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Investigating the Sediments Evacuation

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Abstract

Dam construction alters the natural balance between sediment inflow and outflow by increasing water depth and decreasing velocity. As a result, the sediment transporting capacity of the flow is reduced and sedimentation occurs. Reservoirs around the world have lost major part of their storage capacity due to sedimentation. Since, constructing new reservoirs is difficult due to lack of suitable dam sites and high costs of construction; reclaiming lost storage capacity has recently received an increased attention. An attractive technique for removing deposited sediments from reservoir is flushing. The phenomenon of flushing was studied in this research by performing experiments on a one-dimensional reservoir model. A total of six experiments with pressurized and drawdown flushing using circular, triangular and rectangular bottom outlets were conducted. Sand with a bulk density of 1420 kg/m^3 and a D_{50} of 0.28 mm was used as sediment material. It was found that pressurized flushing has a very local effect. A flushing cone is formed in a short time but only a small amount of sediments in the vicinity of the outlet are removed. Retrogressive erosion takes place during drawdown flushing and a flushing channel is formed, resulting in removal of significant quantities of sediments. Results indicated that the amount of sediments flushed is a function of outflow water discharge, water level in the reservoir, water surface slope and shape of the low level outlet.

Keywords: Experiment, storage, modeling, sedimentation

1 Introduction

Sedimentation occurs when a river is impounded to build a reservoir and results in social, economic, technical and environmental implications. There is no accurate data on reservoir sedimentation rates but estimates made from the available data shows that about one percent of the worldwide storage capacity is lost annually. In order to sustain current global storage capacity, 300 to 400 dams at a cost of around 6 billion dollars per year would need to be constructed (Dahab, 1983). Apart from storage loss, sedimentation can contribute to an increased flood risk, damaging sluice structures, abrasion of turbines and navigational problems. In areas where there is an annual flow cycle and a defined flood season, flushing may be the most favorable option to remove deposited sediments from reservoirs. The removal of sediments is accomplished by passing flows through low level outlets. There are two types of flushing (EI-Moattassem and Abdel-Aziz, 1988):

- Pressurized Flushing: In this type the water level in a reservoir is high; as a result the water velocity is too low to move sediments. Only localized erosion near the flushing outlet occurs (Abdel-Aziz 1991, Makary 1985).
- Drawdown Flushing: In drawdown flushing the water level in the reservoir is lowered below the top of the outlet so that high velocities can be generated throughout the length of the reservoir.

If flushing is carried out with a wedge-shaped depositional pattern, sediments near the outlet are eroded and a flushing cone is formed in a very short time which gradually stabilizes until no further sediments are removed from the flushing cone (Hurst 1965, Jia and Wang 1999). However, if water level in the reservoir is lowered to increase flow velocity, retrogressive erosion occurs and a flushing channel is formed in the reservoir sediment deposits (Zang, 2008).

The emphasis of sediment management around the world has been on soil conservation and erosion control in the watershed. However, this practice alone has failed to sustain long-term storage capacity (Makary, 1982). Sediment management combined with a sediment removal technique like flushing may provide an adequate solution to the problem of sedimentation.

Although flushing has been found to be successful in the field (NRI, 2008), thorough understanding of the flushing operation requires further research in order to prepare guidelines for planning, designing and operation of reservoirs (Abu EL-Atta, 1978). The main objective of this paper is to study the effectiveness of pressurized and drawdown flushing and to enhance the understanding about the affect of shape of the low level outlet on flushing operation.

2 Materials and Methodology

Experiments were carried out in the Hydraulics Laboratory of Civil Engineering Department at UET, Taxila. A rectangular concrete flume with dimensions 21

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m long, 1 m wide and 0.75 m high was modified to model a reservoir. The dam was made of 4.75 mm thick plastic material, placed approximately in the middle of the flume. The bottom of the flume up to a length of 3 m, immediately upstream of the dam was raised by 0.16 m using coarse aggregate which represented dead storage and avoided downstream submerged outlet conditions (Abdel-Aziz, 1997). The coarse aggregate layer was then covered with a thick plastic sheet to avoid mixing of finer aggregate used during experiment with the coarse aggregate. A schematic diagram of the concrete flume along with the dam model is shown in Fig. 1 below.

