures.

Sediment transport equation in this model is based on the principle of mass conservation with transmission/ diffusion method coupled with the possibility of tracking the flow volume to investigate changes in bed (VOF).

Dimensional analyzes:

The most important parameter in the study of partial flushing efficiency is the ratio of sediment discharge to the flow discharge (Q_s/Q_w), and the most important variables included: fluid density (ρ), fluid viscosity (μ), average particle size (d_{50}), particle density (ρ_s), water head on the bottom gate (H), gate diameter (D), flow coefficient (C_d), the acceleration of gravity (g).

Equation 1 shows these effective terms:

$$1. \quad Q_s/Q_w = f(\rho, \mu, d_{50}, \rho_s, H, D, C_d, g)$$

The discharge coefficient represents the geometry of the gate opening. The velocity through the bottom outlet is a function of the head above the center of the gate, gravitational acceleration, and discharge coefficient. Since all of these variables are represented in Equation 1, its explicit inclusion is not required. The discharge coefficient is an implicit measure of the Froude number as shown below.

$$2. \quad Q = C_d A_0 \sqrt{2gH}$$

$$3. \quad C_d = \frac{Q}{A_0\sqrt{2gH}} = \frac{V}{\sqrt{2gH}} = \frac{F_r}{\sqrt{2}}$$

Q is the flow rate and A_0 is the area of the gate. The flow rate through the gate is a function of headwater above the gate, gravity and flow coefficient.

Repeating variables selected are the orifice head, gravitational acceleration, and fluid density. The resulting terms of the dimensional analysis are shown in Equation 4.

$$4. \quad Q_s/Q_w = f\left(\frac{H\rho\sqrt{gH}}{\mu}, \frac{d_{50}}{H}, \frac{\rho_s}{\rho}, \frac{D}{H}, C_d\right)$$

For all tests, the sediments used were sand with the same specific gravity, so the relative density term ($\frac{\rho_s}{\rho}$) can be neglected. Since the discharge coefficient was kept constant, this would imply that the Froude number remained the same for all runs. The remaining parameters included a Reynolds-type term as well as sediment and orifice diameter scaled with the head over the orifice. In order to assess the influence of Reynolds number and only use water, the head over the orifice would need to be varied. The 2 length parameters available included the head, sediment size, and gate opening. A previous study by Bryant (2006) suggested that trends were similar for bounded orifices even when different orifice diameters were used. Thus, the gate opening diameter was set as a constant base on semi-cylinder diameter and the H/D parameter was varied by changing the head over the orifice only.

Results of Numerical Model:

Numerical results showed that the semi-cylindrical structure used around the bottom outlet with a lid on the top and particular under opening (Figure 5 and 6), has the best results for the vortices development and the maximum amount of stress will impose on the reservoir's bed. The results of numerical modeling showed that with using the semi-cylinder structure, volume of suspended sediments that exit from the reservoir (at 6-time intervals) increased up to 5 times compared with normal flushing (without using a new structure). Specification of this model is shown in Table 1. In Figures 8 to 11, the amount of outlet sediments and shape of the reservoir's bed in normal mode and with using the semi-cylinder have been investigated.

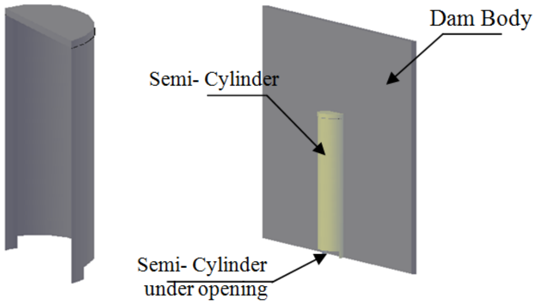


Fig 5. View of dam body and the installed semi-cylinder is in front of the bottom outlet

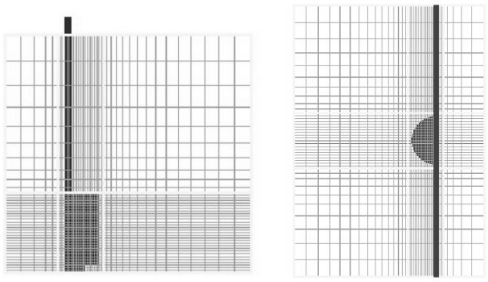


Fig 6. View of numerical model's meshing

In Figure 7, a view of the vortices at the distance of 10 cm below the bottom outlet can be seen in the numerical model, which is absolutely the same as the Powell's results

