Evolution of Developing Flushing Cone during the Pressurized Flushing in Reservoir Storage

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Abstract**—**Sedimentation in reservoirs and the corresponding loss of storage capacity is one of the most serious problems in dam engineering. Pressurized flushing, a way to remove sediments from the reservoir, is flushing under a pressurized flow condition and nearly constant water level. Pressurized flushing has only local effects around the outlet. Sediment in the vicinity of the outlet openings is scoured and a funnel shaped crater is created. In this study, the temporal development of flushing cone under various hydraulic conditions was studied experimentally. Time variations of parameters such as maximum length and width of flushing and also depth of scouring cone was measured. Results indicated that an increase in flow velocity (and consequently in Froude number) established new hydraulically conditions for flushing mechanism and so a sudden growth was observed in the amount of sediment released and also scouring dimenssions. In addition, a set of nondimensional relationships were identified for temporal variations of flushing scour dimenssions, which can eventuallt be used to estimate the development of flushing cone.

Keywords**—**Pressure Flushing, Dam, Sediment, Scouring.

I. Introduction

THE sedimentation in reservoirs occurs at a rate of about 0.3% per year worldwide.

Sedimentation rate in many regions such as Asia is much higher and can be estimated between 0.5 and 1.0 percent annually [1]. Reservoirs sedimentation and its corresponding loss of storage capacity is one of the most serious problems of dams, which was paid more attention in the past few decades.

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Sustaining the storage capacity of existing reservoirs has become an important issue rather than building new reservoirs. The second solution is difficult due to strict environmental regulations, high costs of construction, and lack of suitable dam site [2].

Several methods have been proposed to control sedimentation process. These may include 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. Density current venting is used to route incoming sediments through the reservoir without drawing down the water level [3].

One of the most effective techniques is flushing through which the deposited sediments are hydraulically removed by the flow. 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 [4]. Accelerating the flow, the excess in shear force created by sudden opening of the bottom outlets of dams loosen and re-suspend the sediments. The flow will then wash them up from the system. A process, through which flushing takes place under a pressurized condition while the water level in reservoir remain unchanged approximately, is called pressure flushing. This is only an option in reservoirs with small reservoir capacity to water inflow, and large capacity of sluices [5]. Pressurized flushing has only local effects around the outlet. In pressurized flushing, sediment in the vicinity of the outlet openings is scoured and a funnel shaped crater is created. Fig. 1 illustrates the longitudinal and plan view of flushing cone in the vicinity of bottom outlet.

Pressurized flushing have been studied extensively in the literature [2]-[11]. White and Bettess, studied how far releases affect the sediment deposits. They provided a diagram indicating the interrelationship between the limit distances of scour (in static water), reservoir depth and outlet discharge. Also their results showed that by decreasing water level in the reservoir, the rate of developing of scouring cone increases toward upstream for given discharge[6].

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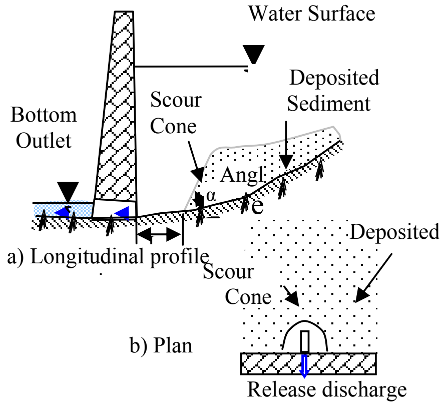

Fig. 1 Longitudinal and plan view of the pressure flushing

Using physical model, Fang and Cao, showed that large amounts of sediment are released in the beginning of flushing. Their study indicated that in equilibrium condition the clear water was released through bottom intake and funnel-shaped crater was developed with an angle of repose of the sediment. They also pointed out that although the effect of the funnel scour was restricted to the zone close to the intake, it has a very important role in preventing coarse sediment to enter power station [7].

For pressure flushing condition, Shen presented a dimensionless regression relation for determining the maximum scouring depth of a flushing cone in non-cohesive sediment [8]. Lai and Shen investigated the flushing processes during drawdown flushing, including outflow sediment discharge, characteristics of the flushing channel and flushing effectiveness[2].

Scheuerlein indicated that in the pressurized 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 is difficult (if not impossible). They also claimed flushing actions are restricted to very limited efficiency and for successful continuation of the flushing action drawdown of water level is required [9].

Experimental studies by Emamgholizadeh showed that by increasing the discharge from outlet and decreasing reservoir's water depth, the amount of flushed sediment increased. Also under same conditions the flushed sediments increased when the size of sediments changed from coarse to fine[10],[11].

