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Development of a Three-Dimensional Numerical Model of Sediment Transport and Bed Level Changes in Reservoir Flushing

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Abstract:

In this research, the process of sediment flushing is simulated by a three-dimensional numerical model in which sediment and flow interactions are reflected in the reservoirs. Reynolds Averaged Navier-Stokes (RANS) equations are solved numerically by Finite Volume method. A RNG k- ϵ turbulence model is used. The resulting flow analysis is given as input data for the sediment model. The convection-diffusion equation for the sediment concentration is solved. The concentration equation derived by Van Rijn is adopted as a boundary condition to compute bed material load. The depth integrated mass balance equation is applied to find the bed changes. The results from the numerical model are compared favourably with the data from physical model studies available in the literature.

Résumé:

Dans cette étude, le procédé de chasse des sédiments est simulé à l'aide d'un modèle numérique tridimensionnel. L'interaction sédiment/écoulement est analysé sur les réservoirs. Les équations de Reynolds moyennées (RANS) sont résolues numériquement à l'aide de la méthode des Volumes Finis. Un modèle de turbulence de type RNG k- ϵ est utilisé. Les vitesses obtenues sont ensuite utilisées pour résoudre l'équation de convection-diffusion. L'équation de concentration de Van Rijn est ici adoptée comme condition aux limites afin d'obtenir la charge de fond. L'équation de conservation de la masse est utilisée pour obtenir les changements du fond. Les résultats obtenus se comparent favorablement à ceux disponibles dans la littérature.

Key-words: Turbulence; Reservoir; Flushing.

1 Introduction

The flushing of the sediments involves several complex processes. Water flow field is three-dimensional with complex recirculation zones and secondary currents. The turbulence is non-isotropic throughout the flow domain. The erosion and sedimentation processes are also complex.

To adopt a numerical model, it is necessary to make some modeling simplifications. Previously, a few one and two dimensional numerical models were developed to describe flow and sediment interaction during the flushing process. Ruland and Rouve (1992) used a two-dimensional finite element model to assess the risk of erosion in a reservoir. In the study Olsen (1999) solved the Navier-Stokes equations on a two-dimensional grid and the resulting flow field was extrapolated to three-dimensions to solve the sediment concentration in flushing processes.

In this paper, a three-dimensional mathematical model for the water flow and sediment are presented in sections 2 and 3, respectively. The finite volume method is briefly described within section 4. Section 5 discusses the results of the numerical simulations which were verified by the previous experimental data. Finally some conclusions are drawn.

2 Mathematical model for the water flow

The equations governing the mean velocities \overline{U}_i and pressure \overline{p} are obtained from Reynolds Averaged Navier-Stokes (RANS) equations which can be written as:

$$\frac{\partial \overline{U}_j}{\partial x_j} = 0 \quad (1)$$

$$\frac{\partial \overline{U}_i}{\partial t} + \frac{\partial}{\partial x_j} (\overline{U}_i \overline{U}_j) = -\frac{1}{\rho} \frac{\partial \overline{p}}{\partial x_i} + \frac{\partial}{\partial x_j} (\nu \frac{\partial \overline{U}_i}{\partial x_j} - \overline{u_i u_j}) \quad (2)$$

where ν and ρ are the kinematic viscosity and the fluid density, respectively. The quantity $\overline{u_i u_j}$ is the Reynolds stress tensor. Since these equations are not closed, additional equations have to be written for $\overline{u_i u_j}$. In order to develop such equations, most of the closure schemes assume the following functional form:

$$\overline{u_i u_j}(x, t) = f_{ij}(\overline{U}_i(x, t), k(x, t), \varepsilon(x, t), x, t) \quad (3)$$

where k and ε are the turbulent kinetic energy and the dissipation rate, respectively. This kind of closure implies that two additional transport equations are required, one for k and the other for ε . In this study we have chosen the RNG $k - \varepsilon$ model.

