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FLUSHING SEDIMENT THROUGH RESERVOIRS[*]

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Abstract – About 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 or turbines. One of the most effective techniques to remove these sediments is flushing, whereby water level is lowered sufficiently to re-erode deposits and flush them through the intakes. Outflow sediment discharge may well be related to the parameters such as the sediment characteristics in the reservoir, during flushing and geometry of flushing channel.

In this study, laboratory experiments were performed on a 1-D reservoir model in a flume in the hydraulics laboratory of Shiraz University to investigate the flushing operation processes by using polymer particles. The polymer particles were lightweight and non-cohesive with an average grain size of about 2.40 mm and density of 1065.3 (kg/m^3). The model was installed in a flume; 30 m long, 1 m wide and 0.75 m height. The length of the test section was 11.5 m, and sediments were placed at a length of 4.8 m long upstream from the dam position. Experimental runs have been performed for two flow conditions; 0.0004678 m^3/s and 0.000628 m^3/s. The very low inflow discharge helped for better monitoring and measuring of the effective parameters. A sluice gate was placed at the central bottom of the dam (as the bottom outlet) and was opened at a constant rate to make the complete drawdown. Results showed that the rate of sediment flushing is strongly associated with outflow rate, water surface gradient with the dam section and the width of the flushing channel. The results from this study were in agreement with that in the literature. It is considered that the low density of the particles causes them to behave as very fine and non-cohesive sediment particles, like loess sediments.

Keywords – Reservoir sedimentation, flushing, retrogressive erosion, cone formation, flushing channel

1. INTRODUCTION

Dam construction has increased during the last decades, particularly in the tropics and semi-arid areas where high sediment yields are prominent, as well as reservoir sedimentation. In 1900 there were 42 large dams (i.e. higher than 15 m) while in 1950 and 1986 there were 5,268 and about 39,000, respectively [1].

Sustainable use of existing reservoirs has become an important issue, since building new reservoirs is rather difficult due to the new environmental regulations, high cost of construction, and lack of suitable dam sites. Therefore, techniques for reservoir desiltation have received increasing attention recently [2]. Approximately 1% of the storage volume of the world's reservoirs is lost annually due to sediment deposition [3]. In some developing countries where population pressures on fragile upland ecosystems have led to accelerated rates of soil erosion and reservoir storage is being lost at much larger rates, the following approaches have been adopted in order to control measures to reduce sediment inflow into the reservoir [2, 3]: 1) Increasing sediment transport through the reservoir during high flows with heavy sediment concentrations, 2) Flushing reservoir-sediment accumulation through the reservoir, 3) Bypassing high flow with heavy sediment concentration from entering the reservoir, 4) Flushing sediment from reservoir by density currents, 5) Removing the reservoir sediment by mechanical means such as dredging and siphoning.

In certain parts of the world, a combination of three approaches: 1, 2 and 5 is an attractive practice. The bypass of flood flow and sediment from entering the reservoir requires certain topographical and flow conditions, and this approach is not commonly used. We do know the necessary condition, but not the

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sufficient condition for the existence of the density condition, and thus it is difficult to rely on the process of density current to flush sediment [4]. Flushing is the only means of recovering lost storage without incurring the expenditure of dredging or other mechanical means of removing sediment. Where feasible, flushing can offer an attractive means of recovering and maintaining a useful storage capacity when compared with the cost of alternative methods (e.g. dredging and siphoning) [3].

a) Sediment flushing

Flushing is the scouring out of deposited sediment from reservoirs through the use of low-level outlets in dams to lower water levels, thereby increasing the flow velocities in the reservoir. The technique is not widely used because: (a) It is usually effective in narrow reservoirs, (b) It involves large volumes of water being passed through the dam, and (c) It requires the reservoir to be emptied.

"Drawdown" is the lowering of the water level in a reservoir. Drawing down a reservoir (for a few weeks or months during a flooding season) is also a form of flushing, although the principal purpose is to pass the high sediment loads carried by flood flows through the reservoir. In the literature this practice is commonly termed as "Sluicing" [3]. Brandt [1] mentioned that flushing is used to erode previously deposited sediments, and sluicing is used to discharge incoming sediments through the reservoir without necessarily drawing down the water level. In this paper, however, sluicing is considered to be a particular kind of flushing [3].

b) Reservoir-sediment depositional pattern

Sediment particles are carried by flows into a reservoir and deposited in the reservoir due to the increase of flow area, and thereby the reduction of flow velocity. As shown in Fig. 1, the deltaic deposition consists of four parts [2, 4, 5]: (a) Front reach (Bottomset), (b) Frontset (Foreset), (c) Topset, and (d)- Tail reach.

In high sediment laden flows, sediment may reach the downstream end of the reservoir quickly, resulting in a wedge-shaped deposition with its apex very close to the dam. A wedge-shaped deposition can also be formed if the water level is allowed to be drawn down regularly. In addition, deltaic deposits may migrate toward the dam and the entire reservoir depositional pattern will become wedge-shaped. Thus, the wedge-shaped depositional pattern could be the equilibrium state of certain reservoirs in a long run [2]. For a wide reservoir (with lateral width much greater than width of flow through outlets), the lateral distribution of sediment deposit may not be uniform [4].

c) Flushing processes

As discussed by Lai and Shen [2], flushing processes may include the following two types: The first type is to use flow to remove previous reservoir sediment deposit. The second type is to pass heavy sediment concentrated flow through the reservoir during high flow.

When the water stage in the reservoir is high, as indicated in Fig. 1, only a local flushing cone is formed and the flushing process is not very effective. However, when the water stage is low (the topset of sediment deposit is closed to the water stage), the flushing of sediment can be very effective in removing previous reservoir sediment deposits and also to pass sediment in the flow, provided the frontset of the sediment deposit reaches a location very close to the dam [4].

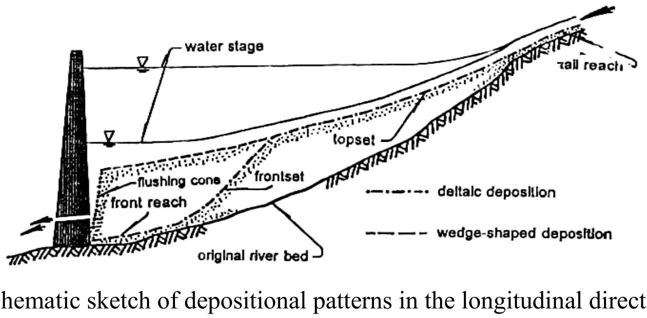


Fig. 1. Schematic sketch of depositional patterns in the longitudinal direction [4]

After forming the deltaic deposition in a reservoir, Fig. 2 illustrates the flushing processes corresponding to the drawdown operation in the longitudinal direction with various water levels. Assuming that the sluicing capacity is large enough for lowering the reservoir water level and there is no sediment clogging at the sluicing outlet, the sluice gate is opened to the lower water level for drawdown flushing. During the drawdown period, the backwater may diminish from the upstream of the reservoir and "progressive erosion" in the tail reach can occur to carry previous deposits or incoming sediment toward the dam. If the reservoir water level is low enough to scour the apex of the deltaic deposition, the apex of the delta can move retrogressively and a flushing channel is developed by cutting through the deposits. This erosion pattern is called "Retrogressive Erosion" which propagates from downstream toward upstream [2].

