Flushing operations with limited sediment availability

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ABSTRACT

This study involves physical modeling of flushing operations in a reservoir, conducted with the aim of getting validation data for assessing the predictive capacity of numerical models. The scale model represents a shallow reservoir controlled by two Creager spillways. The reservoir is 3.8 m wide and 2.8 m long. Several discharges have been tested between 5 and 15 l/s, with a water level ranging between 2.5 and 6 cm above the Creager crest. A non-erodible bottom representing bedrock or consolidated sediments is considered in the model below an erodible layer made of uniform polystyrene cylindrical particles with a characteristic grain size of about 2.5 mm. The model was instrumented with ultrasonic sensors to measure the free surface elevation vs. time. A camera located vertically above the model provides the evolution of the area where the erodible layer has been totally removed.

INTRODUCTION

Sediment related problems are of huge importance in most projects of dam construction and for reservoir management. They may have long term impacts, by decreasing the reservoir capacity as well as short term ones, by damaging the turbines in the case of hydroelectric power plants. Therefore, the detailed analysis of sediment effects is increasingly present in the preliminary design of dam projects and sediment management techniques are elaborated, such as sluicing and periodic flushing (e.g. Garcia 2008). Studies are generally performed by physical modeling (Boillat et al. 2008; Erpicum et al. 2006; Ettema 2000; Lai and Shen 1996; Morris 1997; Schweim et al. 1998; Talebbeydokhti and Naghshineh 2004) or numerical modeling (Bouchard 2001; Dewals et al. 2008; International Commission of Large Dams 2007; Olsen 1999). Empirical approaches may also be used (e.g. White 2001). The present study aims at gathering a dataset to validate numerical models. The test case represents flood flows in a shallow reservoir silted up to the top of the spillway crest. A non erodible bottom, representing bedrock, is considered under the sediment layer. For a series of flow conditions, the evolution of erosion was observed. The results provide the extent and time evolution of the totally eroded area.
EXPERIMENTAL SET-UP AND PROCEDURE

Sediment properties
Sediments used are elliptic cylinders of plastic polistyrol (“Styrolux 656 C” from BASF). Their length is 2.5 mm, their larger diameter 2.6 mm and the smaller one 2.1 mm. The distributions of these three characteristic grain sizes fit with a Gauss law, with all standard deviations below 0.2 mm. The sediments are translucent (transparency of 90%) and they become light grey when agglomerated, as can be seen in Figure 4. Their density is 1020 kg/m³. The porosity, as tested in laboratory, ranges between 0.33 and 0.38 depending on the level of compaction.

The dimensionless shear stress $\tau^*_{c}$ may be determined by the standard Brownlie formula:

$$\tau^*_c = 0.22 \frac{\Re_p}{\rho} - 0.6 + 0.06 e^{-17.77 \frac{\Re_p}{\rho}}, \quad \text{with} \quad \Re_p = \sqrt{g (s-1) d^3 / \nu} \quad \text{and} \quad s = \frac{s}{\rho},$$

where $\Re_p$ is the particle Reynolds number, $\rho_s$ the particle density, $\rho$ the water density, $g$ the gravity acceleration, $d$ the characteristic particle diameter and $\nu$ the kinematic viscosity of water (García 2008). As a result, the dimensionless critical shear stress was evaluated at $\tau^*_c = 0.032$.

Model description
The model represents a shallow reservoir controlled by two 21.25 cm wide Creager spillways (Figure 1). The reservoir is 3.8 m wide and 2.8 m long. The topography is essentially flat and the bottom is covered by painted concrete. The inflow comes uniformly from the 3.8 m wide upstream side. Both lateral sides are confined by multiplex panels. On the downstream side, there are ten spillways separated by 8 cm wide piers, but only two of them are open in the present experiments.

To limit the required volume of particles, sediments were set in a restricted area delimited by a net composed of square holes of 2 mm. This enables water to flow through without significant disturbances, while it prevents the sediments from passing. The net is placed in a semi-circular position (radius of 55 cm) to remain approximately normal to the incoming flow direction, as depicted in Figure 2.

![Figure 1](image-url)
Measuring devices

The model was equipped with a digital camera, free surface probes and an electromagnetic flowmeter.

A digital camera (Sony DCR-TRV300) was placed vertically at a height of 2.4 m to film the evolution of the erosion pattern.

The ultrasonic free surface probes are « mic+25/IU/TC » from Microsonic. Their accuracy is 0.18 mm. The measure was displayed on the probe and simultaneously sent to a computer for recording. Four probes were placed on the model. Two of them in the middle of the active spillways, in line with the head of the piers, while the others were placed 50 cm further upstream, outside the area initially filled with sediments. The later probes provide thus the head in the reservoir. The probes locations are represented in Figure 2.

The flowmeter is a « PROline promag 50 ». Because of the limited accuracy of the flowmeter for the low discharge values considered here, the discharge \( Q \) is better estimated from the level in the reservoir, in combination with the stage-discharge relationship of the spillway, deduced from tests with higher discharges (Table 1). The spillway coefficient \( C_{dev} \) for the two Creager spillways was estimated at the following mean value:

\[
C_{dev} = \frac{Q}{B \sqrt{2gh^3}} = 0.490,
\]

with \( B \) the crest length and \( h \) the head measured above the spillway crest.

Considering that the overall accuracy of reservoir level measurement is ± 2 mm, the discharge may then be obtained with an error not higher than 10% for the lower values and 5% for the higher ones.

Table 1: Stage-discharge relationship and corresponding spillway coefficients.

