Physical modelling of pressurized flushing of non-cohesive sediment using lightweight material

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Abstract. In this study, pressurized flushing of non-cohesive reservoir sediment through a bottom orifice was simulated in laboratory experiments using lightweight material as model sediment. The experiments were carried out by varying flushing discharge, reservoir water level, thickness of sediment deposit layer and opening height of bottom orifice. The volumes of flushing cones formed with lightweight material were compared with volumes calculated using empirical relations proposed by past studies. The good trend observed in variation of dimensionless flushing cone volume against different dimensionless parameters justified the possibility of using the lightweight material as model sediment.

1. Introduction

Reservoir sedimentation is a world-wide problem threatening the capacity and sustainability of large dams. To encounter the sedimentation of reservoirs, several counter and mitigation measures have been proposed ranging from the reduction of the sediment yield in the upstream catchment to hydraulic flushing to scour out deposits and empty the reservoir through low-level outlets [1,2]. Pressurized flushing through bottom outlets scours sediment deposits locally in the vicinity of the outlet openings and creates a funnel shaped crater called flushing cone (also called flushing half-cone because of its shape) [3,4]. During this process, large amounts of sediment are released at the beginning of the flushing [5] and after a short period of time the flushing cone becomes fairly stable in shape and size with no further sediment removal from the cone [6]. This type of flushing is therefore only suitable for reservoirs with small reservoir capacity to water inflow ratio (CIR) and large capacity sluices [7]. Since the effective scour zone is constricted locally near the outlet openings, pressurized flushing is more effective in controlling sediment deposition level at the entrance of the intakes. However, for efficient flushing of large sediment deposits from the reservoir, drawdown of water level is required [8].

Emamgholizadeh et al. [3] carried out laboratory experiments on pressure flushing of non-cohesive sediment. They concluded that the flushing efficiency can be increased by reducing the reservoir level during the flushing while keeping the outlets operating at full capacities and proposed an empirical equation for estimating the volume of the flushing cone:

\[
\frac{V_{1/3}^L}{H_{b,net}} = 0.6139 \left( \frac{u}{\sqrt{gH_{w,net}}} \right)^{0.0062} \left( \frac{H_{b,net}}{d_s} \right)^{0.05} \left( \frac{H_{b,net}}{H_{w,net}} \right)^{0.0036}
\]
where, $V_s$ = the volume of the flushing cone, $H_{w,\text{net}}$ = net sediment height above the centre of the outlet opening, $u$ = flow velocity at the entrance of the orifice, $g = \text{acceleration due to gravity}$, $H_{w,\text{net}}$ = net flow depth above the centre of the outlet opening, and $d_s$ = characteristic sediment particle size.

Shahmirzadi et al. [9] showed that the volume of the flushing cone can, for a constant reservoir level, be increased by increasing the outlet opening size i.e. increasing the outlet discharge. They also suggested an empirical relation for predicting the flushing cone volume:

$$\frac{V_s}{H_{w,\text{net}}} = 0.042 \left( \frac{u}{\sqrt{g H_{w,\text{net}}}} \right)^{0.149} \left( \frac{H_{w,\text{net}}}{H_{w,\text{net}}} \right)^{3.082} \left( \frac{A}{H_{w,\text{net}}} \right)^{0.174}$$  \hspace{1cm} (2)

where, $A = \text{cross sectional area of the orifice}$

Carrying out similar experiments as [9], [4] proposed another empirical relation to determine the volume of the flushing cone:

$$\frac{V_s}{H_{w,\text{net}}} = 4.6 \left( \frac{u}{\sqrt{g (G_s - 1)d_s}} \right)^{0.21} \left( \frac{H_{w,\text{net}}}{H_{w,\text{net}}} \right)^{2.2} \left( \frac{D}{H_{w,\text{net}}} \right)^{0.99}$$  \hspace{1cm} (3)