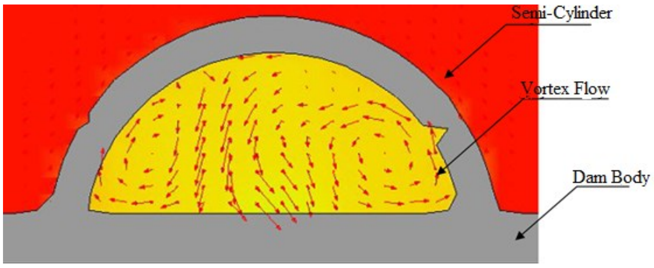


Fig 7. View of the vortices in the semi-cylindrical structure in 3D numerical model

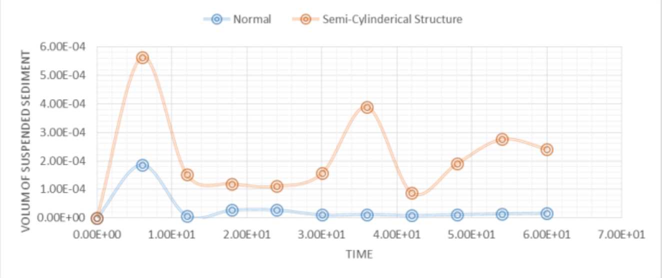


Fig 8. Volume of suspended sediment in reservoir during the flushing time (Numerical model)

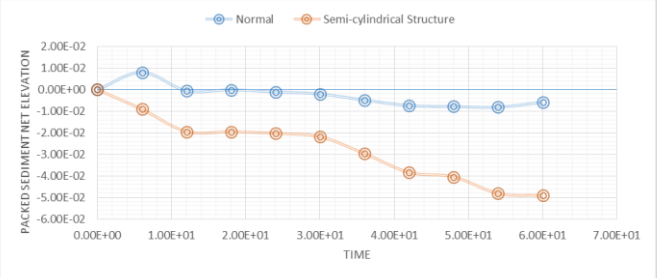


Fig 9. View of net bed Elevation of the reservoir during the flushing time (Numerical model)

(2007). Considering figures 8, 9, 10, and 11 the average increase in the reservoir outlet sediments (around the bottom outlet) by using the new structure installed in front of the bottom outlet is more than 5 times. Now, the new method is prepared to perform on the physical model.

Table 1. Details of 3D numerical model

Row	Dimension	Description
1	1 m	Length
2	1 m	Wide
3	0.8 m	Height
4	0.05 m	Diameter of sluicegate
5	0.014 m	Diameter of semi-cylinder
6	0.00051 m	Diameter of sediment
7	1700	sediment specific gravity
8	RNG	Turbulence model

Physical Model:

Experiments on the physical model in this study were conducted in a rectangular basin with 1.2 m long, 1 m wide, and 0.8 m high, which is made of fiberglass materials. For the bottom outlet gate in this study, a 2-inch circular gate valve was used. The gate valve was placed at a height of 15 cm on the basin bottom (Fig. 12 and 13). To use laminar flow in this study, water is first conducted into a stilling basin and then will go into the main basin. A rectangular sump is located downstream of the reservoir with a triangular weir inside of it which acts as a sand trap. This investigation was limited to the use of uniform, coarse, and non-cohesive sediment with a mean grain size of 0.51 mm (d_{50}=0.51mm) and with specific gravity equal to 1700.0 kg/m^3. The reason for using these sediments with low specific gravity has been better studying sediments transport and the effect of vortex on this transmission. Sediments were placed at a length of 1 m upstream from the dam position. The initial sediment level was 8 cm above the bottom of the sluice gate (surface will be flat in each experiment) and the gate valve opening in each experiment was 1 inch (2.54 cm). To avoid some unwanted errors in the experiments, a small, fixed amount for inflow discharge in each experiment was considered. Two series of experiments in this study are performed: a) normally partial flushing b) partial flushing with the new structure.

During each experiment, output flow rate, sediment weight, and water level in the reservoir at discrete intervals during the run (11-time interval during 50 minutes) was measured. At the end of each experiment, topographic data of the flushing cone and net weight of the total outlet sediment (after drying) were measured. Outflow through the gate valve was sampled at 11 discrete intervals with 13.4-liter calibrated buckets and a stopwatch with 0.01-second precision. The total volume of each sample was measured (water + sediment), and the sediment was removed in each sample, and with oven, dried, and weighed with 0.1-gram precision.