In spite of advances in the investigation of pressure flushing technique at reservoirs storage, studies on time-dependent analysis of flushing cone development are limited and there is lack of information about this. Moreover, formation of flushing cone has a very important role in preventing sediment to enter a downstream powerplant intake (if avilable). However, the lack of water resources and also negative impacts of pressure flushing on environment often makes it impractical to complete the flushing process. In this condition, it is necessary to establish a balance between removal rate of sediments, the limitations of water resources, and the environmental impacts.

This paper experimentally focuses on temporal evolution of scouring cone dimenssions during pressure flushing operation. The objective of this study is to present relations for computing the temporal variation of flushing cone geometry (i.e., depth, width and length) at the vicinity of bottom outlet during pressure flushing.

II. Materials and Method

A. Test Procedure and Set-up

The experiments were conducted at the hydraulic laboratory of Gorgan University of Agricultural Sciences and Natural Resources in Iran. The test apparatus consists of four parts: water supply system, bottom outlet, settling basin reservoir, and V-notch weir.

- Water Supply System: It consists of an underground tank and a pump to recirculate a desired steady flow. The system is also supported by an adjusting valve, a digital flow-meter, and an 11-meter flume. Main reservoir was hexahedral with overall dimensions of 3 m length, 2 m wide, and 1.5 m height. Using two reticulate sheets at the reservoir's entrance, a laminar flow is created.
- Bottom Outlet: The outlet of main reservoir is a 1-inch-diameter gate valve. Sediments in the system include silica particles with uniform size distribution with a median diameter (d_s) 1 mm and geometric standard deviation (σ) of 1.25. Sediments deposited at the end of main reservoir, so that the top layer of the sediment deposits was flattened at a certain level over the bottom outlet.
- Settling Basin Reservoir: This is the region that the water and sediment were mixed and sediments were settled. The basin is a rectangular flume of 3.6 m long, 1 m wide, and 76 cm height.
- V-Notch Weir: The settling basin is set up at its end with a 90^o V-notch weir to measure the outflow discharge.

B. Dimensional Analysis

The funnel-shaped crater in pressurized flushing is characteristixed by many parameters. During the experiment, in a given time, the depth of scour at time (Z_t) is a function of the following variables:

$$Z_t = \varphi(Q_{outlet}, A_{outlet}, R_{outlet}, H_w, H_s, Z_{max}, B, d_s, \rho_s, \rho_w, g, T_e, t) \quad (1)$$

where, Q_{outlet} is discharge at bottom outlet, A_{outlet} is the cross-sectional area of bottom outlet, R_{outlet} is the diameter of bottom outlet, H_w is the height of water, H_s is the height of deposited sediment above the outlet, Z_{max} is the maximum depth of scouring cone in equilibrum time, B is the width of reservoir, d_s is the median size of sediment particles, ρ_s is the density of sediment, ρ_w is water density, g is acceleration gravity, T_e is the time to reach equilibrium scour depth and t is the time during experiment. Fig. 2 illustrates the notation of flushing cone dimensions at the vicinity of bottom outlet.

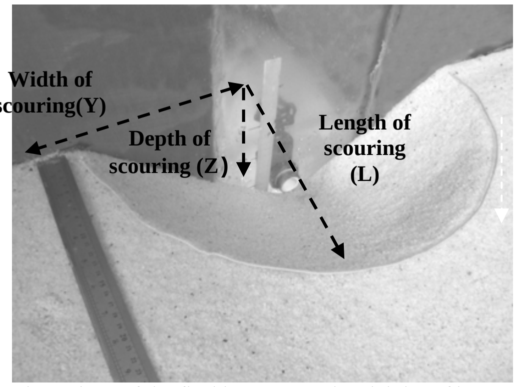

Fig. 2 Dimensions of the flushing cone at the vicinity of bottom outlet

Using a dimensional analysis, the ratio of scouring depth to its maximum value (Z_t/Z_{max}) can be expressed as:

$$\frac{Z_t}{Z_{max}} = \phi\left(\frac{Q_{outlet}/A_{outlet}}{\sqrt{gH_w}}, \frac{H_s}{d_s}, \frac{R_{outlet}}{B}, \frac{\rho_w}{\rho_s}, \frac{t}{T_e}\right) \quad (2)$$

Here the parameters H_s, R_{outlet}, B, d_s, ρ_s, ρ_w and g are constant. Hence, the equation (2) can be summarized as:

$$\frac{Z_t}{Z_{max}} = \phi\left(\frac{Q_{outlet}/A_{outlet}}{\sqrt{gH_w}}, \frac{t}{T_e}\right) \quad (3)$$

