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Free surface algorithms for 3D numerical modelling of reservoir flushing

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ABSTRACT: Three-dimensional numerical modelling of sediment flushing from water reservoirs shows particular problems when the free surface moves. The current paper presents some algorithms for computing the changes in the free surface for these cases. An adaptive grid is used when the bed and the free surface are moving vertically. The unstructured grid allows a variable number of grid cells in the vertical direction, depending on the water depth. This approach has the advantage that only the water phase is modelled. A fixed grid solution would need to include two-phase algorithms with the air. The algorithms presented here are based on the computed pressure field. Earlier studies applied a direct method to compute the water level. This caused some problem when the Froude numbers were close to unity during drawdown of the water level in the reservoir. The alternative algorithm presented in the paper is iterative and more stable for higher Froude numbers. The proposed method is tested for the Kali Gandaki reservoir in Nepal, where laboratory experiments have been conducted to investigate the reservoir flushing process. Comparisons between computed and measured bed elevation changes are presented in the paper, together with figures of the adaptive grid changes during the computation.

Keywords: Numerical modelling, Reservoir flushing, Free surface, Free surface algorithms

1 INTRODUCTION

Between 1 and 2 % of the volumes in the worlds water reservoirs are lost annually due to sedimentation (Mahmood, 1987). The water in the rivers flowing into the reservoirs may contain high concentrations of sand, silt and clay. As turbulence and bed shear stress is reduced when water enters the reservoir, the particles settle. Bed levels rise and the storage volume of the reservoir is reduced. This represents a substantial loss in economical value and it has a negative effect on food supply through a decrease in the availability of irrigation water.

The most common way of reducing the problem is by flushing the water reservoirs. The water level is drawn down to a level where the velocity and turbulence is fairly high throughout the reservoir. The increased shear stress on the reservoir bed causes erosion, and the turbulence keeps particles in suspension passing the dam. However, before using the procedure, there are some problems that must be considered. First, the drawdown of the water level will cause a loss of the water in the reservoir. This must be weighed against the increased value of the added reservoir water volume after the flushing. Another question is how much sediments can be flushed out? And is where erosion taking place? Are sediments removed from most of the reservoir, or only from a part of it? A very wide reservoir might result in a relatively narrow erosion channel, as for example the Cachi reservoir in Costa Rica (Jansson, 1992). To reduce this problem, it is possible to construct guide walls in the reservoir to increase the eroded volume (Badura, 2007). Then the question becomes how effective these guide walls are.

Yet another problem comes from an environmental point of view. During flushing the water downstream of the reservoir will have a relatively high sediment concentration and this can be harmful to the downstream habitat (e.g., fish). Strict regulations are therefore often imposed on reservoir flushing programmes, for example in the Bodendorf reservoir in Austria and the Penas Blancas reservoir in Costa Rica. An estimate of the downstream sediment concentration as a function of different flushing scenarios is therefore very useful.

From an economical, engineering and environmental point of view it is very important to have reliable answers to these questions before a flushing operation is to be carried out. To answer the questions, it is possible to use physical model test. However, the scaling of the sediments is very difficult, especially since the reservoirs are very large and the scale of the physical model must be small from a practical point of view. It is almost impossible to correctly model all the effects of critical shear, bed load, suspended load, secondary currents and possible bed forms in a physical model.

Instead of using a physical model, the current paper describes the use of a numerical model as an alternative. The numerical model does not suffer from scaling problems, and it also has two other advantages: Its economical cost is much smaller than the physical model and the time to carry out the study is also shorter (Gessler, 2005; Chandler et al, 2003).

A numerical model for reservoir flushing has to include three-dimensional effects if the reservoir is not completely straight and narrow, or if effects of guide walls are to be included in the investigations. Only a three-dimensional numerical model can take the secondary currents fully into account. The secondary currents will be important when assessing the effect of the flushing in bends of the reservoir/river, or any deflections due to guide walls.