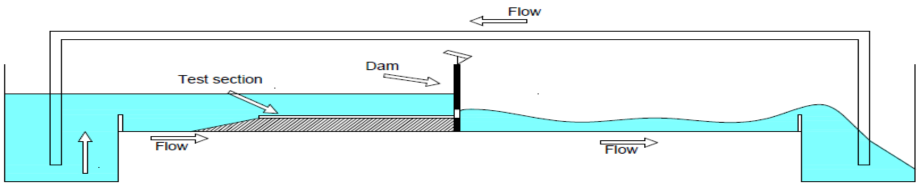

Figure 1a: Cross section of Experimental model

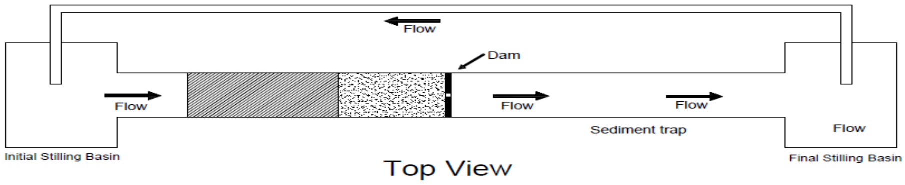

Figure 1b: Top view of Experimental model

Three dam models with bottom outlet opening of circular, triangular and rectangular shape, installed in the center of the dam model were used in this study. The details of these sluice openings are shown in Fig. 2. All the outlets had the same opening area of 0.0135 m^2. Gauges were installed to measure water depth at the sluice gate and upstream of the dam. The sluice gate was manually operated and could be opened by raising the gate. By controlling inflow, water depth in the reservoir could be maintained at any desired level.

The sediment material used in this study is sand with a Bulk density of 1420 kg/m^3, Dry density of 2300 kg/m^3, Specific gravity of 2.77 and a median diameter, D_{50} of 0.28 mm. Sediment was deposited in the reservoir model in a wedge-shaped pattern, 0.2 m in depth (Fig. 3).

3 Results

A total of six experiments were performed in this research. These experiments can be divided into two types: pressurized flushing and drawdown flushing. Since, the features of experiments were the same; a representative run for both types of flushing would give a general overview. For this purpose Run no. 1 and Run no. 6 are selected.

For Run no. 1, the sediments were evenly distributed 3 m from the dam in the form of a wedge-shaped deposit having a depth of 20 cm and zero bed slope. The flume was then filled with water keeping the sluice gate closed. As the water depth reached a height of 30.5 cm, the sluice gate was gradually opened to avoid any disturbance near the outlet. A flushing cone was immediately formed which removed sediments around the outlet. At this point, the inflow discharge was kept less than the outflow discharge and the water level in the reservoir was allowed to drawdown. Initially sediments were removed from the flushing cone only, which stabilized after few minutes during pressurized flow conditions. After 7 minutes from the start of experimental run, open channel flow conditions developed as the water level dropped to 10.7 cm. At this stage retrogressive erosion started in the reservoir deposits in the vicinity of the dam and gradually propagated upstream (EI-Manadely, 1991).

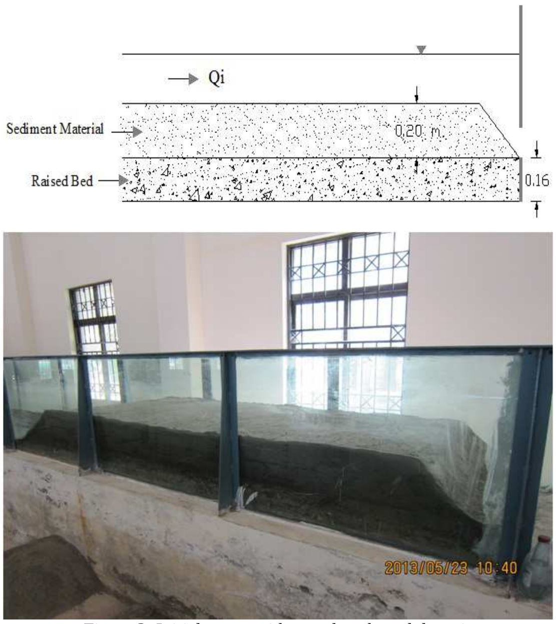

Figure 3: Initial setup, with a wedge-shaped deposit

Significant quantities of sediments were eroded as a result and a main flushing channel along with a network of smaller channels was formed which deepened and widened as time elapsed. The outflow water discharge at this point was 6.52 l/s which was kept constant for the rest of duration of the experimental run. The sediment outflow concentration was high when open-channel flow conditions established and then gradually decreased. The observations recorded are in agreement with previous works (Shalash 1980, Rastogu 1978). The experiment continued for 70 minutes, after which, the pump was turned off and the gate was closed. Fig. 4a shows outflow water and Fig. 4b shows the resulting reservoir bed and flushing channel.