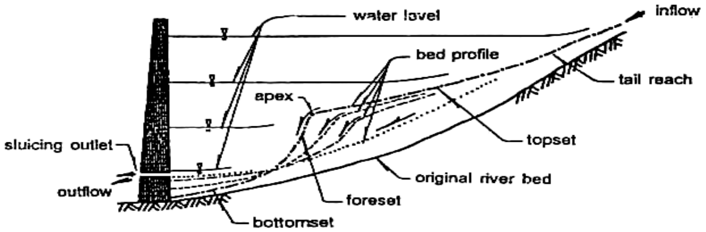


Fig. 2. Schematic diagram of flushing processes in the sediment delta [2]

The developing channel deepens and widens as a result of large-scale erosion in the reservoir. Thus, an effective flushing process occurs. However, sediments scoured from the delta reach may move toward the dead-storage zone near the dam and settle down before they can be flushed out. Under such a condition, the flushing may not be effective. If drawdown flushing is operated with a wedge-shaped deposition, sediment deposits can be scoured in the vicinity of the sluice-gate opening within a very short period of time under pressurized flow conditions, and 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 flowing water is clear through the opening, meaning that the formation of the flushing cone is fairly stable and no sediment will be removed from the flushing cone afterward. If the water surface is to be drawndown significantly to generate high flow velocity near the sluicing outlet, the flowing water will start to erode the rim of the flushing cone and retrogressive erosion may occur [2].

d) Formation of the flushing channel

During deposition processes in a reservoir, sediments deposit in the main channel and then extend laterally across the full width of the reservoir to create a nearly horizontal deposition level. Nevertheless, by operating drawdown near the sluicing outlet, flow conditions in the impounded reaches will be similar to the original riverine patterns. In other words, through flushing processes, channelization by retrogressive erosion creates a channel flow cutting in the deposits to reestablish a new cross-sectional pattern with the main channel and floodplain.

e) Effects of local flushing

As mentioned previously, flushing in a short period could create a stable flushing cone. Field observations by Wan [2] at Sanmenxia reservoir in China indicated that a flushing cone was 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 main function of the flushing cone is to reduce the sediment concentration around the entrance of the intake tower, and thereby prevent hydraulic structures from abrasion by sediments.

f) Objectives and scope of this paper

The objectives of the present study are as follows:

1- To investigate the mechanism of the flushing operation in an experimental, one-dimensional model. 2- To describe the behavior of the cone formation and flushing channel evolution. 3- To variate the outflow water and sediment discharges, water depth in the upstream and downstream ends of the reservoir with time in regard to the flushing operation in the experimental model. 4- To compute the coefficient of erodibility (E) based on the Tsinghua University method with outflow water and sediment discharges, water surface slope and width of the flushing channel in the reservoir. 5- To estimate the flushing efficiency (F_e) and its relationship with outflow sediment discharge, cumulative volume of flushed sediment and experimental duration for each run. 6- To compare of these results with previous works. 7- To present recommendations for sediment flushing operations in existing reservoirs.

2. LITERATURE REVIEW

A large number of studies including theoretical and experimental works have been carried out to explain reservoir behavior during flushing sediments through the bottom outlets.

Flushing is not a new technique. The first known method of flushing (which was in Spain in the 16th century) was reported by D'Rohan (reported in Brandt [1]). However, Bouvard (reported in Brandt [1]) stated that the reservoir should be reasonably large so that it would not be necessary to performe flushing too often, disturbing the normal operation of the intakes. Ramirez and Rodriguez (reported in Brandt [1]) divided the flushing process of the Cachi reservoir in Costa Rica into three phases. The first consists of 25 days of slow water release, lowering the water table one-meter per day down to a few meters above minimum level for power generation. The second phase consists of the rapid release of the remaining water, a lowering of 45 m during a period of approximately five hours. The third phase consists of free flow water out of the reservoir for two or three days.

Lai and Shen [2] pointed out that flushing should be done regularly before deposits consolidate, especially for cohesive clay deposits. Sluicing operations should be timed to meet the higher sediment concentrations brought in by flood flows [7]. Du and Zhang (reported in Brandt [1]) stated that the resistance of cohesive sediment in front of the dam is much greater than the sandy sediment in the middle part of the reservoir. Therefore, the erosion of cohesive sediment near the dam region governs the progress of retrogressive erosion in the reservoir. When erosion of the reservoir bed has commenced, the flow soon becomes hyper-concentrated. When concentration increases, the settling velocity decreases, thus the flow can transport with very high concentrations of sediment under a relatively small flow (Wu, reported in Lai *et al.*) [6]. Nagle (reported in Brandt [1]) made observations on the cross-sectional erosion pattern during flushing (Villar reservoir, Rio Lazoya, Spain). There, sediment was removed only from the old stream channel and the high banks of deposits were left on either side. The main channel underwent aggradation and degradation alternately, and the flood plains alone kept rising slowly (Zhang *et al.*, reported in Brandt [1]). In reaches far from the dam in the Hengshan reservoir, China, the erosion at the foot of the banks broadened the channel, leading to the formation of a rectangular cross-sectional form and causing the coarse floodplain deposits to collapse vertically into the channel [8]. Initially a carved-out channel was narrower than the original river width, but with periodic flushing the scoured channel will approach the pre-dam width of the river (Mahmood, reported in Brandt [1]). Based on data from four different reservoirs, Atkinson [3] found that the channel width formed during flushing correlated well with the flushing discharge alone, with no apparent sensitivity to slope or sediment properties. The side slope, which will develop during flushing, depends on the sediment properties, the degree of consolidation, the depth of the deposits, and perhaps the extent of water-level fluctuation during flushing [3]. The flushing channel may deepen under either small or large flows until it encounters the armored bed of the pre-impoundment river. Afterward, further erosion can occur only by widening of the channel by bank failure, which is the primary mechanism involved in the widening of flushing channels [8].

Di Silvio (reported in Lai and Shen [2]) found that under the pressurized flow condition, a flushing cone in the vicinity of the sluice gate could be formed with a wedge-shaped deposition. He added that if the water level is allowed to be drawndown, two types of erosion patterns can occur: progressive erosion and retrogressive erosion. In the latter case, retrogressive erosion back-cutting in the deposits results in strong and large-scale erosion, which restores useful storage capacity. Fan and Morris [8] presented several models to simulate the flushing processes under draw down operations. Based on the field data they obtained during retrogressive erosion, several empirical formulas have been proposed to estimate sediment outflow discharge which may be related to flow discharge, energy slope or channel width. Shen, *et al.* [6] used a dimensional analysis for non-cohesive sediment to establish a formula to estimate the erosion depth for local flushing in front of the sluice gate. Then Lai and Shen presented a one-dimensional experimental and diffusion model to simulate the general trend of the bed profile evolution, and the amount of reservoir sediment removal during flushing, in order to evaluate the applicabilities and limitations of the diffusion model [2]. They found that the simulated results of the diffusion model agree well with the laboratory data in a narrow flume (with essentially 1-D flow) with a nearly uniform flow condition after rapid draw down operation. At last, Shen [4] reviewed the current status on the flushing sediment through reservoirs statistically and also stressed the needs of an analytical solution for incorporating the risk analysis for the planning sediment operation through dams.

There have also been many numerical and theoretical studies. For example, Ju (reported in Lai *et al.* [6]) presented one-dimensional (1-D) diffusion models which were solved analytically or numerically to simulate the removed sediment volume and bed profile changes with constant discharge and channel width during flushing. White (reported in Lai *et al.* [9]) developed numerical models dealing with sedimentation and flushing to study the feasibility and effectiveness of flushing operations for small reservoirs in Zimbabwe. Olsen and Melaaen (reported in Olsen [10]) used three dimensional models to calculate the local scour and sediment deposition in a reservoir, and in a sand trap they gave a limited description of the two-dimensional numerical simulation of the flushing process.

3. DIMENSIONAL ANALYSIS

During drawdown flushing, the following variables should be considered: C_s = volumetric outflow sediment concentration; u = mean flow velocity; h = water depth; S = energy slope; g = gravitational acceleration; γ = specific weight of water; γs = specific weight of sediment; and w = fall velocity of particles.