The idea of Yakhot and Orszag (1989) was based on the infinite scale expansion in η , which is defined by the ratio of the turbulent time scale to the mean strain scale:

$$\frac{\partial k}{\partial t} + \overline{U}_j \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j} \left(\alpha_k \nu_{eff} \frac{\partial k}{\partial x_j} \right) - \overline{u_i u_j D_{ij}} - \varepsilon \quad (4)$$

$$\frac{\partial \varepsilon}{\partial t} + \overline{U}_j \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j} \left(\alpha_\varepsilon \nu_{eff} \frac{\partial \varepsilon}{\partial x_j} \right) + C_{\varepsilon 1} \frac{\varepsilon}{k} (-\overline{u_i u_j D_{ij}}) - C_{\varepsilon 2} \frac{\varepsilon^2}{k} \quad (5)$$

$$\text{where } \nu_{eff} = \nu + \nu_t \text{ with } \nu_t = C_\mu \frac{k^2}{\varepsilon} \quad (6)$$

$$\text{and } \eta = S \frac{k}{\varepsilon} \quad (7)$$

$$\text{where } S = (2\overline{D_{ij}} \overline{D_{ij}})^{1/2}, \overline{D_{ij}} = (\partial \overline{U}_i / \partial x_j + \partial \overline{U}_j / \partial x_i) / 2.$$

The set of coefficients is:

$$C_\mu = 0.085, C_{\varepsilon 1} = 1.42 - \frac{\eta(1 - \eta/\eta_0)}{1 + \beta\eta^3}, C_{\varepsilon 2} = 1.68, \alpha_k = \alpha_\varepsilon = 1.39 \quad (8)$$

where $\eta_0 = 4.38$ and $\beta = 0.015$.

3 Mathematical model for the sediment

Generally, the first stage of the numerical flushing model consists in the analysis of the existing data. During the second stage, flow models are applied to determine the hydraulic conditions in the existing and the future conditions. The results of these are then used as input data for the morphological model. This is achieved by a dynamic model which computes sediment transport rates and the bed level changes for velocity variations to predict future conditions.

In this study, the total load (sum of bed and suspended loads) is computed by coupling the convection-diffusion equation and Van Rijn reference concentration equation (Van Rijn, 1987).

Suspended load is computed by solving the convection-diffusion equation for the sediment concentration (Ref. Van Rijn, 1993), which can be written as:

$$\frac{\partial c}{\partial t} + \bar{U}_j \frac{\partial c}{\partial x_j} + \omega \left(\frac{\partial c}{\partial x_3} \right) = \frac{\partial}{\partial x_j} \left(\Gamma \frac{\partial c}{\partial x_j} \right) \quad (j = 1, 2, 3) \quad (9)$$

where ω denote the fall velocity of the sediment particles and the diffusion coefficient, Γ , is assumed to be equal to the eddy viscosity (ν_t). The first and second terms on the left side of equation (9) are defined as transient and convection of sediment terms, respectively, while the third term is due to the fall velocity of the sediments. This is an extra convective term, added to the velocities in the vertical direction. The index 3 denotes the vertical direction. The right hand term in equation (9) is the diffusion of sediment.

The Van Rijn reference concentration equation (Van Rijn, 1987) has been applied for all cells in the bed as a boundary condition. Therefore the convection-diffusion equation was not applied for the cells on the bed (Einstein 1950).

$$\text{Hence Van Rijn (1987) equation is: } c_a = 0.015 \frac{d_{50}}{a} \frac{T^{1.5}}{D_*^{0.3}} \quad (10)$$

where the parameter a is the reference level above the mean bed, d_{50} is the median sediment particles diameter, $T = (\tau - \tau_c) / \tau_c$, where τ is the shear stress, τ_c is the critical shear stress for motions of sediment particles and $D_* = d_{50} [(G_s - 1)g / \nu^2]^{1/3}$ is the dimensionless particle size, where G_s is the specific density of sediment particles and g is the acceleration gravity.

Bed level changes were obtained from the depth-integrated mass-balance equation (Ref. Van Rijn, 1993), yielding:

$$(1 - E_p) \frac{\partial Z_b}{\partial t} + \frac{\partial}{\partial x} (q_{b,x} + q_{s,x}) + \frac{\partial}{\partial y} (q_{b,y} + q_{s,y}) = 0 \quad (11)$$

in which Z_b is the bed level with respect to a horizontal datum, E_p is the porosity factor, $q_{b,x}$ and $q_{b,y}$ are the volumetric bed load transport rates and $q_{s,x}$, $q_{s,y}$ are the volumetric suspended load transport rates. The suspended load transport rates are given by:

$$q_{s,x} = \int_a^h (uc - \Gamma \frac{\partial c}{\partial x}) dz \quad \& \quad q_{s,y} = \int_a^h (vc - \Gamma \frac{\partial c}{\partial y}) dz \quad (12)$$

where u is the streamwise velocity, v is the spanwise velocity, a is the reference level above the mean bed and h is the water depth.