2 FREE SURFACE ALGORITHMS

During reservoir flushing, the water level is drawn down. The three-dimensional model therefore needs to include an algorithm for the movement of the free surface. Commercial programs often do this by using a two-phase approach. A fixed grid is used with two phases: water and air. Then several algorithms can be used to compute the changes in the location of the water surface. The most common methods are volume of fluid (VOF) methods, used for example by Flow-3D (Hirth and Nicols, 1981). The algorithm defines a volume fraction, f, of water in each cell. The value of f is between zero (only air) and unity (only water) in every cell of the grid. A transport equation is used to compute how f changes over a time step, as a function of the flow field. A filtering method is used to compute the location of the water surface given the values of f in the grid. This filtering method is not straightforward. Another method that has been popular more recently is the level set method. This method uses a variable l, which is the distance from each cell to the water surface. The value is used instead of the f parameter in the VOF method. A transport equation is solved for l to estimate its value in each cell. Reconstructing the free water surface from the l field is much more straightforward than using the f values from the volume of fluid method.

The fixed grid methods have a few drawbacks. Firstly, it is not always easy to keep water continuity correct. The second drawback is that the cells filled with air also have to be computed. These cells are actually not interesting for our computation of the flushing process. The velocity and turbulence values in the air-filled cells are not necessary to compute the sediment transport.

The alternative to these two fixed-grid methods is the use of an adaptive grid which follows the water surface. This approach is used in the current study. Then only the water is modelled. The water surface is recomputed after each time step, and a new grid is generated based on the magnitude of the water depth. At large depths, up to for example 20 cells can be generated. In fairly shallow areas (in the current study between 2 and 4 cm), only one cell is generated and a two-dimensional computation is done.

Where the water depth is below 2 cm, no cells are generated in the current case. This procedure is then very well suited for computing wetting and drying problems.

The parameter for the number of grid cells in the vertical direction as a function of the water depth was for this case also modified. The value (p) was chosen with 0.5 for the Eq. 1:

$$n = n_{\max} \times \left(\frac{depth}{depth_{\max}} \right)^p \quad (1)$$

where n = number of grid cells in the vertical direction, n_{max} = maximum number of grid cells in the vertical direction, p = parameter for number of grid cells.

A fixed grid algorithm uses the velocities for both the water and the air phase. The algorithm proposed in the current paper only uses the water phase. Also, a known or given pressure and water level is assumed at one reference point, typically the downstream boundary or the spillway. The 3D Navier-Stokes solver computes the pressure by the SIMPLE method in all cells. The pressure difference (dp) between the reference point and any other surface cell in the grid must be related to the elevation difference (dz) between the two points:

$$\mathrm{d}z = \mathrm{d}p / \rho g \quad (2)$$

where ρ = fluid density and g = gravity acceleration.

This is similar to saying the free surface is moved to at the pressure line of computation with a lid that is fixed within each time step. The method has been tested on a number of cases, for example the Danube (Tritthart and Gutknecht, 2007).

Assuming the water level is located at the pressure line will be correct as long as the CFD program computes the energy loss correctly. In some cases, that can be difficult. A typical example is the hydraulic jump. When the Froude number approaches one, the algorithm can become unstable. Also, the energy loss may not be computed correctly in a relatively coarse grid, leading to incorrect water elevation differences between the upstream and downstream side of the jump. The current paper focuses on an improved method to compute the water levels.

The currently proposed numerical algorithm is based on a similar principle as the previously described method. However, when computing the water elevation differences between cells, only local differences between neighbouring cells are used. The water level difference between two cells is computed by the same equation as before (Eq. 2), but is now only applied to neighbour cells, instead of the difference between any cell and the reference cell. An iterative method is used, as the new water level in a cell is unknown for all the cells. In the proposed method, a reference cell may in principle not be needed, but it is used anyway, as it is necessary to specify the downstream water level. Also, the reference cell specification gives added stability.