With substitution of $U_{outlet} = \frac{Q_{outlet}}{A_{outlet}}$ in (3), the following equation can be obtained:

$$\frac{Z_t}{Z_{max}} = \phi\left(\frac{U_{outlet}}{\sqrt{gH_w}}, \frac{t}{T_e}\right) = \phi\left(F_{r_{outlet}}, \frac{t}{T_e}\right) \quad (4)$$

Using the same procedure, the length and width of flushing cone can be expressed as:

$$\frac{L_t}{L_{max}} = \phi\left(F_{r_{outlet}}, \frac{t}{T_e}\right) \quad (5)$$

$$\frac{W_t}{W_{max}} = \phi\left(F_{r_{outlet}}, \frac{t}{T_e}\right) \quad (6)$$

Experiments were conducted with three different water depth (i.e. 50, 80, 110 cm) and with three different discharge (i.e. 0.25, 0.5, 0.75 lit/s). First, deposited sediments was flattened and reached to specific level above the bottom outlet (40 cm), then the model was slowly filled with water until the water surface elevation reached to desired level. Next, the bottom outlet was manually opened so that the outflow discharge being equal to the inflow discharges. Consequently, sediments were released from main reservoir. Experiments were stopped at the end of different test durations (e.g., 5, 10, 20, 30, 50, 80 and 150 seconds) to determine the contours and dimensions of scour cone. Flushing cone geometry was recorded during the time intervals using digital point gages with 0. 1 mm resolution. At the end of each experiment, the flushing outlet closed and water was carefully and slowly drained from the main reservoir and measurements were done in a grid system around the bottom outlet. After each run, the bed was flattened to run the experiment with the next duration. Time dependent flushing cone dimensions were then obtained for the pressure flushing tested. In total, 55 test were carried out.

III. Results and Discussion

Fig. 3 shows the variation of z/Z_{max} against t/T_e for all sets of experiments. It is obvious that by increasing t/T_e, the scour depth increases. The scattering of data also indicates that the data can be classified in two groups according to Froude number. The limit value for classification is 0.6.

Using a regression analysis, the following relations were obtained for assessing the scour depth:

$$\frac{Z_t}{Z_{max}} = 1.11(Fr_{otlet})^{0.045}\left(\frac{t}{T_e}\right)^{0.33} \quad \text{for } Fr>0.6 \quad (7)$$

$$\frac{Z_t}{Z_{max}} = 1.07(Fr_{otlet})^{0.054}\left(\frac{t}{T_e}\right)^{0.42} \quad \text{for } Fr<0.6 \quad (8)$$

The variations of computed and measured scour depth using proposed equations are presented in Fig. 4 and 5. Fig. 6 and 7 show the variations of w/W_{max} and l/L_{max} with t/T_e, respectively. It is obvious that an increasing t/T_e will also increase the width and length of flushing cone. The scattering of data also shows that the data can be classified in two groups according to Froude number.

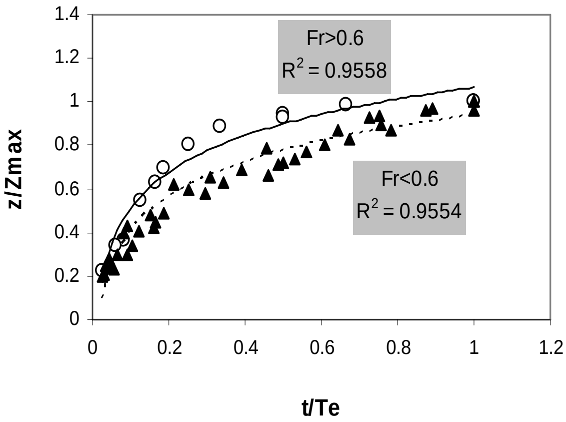

Fig. 3 Variation of scour depth against time

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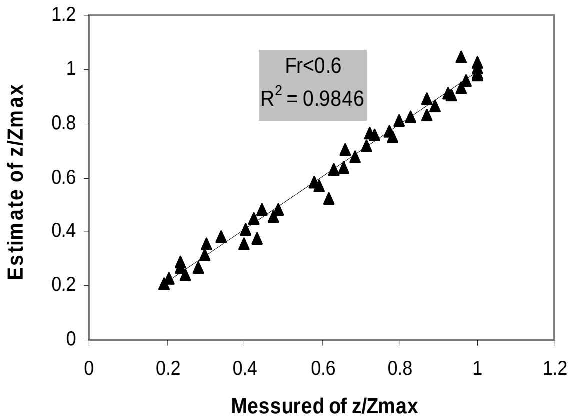

Fig. 4 Compression between measured and estimate data of scouring depth for Fr < 0.6