which includes the diameter of the circular bottom outlet ($D$), specific gravity of sediment particles ($G_s$) and the characteristic particle size of sediment ($d_s$), although only a single sand sample was used in their experiments, i.e. their experiments were carried out with constant values for $G_s$ and $d_s$. Fathi-Moghadam et al. [10] also carried out experiments similar to [3] using three different sand sizes i.e. varying $d_s$ but constant $G_s$. They concluded that the size of the flushing cone increases with decreasing sediment size. Based on their experimental data, they proposed an empirical relation to predict the flushing cone volume:

$$\frac{V_s^{1/3}}{D} = 5.28 \left( \frac{u}{\sqrt{g (G_s - 1)d_s}} \right)^{0.1} \left( \frac{H_{w,\text{net}}}{H_{w,\text{net}}} \right)^{-0.046}$$  \hspace{1cm} (4)

Emamgholizadeh et al. [11] used the data from [3,4] and [10] to train and test an Artificial Neural Network (ANN) and Adaptive Neuro-Fuzzy Inference System (ANFIS), respectively, and concluded that both artificial intelligence based models predicted the flushing half cone volume and length more accurately than the empirical regression-based relations according to equations (1) to (4). They performed a sensitivity analysis which demonstrated that the sediment characteristics, thickness of sediment deposit, mean grain diameter, water depth in reservoir and mean flow velocity through bottom outlet are the most important parameters for predicting the flushing half-cone volume and length.

The present study investigates the practicality of using lightweight materials, having density greater than water but lower than natural sand, as model sediment to simulate pressurized flushing cone in physical hydraulic models. Theoretically, lightweight materials can be used as model sediment in physical hydraulic models if similarity in Froude number and densimetric Froude number are satisfied while compromising similarity in particle Reynolds number, relative density of sediment particles and relative bed roughness. Hughes [12] designated this type of models as Densimetric Froude models. Such a model type is generally applied in studies related to sediment transport processes in fluvial hydraulics when fine sand is present in the prototype situation which, when downscaled to model scale, would require cohesive sediment to be used in the model. Many researchers have used lightweight sediments for different hydraulic experiments such as studying the beginning of motion and predicting pier scour (as cited in [13]). In this study, a lightweight material was used as model sediment to simulate pressurized flushing through a bottom outlet and to assess the possibility of predicting the flushing cone volume.

2. Methodology

2.1. Previous data

The experiments have been designed to investigate the application of lightweight material as model sediment so that only equations (3) and (4) containing $G_s$ as a variable were considered for further comparison. In total 110 experimental datasets, 65 from [4] and 45 from [10] were extracted from published plots in the respective papers. Experimental data from [4] represented variation in flushing
cone volume due to variations in water level, discharge and opening size of the outlet. The experiments were performed with constant sediment layer thickness of 16 cm consisting of sediment with a specific gravity of 2.65 and uniformly sized sediment with a diameter of 1 mm. [10] performed the experiments for different combinations of water levels, discharges and sediment sizes while the sediment layer thickness, specific gravity of sediment and outlet diameter were kept constant. For the whole set of experiments, the sediment layer thickness was 42 cm, specific gravity of sediment was 2.65 and the outlet diameter was 2 inches (5.08 cm). These experimental datasets were used to compare the results according to equations (3) and (4) and with experimental results from this study.

2.2. Dimensional Analysis
The volume of flushing cone (\(V_s\)) depends, as outlined above, on various parameters such as geometrical boundary conditions, hydraulic parameters, fluid properties and sediment properties. Hence, it can be written as a function of the following variables [3,4,9,10]:

\[
V_s = f(u, H_{w,net}, H_{s,net}, A, B, d_s, \rho_s, \rho_w, \mu, g) \tag{5}
\]

where, \(B = \) flume width, \(\rho_s = \) density of sediment, \(\rho_w = \) density of water, and \(\mu = \) dynamic viscosity. In the present experiments (see Section 2.3), \(B, \rho_w, \mu\) and \(g\) were constant so that the following functional relationship can be established for the dimensionless flushing cone volume [4,9]:

\[
\frac{V_s}{H_{w,net}^3} = f\left(\frac{u}{\sqrt{g (\rho_s - \rho_w)}}, \frac{H_{s,net}}{H_{w,net}}, \frac{A}{H_{w,net}^2}\right) \tag{6}
\]