Outflow of water and sediment discharge rates were calculated based on the volume of water, sediment sampling weight, and time measured. The first series of runs were performed normal flushing without using the semi-cylinder as the base of comparison. And then the semi-cylindrical structures were installed in front of the bottom outlet and experiments were performed with the same conditions. Also, multiple measures were used to diminish the error in an experiment and reduce concerns of the reports.

During reservoir filling and submergence of sediment, the gate valve was kept closed. When the reservoir level reached the desired elevation (50 cm above the bottom of the sluice gate, the stopwatch started (t=0) and gate valve was half-opened (t= 10 s). And after this time flushing was started so that $Q_{out} > Q_{in}$ and the water level in the reservoir starts to drop. When the gate valve was first opened, sediment in its vicinity was eroded immediately and forming a flushing cone as described by White and Bettess (1984), Lai (1994), and Morris and Fan (1998), and Powell (2007).

In this study, 5 semi-cylinders diameters with the size of 2, 4, 6, 8, and 10 inches were tested. Also, the effect of semi cylinders under opening height were tested in 2 and 6-inch semi-cylinder with several under opening heights.

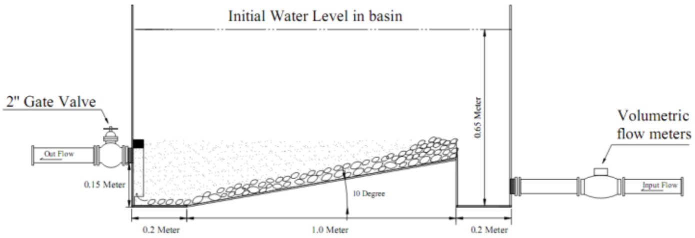


Fig 12. View of Physical Moldel (schematic)

Fig 13. View of Physical Model

Results of physical model:

According to initial observations in the physical model, when normally partial flushing was done (without the use of semi-cylindrical) as shown in Fig. 14, sediments around the gate were eroded and forming a so-called flushing cone. However, during this condition flow velocity around the outlet was high; the scour region did not extend very far from the outlet and only a little below the bottom of the gate valve (about 10% of the gate valve diameter) eroded and after a short time erosion was stopped and flushing cone was stabled, and sediments removed from the reservoir at a very low speed.

Also, when flushing has been done, vortices were clearly observable under the gate. However, these vortices had a short lifetime and poor strength to transport the sediments. These observations agree with Janssen (1999), and Pawell (2007) results.

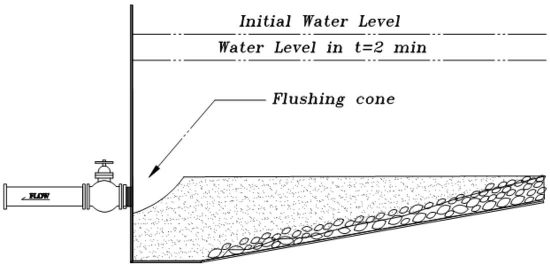


Fig. 14. Flushing cone in normal pressurized flushing (high water level) without semi-cylinder.

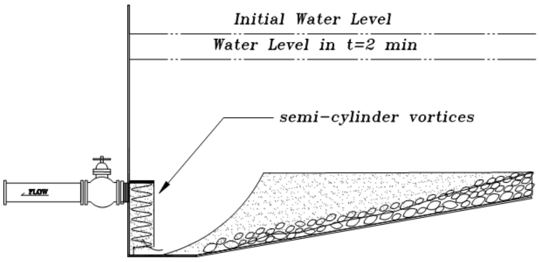


Fig. 15. Flushing cone in normal pressurized flushing (high water level) with semi-cylinder.

By using the semi-cylinder around the sluice gate (with an initial diameter equal to 6 inches), as shown in Fig. 15, sediments around the semi-cylinder eroded much more and a flushing cone was created as big as 6 times more than the normal flushing. As shown in Fig. 15, sediment particles begin to roll down from the slide sides of the scoured area (flushing cone) around the semi-cylinder until they reach the vortical area near the semi-cylinder, then entered into the vortex and are sucked vertically out of the scour hole and through the outlet. Semi-cylinder caused increasing the vortices strength and lifetime. In all performed experiments, two groups of vortices were observed clearly on both sides of the semi cylinder in orderly direction growth and lift sediment into the outlet, as same as the Powell (2007) results and the results of the numerical model. Although, when a semi-cylinder bigger than 8- and 10-inches diameter was installed, only one big vortex around the center of semi-cylinder was observed. In normal flushing, small vortices completely removed after a short distance below the gate (1.3 times more than gate opening amount). But in this new method, by using semi-cylinder around the sluice gate, more than 6 times of the gate opening amount (D), below the gate, vortices were observed.