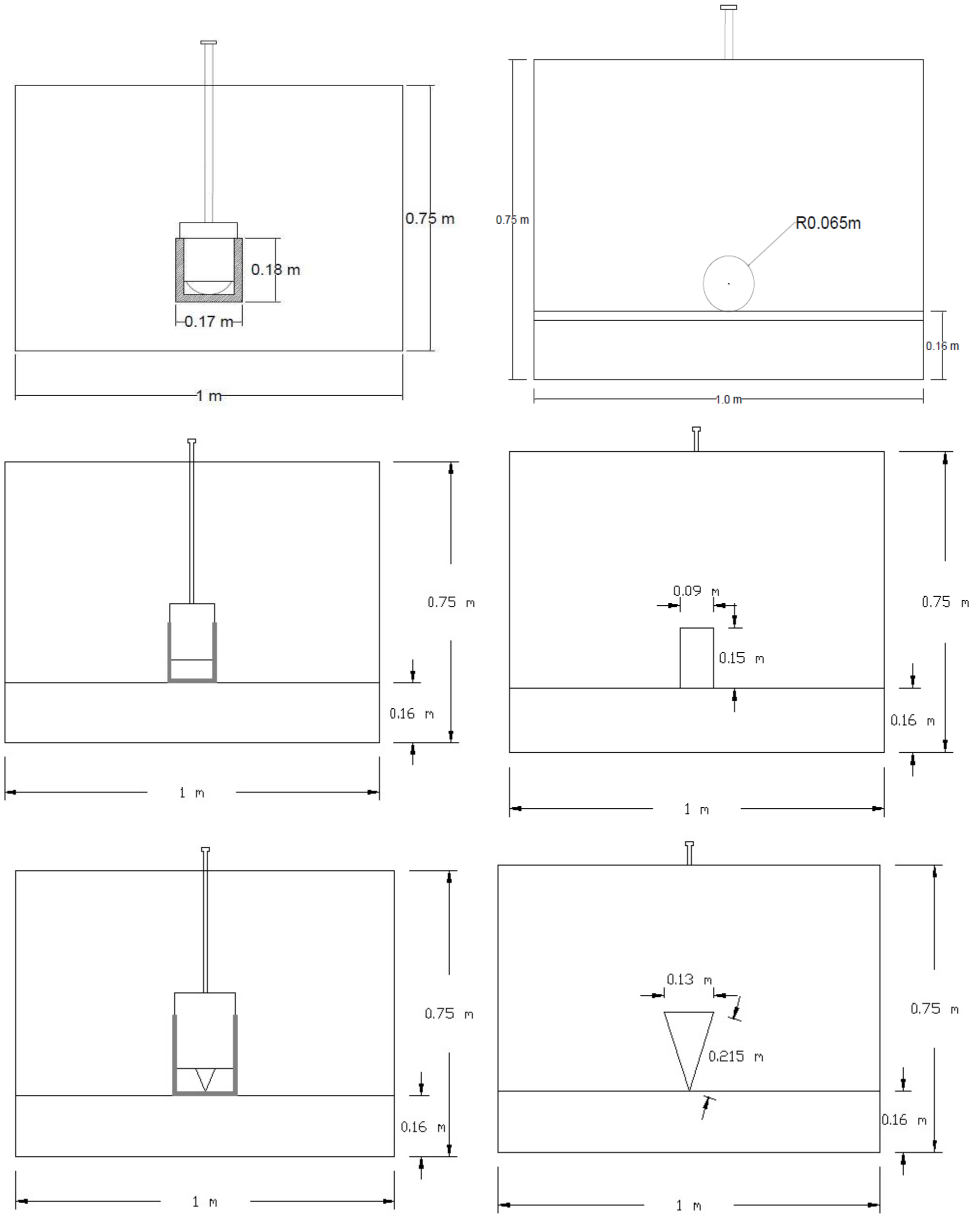

Figure 2: View of sluice gates from d/s (left) and u/s (right)

