Experimental Investigation to study the Hydraulic Performance of Pressure Flushing in Straight Wall Reservoirs

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ABSTRACT

Sedimentation in reservoirs is considered as a serious problem in dams. Pressure flushing is one of the most effective techniques for removing the deposited sediments from reservoirs as well as it has few local effects and used as a clearing process by removing sediments around the entrance of intakes. Few studies were carried out to cover the gap of studying the hydraulic performance of pressure flushing in straight wall reservoirs. In this study, many laboratory experiments were carried out to find out the effects of many hydraulic and geometric parameters on pressure flushing such as discharge, size and type of sediments, lengths of internal offset, water heights and sediment depths above the bottom outlets. The experimental results demonstrated that the flushed sediment volume increased with the increasing of each of: outlet discharge, sediment depth, and internal offset length of the outlet. On the other hand, the research revealed that the optimal ratio of water to sediment depths that introduced maximum volumes of flushed sediments were found between 2.08 and 2.26. Finally, SPSS21 program and ANN tool integrated with the MATLAB 2011 program were utilized to facilitate the calculations of the regression analysis and the dimensionless equations to be used in estimating the flushed sediment volume and the effective duration time.

INTRODUCTION

Reservoir sedimentation rate in many regions, in Asia, is much higher than other continents and can be annually estimated between 0.5 and 1.0%. Permanent use of existing reservoirs has become an important matter, since building new reservoirs is difficult because of the economy, new environmental rules and lack of appropriate dam locations. Therefore, techniques for reservoir desolation have recently received increasing attention (Meshkati, 2009).

Many important steps have to be implemented to reduces the amount of sediment that entered and settled in the reservoir. These steps include firstly, increasing sediment movements through the reservoir during high discharge and sediment concentration. Secondly, by passing high discharge with high sediment concentration...
from inside the Reservoir. Thirdly, flushing sediment from the reservoir by intensity streams. Finally, removing the reservoir sediment by using mechanical methods such as dredging and siphoning.

One of the most active techniques is sedimentation flushing, which the deposited sediment is hydraulically taken away from the bottom outlet. Hydraulic flushing is not a new technique. Flushing method is the oldest technique that has ever been known. It was practiced in Spain in the 16th century as pointed out by D’Rohan (1911). The surplus in shear force of accelerated discharge, which is created by the sudden opening of the bottom outlets of dams, loosens and re-suspends the sediment. If flushing is conducted under a pressurized condition and constant head of water on the bottom outlet, this flushing would be called “pressure flushing” and it would have exact effect only around the outlet. In pressurized flushing, the sediment that is close to the outlet openings is scoured and a cone-shaped crater is created. Figure 1 shows the longitudinal and plan view of the pressure flushing funnel close to the outlet. The hydraulic flushing is considered an efficient technique in narrow reservoirs and strong slopes (Lai and Shen 1996, 1999). Emamgholizadeh (2005 and 2006) proposed by experimental studies that the increasing volume of sediment by increasing the discharge from outlet and decreasing reservoir's water depth and when the changed sediment from coarse to fine the amount of sediment increased. The sediment flushing efficiency changes strongly by many factors like arrange layers of reservoir, elevation of sediment scouring gates, size of sediment, discharge during sediment flushing, duration time of flushing Sumi (2008). Meshkati and et al (2010) proposed an experimental study and they found that the volume of flushing cone was strongly affected by the diameter of bottom outlet and discharge of bottom outlet, also The maximum scour depth of the flushing cone was located very near to the dam wall. Emamgholizadeh (2014), were conducted to laboratory experiments to prove The scour cone of the flushed sediment increases with increase of discharge, and decreases with increase of sediment bulk density(cohesive-soil) and the water level above the sediment. Also, in some dams, the formation of pressure flushing cone has a very important role in preventing sediment entering the power plant intake. Pressurized flushing has been extensively studied and investigation of pressure flushing technique at reservoir outlets has been conducted in wide ranges.

However, studies on the effect of internal bottom outlet offsetting on the flushing cone development are limited. In addition, the loss of water resources and the negative effect of flushing pressure on the environment often make it illogical to finish the flushing process. In this condition, it is necessary to find a balance between removal, discharge of sediments, the limitations of water resources and the impact of the environment. Researches for understanding the volume variations of scouring cone with the discharge bottom outlet, water depth in the reservoir and variations of the height of soil are necessary in order to make a proper design for the bottom outlet. Also, in the planning process of dam operation, it can be right to estimate how much of sediment can be removed, and how much amount of water flushing is required. In the present work experiments are conducted to study the influence of different parameters during pressure flushing operation on the temporal evolution of scouring cone close to the bottom outlet of straight wall dam reservoirs. The purpose of the current work to find how efficient is the mechanism of pressure flushing operation. Also, it aims to describe the evolution of cone formation due to the pressure flushing near the outlet. In addition, it seeks to find the relation between the volume of sediments and all the effective geometric and
hydraulic parameters of the model such as the height of sediment, the height of water, and type of sediment length of internal offset outlet discharge and uniformity coefficient of soil.

