# Experimental and numerical investigations to assess and mitigate sedimentation problems: application to a large dam in India

S. Erpicum[1], B.J. Dewals[1,2], P. Archambeau[1], S. Detrembleur[1] & M. Pirotton1[1]
[1] University of Liège, Department of Hydraulics and Transport, Applied Hydrodynamics and Hydraulic Constructions, Chemin des Chevreuils 1, Bât. B52/3+1, B-4000 Liege
[2] FNRS Research Fellow
Email: S.Erpicum@ulg.ac.be, B.Dewals@ulg.ac.be, Michel.Pirotton@ulg.ac.be

*Abstract:* **In the global framework of river management, sedimentation problems in dam reservoirs and adjacent structures are multiple and of major interest for designers as well as dam owners or managers. Before dam construction, these problems can be assessed by several techniques. In this paper, the experimental and numerical sedimentation studies realized at the Laboratory of Applied Hydrodynamics and Hydraulic Constructions (HACH) of the University of Liège on a large hydropower plant project in India are presented. Three main issues related to sedimentation problems are analyzed in details.**

*Keywords:* **Hydraulic scale model, sediment similarity laws, settling structure, sediment transport numerical model, reservoir siltation, flushing.**

## I. Introduction

Practitioners in hydro-engineering are highly interested in powerful tools for the prediction of a large scope of hydraulic behaviours involving complex solid transport processes. Experimental modelling has been considered for decades as the single tool for the design of hydraulic structures. Today numerical models are steadily more available and supply results with an always increasing level of confidence. They are considered as a credible alternative to classical scale models for a large set of applications.

In this field, the Laboratories of Fluid Mechanic, Applied Hydrodynamics and Hydraulic Constructions HACH-LHM of the University of Liège have been exporting for a long time their experience in hydraulic engineering. Their know-how in this domain has made itself well-known in more than thirty countries all over the world through scale models expert's reports, design and feasibility studies of hydroelectric plants and dams, suitable numerical software development as well as lots of technical articles publications. At an international level, the Laboratories are carrying out coupled numerical and scale model studies that allowed refining the design and better defining numerically local processes complex to scale. This approach is lead with great success for fluid – structure interaction studies and discharge capacity evaluation of dams for example [1, 7].

In this paper, the experimental and numerical studies realized on a large hydropower plant project in India are presented through the analysis of three main issues related to sedimentation problems.

This study has been entrusted to the HACH by EDF.

## II. Project description and sedimentation related issues

The hydropower project involves the construction of a large embankment dam, with a crest 500 meters long, located in a narrow valley of a highly erosive mountainous region (Fig. 1). Hence, during flood periods, the river carries a large amount of sediments. Because of the dam building, all these soils quantities will be trapped in the reservoir, and a first problem is to assess the time delay for a complete reservoir filling by sediments and, as a consequence, the time the dam will be effective for flood regulation and irrigation. To face this first problem, a common solution is to use the release structures to flush the sediments trapped in the reservoir. A second question is how efficient these flushing operations could be and which water storage volume could be recovered. Finally, the main goal of the dam building is electricity production. A hydropower plant is planned at the dam toe. To avoid turbine damage by small solid particles carried out by the flows, the penstocks are located downstream of a sophisticated settling structure, the efficiency of which has to be assessed. This is the third problem.

To achieve this comprehensive study and to answer reliably to the three questions, the HACH used both numerical and physical experimentations, which are detailed in this paper.