Table 1: Summary of initial conditions for each Run

Run No.	Type of Flushing Operation	Volume of Deposited Sediment (m^3)	Initial Water Stage at Dam (cm)	Initial Shape of Deposition	Type of Outlet Opening	Run Time (min)
1	Drawdown	0.541	30.5	Wedge shaped	Circular	70
2	Pressurized	0.541	30	Wedge shaped	Circular	75
3	Drawdown	0.541	31.5	Wedge shaped	Triangular	70
4	Pressurized	0.541	31	Wedge shaped	Triangular	70
5	Drawdown	0.541	30.75	Wedge shaped	Rectangular	75
6	Pressurized	0.541	30.5	Wedge shaped	Rectangular	75

Setup for Run no. 6 was the same. The sluice gate was opened gradually, when water level reached 30 cm. The water level was allowed to drop to 24 cm and was kept constant at the same level for the rest of the experiment. At this depth pressurized flow conditions (orifice flow) existed at the outlet. It was observed that sediments near the vicinity of the outlet were eroded in the first few minutes only and a flushing cone was formed. After about 10 minutes, the water discharge was clear and no or very little sediments were flushed. Only local flushing occurred during pressurized flow conditions. Total time of the experiment was 75 minutes, after which, the pump was turned off and the sluice gate closed.

Figure 4a: Water-sediment mixture outflow during Run no. 1

Figure 4b: Resulting bed profile and flushing channel during Run no. 1

Figure 5: Resulting bed profile during Run no.6 (looking upstream)

Figure 6: Flushing cone formed during Run no. 3 (view from top)

5 Discussion

The measured data like outflow water discharge (Q_o), outflow sediment discharge (Q_{os}), sediment concentration (C_s) and water level at dam (W.L.) are plotted against time in Fig. 7a through 7f for each experimental run. In Run no. 1 and 3, maximum outflow sediment discharge occurs 7 minutes from the start of experiment, while for Run no. 5, after 10 minutes. This is the time when water level in the reservoir drops and results in open-channel flow conditions. Sediment concentration and outflow sediment discharge is high at the establishment of open-channel flow and then gradually drops. The discharge for Run no. 1, 3 and 5 was same (Drawdown flushing with Q_o=6.52 l/s). However, it can be seen that maximum outflow sediment discharge is achieved in the case of Run no. 5 and Run no. 1. The value of maximum outflow sediment discharge in the case of Run no. 3 is fairly low as compared to the other two. This is because, for any constant value of outflow water discharge, outflow sediment discharge is strongly related to water level and water surface slope in the reservoir (EL-Sersawy and Farid, 2005). Shallow water depth generates high velocity with a steeper water surface slope, which erodes more sediment. In order to maintain same discharge through a triangular outlet with apex at the bottom, higher water depth is required. This explains why fewer amounts of sediments are flushed during Run no. 3.

For any given value of water depth during open channel flow conditions, sediment outflow discharge (Q_{os}) also increases with an increase in outflow water discharge (Q_o). For the flushing operation to be successful, the capacity of the bottom outlet should be such that maximum drawdown is produced in the reservoir.