Furthermore, the relation between the volume of the sediments and the time the flushing operation takes. See figure (1).

MATERIALS AND METHOD

2.1. Experimental Set-up

The experiments were conducted at the hydraulic laboratory of the Civil Engineering Department at the University of Salahaddin Hawler in the Kurdistan Region of Iraq. The test apparatus consists of four parts:

Water supply system, bottom outlet, settling basin reservoir, and V-notch weir.

Water Supply System: It consists of an underground tank and an electrical pump with capacity 0.018 (m³/Sec) used to recirculate a desired steady flow. The system is also supported by an adjusting valve and a 5-meter flume upstream of main reservoirs.

Main Reservoir: the Main reservoir was of a rectangular shape of 2-meter length, 0.4-meter-wide and 0.78-meter height. Using two reticulated sheets at the reservoir’s entrance, a smooth flow is created. The outlet of the main reservoir includes a valve of the diameter of 2.08 cm with two lengths of internal offsets (2 and 8) cm. Sediment deposits in the main reservoir. The sediment consists of coarse with gravel and coarse sand with a median diameter of d50=1.44 mm and 0.84 mm, and a specific gravity (Gs) 2.63 and 2.64 respectively.

Settling Basin Reservoir: This is the region that the water and sediment were mixed and sediments were settled. The basin is a rectangular flume of 1.52 m long, 0.75 m wide, and 0.6 cm height used to measure the outflow discharge.

Ground tank: A concrete ground tank with 6" opening, internal dimensions of 0.5m length, 2m width, and 0.75m height, to complete the flow recirculation. Photo 1 shows the main parts of the test apparatus used in the current work.

2.2. Dimensional Analysis

The volume of a flashing cone (V) may be written as a function of the following variables:

\[ V = f \left( H_w, B, u, L_v, H_s, \rho_w, \rho_s, g, v, d_{50}, C_u, \alpha, D \right) \] ………………………………(1)

where, u is velocity of flow at the entrance of bottom outlet, D is diameter of bottom outlet, Hw is the height of water above the center of bottom outlet, Hs is the height of sediment deposited above the center of outlet, B is the width of reservoir, d50 is the median size of sediment particles, ps is the density of sediment, \( \rho_w \) is water density, g is the acceleration due to gravity, \( v \) is kinematic viscosity, \( C_u \) is uniformity coefficient of
sediment (C_u = d_{so}/d_{10}), \alpha is angle of repose, and L_v is length of internal offset. By using Buckingham theorem, and choosing the \rho_s, H_w, and u as repeating variables, the following dimensionless parameters were obtained:

\[ \frac{V}{H^3_w} = f \left( \frac{H_s}{H_w}, \frac{L_v}{H_w}, \frac{d_{so}}{H_w}, \frac{\rho_w}{\rho_s}, \frac{D}{H_w}, B, Fr, Re, C_u, \alpha \right) \]  

Where Fr is Froude number and Re is Reynold number. The parameters B, D and g are constants. Hence, the aforementioned dimensionless parameters can be summarized to four parameters. Consequently, the following functional relationship describes dimensionless flushing volume:

\[ \frac{V}{H^3_w} = f \left( \frac{H_s}{H_w}, \frac{L_v}{H_w}, \frac{d_{so}}{H_w}, \frac{\rho_w}{\rho_s}, Fr, Cu, \alpha \right) \]  

2.3. Experiment Designing

For considering the effect of bottom outlet cross section on dimensions of flushing cone, the experiments were conducted with 3 different values of sediment height (7.46, 20.46, 27.46 cm), six water depths above the center of bottom outlet (32.54, 42.54, 52.54, 57.54, 62.54, 67.54 cm), six different discharges, two length of internal offsets (2, 8 cm) shown in the photo 2, and two different size of sediment with d_{so} (1.44, 0.84 mm).

Table 1 and 2 show the range of variables conducted in this study for measuring experimental data and non-dimensional parameters for dimensional analysis.