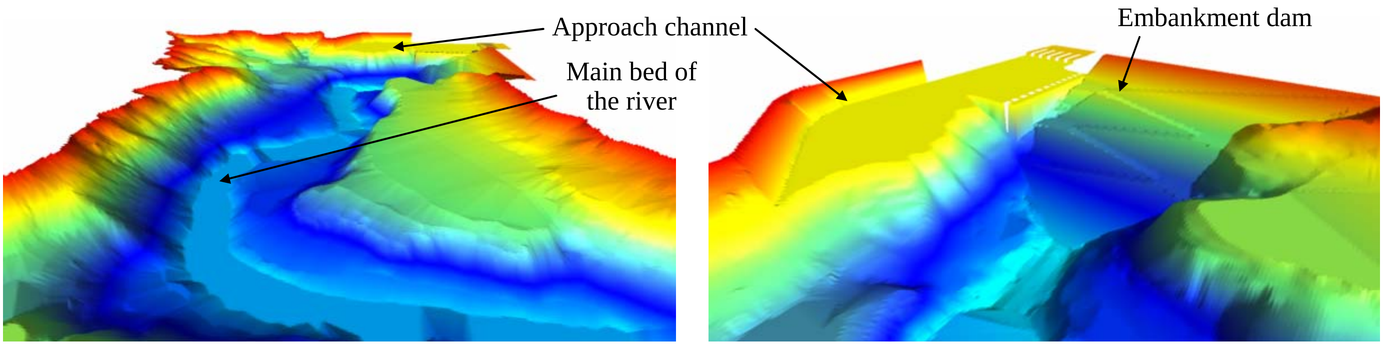


Fig. 1. 3D view of the downstream part of the reservoir (left). Detail of the dam and spillway topography (right).

## III. NUMERICAL STUDIES

The finite volume free-surface flow solver WOLF2D, developed at the HACH for almost a decade, has been used to carry out the numerical simulation of silting processes in the large reservoir and to predict the efficiency of flushing operations through the release structures. The silting process has been simulated by means of the quasi-3D flow model with a quasi-steady approach. For simulating flushing events, both the topography changes and their interactions with the flow have been carefully handled in a strongly coupled hydrodynamics - sediment transport approach.

Besides a brief description of the depth-averaged model for pure hydrodynamics, the model for solid transport is presented before the practical application.

### A. *WOLF software package*

The software package WOLF includes an integrated set of numerical models for simulating free surface flows (Fig. 2), including process-oriented hydrology, 1D and 2D hydrodynamics, sediment transport, air entrainment, … as well as an optimisation tool based on the Genetic Algorithms.

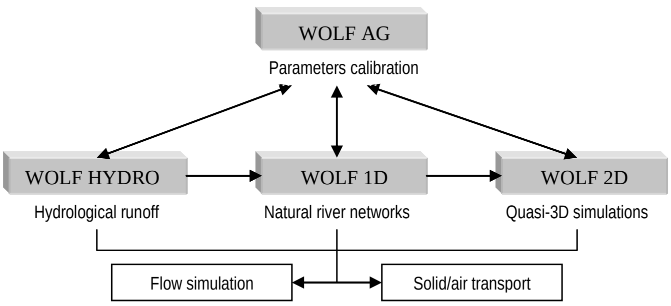


Fig. 2. General layout of WOLF computation units.

The computation unit WOLF 2D described and applied in the present paper is based on the shallow water equations (SWE) and on extended variants of the SWE model, solved with an efficient finite volume technique on multiblock structured grids [5]. It achieves fast computation performances while keeping a sufficiently broad generality with regard to flow regimes prevailing in natural rivers, including highly unsteady flows.

### B. *2D hydrodynamic mathematical model*

In the shallow-water approach the only assumption states that velocities normal to a main flow direction are smaller than those in the main flow direction. As a consequence the pressure field is found to be almost hydrostatic everywhere.

The divergence form of the SWE includes the mass balance:

$$\frac{\partial h}{\partial t} + \frac{\partial q_i}{\partial x_i} = 0 \qquad (1)$$

and the momentum balance:

$$\underbrace{\left[\frac{\partial q_i}{\partial t} + \frac{\partial}{\partial x_i}\left(\frac{q_i q_j}{h}\right)\right]}_{\text{inertia terms}} + gh\left(S_{fi} + \frac{\partial H}{\partial x_i}\right) = 0; \quad j = 1,2 \qquad (2)$$

where Einstein's convention of summation over repeated subscripts has been used. $H$ represents the free surface elevation, $h$ is the water height, $q_i$ designates the unit discharge in direction $i$ and $S_{fi}$ is the friction slope. The SWE model simulates any steady or unsteady situation. A modified-SWE model is available in WOLF to take into consideration the vertical bed curvature thanks to an original approach based on curvilinear coordinates in the vertical plan [3].