The surface cells make up a 2D grid, so that all cells have four neighbours. The application of Eq. 2 in one cell will therefore give four values for the level in that cell. A weighed average of these values is proposed in the current algorithm, where the weighting factors are functions of the Froude number and a parameter telling if the neighbour cell is upstream or downstream of the current cell. The upwind approach is very much used in numerical modelling to get a stable solution. Also in 1D models, the computational direction depends on the flow direction and the Froude number. For subcritical flow, a 1D steady model will start at the downstream cross-section and compute sections in the upstream direction. And it will go in the other direction for supercritical flow. The following formula is therefore suggested for the weighting factor, coeff:

```
if (Froude > 1.0 and m < 0.0) {
  coeff = -m;
  if (m > -0.2) coeff *= -5.0 * m;
  if (Froude < 2.0) coeff *= (Froude-1.0);
} else if (Froude < 1.0 and m > 0.0) {
  coeff = m;                                          (3)
  if (m < 0.1) coeff *= 10.0 * m;
  if (Froude < 0.75) coeff *= (4.0-4.0*Froude);
  coeff += 0.03;
} else {
  coeff = 0.0;
}
```

where m = the dot product of the velocity vector and the direction vector between the centre of the cell and the centre of the neighbour cell to take the upstream/downstream effect into account.

To avoid instabilities, it is important that the function is as continuous as possible. Several alternatives for Eq. 3 were tested, but the combinations given above seemed to give good results.

The new algorithm must be tested to see how accurate and stable it is, especially for Froude numbers close unity. As example a test of the new algorithm on a broad crested weir is shown in Fig. 1.

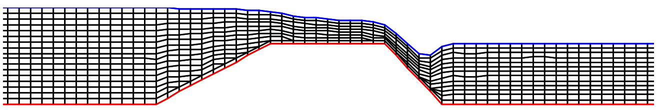

Figure 1. Longitudinal Section of the grid for testing the new free surface algorithm for a flow over a broad crested weir

A method similar to the currently proposed algorithm was actually used by Rüther and Olsen (2007) computing the development of meandering channel from an original straight planform. However, the most relevant case the method has been used for reservoir flushing is the Kali Gandaki hydropower plant in Nepal. The case and the testing of the algorithm are described later.

3 NUMERICAL ALGORITHMS FOR SEDIMENTS

A large number of different empirical formulas exist for computation of the sediment transport. A summary of the methods used in the current paper is given.

The suspended sediment transport was computed by solving the transient convection-diffusion equation. For the sediment concentration the formula by Van Rijn (1984b) was used. The bed load was calculated with an empirical formula by Van Rijn (1984a). When the vertical height of the centre of the bed cell was different from what Van Rijn subscribed, the Hunter-Rouse extrapolation was invoked (Rouse 1937). For the bed cells an algorithm was used where the sediment concentration formula was converted into an entrainment rate. The value for the fraction of compacted sediments in bed deposits was 50 %. A sand slide algorithm was used with the tangent of the angle of repose set to 0.69. Furthermore the thickness of the upper active sediment layer was given as 0.01 m.

4 PHYSICAL MODEL STUDY OF THE KALI GANDAKI HYDROPOWER RESERVOIR

The chosen test case was the Kali Gandaki Hydropower Reservoir in Nepal. The reservoir had a volume of 6.9 million m^3, and supplied water for a run-of-the-river hydropower plant. It was assumed that the prototype reservoir would fill up completely in a very short time if it was not flushed. A physical model study of the project had been carried out at the Norwegian Hydrotechnical Laboratory in 1994. The physical model was 12 m long and 6 m wide and was built of concrete in a scale of 1:50. A photo of the model is given in Fig. 2.

Figure 2. Photograph of the physical model (© by SINTEF, used with permission)

Initially, sand was filled up to a horizontal level 14 cm above the spillway crest. A flushing discharge of 28 l/s was used. Before the flushing started, the gates were closed while the water filled the reservoir gradually to prevent disturbance of the sand bed. When the water reached 35 cm above the spillway, the gates were opened (all water levels from the physical model test are in cm). The water level was drawn down to 15 cm above the spillway during 5 minutes. In this situation, the flow became supercritical right upstream of the dam. The gates were kept open for 2 1/2 hours, giving the water time to erode a large part of the sand in the model. After 2 1/2 hours the water level was down to 5 cm above the spillway. The flushing was then stopped and the bed levels were measured at six cross-sections.