2.4. Experimental Procedure

For running the experiment, the deposited sediment was flattened and leveled firstly to a specific level above the bottom outlet (30 cm), and the model was slowly filled with water until the water surface elevation reached to the desired level. Then, the bottom outlet was manually opened until the steady state flow...
condition was attained. Consequently, the sediment was released from the main reservoir. At the beginning of the experiment when the downstream outlet opened, sediment was discharged with high concentration, but the concentration of sediment flushing decreased with time. Experiments were continued until the flushing cone reached to an equilibrium condition in which the sediment concentration was negligible at the end of the experiment. The time required for the formation of the flushing cone depends on an equilibrium conditions. The development of flushing cone was very fast, and the process finished in less than 15 minutes to 25 minutes in the experimental model. In this study, the time for running the experiment was set to 2-3 hour. At the end of each experiment, the flushing outlet was closed and water was carefully and slowly drained from the main reservoir and the measurement of bed configuration was done in a grid system around the bottom outlet. At the end of each experimental test run, the bed level of scour was measured using point gages, and the volume of flushing cone was calculated by Excel sheet, as shown in photo 3 and figure 2 the maximum scours depth of the cone was found very close to the dam wall.

Top view of flushing cone (Photo 3)

Three-dimensional and bed topographic of the flushing cone after the experiment with $Q=5.58 \text{ lit/s}$, $H_w=60\text{cm}$, $H_s=12\text{cm}$, $L_v=2\text{cm}$, and $d_{50}=1.44\text{mm}$. (Figure 2)

**General phases of flushing operation**

The flushing process is usually divided into four phases. The first phase the water is slowly released due to the effect of seepage water through the soil, it is represented by lowering the water table down to a few meters above minimum level for power generation. The second phase is the release of high concentration of sediment due to the impact of the pressure of soil and water above the bottom outlet. When concentration increases, the settling velocity decreases, thus the flow can transport with very high concentrations of sediment under a relatively small flow (Lai et al.1993). The third phase is rapid release of the
remaining water, resulting in the release of a free flow water and sediment out of the reservoir due to hydraulic scour. Finally, the fourth phase is the free flow of water out of the reservoir.

3. RESULTS AND DISCUSSION

A funnel shape of scouring is created in the vicinity of outlet gates in the pressure flushing operation. The maximum scouring depth of this cone is found very close to the dam wall. The cone slopes of both longitudinal and side are approximately equal, and also these are similar to the repose angle of the submerged sediment.

3.1 Relation between outlet discharge and volume of flushing cone

To illustrate the effects of volume of flushing cone, the percentage of \( V/(VHv=65)\ast 100 \) and \( Q/Qmax\ast 100 \) will be used instead of \( V \) and \( Q \) directly. The figure 3 shows the relation between volume of sediment ratio and the outlet discharge ratio for different offsets and sizes of sediment particles values. The figure reveals that the maximum volume of sediment ratio which is about 115.5% will happen at 84.7% outlet discharge ratio. Fig. 4 and 5 also present the variation of \( V/(VHv=65)\ast 100 \) and \( Q/Qmax\ast 100 \) for 25 and 32 cm depths of sediment above the bed of channel and the maximum volume is 105%, this increasing due to hydraulic mechanism increase. The figures show the same trend for volume release of sediment with the depth of water.

3.2 Relation between size of sediment and the volume of flushing cone

Emamgholizadeh (2006) proposed by experimental studies that when the changed sediment from coarse to fine the amount of sediment increased. In the present study as shows in figure 6 the relation between the volume of sediment and size of sediment particles for sediment thickness = 25cm, the same trend for other values of sediment height (12 and 32cm). The figure shows that the sediment flushing cone volume increased when the sediment size is decreased, due to the increase of pressure on the sediment.
Effect of type of sediment on the volume of the cone when the height of sediment = 25 cm. (Fig. 6)

3.3 Relation between length of internal offset and the volume of flushing cone

Figures 7 and 8 show the effect of different length of internal offset on the volume of flushing cone for different size and depth of sediment.

The figures illustrate that increasing the length of internal offset from 2cm to 8cm (30%) causes an increase of the volume of flushing cone about 80%, because this increase in the length of offset leads to increase the distance affected by scouring, and this gets a large amount of sediment flushed.

Effect of offset on the volume of cone for the first type of sediment (d50=1.44). (Fig. 7)

Effect of offset on the volume of cone for the second type of sediment (d50=0.84 mm). (Fig. 8)

3.4 Relation between height of sediment and the volume of flushing cone

Figures above 7 and 8 show the effect of height of sediment on the volume of flushing cone for different size of sediment and internal length of offset.