The total friction includes three components: bottom, wall and internal friction. The first one is modelled thanks to an empirical law, such as the Manning formula. The friction along vertical boundaries, such as bank walls, is introduced thanks to a physically-based original model. The internal friction is properly reproduced by a turbulence closure model based either on the Prandtl mixing length concept or on the $k$-$\varepsilon$ transport model.

### C. *Solid transport modelling*

A depth-averaged mass balance for the transported solid phase is added to the model.

#### 1) *Mass balance for the sediments*

The time evolution of the bed level is balanced by the advective fluxes of solid materials. Hence the continuity equation for the sediments is stated by the well-known Exner equation:

$$(1-p)\frac{\partial z_{\text{b}}}{\partial t} + \frac{\partial q_{\text{b}x}}{\partial x} + \frac{\partial q_{\text{b}y}}{\partial y} = 0 \qquad (3)$$

where $z_{\text{b}}$ stands for the bed level, $p$ is the porosity and $q_{\text{b}x}$, $q_{\text{b}y}$ represent the unit solid discharges in both horizontal directions. Solid load discharges are evaluated by using algebraic relations for both bed and total load. Several of them are available within WOLF2D.

#### 2) *Gravity-induced solid transport*

The sediment discharges result not only from the action of flow-related forces but also from gravity or from a combination of both origins. In the scope of the herein-presented study, this class of phenomena is modelled by an appealing approach in terms of computation time as well as realism of the results [6]. As soon as the bank becomes locally unstable, solid particles are assumed to move from one element to its neighbour so that the local slope tends to be reduced to the slope of natural repose $\gamma_{\text{nat}}$. The stability analysis is based on a threshold value of the local slope, called "critical slope" $\gamma_{\text{cr}}$. Although simple, this model reproduces the sudden bank collapses, which occur in the case of flushing operations.

#### 3) *Sediment characteristics*

As realistic values as possible have been retained for the sediment characteristics in this work. In particular the relative density of the sediments is taken equal to 2.5 and the bed porosity, used in the sediment mass balance only, is estimated at 30 %.

### D. *Numerical implementation of the conceptual model*

A finite volume technique is used to solve the equations formulated in a conservative form. An original upwind scheme has been developed for both the hydrodynamic part and the fully coupled model [3]. The stability of this second order upwind scheme has been demonstrated through a theoretical study of the mathematical system as well as a von Neumann stability analysis. The source terms representing topography gradients are handled properly.

The numerical implementation of the model is made more sophisticated by several specific features, such as the realistic modelling of transitions between submerged and emerged areas, the interactions between these transitions and the mobile topography, as well as the ability of the solid transport model to distinguish both erodible and non-erodible topographies.

In addition, an automatic mesh refinement tool is available in the model to enhance the convergence rate towards accurate steady-state solutions.

The validation of WOLF has been performed continuously by comparisons with analytical solutions as well as field and laboratory measurements.

### E. *Application to the simulation of the silting process in the reservoir*

The main goals of the first part of the numerical study are the evaluation of the duration of the reservoir complete silting, and the description of the evolution of the sediment front in the 50 km long river valley.

#### 1) *General strategy*

The long-term and large-scale study of silting in a reservoir requires so huge computational resources that it is not possible to perform the simulation with a fully unsteady and coupled numerical model. In the present case, a lighter approach, well sustained on the physical point of view, is applied to drastically reduce the CPU time while reserving reliable results. The strategy adopted consists in describing the water flow by a series of 2D equilibrium states, while the bathymetric evolutions remain estimated by a transient computation.

#### 2) *Discharge and boundary conditions*

The simulation takes into account the seasonal discharges deduced from the measures obtained at a gauging station located 6 km upstream of the dam. This hydrograph is characterized by high seasonal variations. During the main part of the year the upstream discharge in the reservoir is about 200 m³/s, while this latter can be multiplied tenfold during the monsoon. This hydrograph has thus been divided into two parts: the first corresponding to a non-monsoon discharge and the second to a monsoon one. Furthermore both levels have been simply characterized by as seasonal mean value.

At the spillway, a water depth boundary condition is applied in order to respect the mean operation level of the free surface at the elevation 642 m.