<table>
<thead>
<tr>
<th>Discharge [m³/s]</th>
<th>Head [m]</th>
<th>( C_{dev} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0224</td>
<td>0.084</td>
<td>0.491</td>
</tr>
<tr>
<td>0.0345</td>
<td>0.112</td>
<td>0.492</td>
</tr>
<tr>
<td>0.0467</td>
<td>0.138</td>
<td>0.487</td>
</tr>
<tr>
<td>0.0594</td>
<td>0.161</td>
<td>0.489</td>
</tr>
</tbody>
</table>
Experimental procedure

Eight discharges were tested, by means of three sets of experiments. Each series of experiments involves tests with two to three successive discharges, without the flow being stopped nor sediments being added during a test series. Figure 3 shows the time evolution of the reservoir level during the three sets of experiments, from which the corresponding discharges were deduced (Table 2).

Table 2: Discharges considered in each set of experiments.

<table>
<thead>
<tr>
<th>Test series ID</th>
<th>Discharge [l/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.3 ; 11.6 ; 14</td>
</tr>
<tr>
<td>2</td>
<td>5.1 ; 8.3 ; 14.7</td>
</tr>
<tr>
<td>3</td>
<td>5.3 ; 7.4</td>
</tr>
</tbody>
</table>

RESULTS: EROSION PATTERN

The videos recorded with the digital camera enabled to extract images at regular time intervals. These images were next corrected for distortion and other geometric errors, using simple mathematical relationships between the indices of pixels in the original images and the corresponding real coordinates. Polynomials of second order were exploited as mapping functions between the two systems of coordinates (Richards and Jia 2006):

\[
\begin{align*}
    u &= a_0 + a_1 x + a_2 x^2 + a_3 x y + a_4 y + a_5 y^2 \\
    v &= b_0 + b_1 x + b_2 x^2 + b_3 x y + b_4 y + b_5 y^2
\end{align*}
\]

with \((u,v)\) the coordinates in the original distorted image and \((x,y)\) the real coordinates. The polynomial coefficients \(a_i\) and \(b_i\) are unknown parameters, the value of which may be estimated from a minimum of six control points.
Control points are features that can be identified in the image and for which the real coordinates are known (e.g. edges of the piers). In practice, at least eight control points were used and the parameters were evaluated using least square estimations. This reduces the influence of positional errors of the control points.

Resampling of the corrected images was performed based on a bilinear interpolation involving the four closest pixels of the original image.

The results in Figure 4, Figure 5 and Figure 6 reveal two types of erosion shapes. For low discharges, such as 5.1 and 5.3 l/s, three eroded areas may be identified at the bottom of each active pier, similar to scouring near bridge piers due to high turbulence and creation of vortices (Ettema 2000; Ting et al. 2001). For higher discharges, the eroded area splits into two large parts located in-between the piers, as can be seen in Figure 4 for a discharge of 11.6 l/s. These two areas eventually merge for the highest considered discharges.

<table>
<thead>
<tr>
<th>Time [min]</th>
<th>5.3 l/s</th>
<th>11.6 l/s</th>
<th>14 l/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
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<tr>
<td>5</td>
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<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
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<tr>
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<td><img src="image9.png" alt="Image" /></td>
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<tr>
<td>15</td>
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<td><img src="image12.png" alt="Image" /></td>
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<tr>
<td>20</td>
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<td><img src="image15.png" alt="Image" /></td>
</tr>
<tr>
<td>30</td>
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<td><img src="image18.png" alt="Image" /></td>
</tr>
<tr>
<td>40</td>
<td><img src="image19.png" alt="Image" /></td>
<td><img src="image20.png" alt="Image" /></td>
<td><img src="image21.png" alt="Image" /></td>
</tr>
</tbody>
</table>

*Figure 4: Results of test series n°1 (Resampled images corrected for geometric distortion using mapping polynomials).*

4293
For each image, the completely eroded area was determined, as shown in Figure 6 after 30 minutes. The corresponding surfaces were calculated based on a Delaunay triangulation and their time evolution is displayed in Figure 7, which shows that equilibrium is almost systematically reached at the end of each experiment. Besides, the completely eroded area shows some non-monotonous evolutions with time (e.g. for a flow of 11.6 l/s, the eroded area decreases in front of the piers between the 10 and the 15 minute, see Figure 4). This behavior could be correlated with migration of dunes.

It is found that the completely eroded surface after 30 minutes or 40 minutes varies linearly with the discharge, as demonstrated in Figure 8. After 30 minutes, the evolution is almost linear, while this trend is even better confirmed after 40 minutes, in spite of less comparison points being available in the latter case.
CONCLUSION

By means of physical modeling, flushing operations were simulated in a shallow reservoir for discharges ranging between 5.1 and 14.7 l/s. A confined area of the reservoir in the neighborhood of the spillways was initially filled with sediments up to the spillway crest. A non erodible bottom was considered under the sediments layer, with the purpose of representing bedrock.
Besides time series of the head in the reservoir and the flushing discharge, the time evolution of the completely eroded area was obtained using a digital camera placed above the model. The images were corrected for geometric distortions. From each image, the surface of the completely eroded area was calculated using a Delaunay triangulation. This enabled to monitor the evolution of the totally eroded area for the three sets of experiments and revealed that equilibrium was almost reached at the end of the tests. The totally eroded area at two times of reference, namely after 30 and 40 minutes, was found to vary linearly with the discharge. The gathered results constitute valuable reference data for validating numerical models of flow and sediment transport. The development and exploitation of such a model is currently in progress and will be presented in a subsequent paper.

REFERENCES