The figures illustrate that increasing height of sediment from 12cm to 32cm causes an increase of the volume of flushing cone about 80%. This increase occurs as a result of increasing the pressure of sediment on the bottom outlet of the reservoir. The upper curve shows the maximum volume of flushing sediment occur when the water depth in the reservoir is 55 and 60cm for Lv is 8cm, d50 is 1.44 and 0.84mm respectively. So, appropriate optimal ratio of water to sediment depths ratios in the reservoir that introduce maximum volumes of flushed sediment are when the ratio of the water depth to the sediment depth in the reservoir is between 2.08 and 2.26 (Hw/Hs=2.26).

3.5 Variation of flushing sediment concentration with time

For a better understanding of the mechanism of flushing processes, the data has been presented graphically. Figure 9 shows the variations of outflow sediment concentration with flushing time for height of sediment 25cm, height of water above the valve 40cm and length of internal offset 2cm. The figure shows that during about the first 10 seconds, the concentration reaches its highest-level due to the pressure flushing mechanism. After that, the concentration level will be damped down rapidly due changing the transport mechanism of the sediment from pressurized flushing process to hydraulic scouring process. The figure also shows that the effective times
when the flushed sediment reach at equilibrium condition) of flushing is between (60 – 70) secs.

**Variation flushing sediment concentration with time of (Hs=25cm, Hw=40cm, Lv=2cm).** *(Fig. 9)*

### 3.6 Statistical analysis for estimating pressure flushing cone volume (V)

In order to obtain a general relationship to all the pi terms that affected the volume of flushing cone (V), SPSS21 and ANN were used to find the correlation coefficient. Many cases of choosing extra pi terms relating to sediment type will be discussed in this section. Table 3 shows the effect of uniformity coefficient and angle of repose on the volume of flushing for straight wall model with a correlation coefficient of 0.944. The table shows it can be used Cu instead of d50, since it is the dimensionless term, in the calculations of the volume of sediment. Fig.10 shows the comparison between the calculated flushing cone parameters using below equations and observed values.

**Table 3: Summary of statistical equations with the correlation coefficient for different cases of Straight wall model.**

| Case | Parameters | Equations | R² |
|------|------------|-----------|----|
| A    | V=f(Hw,Hr,d<sub>50</sub>,ρ<sub>s</sub>,ρ<sub>w</sub>) | V/Hw<sup>3</sup> =3.784(H<sub>s</sub>/Hw)<sup>1.776</sup>(d<sub>50</sub>/Hw)<sup>0.156</sup> | 0.944 |
| B    | V=f(Hw,Hr,ρ<sub>s</sub>,ρ<sub>w</sub>,Cu) | V/Hw<sup>3</sup> =0.716(H<sub>s</sub>/Hw)<sup>1.774</sup>(d<sub>50</sub>/Hw)<sup>0.158</sup> | 0.9 |
| C    | V=f(Hw,Hr,ρ<sub>s</sub>,ρ<sub>w</sub> Cu) | V/Hw<sup>3</sup> =-1.28(H<sub>s</sub>/Hw)<sup>1.915</sup>(d<sub>50</sub>/Hw)<sup>0.044</sup> Cu<sup>-1.837</sup> | 0.9 |
| D    | V=f(Hw,Hr,ρ<sub>s</sub>,ρ<sub>w</sub>,α) | V/Hw<sup>3</sup> =0.17(H<sub>s</sub>/Hw)<sup>1.918</sup>(d<sub>50</sub>/Hw)<sup>10.8</sup>(Fr)<sup>-0.044</sup> α<sup>0.79</sup> | 0.9 |

**Multivariable power regression yielded for straight wall model.** *(Fig. 10)*

### Conclusions

The analysis of the experimental data in this study leads to the following findings:

1. The results of the present study revealed that in order to maximize the pressurized sediment flushing efficiency should be made to increase outflow discharge to an optimum value.

2. The optimal ratio of water depths to sediment depth in the reservoir was introduced when a maximum volume of flushed sediment was set 2.26 (Hw/Hs = 2.26).

3. The flushing volume increased with the increasing of the sediment layer thickness in reservoirs, due to the impact of sediment pressure.
4. The maximum scours depth of the cone was found very close to the dam wall.

5. Increasing the internal offset length from 2cm and 8cm caused an increase in flushed sediment volume to about 80%.

6. The effective time of flushing for the two models was found between 60 and 70 sec.

7. One can use Cu instead of d50 to estimate the sediment volume.

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