#### 3) *Results*

The transient evolution of the bathymetry shows that the propagation of the sediments is widely influenced by the bi-dimensional geometry of the reservoir (Fig. 5). This confirms the relevance and the usefulness of using a fully 2D computation model. It can also be seen that the sediments front keeps a stiff shape.

#### 4) *Conclusions*

An equilibrium state has been determined for the global topography in the reservoir. This state is obtained for a flood mean discharge of 1762 m³/s and solids inflows in accordance with observations performed in the Bhakra reservoir on the same river [8]. From this result the total volume of silted material can be easily deduced and then the filling duration estimated thanks to the hypothesis formulated for the inflow sediment concentrations. The total silting time is evaluated to about 1660 days of flood, which represent approximately 18 years.

When reading these final results, the different sources of uncertainties affecting the computation accuracy (lack of accurate data for inflows, grain sizes and transport mechanisms) have obviously to be kept in mind. Nevertheless, let's recall that fully 2D simulations, mainly unsteady, constitute the state-of-the-art approach accessible up to now for modellers in terms of an acceptable balance between computation time and faithfulness to the physical

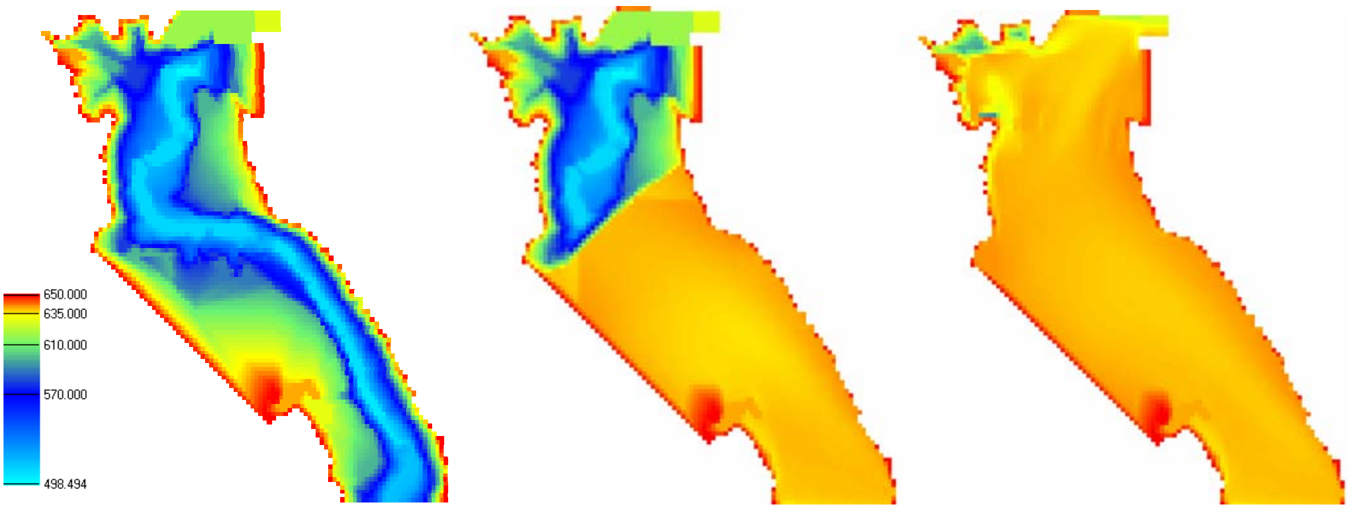


Fig. 5. Topography (m) of the reservoir downstream area to time 0 (a) and after 300 (b) and 568 days of flood (c)

processes for engineering purpose.

### F. *Analysis of flushing operations*

The main goal of the second part of this numerical study consists in predicting the effect of a given flushing scenario in terms of changes in bathymetry in the reservoir.

#### 1) *General strategy*

On the contrary of the gradual silting process induced by sediments reaching the reservoir during several decades, a flushing operation is performed in a much shorter period of time. As a consequence the physical characteristic times of morphology changes are likely to take values of the same order of magnitude as those prevailing for the hydrodynamic phenomena. The computation must thus guarantee a tight coupling between the hydrodynamical part of the model and the sediment transport simulation. A proper computation strategy has thus been applied, ensuring a perfect coupling between the flow and the corresponding solid transport.