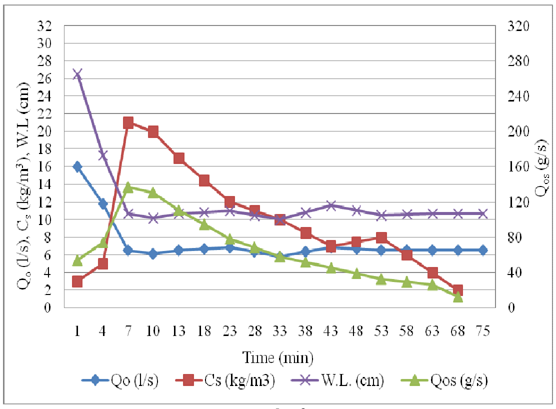

Figure 7a: Results for Run no. 1

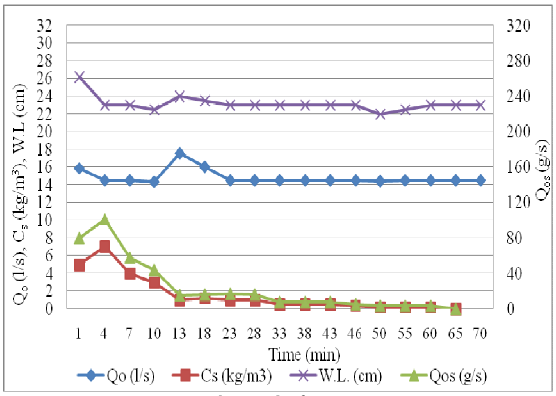

Figure 7b: Results for Run no. 2

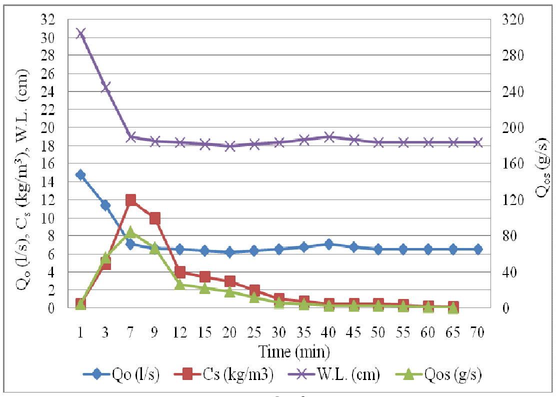

Figure 7c: Results for Run no. 3

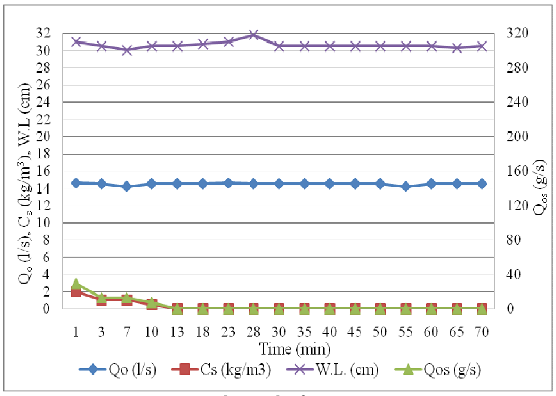

Figure 7d: Results for Run no. 4

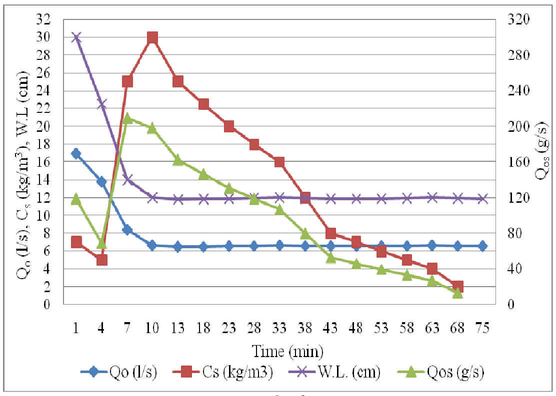

Figure 7e: Results for Run no. 5

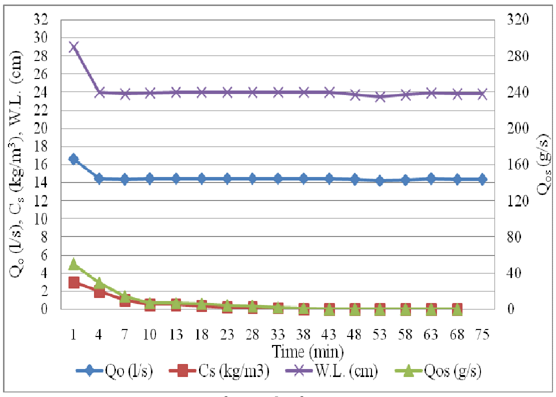

Figure 7f: Results for Run no. 6

In case of Run no. 2, 4 and 6 (Pressurized flushing with Q_o=14.47 lit/s), maximum outflow sediment discharge is achieved during the first few minutes. For example, during Run no. 6, maximum outflow sediment discharge is observed after 1 minute. This is due to the fact that sediments in the vicinity of the outlet are eroded and a flushing cone is formed immediately after opening of the gate. Sediment outflow concentration after first few minutes, in the case of pressurized flushing becomes fairly low.

The cumulative volume of flushed sediments and the cumulative volume of water consumed to carry out flushing can be used to calculate flushing efficiency, which is given by:

$$F_e = \frac{V_s - V_{si}}{V_w} \qquad (1)$$

Where V_s is the volume of flushed sediments, V_{si} is the volume of sediment inflow into the reservoir and V_w is the volume of water used to carry out the flushing operation during time interval Δt. Flushing efficiency gives an idea about the effectiveness of flushing for any reservoir and may be an important criterion to decide whether to undertake flushing or not, when there are constraints.

