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INVESTIGATION AND EVALUATION OF THE PRESSURE FLUSHING THROUGH STORAGE RESERVOIR

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ABSTRACT

When a dam is constructed on the rivers, it causes the sediments settle in the reservoir. Therefore, the initial storage of the reservoir would reduce and it will have negative effects on the operation of the reservoir. Considering the importance of this issue, different methods for control of sedimentation and maintenance of dams are used. These methods include: watershed management, dredging, density current venting and flushing. In flushing methods, the previously deposited sediment would be flushed from the reservoir by opening of the outlets. In the pressure flushing the amount of the flushed sediments depend on many parameters such as water depth on the bottom outlets, discharge released through bottom outlets, the size of the outlets, the geometry of the reservoir, the size and the kind of the deposited of the sediments in the reservoir. In this study, the effects of discharge released from the bottom outlets and the water depth on the bottom outlets was investigated using three sizes of non-cohesive sediments (fine, medium and coarse). Laboratory experiments were carried out to investigate the flushing processes during pressure flushing. A physical model was constructed in the Hydraulic Laboratory, Water Sciences Engineering Collage, University of Shahid Chamran, Ahwaz, Iran. The results of the experiments indicated that the flushed sediment increased with the decrease of reservoir's water depth and with increasing of discharge from outlet. Similarly, under same conditions the flushed sediment increased when the size of sediment changed from coarse sediment to fine sediment.

Keywords: flushing, pressure, sediment, outlet, storage, reservoir, desilting.

INTRODUCTION

During the past few decades reservoirs have been built with increased frequency, and even more are under considering or construction. Without dams, the eroded soil is transported by river flows to the sea. However, when dams are built, the still water in the reservoirs allows the transported sediment to deposit. This can be a problem as the reservoir cannot function as originally thought, due to its filling up with sediments. Numerous reservoirs in different parts of the word have accumulated significant amounts of sediments, thus reducing the performance of reservoirs. To sustain the storage capacity of existing reservoirs has become an important issue since building new reservoirs is rather difficult due to stricter environmental regulations, high costs of construction, and lack of suitable dam site (Shen and Lai, 1996).

Impact of reservoir sedimentation

There are around 40,000 large reservoirs worldwide used for water supply, power generation, flood control, etc. Between a half and one percent of the total storage volume is lost annually as a result of sedimentation and 300 to 400 new dams need to be constructed annually just to maintain current total storage. However, increasing populations and increasing consumption per capita mean that the demand for storage is rising inexorably despite the increasing use of alternative sources and the more efficient use of water (Rodney White, 2000). An estimated cost of $ 9 billion just to replace existing storage capacity, not counting the cost to deal with environmental and social issues (Annandale, 2001). In some developing countries, where watershed management measures are not carried out effectively, reservoir storage is being lost at a much larger rate. This amount in the Asian nations is generally higher than the world average (Liu *et al.*, 2002). Reservoir conservation and sediment management in reservoirs is an effective approach to maintaining existing storage capacity, thus minimizing the need to construct as many new dams. It is also advisable to design new dams in a manner that will facilitate sediment management and long-term reservoir conservation.

Sediment management techniques

Sediment management is often in conflict with short termed water use management. For example high water levels, wanted for electricity generation, will increase the deposition of sediment. Some times building a new dam may be more economic than reducing sedimentation or removing the deposited material (Qian, 1982). Therefore, an economic analysis should be conducted to determine the economic feasibility of incorporating sedimentation reduction measures in the dam building and reservoir operation schemes.

Existing sediment management techniques that have been successfully applied to conserve reservoir storage space are: catchment's Management, flushing, sluicing, density current venting and dredging. Flushing is used to erode previously deposited sediments, sluicing is used to route incoming sediments through the reservoir by drawing down the water level, and density current venting is used to route incoming sediments through the reservoir without drawing down the water level (Brandt, 2000).

Although the reduction of sediment yield via a watershed management program is the best option for reducing the rate of reservoir sedimentation, flushing may

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be one of the most economic methods which offer recovering lost storage without incurring the expenditure of dredging or other mechanical means of removing sediment. The studies of HR Wallingford on 50 reservoirs which are being, or have been flushed, show that in some cases the flushing was successful, and in others there was little or no success. Also studies show that successful flushing depends on some characteristics such as the catchment's area, the storage capacity of the reservoir, the shape of the reservoir basin, the deployment of full or partial draw down, the low level outlet facilities provided and downstream impacts (Rodney White, 2000). Hemphill (1931) stated that it is doubtful whether flushing is effective in larger reservoirs and Bellouni (1980, ref. Qian, 1982) argued that this solution is only suitable for reservoirs with a yearly excess input of water.

However it has been proved that flushing can be highly effective at some sites. For example the Baira reservoir in India, Gebidem reservoir in Switzerland, Gmund reservoir in Austria, Hengshan reservoir in China, Honglingjin reservoir in China, Mangahao reservoir in New Zealand, Naodehai reservoir in China, Palagneda reservoir in Switzerland, Santo Domingo reservoir in Venezuela (Atkinson, 1996), and Sefid Roud reservoir in Iran.