#### 2) *Boundary and initial conditions*

At the upstream boundary of the reservoir a suitable hydrograph suggested by EDF, including the effect of the more upstream section of the reservoir, has been applied. The specific hydrograph flowing into the simulated part of the reservoir during a typical flushing operation is characterized by a decreasing phase, starting from a typical flood discharge (2000 $m^3/s$) and finishing at the constant discharge of 1200 $m^3/s$. These boundary conditions, in two successive intervals, are directly considered for the numerical simulation and are extracted from the hydrograph presented on figure 6 (left).

The downstream boundary condition at the outflow has been directly deduced from the limnigraph of figure 6 (right), which represents the time variation of the free surface elevation in the vicinity of the flood spillway as the gates are progressively lifted. The free surface elevation is assumed to remain uniform along the width. The sub-critical regime of the flow at the outflow boundary has been confirmed after the computation in order to warrant that the problem is not ill posed.

A hydrograph similar to figure 6 (left) but giving the solid discharge has to be supplied to the model. This one is simply deduced by applying the solid transport capacity law to the hydrodynamic conditions calculated in the most upstream area of the computation domain.

The initial bathymetric configuration to be considered for simulating the flushing program corresponds to the reservoir nearly fully silted with alluvia, and is thus similar to the final topographic conditions reached after the numerical simulation of the gradual silting process in the reservoir.

#### 3) *Results*

Figure 7 shows the transient evolution of the bottom level in the reservoir. The rate of increase in the regenerated storage volume reaches its maximum value between the fourth and the fifth days of flushing. The instantaneous flushing efficiency is thus optimal during this period of time.

The total recovered storage capacity at this time is estimated to a value higher than five million cubic meters. The sediments on the approach channel are however not completely washed out because the main flow “rushes” towards the flood spillway. The intense erosive effect induced by the flow acceleration is concentrated in a new channel created in the neighbourhood of the dam wall.

#### 4) *Conclusion*

Highly erosive effects are observed locally but seem unable to extend to a very broad part of the reservoir width and, more particularly, are insufficient to clean completely the approach channel. A well-defined channel appears next to the flood spillway and extends along the dam wall. Not surprisingly, this channel generated by the flushing effect remains relatively narrow in comparison with the total width of the reservoir. According to the modelled flushing scenario, the total recovered storage volume is as high as about 5 millions cubic meters.

In conclusion, the numerous and various reported observations based on the results of the 2D simulation lead finally to a global assessment of the flushing effectiveness. The large set of results can be advantageously exploited in the framework of an economical appraisal of the flushing impact and its general efficiency, by balancing the advantage brought