Using the "Buckingham" theory [11] for dimensional analysis, function of variables is then presented as

$$f\left(C_s, u, h, S, g, \gamma, \gamma_s - \gamma, w\right) = 0 \tag{1}$$

The above function is changed to

$$f_1\left(\frac{C_s g}{\gamma}, \frac{uS}{w}, \frac{\gamma}{\gamma_s - \gamma}, \frac{u^2}{gh}\right) = 0 \tag{2}$$

If g and γ are considered constant, we can bring one of the dimensionless parameters to the left side and say

$$\frac{C_s g}{\gamma} \propto \left(\frac{\gamma}{\gamma_s - \gamma}\right) S \left(\frac{u^3}{ghw}\right)^m \tag{3}$$

Or one can write it simpler

$$\frac{C_s g}{\gamma} = k\left(\frac{\gamma}{\gamma_s - \gamma}\right)\left(\frac{u^3}{ghw}\right)^m \tag{4}$$

and as g and γ are constant so

$$C_s = k_o\left(\frac{\gamma}{\gamma_s-\gamma}\right)\left(\frac{u^3}{ghw}\right)^m \tag{5}$$

In which

$$k_o = \frac{k\gamma}{g}$$

and we can substitute some of above parameters with new parameters

$$G_s = \frac{\gamma_s}{\gamma} \Rightarrow G_s - 1 = \frac{\gamma_s-\gamma}{\gamma} \Rightarrow \frac{1}{G_s-1} = \frac{\gamma}{\gamma_s-\gamma} \tag{6}$$

In which k_o and m are coefficients to be determined; G_s is the specific gravity of sediment. The value of m was determined from field data in China and are about unity [2]. For practical purposes, let m equal unity. Assuming the approach flow to be uniform during flushing, the Manning equation can be applied as below (in metric system)

$$u = \frac{1}{n}R_h^{\frac{2}{3}}S_w^{\frac{1}{2}} \tag{7}$$

Having a wide rectangular flume leads the relation change to

$$u=\frac{q}{h},\ R_h\approx h,\ q=\frac{Q_o}{B},\ m\approx 10,\ u=\frac{1}{n}S_w^{\frac{1}{2}}R_h^{\frac{2}{3}} \Rightarrow C_s=\frac{k_o}{(G_s-1)}\left(\frac{u^4}{gqw}\right)=\frac{k_o}{gw(G_s-1)}\left(\frac{1}{n^3}S_w^{\frac{3}{2}}h\right) \tag{8}$$

Let’s take $k'=\dfrac{k_o}{gw(G_s-1)}$

Then we will have

$$C_s = \frac{k'}{n^3}S_w^{\frac{3}{2}}\left(\frac{Q_o}{B}\right)n\frac{1}{S_w^{\frac{1}{2}}h^{\frac{2}{3}}} \tag{9}$$

From this point an iterating method will begin. We should substitute h with *(q/u)* and put *(Q_o/B)* instead of q and use the Manning equation for the parameter u, until their power is fixed within 10% accuracy, and assume the powers which are too small to consider, such as zero.

We will write the result of some iterating runs below

Iteration#1

$$\Rightarrow\ C_s = \frac{k'}{n^{\frac{8}{3}}}\left(\frac{Q_o}{B}\right)^{\frac{1}{3}}S_w^{\frac{4}{3}}h^{\frac{4}{9}} \tag{10}$$

Iteration#7

$$\Rightarrow\ C_s = \frac{k'}{n^{\frac{5300}{2187}}}\left(\frac{Q_o}{B}\right)^{\frac{1261}{2187}}S_w^{\frac{2650}{2187}}h^{\frac{256}{6561}} \tag{11}$$

Following the iteration, the end result would be

$$C_s = \frac{k'}{n^{\frac{15644}{6561}\approx 2\cdot 4}}\left(\frac{Q_o}{B}\right)^{\frac{4039}{6561}\approx 0.6}S_w^{\frac{7822}{6561}\approx 1\cdot 2}h^{-\frac{512}{19683}\approx 0} \Rightarrow C_s = \frac{k_o}{gw(G_s-1)n^{2.4}}\left(\frac{Q_o}{B}\right)^{0.6}S_w^{1.2} \tag{12}$$

So the outflow sediment discharge by weight will be as follows:

$$Q_{os}=\gamma_s C_s Q_o=\frac{\gamma_s k_o}{gw\left(G_s-1\right)n^{2.4}}\left(\frac{Q_o}{B}\right)^{0.6} S_w^{1.2} Q_o \Rightarrow Q_{os}=\frac{\gamma_s k_o}{gw\left(G_s-1\right)n^{2.4}}\frac{Q_o^{1.6} S_w^{1.2}}{B^{0.6}} \tag{13}$$

The main formula for calculation of outflow sediment discharge is as follows:

$$Q_{os}=E\,\frac{Q_o^{1.6} S_w^{1.2}}{B^{0.6}} \tag{14}$$

where Q_{os}=outflow sediment discharge (ton/sec); Q_o=outlet water discharge (m^3/sec); n=Manning roughness; B=width of flushing channel (m); S_w = water surface slope = S_o = bed slope; and E = coefficient of erodibility which is as below [2, 3]

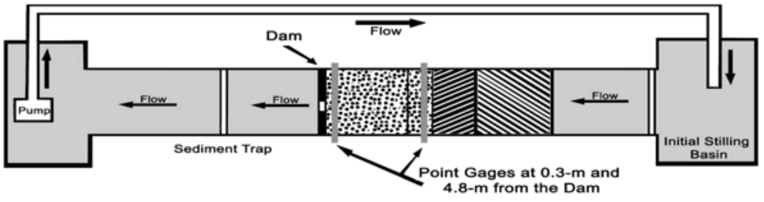
$$E=\frac{\gamma_s k_o}{gw\left(G_s-1\right)n^{2.4}} \tag{15}$$

4. METHODS AND EXPERIMENTS

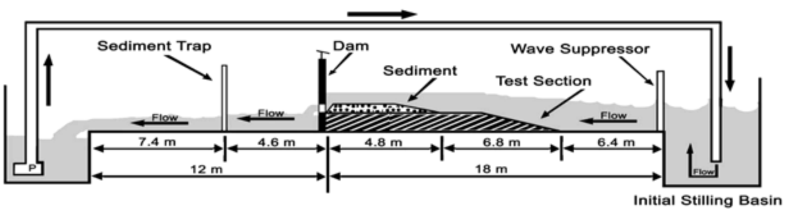
a) Setup and procedure

From both previous laboratory and field data by Lai and Shen [2], it has been found that outflow sediment discharge can well be related to some hydraulic parameters, which are functions of outlet discharge, water-surface gradient and flushing channel width. A one-dimensional experimental model presented herein is employed to simulate the general trend of bed profile evolution and the amount of reservoir sediment removal during flushing in order to evaluate the applicabilities and limitations of this model.

A rectangular concrete flume 30 m long, 1.0 m wide and 0.75 m in height, located in the hydraulic laboratory at the Civil Engineering Department of Shiraz University in Shiraz was modified to model a reservoir. Part of the flume was elevated up to 0.16 m to prevent the outlet from being submerged at the downstream of the dam (this value has been found based on the dimensions of the Sefid Rud reservoir, which is the only reservoir in Iran that has been saved by flushing operation). Water was re-circulated by a pump at two desired steady flow rates of 0.0004678 and 0.000628 (m^3/sec) by controlling a sliding valve at the end of the pipeline (see Fig. 3).



(a) Topview



(b) Sideview

Fig. 3. Schematic sketch of the experimental model (a) Top-view, (b) Side-
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A one dimensional model with a central sluice gate, dimensions of about 0.15 m in height and 0.09 m wide was made and used (see Figs. 4a and 4b). The sediment material used in the experiments was a lightweight and non-cohesive polymer with the traditional name of “Polystyrol 143E”, which was one of the BASF products. The choice of the sediment type and size was based on the dimensions of the flume and the capacity of water supply. Polystyrol 143E had a bulk density of about 650 kg/m^3, specific gravity of about 1.0653, and median diameter of about 2.4 mm. Furthermore, using the “Polystyrol 143E” repeatedly in the experiments did not change the sediment properties. The density of this material was very close to the density of water and this made problems in distinguishing the threshold time for the retrogressive erosion in each experimental run. At the beginning of each experimental run, sediment was wetted and paved without any compaction and consolidation at a 4.8-m length by 0.06 m height upstream of the dam. The zero elevation was set at the bottom of the sluice gate (which was 0.16 m above the original flume bed).