The sand used in the physical model was sieved, and a grain size distribution obtained. Based on this, four sediment sizes of equal fraction in the bed were simulated in the numerical model. The average diameters of the four sizes were: 0.35 mm, 0.85 mm, 1.7 mm and 3.3 mm.

5 RESULTS AND DISCUSSION

The numerical model was used to compute the water and bed elevation changes during the flushing process in the physical model of the Kali Gandaki reservoir.

The numerical algorithms described earlier for computing the water flow, sediment transport, water surface and grid described were used. The resulting changes in the water level over time during the flushing process are given in Fig. 3 with the corresponding changes in the grid given in Fig. 4.

Figure 3. Water level (in cm) after the flushing progresses (t = 9000 s)

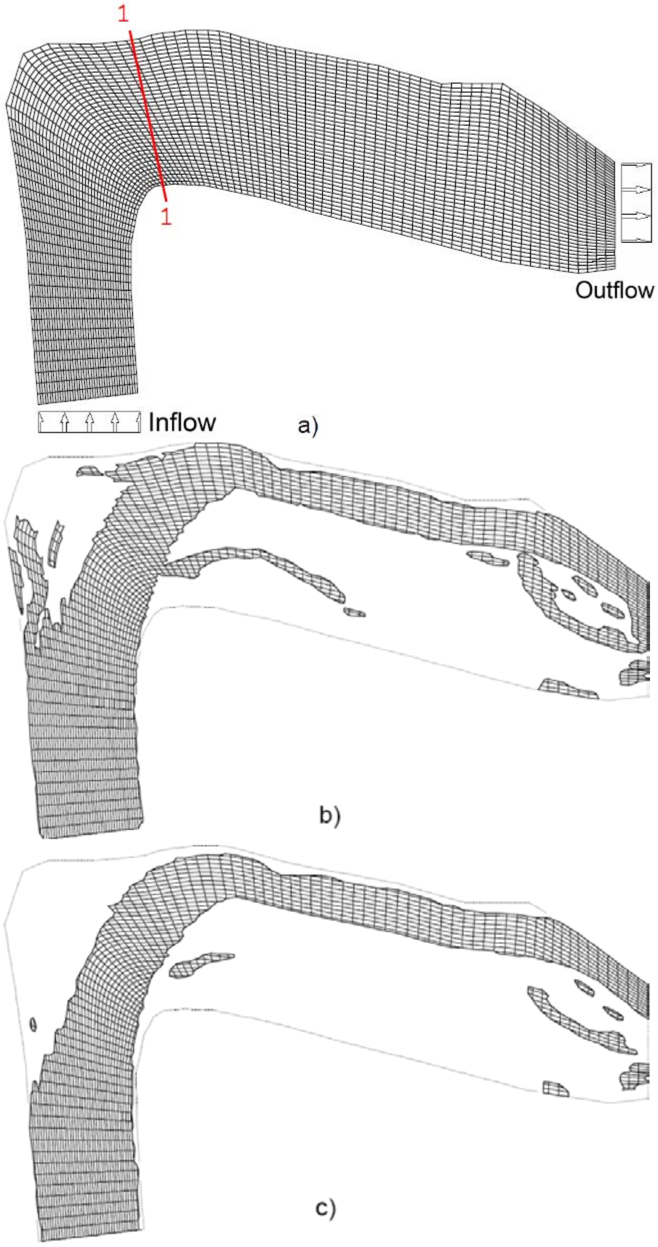

Figure 4. Plan view of the grid a) t = 0 s, b) t = 4500 s, c) t = 9000 s

The figures show that as the water level is lowered, erosion of sediments takes place in areas of high velocity. A channel is then formed. The channel becomes deeper over time and further drying on the channel sides occur. In the bend this process is very much in accordance with observations from the physical model study. The channel moves to the outside of the curve in the reservoir. A cross-section taken at the bend is given in Fig. 5 showing the computed and measured bed elevation after the flushing. The left side of the figure is the outside of the bend. The location of the cross-section is given in Fig. 4 a. Fig. 5 also shows results from an earlier 2D computation of the case (Olsen, 1999).