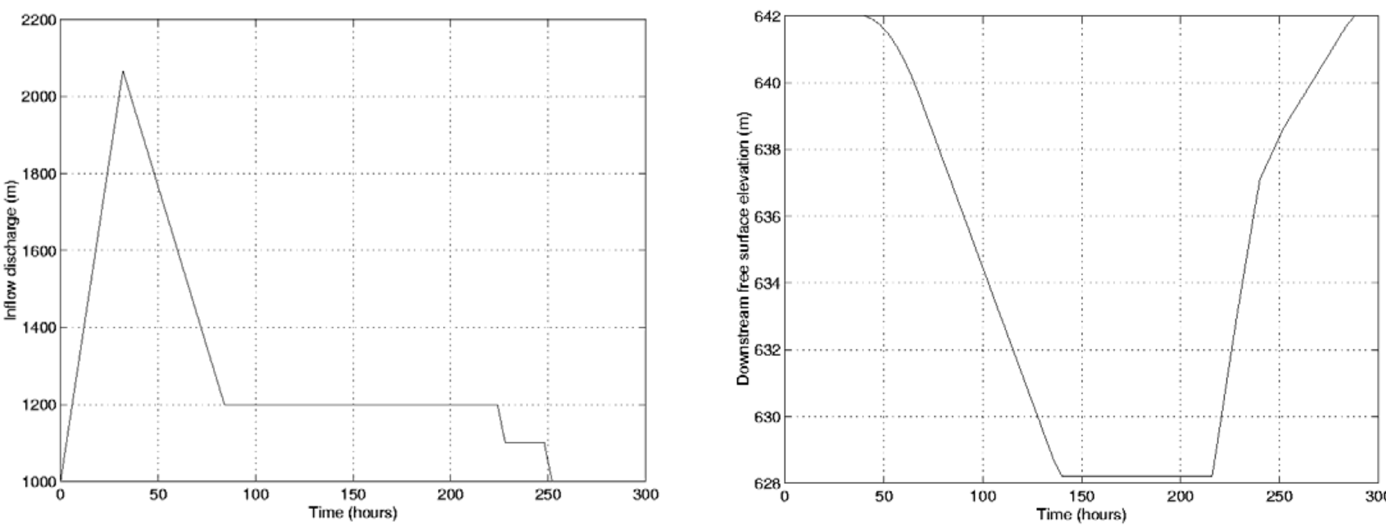


Fig. 6. Typical hydrograph reaching the downstream area of the reservoir at a suitable time for executing a flushing (left) and limnigraph downstream of the reservoir, according to the flushing program (right).

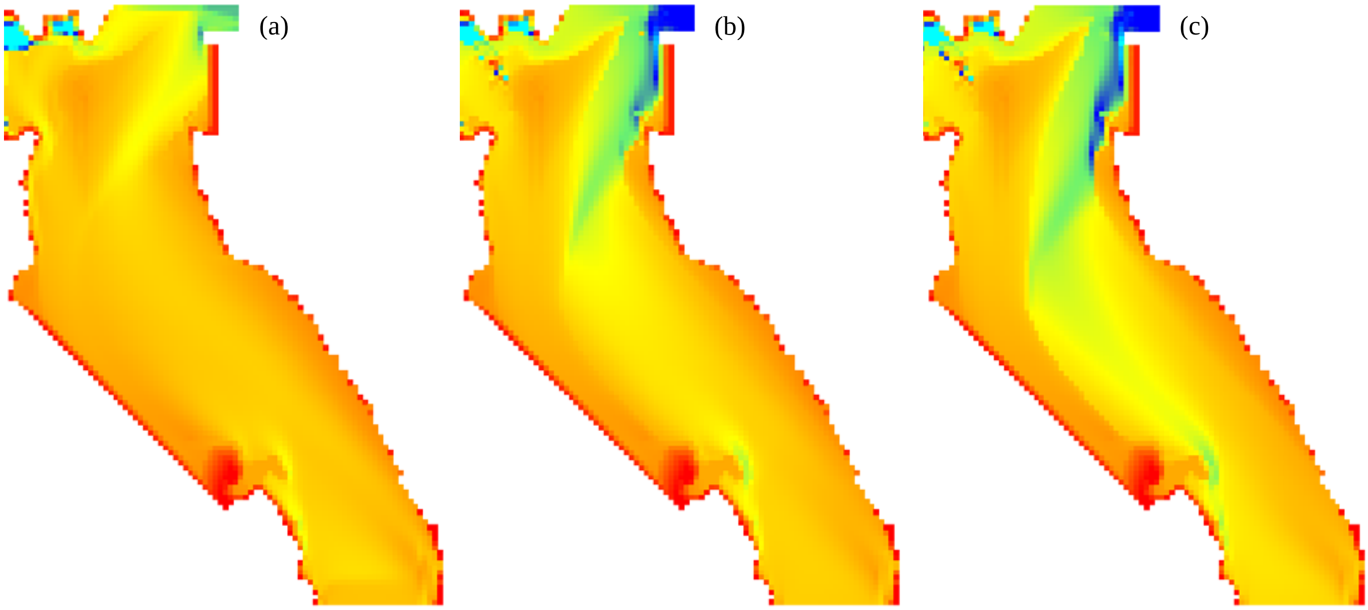


Fig. 7.  Topography (m) of the bottom of the reservoir after 3 days (a), 6 days (b) and 9 days (c) of flushing.

by the recovered storage capacity with the opportunity cost of the volume of lost water [2]. They also recall the question of an economically effective use of a settling structure.