2.3. Experimental setup
The experiments were carried out at the hydraulic laboratory of Norwegian Institute of Science and Technology (NTNU) in Norway. The experimental setup consisted of a 0.60 m wide horizontal flume with a 5 cm wide rectangular orifice at the mid-width of the flume. The orifice was kept 6 cm above the flume bed to allow free formation of the flushing cone and also to avoid the influence of flow downstream. A layer of sediment with uniform thickness \(H_s\) was deposited upstream of the orifice at the beginning of each experiments. A simplified sketch of the experimental setup after the formation of the flushing cone is shown in Figure 1.

![Figure 1. Experimental setup and associated parameters](image)
2.4. **Material**

Poly-methyl methacrylate (PMMA) grains were used as model sediment for the experiments. The PMMA grains had specific gravity of 1.18 and were uniformly sized ($d_s = 2.4$ mm). They were slightly cylindrical in shape and were light blue in colour.

2.5. **Experiments**

The experiments were carried out with steady flow condition without any sediment inflow for a range of different parameter values (Table 1). The width of the flume and the width of the orifice were kept constant throughout all the tests. For each test, the flume was initially filled with a sediment deposit of constant thickness $H_s$. Then, the inflow discharge was slowly fed into the flume without disturbing the initial sediment deposit, and the water level was allowed to rise. When the desired water level was reached, the gate was opened up to the desired opening height. The water level was chosen from the rating curve of the outlet orifice such that the outflow discharge would be equal to the inflow discharge for given opening height of the orifice. The test was run in the steady state until the flushing cone reached the equilibrium state i.e. no more scouring in the flushing cone. Then the orifice gate was closed and water inside the flume was drained slowly without disturbing the shape and size of the flushing cone. The surface profile of flushing cone for each test was measured using SeaTec 5 MHz ranging system consisting 32 acoustic transducers. The transducers were placed in a movable plate to form a 25 mm grid. The plate with the transducers was hovered above the flume bed at different positions to scan the cone surface with finer resolution (<25mm). Then the data were used to calculate the flushing cone volume for each test with the help of 3D data interpolation function in Matlab.

| Parameters                          | Range         |
|-------------------------------------|---------------|
| Discharge ($Q$)                     | 0.9 – 5.0 lps |
| Net flow depth ($H_{w,net}$)       | 107 – 408 mm  |
| Thickness of sediment deposit above flume bed ($H_s$) | 100, 120 and 140 mm |
| Opening height of outlet orifice ($a$) | 20, 30, 40 and 50 mm |

**Figure 2.** Flushing cone formed with PMMA.

3. **Results and discussion**

In a first step, the experimental data from [4] and [10] were compared using equations (3) and (4), and Figure 3 illustrates that both equations perfectly fit the data used for their derivation. However, equation (4) overestimates $V_s$ for the data from [4] by about 5 times, and equation 3 over-estimates $V_s$ for data from [10] by about 2 times. This shows that both equations do not comply with the experimental data from the other study because the experiments by [4] were performed with constant $d_s$ and $H_s$ while the experiments by [10] were carried out with constant $D$ and $H_s$. However, the two datasets complement each other and when combined may be used to capture the effects of variation in $d_s$, $H_s$, and $D$. Equations (3) and (4) were further applied to the experimental data from this study to
assess whether any of them correctly predicts the volume of the flushing cone formed with lightweight material characterised by a different $G_s$.