According to figures 14 and 15, in more than 90% of the experiments, erosion occurred in the first 2 minutes of the experiment and after 5 minutes erosion nearly stopped and flushing cone took steady state. After a short transition period (less than 5 minutes) the scour hole (flushing cone) at the vicinity of the bottom outlet, reached its stable dimensions, and afterward, sediment removal slowed down. However, with descending water level, after this time (5 minutes) flow velocities in the reservoir increased but have no considerable effect on the scouring process around the sluicegate until full drawdown.

According to dimensional analyzes to check the flushing efficiency, dimensionless parameter Q_s/Q_wagainst dimensionless parameter D/H was used which results in a logarithmic graph is presented in Figure 16.

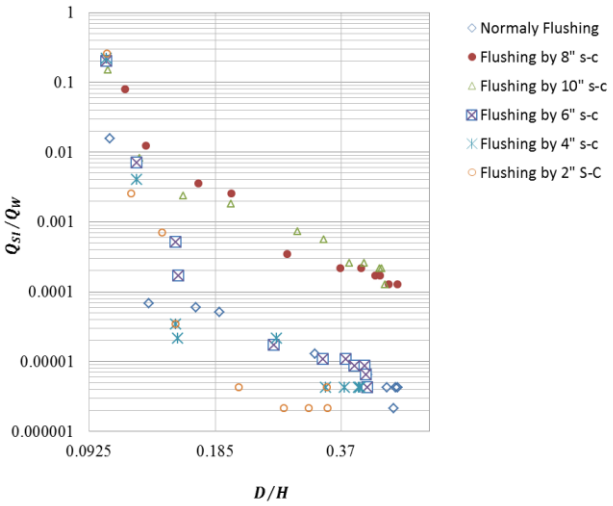


Fig. 16. Flushing efficiency comparison in different semi-cylinders (3 cm under opening height).

In Figure 17, the comparison between the total output sediment of the basin is shown in various experiments. The total volume of sediment (which is obtained by the mass divided by weight density) and D is the diameter of the gate opening.

As seen In Figure 16, by reducing the water level and thus increasing in the ratio of D/H we are faced with a reduction in flushing efficiency.

Therefore, it can be noted, which by increasing the semi-cylindrical diameter, Vortex strength would be also reduced. Based on Fig 17, the maximum amount of outlet sediment in total flushing time respectively belongs to 2, 4, and 6-inch semi-cylinders.

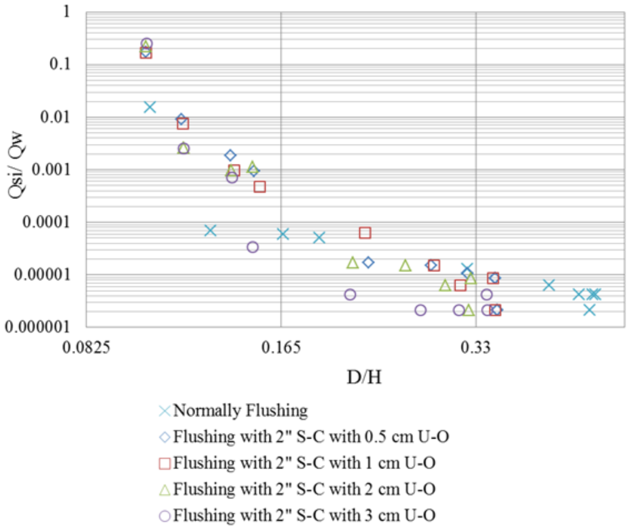
It should be noted that determining the optimum diameter for a semi-cylinder is depend on several parameters. This election was widely affected by the level of outlets. Any decrease in the level of sluice gate, leads an increase in the value of the optimal diameter and consequently increase in sediment discharge. Because low-level outlets, need poor vortices to suck sediments out of the dam.