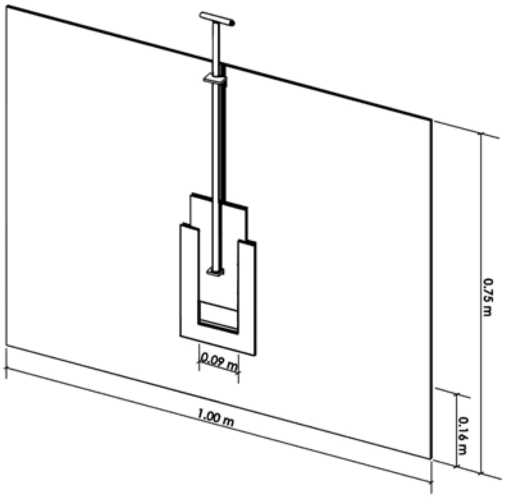


Fig. 4a. Downstream face of the dam and sluice gate in the experimental model

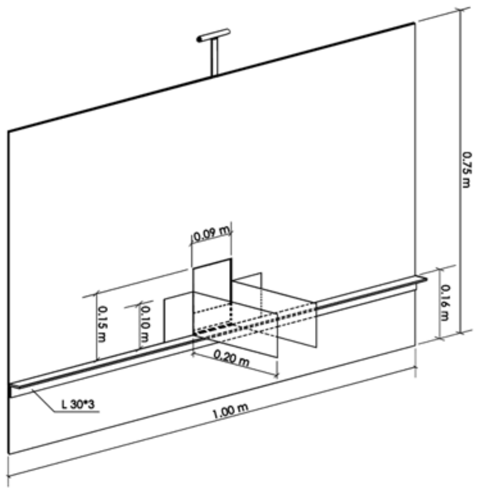


Fig. 4b. Upstream face of the dam and sluice gate in the experimental model

The same procedure of wetting and placing was performed for all the sediment particles (110 Kg of the polymers), and then the “distributing and smoothing operation” began. A T-shaped device was used for distributing and smoothing.

The smoothness of the polymer particles (sediment) was checked on the sidewalls of the flume. The level was exactly 0.06 m above the raised wooden bed. The middle part of the sediment bed was also checked by a point gage located at the centerline of the flume to make sure of the smoothness of the whole sediment in the test section. The central point gage was moved from the dam to the upstream end of the test section to reach to the same height of the sediment (0.06 m) by compensating or removing polymer particles. This operation usually took about 1.5~2 hours. The pattern of the gate was modified by adding a small steel channel at the back of the gate to represent the original river channel. The dimensions of this pattern were as follows: 0.09 m width (equal to the width of the sluice gate) and 0.2 m long. The polymer particles within these walls were removed prior the experimental runs to represent the natural condition (bottomset and forset of the long-term sediment deposits in reservoirs) at or near the bottom outlet (sluice gate).

The steady state condition was attained by regulating the sluice gate opening. It should be mentioned that one of our main assumptions in these experimental runs was the steady state flow condition. To obtain this condition, the inflow discharge must be equal to outflow discharge. The inflow discharge was constant in each experimental run. The outflow discharge was controlled only by the opening of the sluice gate. The water depth was kept constant of 0.10 m height in all-experimental runs at the test section. Due to the length and size of the experimental model, the change in gate opening was gradual to prevent unnecessary water fluctuations and waves in the reservoir. Because the sudden changes were caused the lightweight polymer particles floatation, the gate was opened slowly and gradually in several steps to obtain a steady state condition without any sediment disturbances. The main experimental runs began right after reaching a steady state condition. It is worthwhile to mention that the height of sediment, the length of sediment, water depth and the inflow discharge for each experimental run were kept constant in order to evaluate the flushing sediment behavior through the reservoir.

To start the experiment, the sluice gate was manually opened at a constant rate and the outflow water-sediment mixtures were sampled every two minutes. The total time of each experiment was about 50 minutes. This is equivalent to around 25 samples. Two point gages; one at 0.3 m from the dam and the other at 4.8 m from the dam (at the upstream end of sediment deposit) were installed to measure water surface elevation. The former one was used to measure the head of water above the weir to calculate the outflow water discharge. Based on previous works [9] and cited observations in the literature, the width of the flushing channel in each time step was measured in the middle reach of the reservoir (at 2.4 m from the dam) where the effects of upstream and downstream ends are minimum. At each experimental run, the bed sediment profile was measured by a point gage at the centerline of the flume. Water temperatures ranged from 25 to 28 degrees Celsius in the experimental runs.

b) Sediment flushing observations

A detailed description of a representative experimental run provides a general overview of the series of experiments. For this purpose, Flow1 was selected as the representative run to be described in this section. Following experimental procedures, Flow1 was initially set with zero bed slope and with an initial channel. To reach a steady state flow for the initial setup with a constant inflow discharge rate of 0.0004678 m^3/sec and a water depth of 0.10 m above datum, the central sluice gate was opened by 1 cm; meanwhile, a flushing cone was shaped by the flushing water, which removed sediment deposits only in the vicinity of the gate opening. Two to three minutes after the gate was opened, the outlet discharge was almost clear and a stable cone was formed. The side slope of the flushing cone was close to the angle of repose of the submerged polymer particles. At this phase, the stable condition was defined as the initial setup of Flow1. Opening the sluice gate at the incremental rate of 3 cm per minute was performed at the start of the experimental Flow1 until the opening reached 6 cm in height.

The water surface then dropped because the outflow capacity was much greater than the inflow discharge. When the water surface elevation near the gate was fully drawn down and became close to the rim of the flushing cone (or the apex of the deposition), the flow condition changed from pressurized flow into the free surface flow condition. At this stage, water surface gradient near the sluice gate increased significantly. The flow first eroded the rim of the flushing cone and began cutting through the sediment deposits. Consequently, retrogressive erosion took place along the initial channel and propagated toward the upstream creating somehow a straight flushing channel. At this phase, a significant amount of sediment deposits was flushed through the reservoir, and the initial channel deepened and widened as a result of large-scale erosion in the reservoir. Lateral erosion on the floodplain was also observed before the flushing flow was drained and confined into the flushing channel, especially near the dam. The entire experiment lasted for about 50 minutes. The bed form observed in this straight flushing channel was in the form of a plane bed. The experimental data are summarized in Table 1.

Table 1. Summary of experimental data

Flow No.	Inflow discharge (m^3/s)	Ex. No.	Initial water stage at dam (m)	Initial deposit depth (m)	Length of sediment bed (m)	Initial bed slope(%)	Running time (min)
1	0.0004678	1, 2, 3, 4, 5	0.10	0.06	4.8	0.0	65
2	0.0006280	6, 7, 8, 9	0.10	0.06	4.8	0.0	65

5. RESULTS AND DISCUSSION

a) Behavior of cone formation processes and flushing channel evolution

After conducting two of the initial experimental runs, it was seen that the shape of the sluice gate's entrance was the dominating factor in dictating the flushing channel to follow a straight path. In experimental run no.1 (Flow1), the lack in the sluice gate's entrance caused the flushing channel to be formed at the left bank of the flume, right behind the gate. Therefore, it modified the entrance of the sluice gate by installing two steel plates with a length of 20 cm and height of 10 cm at each side of the gate (see Fig. 4b). But the flushing channel still followed a meandering pattern. Modifying the entrance of the gate also made the flushing cone bigger and more evident.