Hydraulic flushing

Hydraulic flushing is not a new technique. The oldest known method of flushing, practiced in Spain in the 16th century, was referred to by D'Rohan (1911, ref. Brown, 1943). Hydraulic flushing is used for the scouring out of deposited sediments from reservoirs through the use of low level outlets in a dam by lowering water levels or without lowering water levels and thus increasing the flow velocities in the reservoir. Then flushing can be classified into flushing under pressure and free-flow flushing. During under 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 has been emptied and the inflowing water from upstream is routed through the reservoir, resembling natural riverine conditions. A detailed presentation of procedures and features of empty (or free flow) flushing, and pressure (or drawdown) flushing techniques, is found in Morris and Fan (1998).

Pressure flushing

If flushing takes place under a sustained water level, only a very limited area in the reservoir is cleared. This is only an option in reservoirs with small reservoir capacity to water inflow, and large capacity of sluices (Qian, 1982). In the pressure flushing (under pressurized flow condition) sediment deposits can be scoured in the vicinity of the sluice-gate opening within a very short period of time. A funnel shaped crater called flushing cone will be formed by the flushing flow. Once the flushing cone has been formed and there is no sediment moving into the cone, the water flowing through the opening is clear, that is the formation of cone is fairly stable and no sediment will be removed from the flushing cone afterward (Di Silvio, 1990). In generally, the scour cone geometry which can be typically developed in the reservoirs after a pressure flushing, influenced by factors including submerged angle of repose of the sediment, inflow and outflow of water and sediment, outlet geometry, characteristic of the sediments, etc. If the water surface can be drawdown significantly to generate high flow velocity near sluicing outlet, the flowing will start to erode the rim of the flushing cone and retrogressive erosion can occur. Figure-1 illustrates the schematic diagram of pressure flushing.

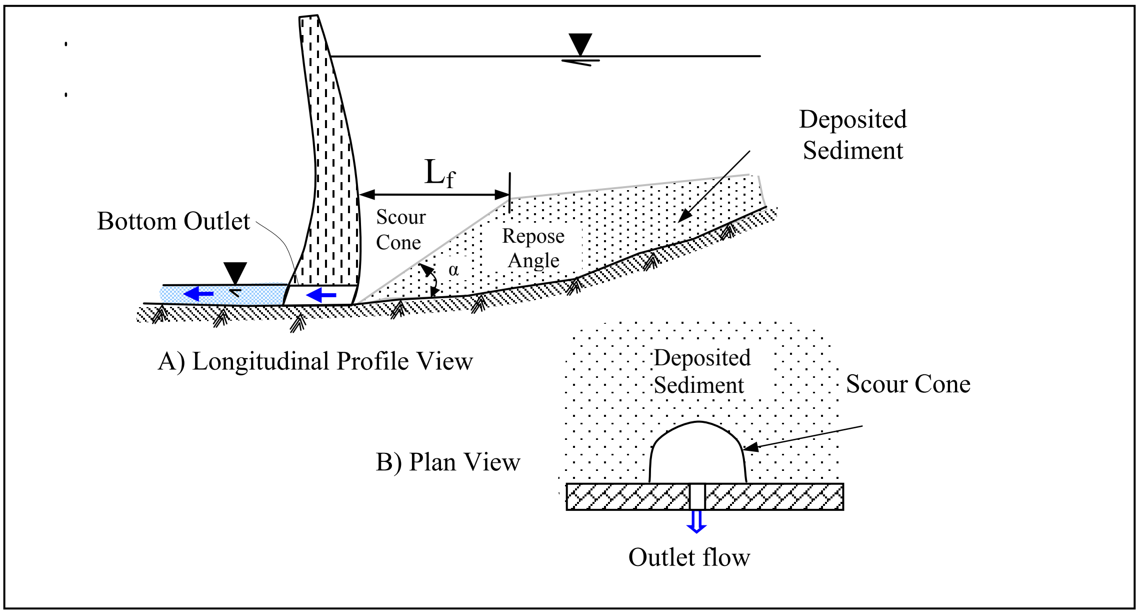

Figure-1. Longitudinal and Plan View of the pressure flushing.

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If the water level is drawn down during flushing, the sediment removal can be divided into several phases. Flushing is most effective during the first hours after the stored water in the reservoir has been released (Brown, 1943).

A stable flushing cone could be created by the flushing flow in a short period: for instance from field observations at Dez Reservoir in Iran, Samenxia reservoir in china, a flushing cone can be formed within ten to twenty minutes. Compared with the erosion scale of drawdown flushing, the scale of the flushing cone is relatively small.