## IV. Experimental Studies

Using suited and theoretically justified similarity laws coupled with realistic scales for the models, experimental studies focused mainly on the hydrodynamic behaviour and solid transport phenomena in the complex under pressure settling structure upstream of the hydropower plant penstocks. Special care has been taken to evaluate the trap efficiency, the evacuation system and the global discharge repartition in the structure. Sawdust, plastic balls or very small sand particles have been used to reproduce real sediments behavior.

### *A. Settling structure characteristics*

The projected settling structure is made up of fourteen identical settling chambers 17 meters wide, 12 meters high and 200 meters long placed side by side and working totally under pressure, and is supplied by a vertical shaft 12 meters wide and 277 meters long. All the chambers discharge through a control section into a collecting chamber, which ensures the clean water feeding of four penstocks downstream of a free surface basin (See fig. 8). The bottom of each settling chamber is subdivided into pyramidal hoppers 17 meters x 19 meters at the top and 3 meters x 3 meters at the bottom. A collector network, under the chambers, ensures the downstream evacuation of the sand trapped in the hoppers.

For the equipment discharge of 784 m³/s, the flow velocity in each chamber is more or less 0.3 m/s and the theoretical cut off diameter for suspended particles is 250 µm

### *B. Scale models characteristics*

The goals of the studies on scale models were to confirm the trap efficiency of a settling chamber at the equipment discharge, to validate the sediments evacuation system at the bottom of the hoppers and to estimate the time and water volume necessary to the cleaning of a chamber, the silting up

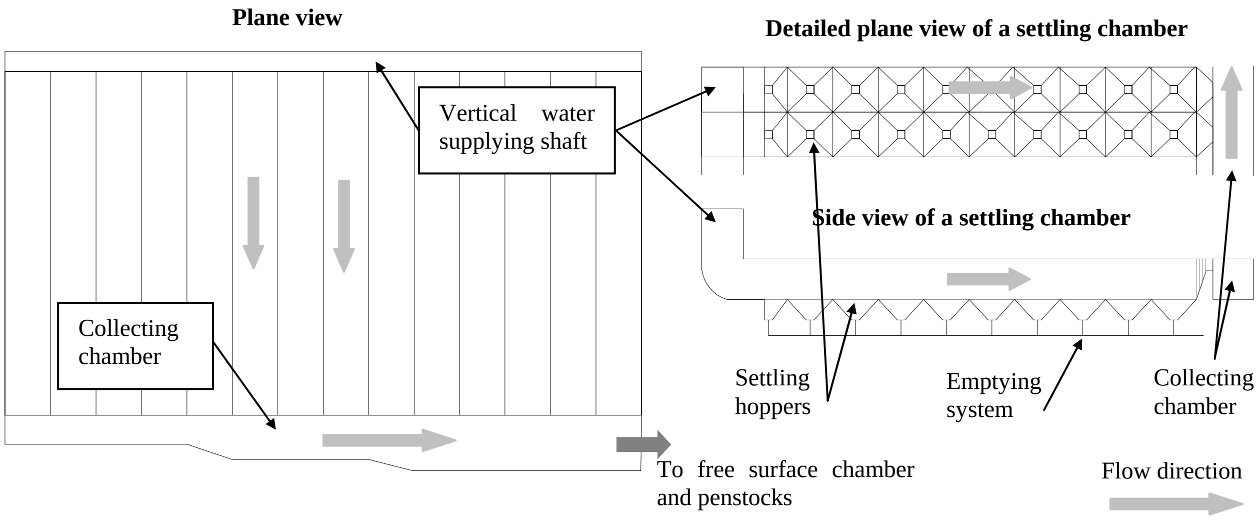


Fig. 8. Scheme of the projected settling structure

of which has reached a critical height. Due to the diversity of the phenomena to be studied and of the physical processes involved, three physical scale models have been built.

A first one represented one settling hopper, at a scale of 1/18.5 (fig. 9). It was designed to study the sediments evacuation system efficiency and to find the maximal filling rate of one hopper before flushing.