Figures 5-7 show the cone formation, extension and destruction near the sluice gate during an experiment with modified sluice gate's entrance. At first, the sediment deposited in the modified section was flushed out and then the flushing phenomena locally progressed retrogressively. In this situation, the retrogressive erosion did not extend into the reservoir and the sediments were eroded in the vicinity of the sluice gate's entrance. When the uniform flow condition was satisfied, the gate was opened manually at a constant rate. At this stage, the upper layers of the polymer particles were all moved through the whole of the reservoir to the gate, and for the first five minutes, there was no clear local cone or flushing channel formation. But after this, by further lowering the water level, the reservoir reached to a temporary stable situation and the flushing cone formed. Figure 5 shows the heart-like flushing cone formation. The shape of this flushed formation indicated the symmetry of the flushing operation in the reservoir. Figure 6 shows the flushing cone five minutes later when the heart shape was getting bigger and extending laterally. A few minutes later, when the water level in the reservoir was lowered completely and reached the open channel flow condition, the cone symmetry vanished and extensive changes took place. At the end of the experiment, when the inflow and outflow discharges were almost identical to each other for the second time, the heart like shape of the flushing cone was seen again, but it was no longer symmetrical (see Fig. 7).

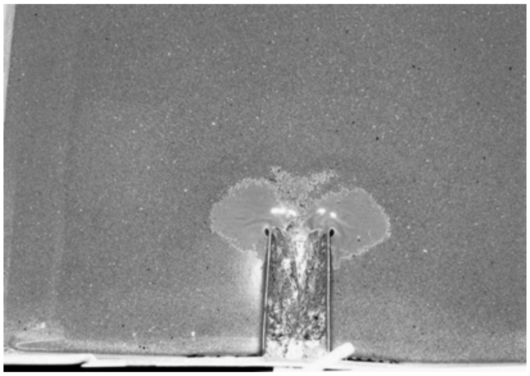


Fig. 5. Local flushing at the beginning of an experiment, near the sluice gate, fully symmetric

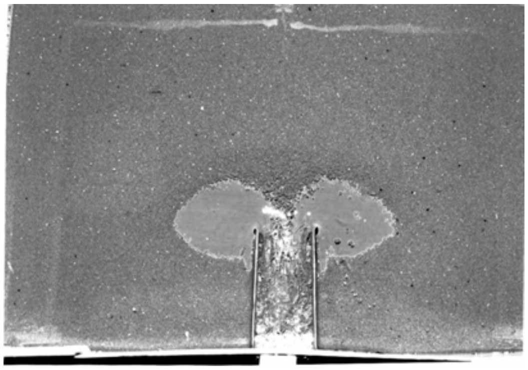


Fig. 6. Local flushing after a few minutes of the same experiment, near the sluice gate, still symmetric

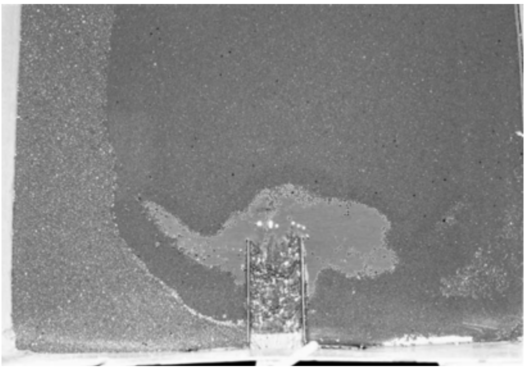
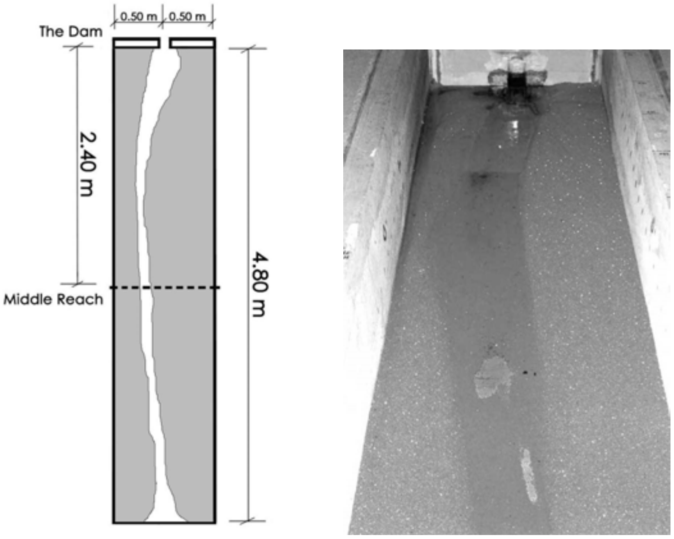


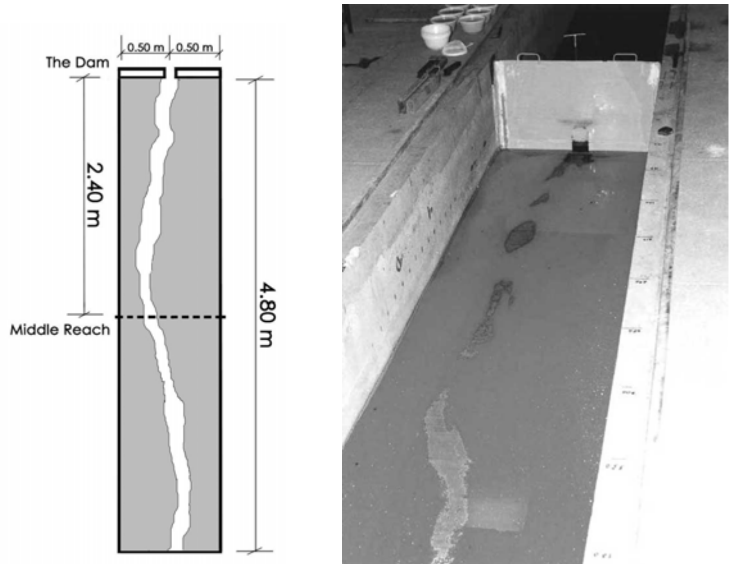
Fig. 7. Flushing formation near the sluice gate at the end of the experiment, unsymmetrical

A flushing channel was formed about 15 minutes after opening the gate, when the water level was less than 6 cm (the optimum size of gate opening). The flushing channel could be recognized when the left and/or right banks in the reservoir were evident. Gradually the flushing channel deepened and its width decreased. Figures 8 and 9 show the sketches and photos of the flushing channel at the end of experimental run no.1 (Ex.1) of Flow1 and experimental run no.6 (Ex.6) of Flow2, respectively. The resulted flushing channel was not as straight as expected based on results of previous works [4]. There were some reasons that explain the meandering pattern of the flushing channel. The major cause of this behavior stems from the non-uniform distribution of sediment particles or small changes in polymer particle shapes.



(a) (b)

Fig. 8. Flow1, Q_{in} = 0.4678 (Lit/sec), Ex.1: a) Plan-view of the flushed reservoir, b) The same experiment (looking downstream)



(a) (b)

Fig. 9. Flow2, Q_{in} = 0.628 (Lit/sec), Ex.6: a) Plan-view sketch of the flushed reservoir, b) The same experiment (picture is taken from the upstream end)

It has been seen that flushing characteristics of these types of sediment particles are (e.g., polymer particles with density close to water and without cohesion) similar to loess sediment. A large amount of the sediment was flushed in the first 30 minutes of flushing duration. Of course in this duration, the flushing channel might have had some changes in its bed, but the general bed trend remained stable. After this time, the sediment outflow discharge was almost constant and decreased at a gradual rate, but the flushing channel was stabilized and its bed no longer changed.

The shape of the flushed sediments at the upstream end of the reservoir where the flushing channel finished, looked like a funnel. This is because of the presence of the flushing channel, which led the water to pass through the reservoir. Sometimes, it was observed that the lateral banks of the flushing channel slid into the flushing channel and flushed through the reservoir which was related to the angle of repose of the sediment particles and pore water pressure. Of course this was a long-term behavior and couldn't be observed right after lowering the outflow sediment discharge.

b) Variation of measured parameters with time due to flushing

For better understanding of the flushing processes, the data have been presented graphically. Figures 10 and 11 show the variations of outflow water discharge, outflow sediment discharge and water depth at the upstream and downstream ends of the reservoir with flushing time. Figure 10 is related to Flow1 and Fig. 11 is for Flow2.