In general, the functions of the flushing cone are to reduce the sediment concentration around the entrance of intake and to prevent hydraulic structures from abrasion by sediments. As mentioned previously, this kind of flushing is used in the Dez Reservoir. In this dam the increasing of erosion and thus the increasing of sedimentation has caused the sediment level near the power intakes to increase significantly. In this operational period, a sedimentation rate of 15 to 20 MCM/year has caused the sediment level behind the dam to raise up to 12 m below the power intakes (with a rate of 2 m/year) and the delta front has progressed 0.5 to 1 km/year towards the dam. Currently, the major issue which threatens the Dez Dam is the continual accumulation of silt and clay in the reservoir near the dam. This situation has potential impact on the physical operations at the dam, including power generation and reservoir operation in general. Thus it is vital that the sediment level near the power intakes be decreased. Accordingly for removing of the deposited sediments near the power intakes the pressure flushing used 7 times from operation of this dam (1942) until now. The Figure-2 shows the bottom outlets when they are used for flushing (Emamgholizadeh *et al.*, 2005).

Figure-2. The outlets after the opening (Dez Reservoir, Iran).

MATERIALS AND METHODS

Dimensionless Analysis

As mentioned previously, when the bottom outlets were opened the motion of the flow caused the deposited of the sediments moved. If flow condition was pressurized after a few minutes a scour cone as funnel shaped at the vicinity of the bottom outlet. The geometric characters of a score cone depend to many factors including the hydraulic conditions in front of bottom outlet; such as water depth(H_w), flow discharge(Q_f), the depth of deposited sediment (H_S), sediment properties such as size(d_s), specific weight (ρ_s) and its kind (cohesive or non-cohesive), the geometry of the outlet (b_G , d_G). Therefore in pressure flushing, volumetric of scour cone (V_f) may be written as a function of the following variables:

$$f(V_f, Q_f, H_w, H_S, B, A_G, g, \rho_s, \rho_w, d_S) = 0$$

$$V_f = f(Q_f, H_w, H_S, B, A_G, g, \rho_s, \rho_w, d_S)$$

By dimensional analysis, volumetric of scour cone can be expressed as:

$$\frac{V_f^{\frac{1}{3}}}{H_S} = f\left(\frac{\frac{Q_f}{A_G}}{\sqrt{g.H_W}}, \frac{H_S}{d_S}, \frac{H_S}{H_W}, \frac{r_G}{B}, \frac{\rho_W}{\rho_S}\right) \quad (1)$$

As the parameters B , ρ_S , ρ_W and r_G are constant, therefore the equation(1) cab be written as:

$$\frac{V_f^{\frac{1}{3}}}{H_S} = f\left(\frac{\frac{Q_f}{A_G}}{\sqrt{g.H_W}}, \frac{H_S}{d_S}, \frac{H_S}{H_W}\right)$$

(2) With Substitution of $u = \frac{Q_f}{A_G}$ in equation (2), it can be written as:

$$\frac{V_f^{\frac{1}{3}}}{H_S} = f\left(\frac{u_f}{\sqrt{g.H_W}}, \frac{H_S}{d_S}, \frac{H_S}{H_W}\right) \quad (3)$$

The focus of attention in this research is extraction a

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dimensional graph and equation based on the experimental data for estimation of the volumetric of the scour cone.

Description of the physical model

With respect to this issue in the pressure flushing the flow pattern in the vicinity of the flushing outlets is three dimensional and also due to the high number of parameters involved in the phenomena, analytical treatment of it is difficult (Scheuerlein, 2004). Therefore in order to achieve the objective of this study a physical modeling is considered. Thus a hydraulic rectangular flume which located in the Hydraulic Laboratory at the Water and Science Collage of the University of Shahid Chamran, Ahwaz, Iran was used to simulate a research of pressure flushing. The overall dimensions of the flume were length, 7m long, 1.5m wide and 1.5m height. A schematic diagram of the flume is shown in Figure-3. Figure-3 presents the plan and longitudinal view of the model.