The effects of under opening height in semi-cylindrical structures also were performed on semi cylinders 2 inch and 6 inches. The results showed that most sediment scouring is belonging to semi cylinders 2 inch (1D), with 3 cm (0.2D) under opening height (Figure 18 and 19). Flushing efficiency, in this case, was approximately 5 to 10 times more than the amount of normal flushing. Between 6-inch semi-cylinders, 0.5 inches under opening height has been the maximum scouring (Fig. 17 and 19).

The reason for this difference can be defined by measuring semi-cylindrical under opening area and compare it with the gate opening. By done measurements, results were shown that area of 2-inch semi-cylinder with 0.5, 1, and 2 cm under opening height was less than the gate opening area, but the area of 6-inch semi-cylinder with 3 cm under opening height was almost equal to gate opening area.

Therefore, generally can be said that to increase the efficiency of semi-cylindrical, the area of semi-cylindrical under the opening should be at least equal to the area of gate opening to achieve the best performance.

However, by reducing the height & area of semi-cylindrical under opening, the flow velocity will be increased and thus the Vortex intensity and also scouring (Results of Hajhosaini and e.t 2008). But it should be minded that reduction limit of under opening area, is the area of gate opening (reservoir bottom outlet opening).



In this study, the effect of semi-cylinder diameter on the vortices strength, evaluated by sand particles with 4mm diameter (d_{50} = 4 mm) and specific gravity equal to 2650.0 kg/m^3., which settled on the bed of reservoir at the mouth of the semi-cylindrical structure in each experiment. The results were shown that in the 2-, 4-, and 6-inches semi-cylinder diameter vortices sucked these sand particles, but in the 8- and 10-inches diameter vortices have not had enough strength to lift the gravel out of the scour hole and transfer to the outlet. As a result, with an increase in semi-cylinder diameter, the strength of the vertices begins to decline, because the flow velocity decreases around the sluice gate with go away from the sluice gate. These results entirely agree with the results of Powell (2007) and Jansson (1999).

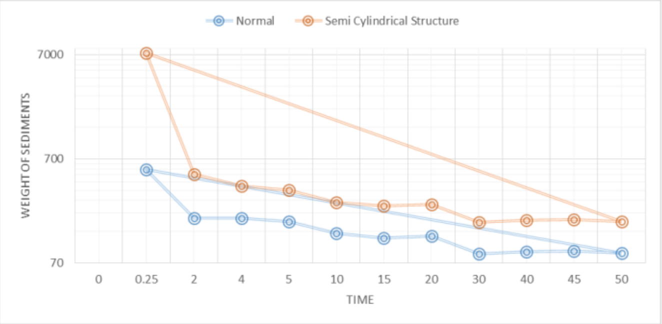


Fig.22.Weight of the sediments during the flushing time (Physical model)

In figure 22, the weight of sediment during the time has been shown, base on this result weight of the outlet sediment at the first 2 minutes is really high but during the time this difference between normal flushing and equipped flushing (use of semi-cylinder), has been descended and all in all the area of the equipped flushing is 6 times more than normal flushing.

As a result, with a comparison between fig 22 and fig 8, it can be found a sinusoidal model at 2 figures, which is clearly observable in the numerical model (Fig 8, volume of suspended sediments), and a slightly weaker one in fig 22 (Weight of the sediments removed from the physical model). It may be had a direct relation with vortex flow behavior.