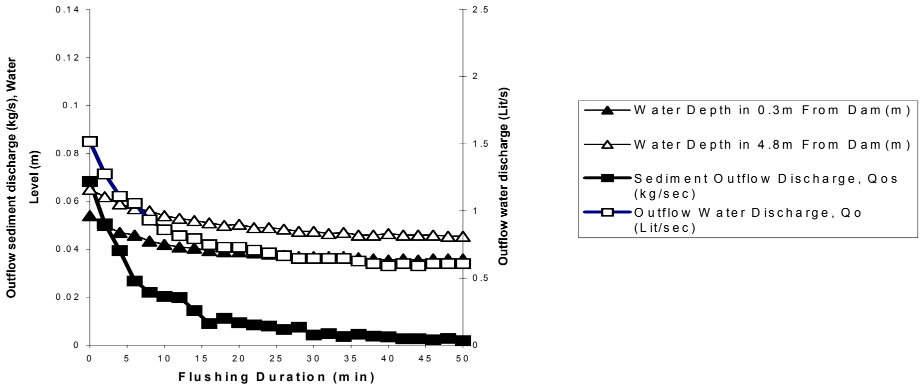


Fig. 10. Relationship between sediment outflow, water outflow and water depth at two ends of the reservoir (Flow1, Q_{in} = 0.4678 (Lit/s), Ex.1)

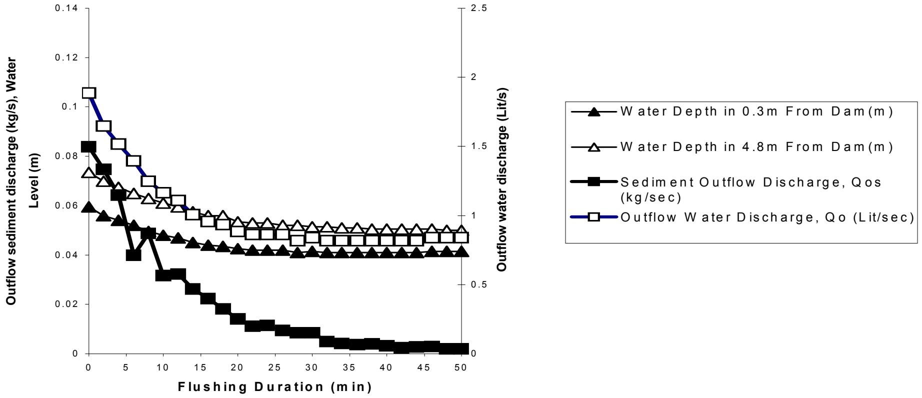


Fig. 11. Relationship between sediment outflow, water outflow and water depth at two ends of the reservoir (Flow2, Q_{in} = 0.628 (Lit/s), Ex.6)

All the figures show the same trend for water depth variations with time. The water depth variation with time at the upstream end of the reservoir is higher than the downstream end for all the experimental runs. The water surface profile in the reservoir after opening the sluice gate represents M_2 profile.

After analyzing the data of the experimental results, it was found that the measurements should be performed right after opening the sluice gate. Unfortunately, we missed recording and documenting the peak of the water and sediment discharges. By calculating the approximate falling rate of the outflow water and sediment discharges for each experimental run, it was found that the falling rate of the outflow sediment discharge is about 30% higher than outflow water discharge. This means that the flushing was performed successfully.

c) Tsinghua university method (TUM)

The transporting capacity of flushing flows can be estimated using an empirical method reported in IRTCES [2]. This method is based on observations of flushing at reservoirs in China, where the predominant practice is annual flushing and so relatively little consolidation occurs between flushing operations. The method is based on the following equation [2, 3, 4, 5]:

$$Q_s = E \frac{Q_f^{1.6} S^{1.2}}{B^{0.6}} \tag{16}$$

where Q_s is sediment transporting capacity (ton/s), Q_f is flushing discharge (m^3/s), S is bed slope, B is channel width (m), and E is a constant set from the sediment type: 1600 for loess sediments, 650 for other sediments with a median size finer than 0.1 mm, 300 for sediments with a median size larger than 0.1 mm, 180 for flushing with a low discharge.

Equation (16) was attributed to Tsinghua University by IRTCES (1985) and is referred to here as the “Tsinghua University method” (which was derived in section-3 as Eq. (14)).

The validity of the Tsinghua University method (TUM) was examined for calculation of transporting capacity of flushing flow for “Polystyrol 143E” particles. All the parameters in TUM (i.e. outflow sediment discharge and the parameter contains the effect of outflow water discharge, water surface slope and width of the flushing channel in each time interval) were measured in these experiments. Figure 12 shows the relationship between Q_{os} and $Q_o^{1.6}S_w^{1.2}/B^{0.6}$. The coefficient of erodibility (E) is the slope of the best-fitted line (which should follow the format of $Y = aX$).

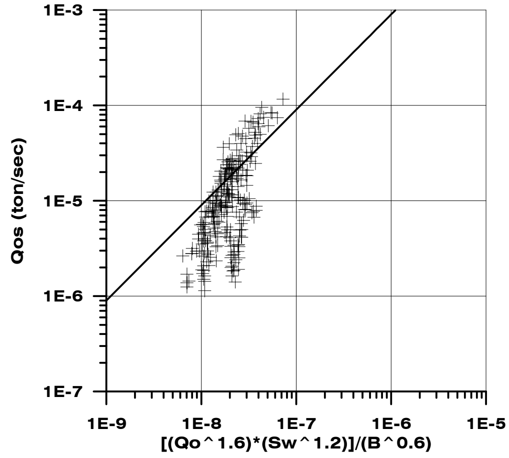


Fig. 12. Relationship between sediment outflow and $Q_o^{1.6}S_w^{1.2}/B^{0.6}$
from the experimental data (TUM)

All the data of all experimental runs (both Flow1 and Flow2) were used for drawing Fig. 12. The formula for the best-fitted line was as follows:

$$Y = 898.757\, X \tag{17}$$

with the correlation factor of: $R^2 = 0.69$ more than 2/3 of the data points follow the best-fitted line trend.

From the results of this study, the coefficient of erodibility for the polymer particles is around 900, which is within the range of above the values. The polymer particles density is close to water, the particles are non-cohesive, and they behave the same as loess sediment and fine-grained particles. This result validates the results which were mentioned by Chinese field data [2].

d) Efficiency of flushing

Efficiency of flushing sediment through the reservoir is important in determining the feasibility of flushing operations when the value of stored water is high. In the present study, flushing effectiveness was analyzed in one of the flushing events through the flume. With respect to the amount of water usage and the value of flushed sediment, flushing efficiency, F_e, is defined as [1, 2]

$$F_e = \frac{V_{os} - V_{is}}{V_w} \tag{18}$$

in which V_{os} is volume of flushed sediment in the time interval Δt; V_{is} is newly-added volume of deposits from the upstream sediment supply in Δt, and V_w is water volume used in Δt. Without sediment supply from the upstream of the reservoir, flushing efficiency, F_e, outflow sediment discharge, Q_{os}, and cumulative volume of flushed sediment, V_t, are plotted against time in Figs. 13 and 14 for Ex.1 of Flow1 and Ex.6 of Flow2, respectively.

As seen in the mentioned figures, the general trend of the curves is similar. Table 2 clarifies the behavior of the parameter V_t and cumulative volume of flushed sediments for both inflows. This table indicates that the average of the peaks of V_t in Flow1 (with lower inflow discharge) is about 10% less than that in Flow2 (with higher inflow discharge), which is in agreement with what was expected. Within the first 2~4 minutes of the flushing duration, the cumulative volume of flushed sediment reached to fifty percent of its ultimate amount, and then increased smoothly. This is the general trend for all V_t curves. Comparing the average percentages of the time to reach the 50% of the maximum amount, a difference of about 8~10% between Flow1 and Flow2 is evident. Due to higher inflow discharge in Flow2, more sediment flushed in a shorter period of time in comparison with Flow1, which had less inflow discharge.