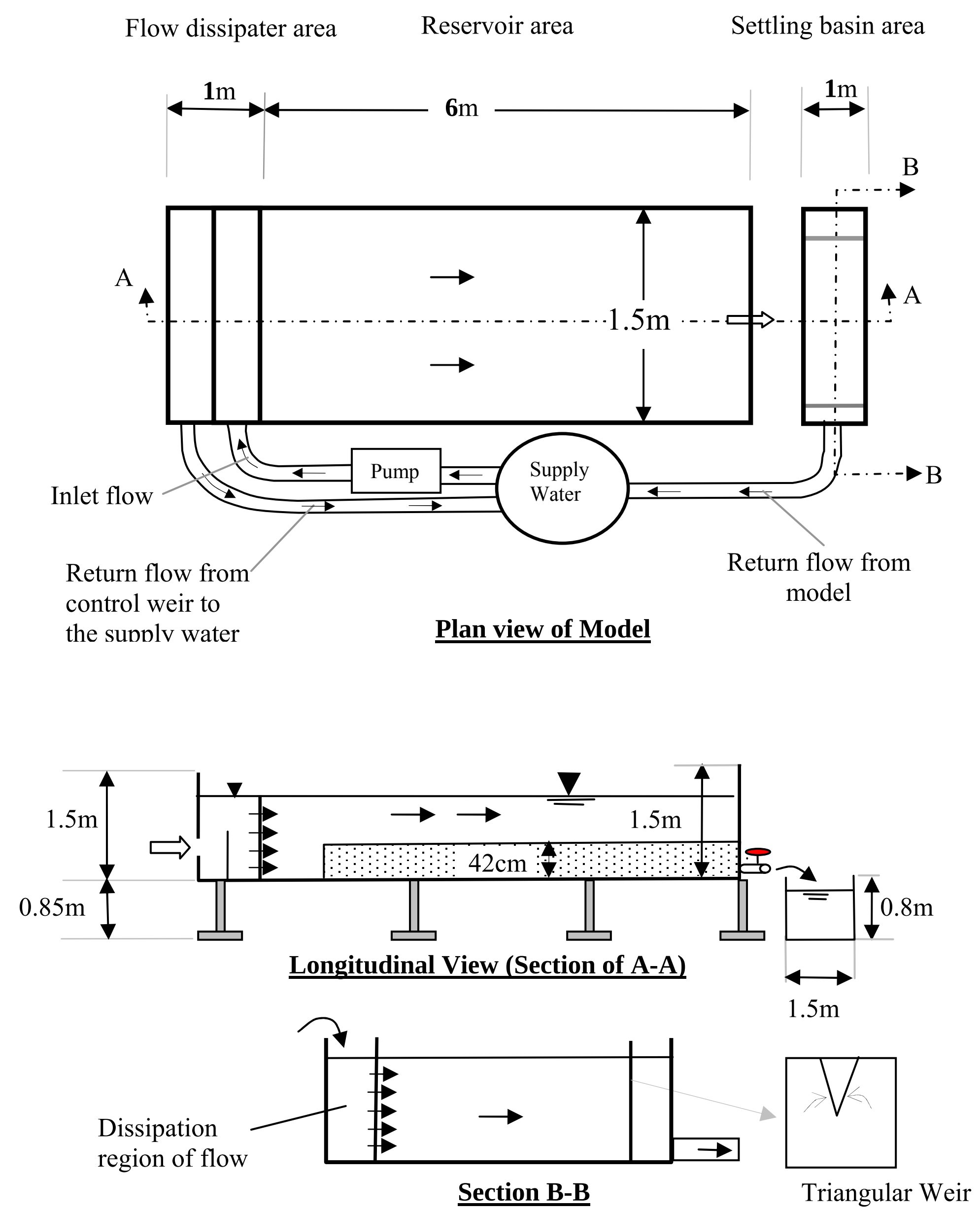

Figure-3. The plan and longitudinal view of the model and its detail

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The model consists of three main areas:

1- Flow dissipater area with 1m length, 1.5m depth and 1.5m wide (in this region the turbulent of inflow will be dissipated and flow as uniform flow entrance to the reservoir);
2-Reservior area with 6m length, 1.5m height and 1.5 m wide; and
3-Setlling basin area with 1.5m length, 1m wide and 0.80m height (the outflow from the outlet (mixed water and sediment released to this region and the sediment settle in it).

In order to regulate the water elevation in the reservoir, a spillway was considered in the Area 1. For the measurement of the outflow discharge from the outlet a triangular weir with angle of 26^0 is placed on the rectangular channel. Water was supplied by a pump at desired steady flow by controlling the valve of the pipe. Typically for flushing, a valve gate with diameter of 2 inch is placed on the centerline of the dam. When the water level behind (upstream of) the gate reaches a predetermined level, the gate is opened and water is released to flush sediment downstream of the gate.

Types and size distribution of the sediments

The used sediment in this study was sand as non-cohesive sediment. The specific gravity of the sand was 2.65. Sieving was used in order to achieve consistency in the materials. Three sizes of sediments were selected for the experiments:

- **Size-1:** Coarse sand (sediment between sieve No. 10 and 30)
- **Size-2:** Medium sand (sediment between sieve No. 30 and 60)
- **Size-3:** Fine sand (Sediment less than of sieve No. 60).

During the experiments, the sediments were evenly spread over the surface of the physical model.

Number of Experiments

Experiments were conducted with three sizes of sediments and with each size, three different water depth i.e. , 52, 90, 120 cm and five different discharges for each level i.e., 1, 3, 4.5, 6, 8 lit/s were used. 15 tests for each size of sediment, 45 in general, were done during the study. Table-1 gives the relative information for each size of sediment.

Table-1. Number of experiments and relative information for each size of the sediment.