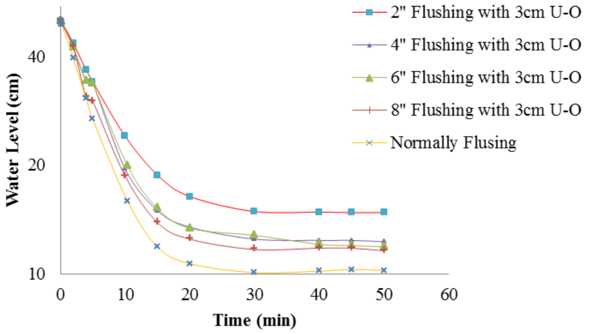


Fig. 23. Comparison of water levels in different semi-cylinder

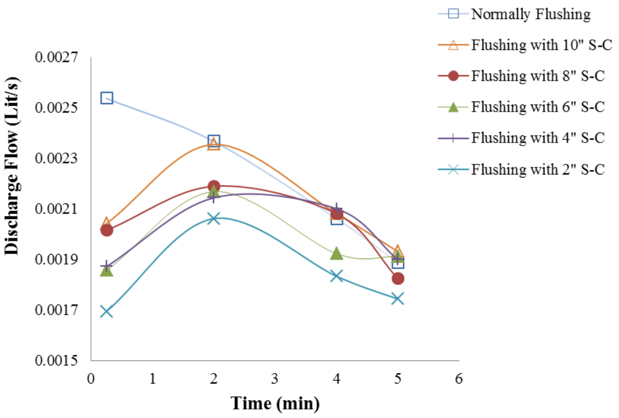


Fig. 24. Outlet discharge through time in the first 5 minute

As shown in figure 23, the maximum flow rate was happened in the first 2 minutes of the experiments (4% of the total flushing time), that according to the previous statements, the maximum amount of sediment discharge happened at the same time (2 first minutes).

According to the obtained results from the data of the bed topography around the bottom outlet, as shown in Figure 25, dimensions of the flushing cone dramatically were increased by using the semi-cylindrical structure.

Another result of the flushing cone was obtained in this study, was half ellipse shape of the cone. This confirmed Powell’s (2007) results. Powell’s (2007) results showed that by increasing the rate of H/D shape of flushing cone will switch from half-circle to half ellipse. In this study was selected a larger amount of H/D comparing with Powell’s (2007) experiments and in consequence, the measurements showed a half ellipse flushing cone shape.

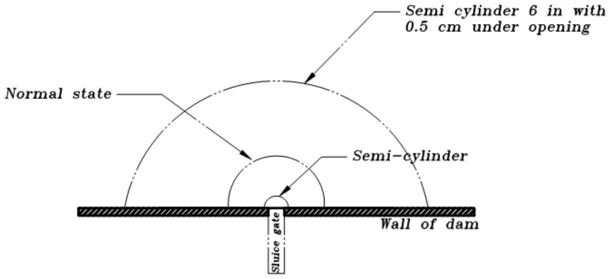


Fig. 25. Plan of flushing cone in normal state and when used a semi-cylinder

Conclusions

The purpose of this study was to monitor the scour hole in order to increasing the partial flushing efficiency and thereby increasing sediment erosion at the reservoirs. This purpose will be possible by installation a semi-cylindrical structure with an opening at the bottom exactly around the bottom outlets. The following results were obtained by examined 2, 4-, 6-, 8- and 10-inches semi-cylinders with different under opening height.

1. As a general conclusion, the best structure is a semi-cylinder which has the following specifications: a) a wide range of area around the bottom outlet expose to the vortices. b) Created vortices by semi cylinder, have enough power to exit the sediments from the reservoir.

2. in this study (with the bottom outlet installed height equal to 15 cm or 6D from the reservoir bottom), 2-inch semi-cylinder with 3 cm under opening height, with 6 times more increase at the amount of weight of outlet sediment was allocated the best results.

3. Approximately, more than 90% of all sediments erosion in partial flushing was done in less than 4% of the entire flushing time (2 first minutes).

4. Vortices strength from 6 inches (3D) to up diameter began to decline. Also, shape of these vortices from 8 inches (4D) to up diameter began to change.

5. By reducing semi-cylinder under opening height, sediment erosion began to increase. But this reduction should not be less than the bottom outlet opening area, because it has shown adverse results.

6. Normal flushing in both partial and full drawdown conditions are more effective when the deposition of sediments reaches the critical situation (i.e. the level of sluice gate). It takes several years until the dead storage of a dam to be filled and flushing became effective. But in this method by extending the vortex flow around the sluice gate deposited sediments around the sluice gate will continuously be removed (i.e. do not need dead-storage to be filled). Since deposited sediments are lifted out of the reservoir's bed, therefore the dead storage of a dam could be minimized.

7. This method always guarantees the proper functioning of the bottom outlets.

8. Possibility of eroded dead storage in the reservoirs is one of the advantages of this method. Because the vortex fed than sediment in the reservoir`s bed and

therefore all the sediment around the semi-cylinder eroded and sucked vertically out of the scour hole and through the outlet.

9. Large amounts of sediment around the semi-cylinder with each opening of the sluice gate in a short time, discharged and upstream sediment goes to the unstable state and cause the sliding down to the flushing cone. So, always with little water losses, an enormous amount of sediment discharged, and always well working of gates are warranted.

10. As a result, using the semi-cylinder structure around the reservoir outlets, will not accumulation occur in the natural working of outlets, and even by this structure fully drawdown flushing in the reservoirs can be performed.

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