Table 2. Statistical results of the cumulative volume of flushed sediments in Flow1 and Flow2

Flow1 (Q_{in} = 0.4678 Liter per second)					
Ex. number	Max. cumulative volume (m^3)	Time of reaching 50% of the Max. over the flushing duration*	Time of reaching 50% of the Max. over the flushing duration (%)	Time of reaching 50% of the peak over the total time	Time of reaching 50% of the peak over the total time (%)
1	0.026	2/50	4	18/66	27
2	0.006	4/50	8	20/66	30
3	0.016	2/54	3.7	14/66	21
4	0.020	2/54	3.7	14/66	21
5	0.014	16/56	28	26/66	39
Ave.	0.016	-	9.48	-	27.6
Flow2 (Q_{in} = 0.628 Liter per second)					
6	0.008	8/42	19	22/58	37.9
7	0.027	4/50	8	20/66	30.3
8	0.017	4/52	7.7	18/66	27.2
9	0.021	4/54	7.4	16/66	24.2
Ave.	0.018	-	10.5	-	29.9

*The flushing duration is about 10~15 minutes less than the total experimental duration because of the delay in formation of flushing channel.

Table 3 shows the values of maximum flushing efficiency values for all the experimental runs of Flow1 and Flow2. Comparing the averages of the maximum flushing efficiencies (F_e) of each inflow discharge shows that F_e for Flow2 is 27% higher than Flow1 (with lower inflow discharge) and this is in agreement with what we had expected due to the literature.

Table 3. Results of the maximum flushing efficiency in all experimental runs of Flow1 and Flow2

Flow1 (Q_{in} = 0.4678 Liter per second)		Flow2 (Q_{in} = 0.628 Liter per second)	
Ex. number	The Max. of flushing efficiency (F_e)	Ex. number	The Max. of flushing efficiency (F_e)
1	0.244	6	0.128
2	0.122	7	0.284
3	0.145	8	0.125
4	0.152	9	0.296
5	0.091	-	-
Ave.	0.1508	Ave.	0.2082

The trend of outflow sediment discharge (Q_{os}) rises rapidly at the beginning (start of the experimental run) till it reaches a peak, and then gradually fall till the end of the experimental run. The comparison between two curves of Flow1 and Flow2 (see Figs. 13 and 14) shows that the falling rate of Flow2 (with higher inflow discharge) is 3% less than Flow1 (with lower inflow discharge).

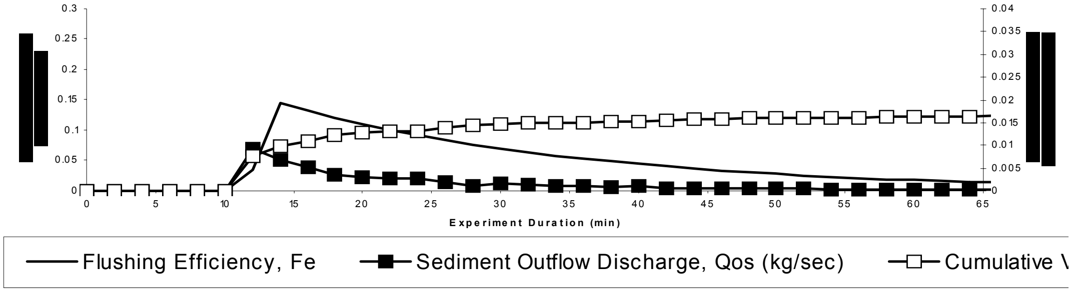


Fig. 13. Flushing efficiency and cumulative volume of flushed sediment *vs*. time
(Flow1, Q_{in} = 0.4678 (Lit/s), Ex.1)

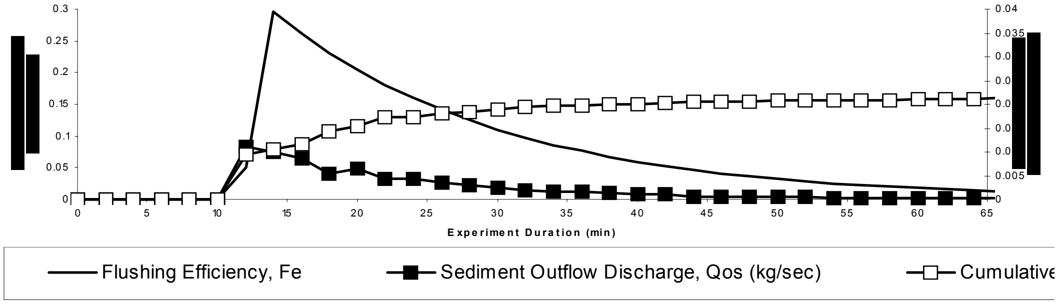


Fig. 14. Flushing efficiency and cumulative volume of flushed sediment *vs*. time
(Flow2, Q_{in} = 0.628 (Lit/s), Ex.6)

6. COMPARISON WITH PREVIOUS WORKS

In 1985, IRTCES (International Research and Training Center of Erosion and Sedimentation) presented Equation (5-1), which was attributed to Tsinghua University and is referred to here as the “Tsinghua University Method” (TUM) [5]. The data used to develop the method were collected from reservoirs in China, where flushing practice and predominant sediment characteristics may not be representative of other regions. Therefore it seemed necessary to investigate and control the Tsinghua University method by collecting more data about flushing with different types of sediment particles.

Lai and Shen [2] performed an experimental one-dimensional model of a reservoir to examine the TUM method. They modified a rectangular flume, 50 m long, 2.44 m wide, and 1.52 m high by elevating a part of its bottom up to 0.60 m to prevent the outlet from being submerged at the downstream of the dam [2]. Water was recirculated by a pump at the desired rate ranging from 0.00056 to 0.00487 (m^3/sec) by controlling the pipe valve [2]. Three sluice gates were installed on the dam and manually operated by rotors; each gate could be set separately. But only the central sluice gate (0.25 m high and 0.15 m wide) was used [2]. The sediment material used in the experiments was the walnut shell grit, a non-cohesive lightweight material. The choice of the sediment size was based on the incipient motion criterion, the dimension of the flume and capacity of water supply. The density of walnut shell grit was about 1390 kg/m^3, a median diameter of 1.25 mm, and porosity of 0.55; the gradation coefficient is 1.18 and the angle of repose for submerged walnut shell grits is about 35 degrees [2]. Lai and Shen, [2] mentioned that at the beginning of each run, sediment within 9 m from the dam was placed in the depositional depth of 0.1 m above the datum (i.e. the zero elevation set at the bottom of the sluice gate) with zero bed slope. A total of six inflow discharges have been performed in the Lai and Shen study and each experimental run lasted for 30 minutes. The initial water stages at the reservoir for all the experimental runs were about 0.17 m [2]. Tables 4-6 show the comparison between the present study and that of the Lai and Shen [2]. By referring to these tables, it can be seen that Lai and Shen [2] have had a larger flume, which behaved closer to the prototype, and also with particle density higher than that in the present study. This made their work faster in the flushing operation and the flushing channel was seen at the beginning of its formation through the sediment particles.

Table 4. Sediment particles characteristics in present study and Lai and Shen, [2]

Characteristics of the Sediment particles	Present study (2001)	Lai and Shen (1996)
Density (Kg/m^3), γ_s	1065	1390
Median diameter (mm), D_{50}	2.40	1.25
Gradation coefficient, C_c	0.92	1.18
Angle of repose (degree), θ	30	35
Porosity, n	0.71	0.55

Table 5. Dimensions of the experimental model in present study and Lai and Shen, 1996

Dimensions of the experimental model	Present study (2001)	Lai and Shen (1996)
Length of the flume (m)	30	50
Width of the flume (m)	1.00	2.44
Height of the flume (m)	0.75	1.52
Height of the elevated flume bottom (m)	0.16 *	0.60
Length of the test-section in the flume (m)	11.5	Close to 19
Width of the sluice gate (m)	0.09	0.15
Height of the slice gate (m)	0.15	0.25

It follows the relationship between the bottom outlet position in Sefid-Rud Reservoir with total height of the dam.