The cumulative mass of flushed sediments ($\sum W$) for each experiment is calculated and plotted along with flushing efficiency (Fe) against time in Fig. 8a through 8f.

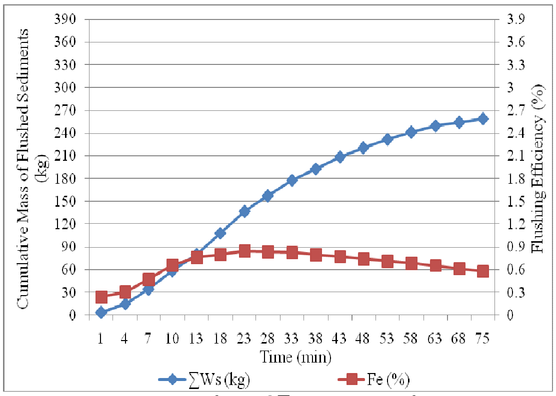

Figure 8a: Variation of Fe and $\sum W$ against time for Run no. 1

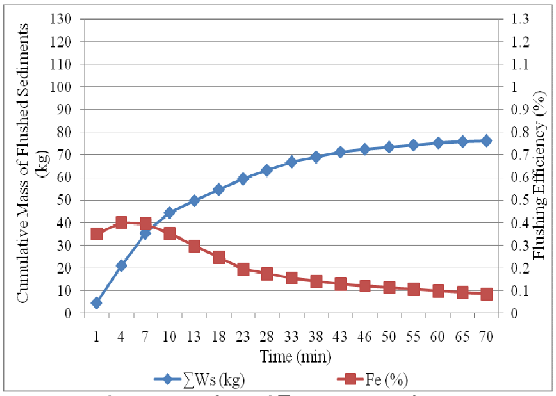

Figure 8b: Variation of Fe and ∑W against time for Run no. 2

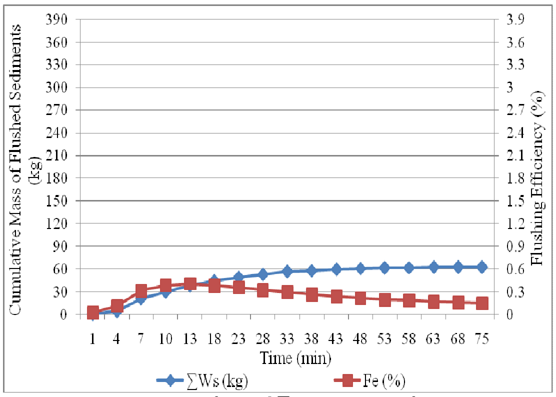

Figure 8c: Variation of Fe and ∑W against time for Run no. 3

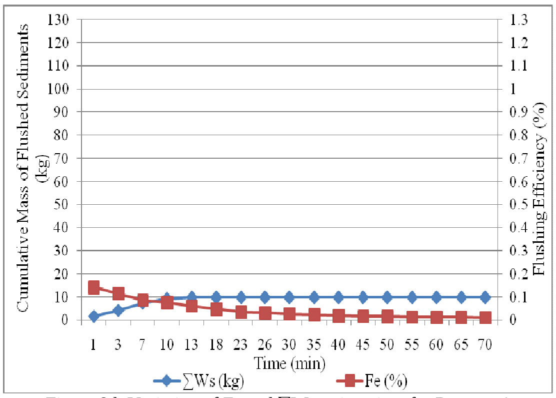

Figure 8d: Variation of Fe and ∑W against time for Run no. 4

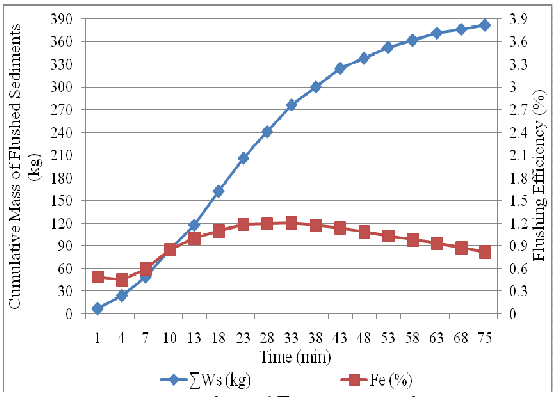

Figure 8e: Variation of Fe and ∑W against time for Run no. 5

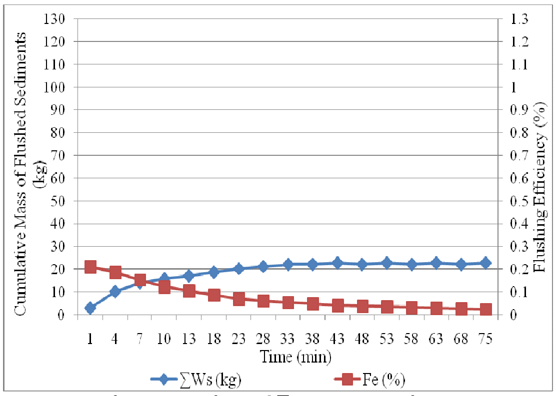

Figure 8f: Variation of Fe and ∑W against time for Run no. 6

In the case of drawdown flushing, maximum flushing efficiency is achieved after establishment of open channel flow conditions. During Run no. 1, maximum flushing efficiency happens after 23 minutes, in Run no. 3, after 12 minutes and in Run no. 5, after 33 minutes from the start of experiment. In drawdown flushing maximum flushing efficiency does not occur at the same time as maximum outflow sediment discharge. The difference is due to the fact that water volume consumed during the period of maximum outflow sediment discharge is high.

In the case of pressurized flushing, maximum flushing efficiency, which is fairly low as compared to drawdown flushing, occurs in the beginning of the experiment when a flushing cone is formed. In Run no. 6, maximum flushing efficiency occurs after 1 minute. The same trend follows for the rest of the pressurized flow experiments.

Maximum volume of sediments is flushed during Run no. 5. A total of 381.7 kg of sediments are flushed which is 48.9% of the deposited sediments in reservoir model. The total mass of flushed sediments in Run no. 5 is 16.75 times more than that flushed in Run no. 6. Both experiments were performed with the same outlet opening but in the former case, drawdown flushing (Q_o=6.52 l/s) was employed while the later was conducted under pressurized flow conditions (Q_o=14.47 l/s). Similarly, the maximum flushing efficiency for Run no. 5 is 5.72 times more than the maximum flushing efficiency for Run no. 6.

6 Conclusions and recommendations