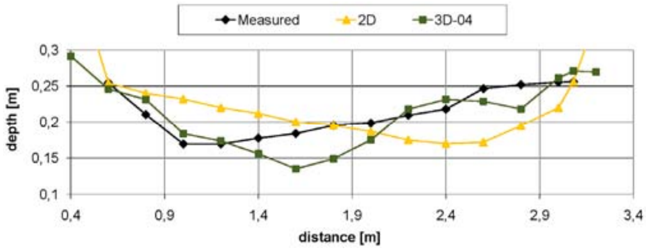

Figure 5. Computed and measured bed elevation in the bend

There is reasonable agreement between the computations and the measurements. The results from the 3D computation show the deepest part of the channel to be on the outside of the bend, similarly to the measurements. The earlier results from the 2D model are not able to capture the secondary current, and predicts the deepest part of the cross-section to be on the inside of the bend.

Downstream of the bend, the computed channel becomes too narrow compared with the observations from the physical model study. Future research will focus on improved formulas for the sediment transport process for this case in order to achieve better results here.

6 CONCLUSIONS

New algorithms for computation of the changes in the free water surface location for a 3D numerical model with an adaptive grid have been proposed. The algorithms were tested on a reservoir flushing case where laboratory data had been obtained. Reasonable results were obtained for the pattern of the water level lowering and the corresponding drying in the sides of the geometry. Fig. 6 (at the end of the paper) shows the secondary currents in a bend of a reservoir that is being flushed. The computed bed elevation changes in a bend also compared reasonably well with measurements from the physical model study.

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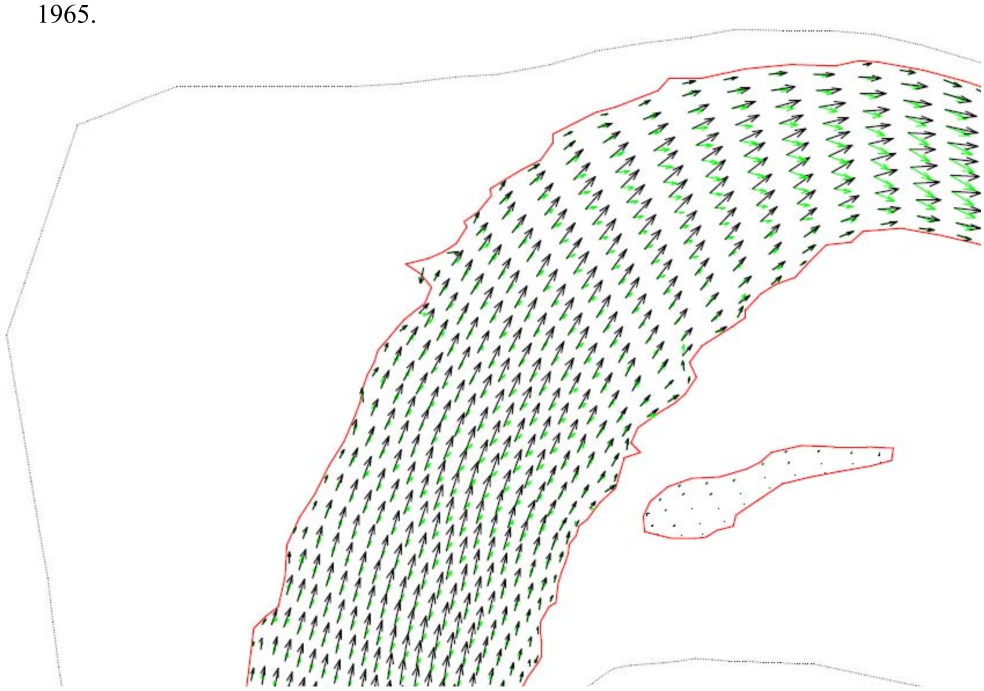

Figure 6. Velocity vectors at the surface (black) and the bed (grey), showing secondary currents in the bend