Table 6. Experimental data in present study and Lai and Shen [2]

Experimental data	Present study	Lai and Shen [2]
Number of inflows	2	6
Range of the inflow discharges (m^3/s)	0.0004678 and 0.000628	0.00056 to 0.00487
Length of the distributed sediment particles in the reservoir (m)	4.8	9.0
Thickness of the distributed sediment particles in the reservoir (m)	0.06	0.10
Initial water stage in the reservoir (m)	About 0.10	About 0.17
Initial bed slope and topset slope in the deposits (%)	0.0	0.0
Opening size of the sluice gate (m)	0.06	0.10
Running time (min)	About 65 *	About 30 **

* This is the total time of each experimental run. But the flushing started with 12-15 minute delays (after complete drawdown in water depth and starting the retrogressive erosion and the flushing channel appearing in the reservoir).

** The delay in Lai and Shen [2] was about 5~7 minutes.

A higher amount of density for the sediment particles in Lai and Shen's work made the data points to follow the trend of Curve III with a coefficient of erodibility (E) of about 180 [2, 4]. Comparing the calculated coefficient of erodibility (E) from the present study and that of Lai and Shen [2] shows very high value for this parameter in the present study. The "E" value is estimated to be about 900. This is because of the very low amount of density for the sediment particles in the present study (close to water). The high value for "E" proves that the flushing operation is much more successful in this study. Comparing the maximum amount of the flushing efficiency and cumulative volume of flushed sediments shows that these values are about twice of those in the present study in comparison with the study of Lai and Shen [2]. This is due to the type of used sediment particles (polymer particles with very low density). Lai and Shen [2] also have mentioned that fifty percent of the total volume of removed sediment was flushed out in one third of the experiment duration, which is close to the present study. The general trend of Lai and Shen [2] curves and the present study are the same. This means that the flushing operation has had a unique trend for these two different types of sediment particles. Figure 15 shows all the reported data points in one graph. It contains the range of the field data points reported by IRTCES [2] and that of the study of [2], beside the data points of the present study.

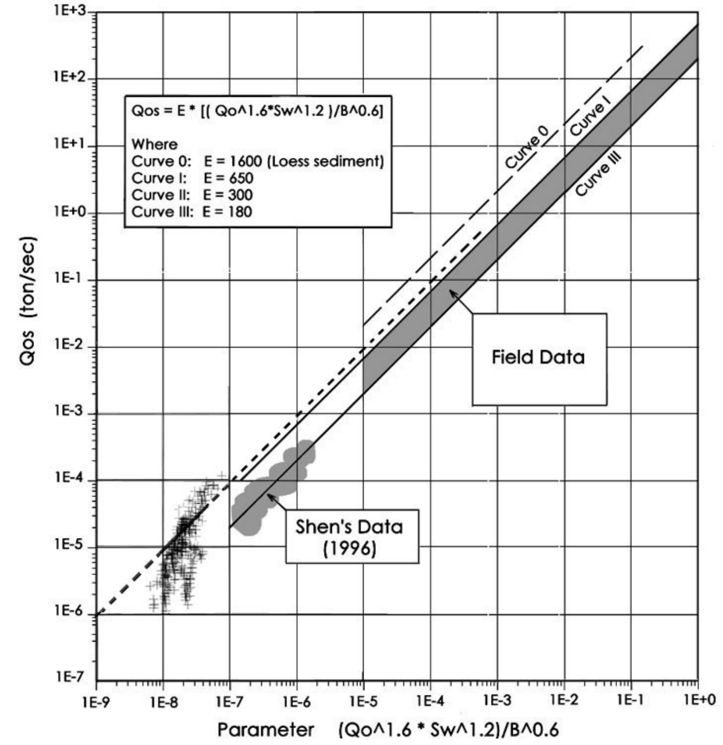


Fig. 15. Comparison between reported data points of flushing operation, using TUM method, contains field data points of Chinese reservoirs (IRTCES, 1985), Lai and Shen [2] data points of an experimental model (with the coefficient of erodibility, E, about 180) and experimental data of the present study (E is about 900) [2, 4, 5]

As seen in Fig. 15, the field data points (which was collected from the Chinese reservoirs) stand higher than the data points of the laboratory models and this is because of the dimension of the reservoir, water depth, water and sediment discharges and flushing channel width in the prototype. Lai and Shen [2] data points are lower than the present data, and that is because of more resistant sediment particles against flushing. The data points in the present study follow the same trend as other data points, but are located in the lower part of the graph and that is due to the characteristics of polymer particles. It seems that the very low density of particles in this model made them behave similar to very fine sediment particles in the prototype. So the data points are located close to the area of loess sediment particles.

7. CONCLUSIONS AND RECOMMENDATIONS

A one-dimensional experimental model was used to investigate the flushing processes using very lightweight, uni-sized polymer particles as the deposited material in a reservoir. Two different inflow rates 0.0004678 and 0.000628 m^3/s were used (i.e. Flow1 and Flow2, respectively), and a total of nine experimental runs were performed for both inflows.

The results are presented in two parts, qualitative and quantitative results. In the qualitative part, the processes of cone and flushing channel formation were observed and documented and are in agreement with the literature. The heart-shaped and symmetric cone formation at the beginning of the flushing period and the meandering effect in the flushing channel were also observed.

In the quantitative part, the Tsinghua University Method (TUM) was used by measuring the outflow sediment and water discharges, water surface slope and flushing channel width in every time interval of two minutes to calculate the coefficient of erodibility (E) and to examine the TUM method. It was found that the values of "E" are in the expected area (and was about 900). The result is in agreement with the physical characteristics of the used polymer particles, and this validates the TUM equation. Values of the flushing efficiency, F_e, for each experimental run show that F_e for Flow2 is 27% higher than Flow1 (with lower inflow discharge), which is in agreement with what we had expected.

Within the first 2~4 minutes of the flushing duration, the cumulative volume of flushed sediment, V_t, reaches to fifty percent of its ultimate value and then increases smoothly. This is the general trend for all V_t curves. Comparing the average percentages of the time to reach 50% of the maximum value, shows a difference of about 8~10% between Flow1 and Flow2. Higher inflow discharge in Flow2 resulted in more sediment flushed in a shorter period of time than in Flow1 with less inflow discharge. Comparing the present results with the previous results of TUM shows a similar trend for all data.

REFERENCES

1. Brandt, S. A. (2000). A review of reservoir desiltation. *International Journal of Sediment Research, 15*(3).
2. Lai, J. S. & Shen, H. W. (1996). Flushing sediment through reservoirs. *Journal of Hydraulic Research, 34*(2).
3. Atkinson, E. (1996). The feasibility of flushing sediment from reservoirs. Report OD137, HR Wallingford.
4. Shen, H. W. (1999). Flushing sediment through reservoirs. *Journal of Hydraulic Research, 37*(6).
5. Atkinson, E. (1998). Reservoir operation to control sedimentation: techniques for assessment. In: The Prospect for Reservoirs in the 21st Century, *Proceeding Of the Tenth Conference of the BDS held at the University of Wales*, British Dam Society.
6. Shen, H. W., Lai, J. D. & Zhao, D. (1993). *Hydraulic desiltation for non-cohesive sediment. Proceeding of the 1993 Annual ASCE Hydraulic Engineering Conference*, San Fransisco, H. W. Shen, S. T. Su and F. Wen, eds.
7. Brune, G. M. (1953). Trap efficiency of reservoirs. *Transactions, America Geophysical Union, 34*(3).
8. Fan, J. & Morris, G. L. (1992). Reservoir sedimentation. II: Desiltation and long-term storage capacity, *Journal of Hydraulic Engineering, 118*.
9. Lai, J. S. & Shen, H. W. (1995). *Degradation flushing processes in reservoir*. HYDRO 2000, 4, Thomas Telford, London.
10. Olsen, N. R. B. (1999). Two-dimensional numerical modeling of flushing processes in water reservoirs. *Journal of Hydraulic Research, 3*(1).
11. Streeter, V. L. & Wiley, E. B. (1985). *Fluid mechanics*. 8th edition, New York: McGraw-Hill Book Company.