Size of Sediment	Outlet's diameter	Thickness of the sediment in the model (cm)	Number of Water depth	Number of Discharge	Number of experiments for each size of sediment
Coarse Sediment	2 inch	42cm	3	5	15
Medium Sediment	2 inch	42cm	3	5	15
Fine Sediment	2 inch	42cm	3	5	15
Total number of Experiments					**45**

Experimental procedure

For carry out of experiment in each stage firstly sediments were evenly spread over through the model with a thickness of 42cm. After the intended water depth was selected, the downstream outlet of the physical model opened. At the beginning of the experiment when the downstream outlet would opened, sediments were discharged under water flow pressure with high concentration though the concentration decreased in time. Experiments were continued until the flushing cone reached balance so that the sediment concentration was negligible at the end of the experiments. The time required for formation of the flushing cone and its balancing depends on flow discharges, the water depth of the reservoir and size of the sediment. In this study, the experiments took one hour to carry out.

At the end of each experiment, in order to preserve the shape of the resulting flushing cone, first the flushing outlet closed, and then a 3-inch valve which placed at the beginning of the model was used to discharge of the water in the model. The water disposal was continued until it reached the sediment level and only water inside the flushing cone would remain. To discharge this water, the downstream outlet's valve was gradually opened until the water discharge without to affect the shape of the flushing cone. Depending on the flushing cone volume the procedure might take several hours.

Measuring of flushing cone volume

After the water inside the flushing cone was discharged, cross-section profiles of the physical model after each experiment were measured by a point gage device with accuracy of 1 mm. Then with introduce of measured cross sections to the software of SURFER 8.0, the flushing cone volume in various scenarios was calculated. For example, in Figure-4a and Figure-4b, a 3D view and topography of the flushing cone after the experiment with a discharge of 3 lit/s and water depth of 90cm with coarse sediment are presented, respectively.

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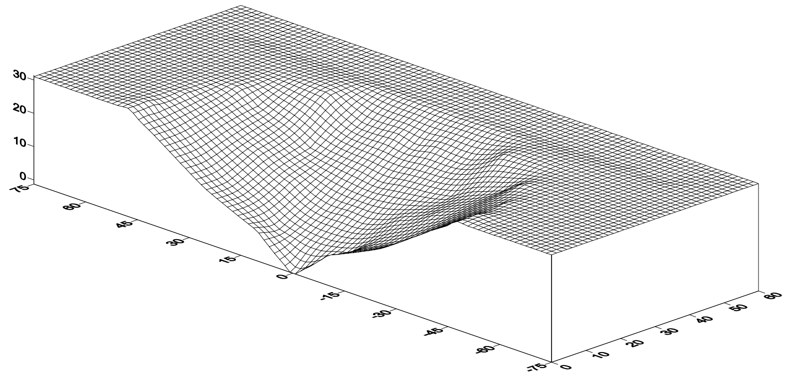

Figure-4a. 3-Dimensional view of the flushing cone after the experiment with 3 lit/s, 90cm water depth and coarse sediment.

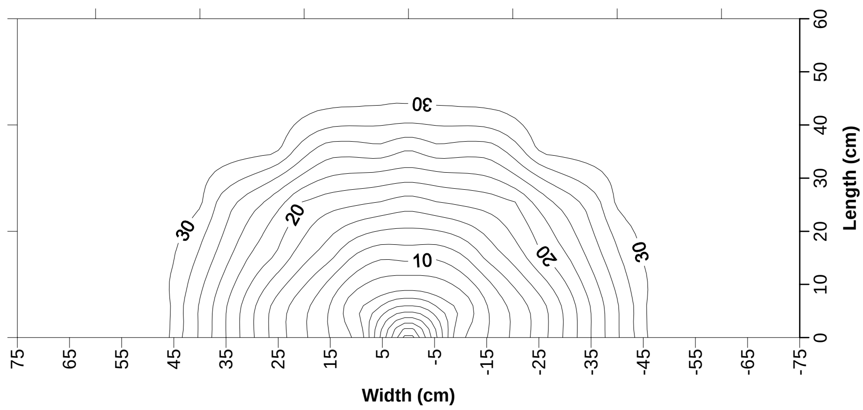

Figure-4b. The bed topographic of the flushing cone after the experiment with 3 lit/s, 90cm water depth and coarse sediment.

RESULTS AND DISCUSSION

As discussed earlier, in the pressurized flushing, the flushing cone volume (V*f*) is influenced by various parameters such as the outflow discharge of the bottom outlet (Q*f*), water depth in the reservoir (H*w*), accumulated sediments behind the reservoir (H*s*), dimensions of the bottom outlet, diameter of the accumulated sediment particles (d*s*), and the type of the sediments (cohesive or non-cohesive). In order to investigate these parameters, three sizes of non-cohesive sediments were used in the experiments:

1- Coarse sediments (sieve 10-30).
2- Medium-sized sediments (sieve 30-60)
3- Fine sediments (sieve less than 60)

In order to better investigate of the parameters which influenced the flushing cone volume, it is tried the results of the experiments presented as dimensionless graph. Therefore, the dimensional analysis of the parameters which mentioned earlier used for this purpose. The results of the experiments are presented in Figures 5, 6, and 7 for each type of sediments. Each Figure has 3 curves: the upper curve shows when the water depth in the reservoir is 52cm. i.e. when the ratio of the water depth to the sediment depth in the reservoir is 1.24 $(\frac{H_W}{H_S} = 1.24)$.