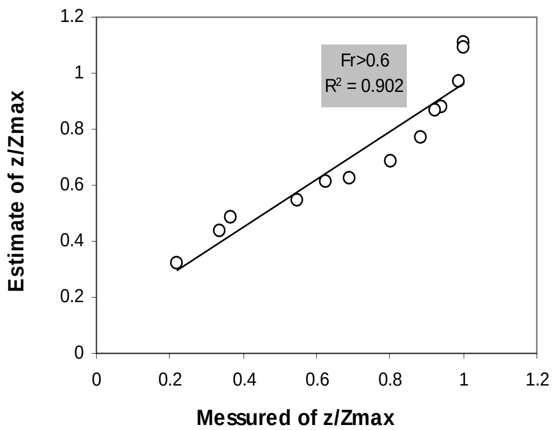

Fig. 5 Compression between measured and estimate data of scouring depth for Fr>0.6

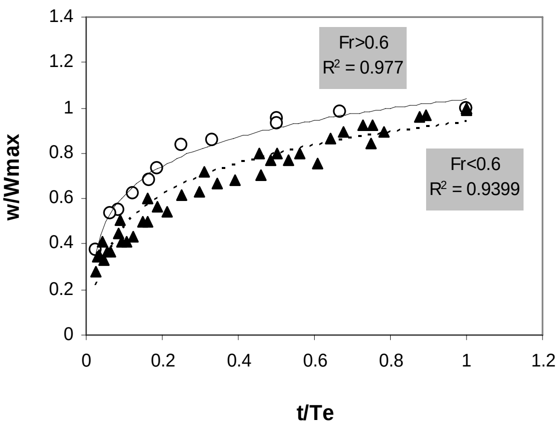

Fig. 6 Variation of scour width against time

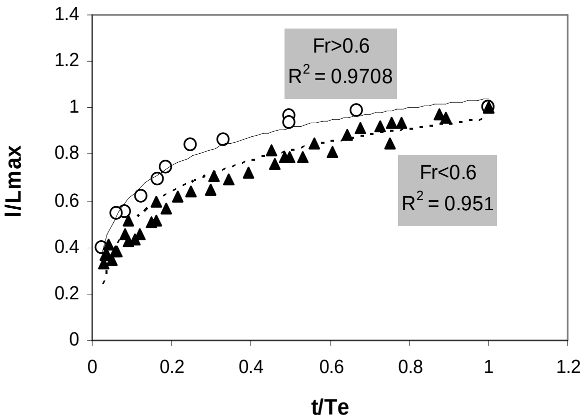

Fig. 7 Variation of scour length against time

TABLE I
THE PRESENTED EQUATIONS WITH STATISTICAL ANALYSIS

Fr	Equations	RMSE	MAPE	R^2
>0.6	$\frac{L_t}{L_{max}} = 1.06(Fr_{otlet})^{0.018}(\frac{t}{T_e})^{0.23}$	0.04	0.8	0.94
<0.6	$\frac{L_t}{L_{max}} = 1.02(Fr_{otlet})^{0.019}(\frac{t}{T_e})^{0.32}$	0.02	4.1	0. 98
>0.6	$\frac{W_t}{W_{max}} = 1.06(Fr_{otlet})^{0.019}(\frac{t}{T_e})^{0.24}$	0.04	0.7	0.94
<0.6	$\frac{W_t}{W_{max}} = 1.03(Fr_{otlet})^{0.039}(\frac{t}{T_e})^{0.33}$	0.03	4.6	0. 97
>0.6	$\frac{Z_t}{Z_{max}} = 1.11(Fr_{otlet})^{0.045}(\frac{t}{T_e})^{0.33}$	0.08	3.2	0..90
<0.6	$\frac{Z_t}{Z_{max}} = 1.07(Fr_{otlet})^{0.054}(\frac{t}{T_e})^{0.42}$	0.03	5.1	0..98

By regression analysis, the relations were obtained and presented in Table I for assessing the width and length of flushing cone. For more information and also to verify of results, the statistical parameters such as root mean square error (RMSE), mean absolute percentage error (MAPE) and R-squared value was calculated and presented in Table I.

IV. CONCLUSIONS

An experimental study was performed to observe the time-dependent geometric characteristics of flushing cone at the vicinity of bottom outlet in water storage reservoirs with uniform silica bed. Results indicated that an increase in flow velocity (and consequently in Froude number) established new hydraulically conditions for flushing mechanism and so a sudden growth was observed in the amount of sediment released and also scouring dimenssions. In addition, a set of nondimensional relationships were identified for temporal variations of flushing scour dimenssions, which can eventuallt be used to estimate the development of flushing cone.

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