4 Numerical method

The method used to solve the set of equations is of the classical finite volume type. The conservation equations are integrated over a control volume, and then the Gauss theorem is used to transform the volume integrals into surface integrals. The method uses a staggered mesh. The quadratic upstream interpolation scheme for the convective kinematics (QUICK) from Leonard (1979) is used to evaluate the advection terms for the momentum equation. The stationary solution was obtained by a time-marching algorithm. The convective, diffusive, production and dissipation terms of the different transport equations are treated by an explicit Euler scheme. The diffusion terms are discretized with a second-order cell centered scheme. The decoupling procedure for the pressure is derived from the Mark and Cell (MAC) algorithm proposed in Harlow and Welch (1965). With this method, the pressure at the time is obtained by the resolution of the discretized Poisson equation. Then, the velocities are calculated from the momentum equation. The linear system for the pressure is solved using the Cholesky procedure because the matrix of this system is positive definite and symmetric.

A fully implicit hybrids differencing scheme (Spalding, 1972) is applied to solve the convection-diffusion sediment concentration equation.

For the first time-step, at the inlet of the reservoir, a constant profile was given to U, k, ε and c . The secondary velocities were initialized as nil all over the domain. At the outlet, a zero gradient was used for all variables. In the next time-step, the calculated outlet values of the water flow were used for the inlet condition. The same procedure is used for the following time-steps up to the convergence. The boundary condition values for k and ε , at the first grid point near the wall, were calculated taking into account the fact that this point was in the viscous sub layer. Also, due to the use of a staggered grid, the value of k and ε are not defined on the wall. At the wall, the boundary conditions for these quantities were (Ref. Patel *et. al.*, 1984):

$$\frac{\partial k}{\partial y} = 0 \quad \text{or} \quad \frac{\partial k}{\partial z} = 0, \quad \text{and} \quad \varepsilon = \nu \frac{\partial^2 k}{\partial y^2} \quad \text{or} \quad \varepsilon = \nu \frac{\partial^2 k}{\partial z^2} \quad (13)$$

The homogeneous Neumann, was used for all the variables along the walls (for more details see Mompean, 1998).

The boundary condition for the sediment concentration in the bed has been already discussed in section 3 (Equation 10). The boundary condition for the sediment concentration at the water surface was defined as follows (Ref. Van Rijn, 1993):

$$\omega c + \Gamma \frac{\partial c}{\partial z} = 0 \quad (14)$$

Initial water surface has been used as a rigid-lid, and it is assumed where water level at the reservoir is lowered during flushing process in present study. Any way, this lid was adjusted after each time step based outflow of the sluice gate(s), inflow and actual volume of the reservoir.

5 Result and Model verification

The numerical model was verified by experimental data obtained from a physical model study by Lai and Shen (1995). The experiments were conducted in a horizontal (i. e. zero slope) concrete rectangular flume with dimensions 50 m long, 2.44 m wide, and 1.52 m high to simulate reservoir flushing. Sediments were paved in a 9 m reach upstream from the dam and in the depositional depth of 0.1 m above the datum. Three sluice gates (15 cm each in width) and eight sluice pipes were installed on the dam. In the current study, only results of two sluice gates (Central and left) were used. Details of the experiments together with sediment characteristics are reported in Table (1).

Table. 1- Details of sediment and flow characteristics in experimental model

Sediment material	Specific gravity	Mean diameter (mm)	Porosity	Angle of repose (degrees)	Inflow discharge (lit/s)	Initial water surface (m)	Running time (min)
Walnut shell grit	1.39	1.25	0.55	35	0.59	0.122	30

Above data was simulated numerically with the same input data as in the physical model test. In the numerical model, x, y and z-axes are longitudinal, lateral and vertical directions, respectively (Figure 1). A non-uniform structured grid $35 \times 31 \times 16$ has been used. In this simulation, calibration was based upon the equality outflow discharge values from the sluice gates to compare sediment flushing rates (Figures 2 and 3). As it is shown in these figures, experimental and numerical model results are comparable. However, some discrepancies are noticeable. These may partly occur due to the experimental setup or simplifications of the

numerical simulation among which considering water surface as a rigid-lid is the most important one. This may not be able to present water surface profile correctly, particularly, when free-flow flushing occurs.