Figure 3. Calculated $V_s$ against measured $V_s$ using equations (3) and (4) for experimental data from (a) Meshkati et al. [4] and (b) Fathi-Moghadam et al. [10]

The empirical relations according to equations (3) and (4) comply with the functional relationship given in equation (6) since both parameters $A$ and $D$ represent the opening size of the outlet. The functional relationship according to equation (6) was further justified with a good trend followed by the variation of each of the chosen dimensionless parameters when plotted against dimensionless flushing cone volume. Figures 4a and 4b show the plots of $\frac{V_s}{H_{w,net}}$ against $\frac{u}{\sqrt{g (G_s-1)d_s}}$ and $\frac{H_{w,net}}{H_{w,net}}$ for different outlet opening heights when thickness of sediment deposit was 140 mm, and Figure 4c presents the plot of $\frac{V_s}{A}$ against $\frac{u}{\sqrt{g (G_s-1)d_s}}$ for different outlet opening heights and different thickness of sediment deposit. Similar trends were observed for the variation of $\frac{V_s}{H_{w,net}}$ against $\frac{u}{\sqrt{g (G_s-1)d_s}}$ and $\frac{H_{w,net}}{H_{w,net}}$ for a thickness of the sediment deposit ($H_s$) of 120 mm and 100 mm. The dimensionless flushing cone volume decreased with decreasing sediment deposit thickness which can be expected as a smaller sediment deposit thickness means less sediment is available for flushing. Similarly, it can be seen from the plots in Figure 4 that the dimensionless flushing cone volume increases with increasing outlet opening area as concluded by Meshkati et al. [4]. Thus, it can be concluded that the lightweight PMMA in the model experiments behaved similar as natural sediments.

Using equation (3) and the experimental data from the present study, $\frac{V_s}{H_{w,net}}$ for each experiment was calculated and compared with the measured values as shown in Figure 5. Similarly, $\frac{V_s^{1/3}}{D}$ for each
experiment was calculated using equation (4) and compared with measured values as illustrated in Figure 6. Equation (3) underestimated the dimensionless flushing cone volume whereas equation (6) overestimated it. Besides differences in the experimental setup, the deviation of measured values from calculated values using equations (3) and (4) can also be associated with the different shape of the outlets. In this study, a rectangular bottom outlet was used with constant width and varying height whereas [4] and [10] used a circular bottom outlet. In order to apply equations (3) and (4) to our experimental data, the diameter of the bottom outlet was taken as an equivalent diameter of a circle with same area as the rectangular orifice. This assumption is one reason for the observed deviation between measured and calculated values of the dimensionless flushing cone volume. However, [14] showed that the size of flushing cone depends on the shape of the outlet and concluded that flat rectangular and square outlets produced bigger flushing cone compared to a round one. This statement provides thus an explanation for the underestimation of the flushing cone volume by equation (3). On the contrary, the flushing cone volumes were overestimated by equation 4.

![Figure 5. Plot of measured $\frac{V_c}{H_{w,net}}$ against calculated values using equation 3](image1)

![Figure 6. Plot of measured $\frac{V_c^{1/3}}{D}$ against calculated values using equation 4](image2)

Another possible reason for the observed deviations is the use of single sediment thickness in the experiments forming the basis for equations (3) and (4). Using only a single sediment thickness, each of the empirical regression-based relations developed from experimental data cannot predict the variation in dimensionless flushing cone volume for varying thickness of sediment deposit above the centre of the outlet opening ($H_{s,net}$). Similarly, equations (3) and (4) were developed from experiments with natural sand i.e. constant $G_s$ and hence might not be effective to predict the effect of variation in $G_s$. In short, equations (3) and (4) might be applicable to limited range of parameters and hence cannot be applied for the range of parameters in this study.

4. Conclusion

The variation in each of the chosen dimensionless parameters had a good trend against variation in dimensionless flushing cone volume for experimental data with PMMA as shown in Figure 4. This shows the potential of PMMA grains to be used as model sediment to simulate pressurized flushing cone in physical model experiments. However, the experimental data for PMMA cannot be described by the empirical relations according to equations (3) and (4) proposed to predict dimensionless flushing cone volume for sand. The possible reasoning for this deviation have been discussed but should be verified via more experiments using model sediments with different specific gravities and characteristics particle sizes. Experiments with sand in identical experimental setup should also be performed so that the possible deviation due to differences in the experimental setup can be avoided so that the experimental data can be compared directly. Finally, if all the data from previous studies are combined and used to develop a new regression based empirical relation, it will cover a bigger range of parameters and may improve the prediction capability.
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