Two other curves, medium and lower, demonstrate when the water depth of the reservoir is 90cm and 120cm, respectively $(\frac{H_W}{H_S} = 2.14 \ \ and \ \ \frac{H_W}{H_S} = 2.86)$.

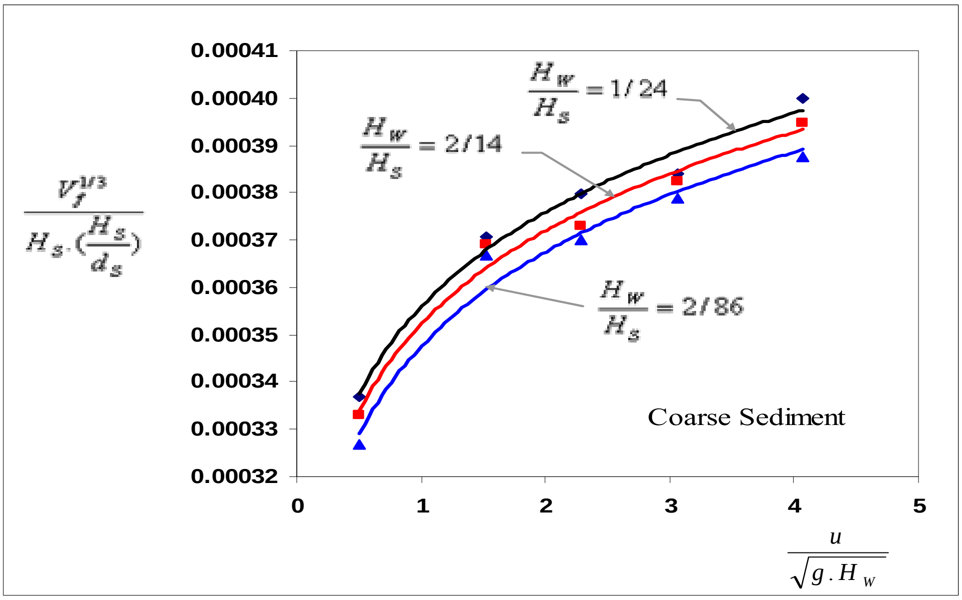

Figure-5. The dimensionless graph of the flushing cone volume for coarse sediment (between sieve No. 10 and 30).

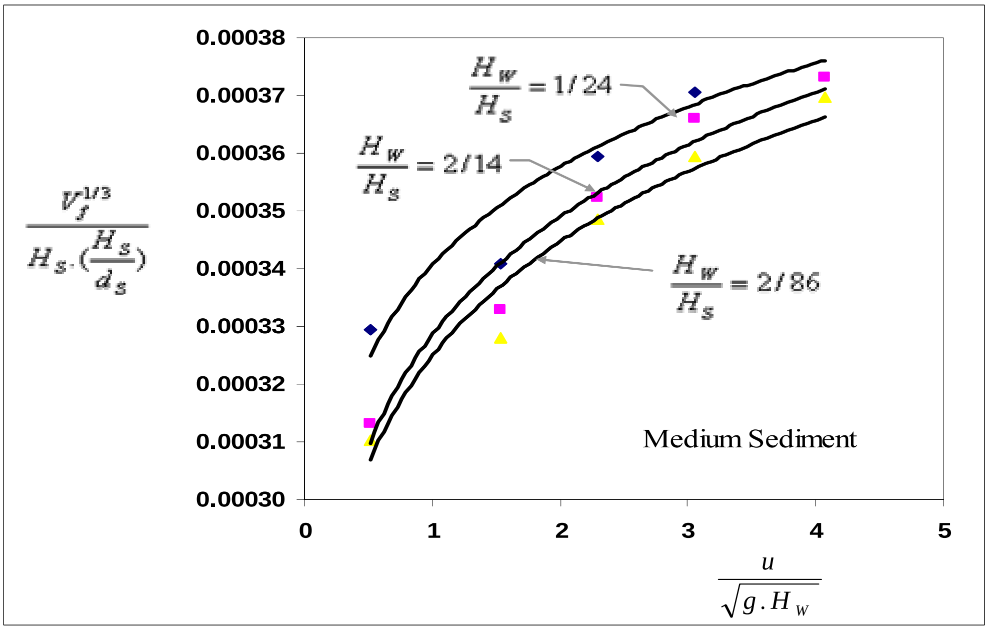

Figure-6. The dimensionless graph of the flushing cone volume for coarse sediment (between sieve No. 30 and 60).