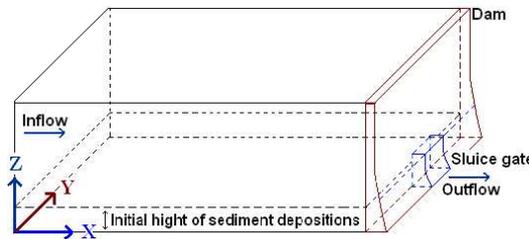


FIG. 1- Schematic shape of reservoir and coordinate system

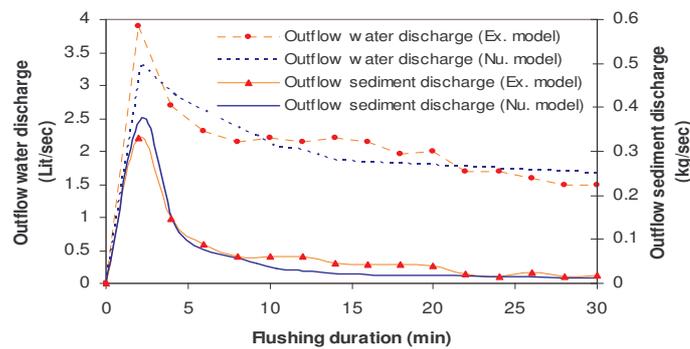


FIG. 2 – Numerical results in comparison with experimental results

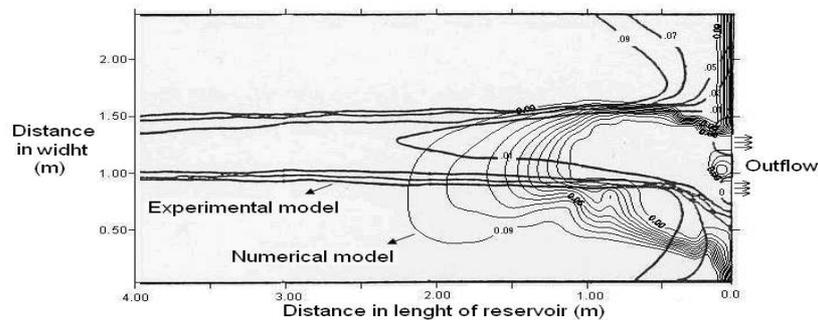


FIG. 3 – Contours of high of sediment depositions in reservoir after 30 min. of flushing (m)

In Van Rijn equation (1987), 'a' is the vertical distance from the bed to the point where the concentration was calculated. In this study, it was calculated at the center of the bed cell (i. e. half of the height of the bed cell). Einstein (1950) suggested that its value is twice the median of bed material size while Van Rijn (1987) recommended 5% of the water depth. Both criteria were applied, the latter showed 1.15% in flushed sediments.

Further on, the model was run for different flushing management conditions for validation as follows:

i)-For a constant volume of water in the reservoir, flushing efficiency which is defined as $E_F = (V_{Sin} - V_{Sout}) / V_W$, where V_{Sin} and V_{Sout} are volume of flushed and inflow sediments, respectively, and V_W is volume of consumed water during flushing; is increased by increasing the water discharge value through the sluice gates (Figure 4-a).

ii)-For constant discharge through the gates under a controlled volume of water, flushing efficiency are increased by a reduction in water surface in the reservoir (Figure 4-b).

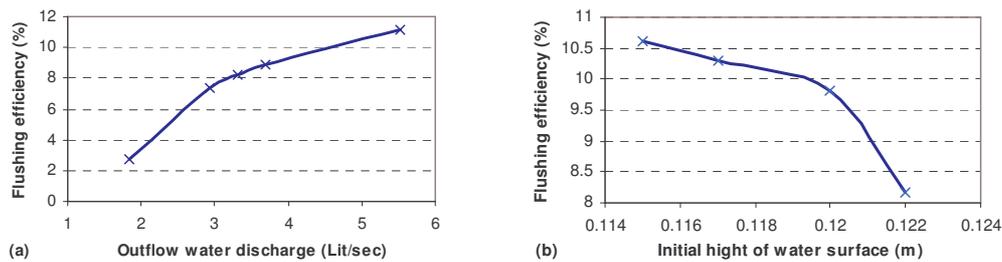


FIG. 4 – Flushing efficiency according to (a) different water outflow and (b) different initial height of water surface

6 Conclusion

The numerical model was able to simulate flushing of the reservoirs. This included complex phenomena such as drawdown of water surface during flushing process. Comparison with the physical model study showed that sediments flushed in two models are the same. The main features of the erosion pattern were also reproduced, chiefly in pressure flushing. The main deviation between measured and calculated in bed level profiles was most likely due to rigid-lid assumption for water surface.

Future research on sediment flushing from reservoirs with complex geometries should therefore be conducted with a more realistic water surface profile.

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