Pressurized flushing is found to have a very local affect. Experiments proved that a funnel shaped flushing cone is formed in a very short time but only a small amount of sediments in the vicinity of the outlet can be removed. Flushing efficiency for pressurized flushing was fairly low and most of the removed sediments were flushed during first few minutes of the experiment run.

During drawdown flushing, when the water level in the reservoir drops and open-channel flow conditions are achieved, retrogressive erosion takes place, initially near the outlet and then propagates upstream. As a result, a flushing channel is formed and significant quantities of sediments are removed from the reservoir deposits. During drawdown flushing through rectangular outlet, 48.9% of the deposited sediments were flushed which is 16.75 times more than that flushed during pressurized flushing through the same outlet. A high flushing efficiency is achieved during drawdown flushing. However, maximum flushing efficiency does not occur at the same time as maximum outflow sediment discharge does, because it may consume more water during the period of maximum outflow sediment discharge.

Drawdown flushing can be employed to remove sediments from reservoirs effectively. However, it may result in deposition of sediments immediately downstream of the dam. Pressurized flushing may be useful, when sediments in the vicinity of the power intakes are required to be removed and to avoid downstream deposition.

For a constant outflow water discharge during drawdown flushing, outflow sediment discharge is strongly related to water depth in the reservoir and water surface slope. Shallow water depth generates higher velocities and steeper water surface slopes, which remove larger amount of sediments. Similarly, for a constant water depth, during drawdown flushing, outflow sediment discharge increases with an increase in outflow water discharge.

Volume of flushed sediments and flushing efficiency depends on the shape of the outlet. Amount of flushed sediments during drawdown flushing through triangular outlet is low as compared to rectangular and circular outlet. Maximum volume of sediments was flushed through rectangular outlet and is 6 times more than that flushed through triangular outlet. In order to achieve maximum flushing efficiency, the shape of the outlet should give the lowest water level in the reservoir for the same discharge. Ratio between the width of the outlet and the width of the reservoir should be included in studying the feasibility of flushing. A larger ratio will produce maximum drawdown and is preferable.

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