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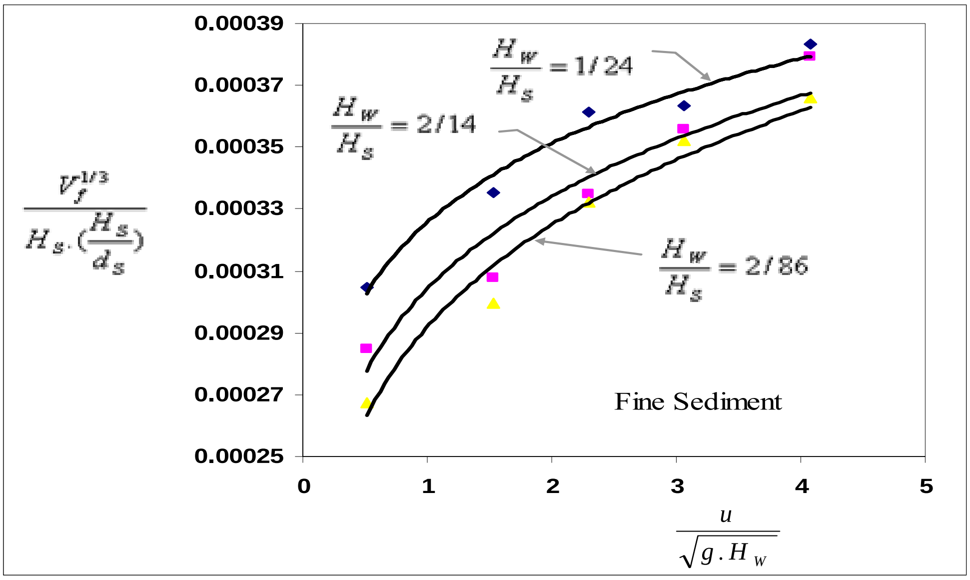

Figure-7. The dimensionless graph of the flushing cone volume for coarse sediment (less than of sieve No. 60).

Effects of reservoir's water depth on the sediment volume flushed

In order to investigate the effects of reservoir's water depth on the sediment volume flushed a comparison was made between flushing cone volumes when the water depth in the reservoir was reduced from 120cm to 52cm (a reduction of water depth equal %56. 7), also when it was reduced from 120 cm to 90cm (a reduction of water depth equal % 25). The increase of the flushing cone volume relative to the status when the water depth in the reservoir was 120cm was calculated for 5 different discharges (Table-2).

Table-2. The effect of reservoir's water depth on the flushed sediment.

Discharge (lit/s)	Decrease of reservoir's water depth (%)	Fine Sediment (less than of sieve no. 60)	Medium Sediment (between sieve no. 30 and 60)	coarse Sediment (between sieve no. 10 and 30)
1	56.7%	8.93%	16.40%	32.32%
3	56.7%	3.18%	10.93%	28.84%
4.5	56.7%	7.47%	8.74%	22.37%
6	56.7%	4.11%	8.75%	9.01%
8	56.7%	9.06%	8.92%	13.11%
1	25 %	3.63%	14.22%	18.22%
3	25 %	1.15%	6.98%	22.80%
4.5	25 %	5.43%	5.86%	20.33%
6	25 %	1.19%	3.55%	6.01%
8	25 %	3.92%	6.42%	11.67%

From Table-2, the results show that for a constant discharge, any decrease in the water elevation correspondingly leads to an increase in the sediment volume flushed. For example the first row of the Table-2 shows when the experiment carry out with 1 lit/s and the water depth of the reservoir was reduced from 120 to 52cm (%56.7 reduction), a comparison between the results of the flushing cone volume while the sediments used were of coarse, medium-sized and fine, the sediment flushing cone volume increases %32.32, %16.40 and %8.93 for each type, respectively. Also, it is clearly shown in Figures 6,7 and 8. Therefore, in order to maximize the efficiency of pressurized sediment flushing i.e. increasing sediment flushing volume to the extent possible, it is advised to reduce the water elevation of the reservoir until it is not further allowed by the operational limits. In the reservoirs where free sediment flushing is not feasible, it is recommended the pressurized sediment flushing be applied at the time the water elevation of the reservoir is at the minimum operational level. As a general rule in pressurized sediment flushing the water depth of the reservoir should be minimized or flushing be best carried out when the water elevation drops to the minimum operational level with bottom outlets fully in swing.

Effects of bottom outlets discharge on the sediment volume flushed

For further investigate how the bottom outlet discharge influence the sediment volume flushed out from a reservoir the results obtained is compared in the Table-3. For this purpose for each water depth (i.e. 52, 90 and 120cm), the flushing cone volume of the experiments which carried out with 3, 4.5, 6 and 8 lit/s is compared to 1 lit/s at the same water depth.

Table-3. The effect of outlet's discharge on the flushed sediment.

Water depth of reservoir (cm)	**Discharge** (lit/s)	**The percentage of increase of discharge relative to the discharge of 1 lit/s**	**Coarse Sediment** (between sieve No. 10 and 30)	**Medium Sediment** (between sieve No. 30 and 60)	**Fine Sediment** (less than of sieve No. 60)
			Increase of flushed sediment volume (%)	**Increase of flushed sediment volume** (%)	**Increase of flushed sediment volume** (%)
52	3	67%	25%	10%	25%
52	4.5	78%	40%	23%	30%
52	6	83%	45%	30%	32%
52	8	88%	50%	36%	40%
90	3	67%	21%	17%	27%
90	4.5	78%	38%	30%	29%
90	6	83%	49%	37%	34%
90	8	88%	54%	41%	40%
120	3	67%	29%	15%	29%
120	4.5	78%	48%	29%	31%
120	6	83%	56%	36%	36%
120	8	88%	61%	41%	40%

As it is observed from Table-3, when the water depth of reservoir is constant, the flushing cone volume increases with increase of discharge of bottom outlet. For example the last row of Table-3 shows that when the reservoir's water depth in the reservoir is 120 cm, the increase of the discharge from 1 to 8 lit/s, enhances the sediment flushing cone volume. This for coarse, medium-sized and fine sediment would be 61, 41 and 40%, respectively (Figures 6,7 and 8). In other words, to maximize sediment flushing efficiency, it is necessary to operate the flushing outlets at their maximum operational capacities.

Relationship for determining sediment flushing cone volume

When bottom outlets are open for the purpose of sediment flushing, previously deposited sediments are flushed out along water and under water pressure. This causes retrogressive erosion which initiates from near the outlets and moves on to the upstream of the reservoir. If the water depth in the reservoir remains constant, the moving of the sediment flushing cone towards upstream is stopped. To study the relation between sediment flushing cone and other involving parameters such as water depth in the reservoir, outflow discharges, types and size distribution of the sediments, etc, the experiments were performed using three sediment size distributions with three water levels i.e. 52, 90 and 120 am, each with three discharges i.e. 3.1, 4.5,6 and 8 lit/s, respectively.

To provide a non-dimensional relation in determining the sediment flushing volume, SPSS software was applied. The results are represented in Figure-4 and dimensionless equation (4).

$$\frac{V_f^{\frac{1}{3}}}{H_S} = 0/6139\left(\frac{u_f}{\sqrt{g.H_W}}\right)^{0/0062}.\left(\frac{H_S}{d_S}\right)^{0/05}.\left(\frac{H_S}{H_W}\right)^{0.0036} \quad (4)$$

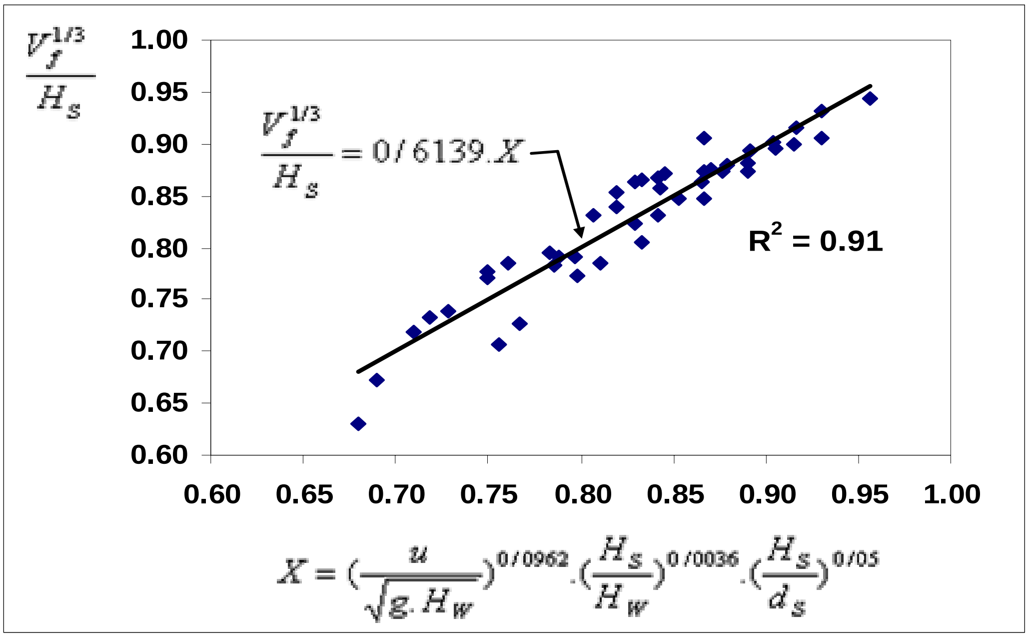

Figure-8. The dimensionless graph of the flushing cone volume and other parameter.

CONCLUSION

Pressurized sediment flushing method has local effects in sediment disposal and is recommended when local disposal of the sediment deposits (such as sediments around an intake inlet) is intended. The results of the present study revealed that in order to maximize the pressurized sediment flushing efficiency efforts should be made to reduce the water depth in the reservoir as low as possible or the time of the flushing activity should correspond to the lowest operational water level in the reservoir while the bottom outlets operating at full capacities.

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