A second model represented a settling chamber on its own at a scale of 1/18.5 (fig. 12). Sedimentation has been studied in this model, as well as hoppers and supplying shaft geometry. The evacuation system designed on the first model has also been tested on this second model for some exploitation ways.

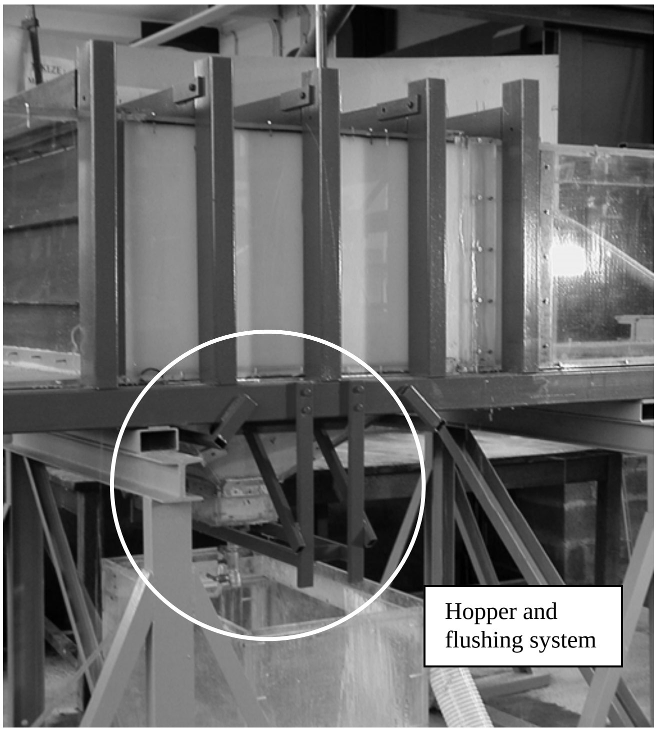


Fig. 9. Scale model of one hopper

Finally, the full settling structure has been represented at a scale of 1/100 in order to analyze the whole hydraulic behavior of the dam complex and more specifically the discharge repartition between the chambers and inertia effects in the system following a sudden closure of the turbines.

The choice of all the different length scales resulted of impositions of measurements accuracy, elimination of disruptive scale effects which could make the similarity imperfect as well as the bulk of the models. Special cares have been taken to find suitable materials to represent real sediments, as a function of the phenomenon to be analyzed in each model. In particular, similarity laws have been carefully studied.

### *C. Similarity laws*

#### *1) Hydrodynamic similarity*

As the flows studied were mainly controlled by gravity and as the friction forces could be supposed negligible, the studies were realized with the same ratio between inertia and gravity forces as on the prototype. This similarity results in the conservation between model and prototype of the non-dimensional number of Froude which leads to the following relation setting the velocity scale $V^*$ when the geometric length scale $L^*$ is chosen:

$$\frac{Fr_m}{Fr_r} = 1 \Rightarrow V^* = \frac{u_m}{u_r} = \sqrt{\frac{h_m}{h_r}} = \sqrt{L^*} \quad (4)$$

where *m* subscripts refer to scale model characteristics, *r* subscripts refer to the real model (prototype) characteristics, *u* is the flow velocity, *h* is the water depth.

The only hypothesis made at this stage is the conservation of the gravity acceleration *g*. The discharge scale $Q^*$ and the time scale $T^*$ can be obtain from relations (4):

$$Q^* = V^* L^{*2} = L^{*5/2} \text{ and } T^* = \frac{L^*}{V^*} = \sqrt{L^*} \quad (5)$$

### *D. Sediments similarity*

#### *1) Entrainment phenomena*

For the study of the emptying of one hopper, and to model sediments entrainment phenomena in general, it is very important to respect the length scale when choosing the size of the solid particles, and this in order to avoid all undesirable effect of mechanical obstruction of the system studied. Therefore, the scale of the particles dimension $d^*$ is given by:

$$\boxed{\frac{d_m}{d_r} = L^*} \quad (6)$$

Moreover, the conservation of the non-dimensional ratio between carrying and resisting forces was imposed to well represent sediments state. The carrying force exerted on particles in a moving liquid of density $\gamma_e$ can be given by the law of Flamant:

$$F_e = \frac{k\,\gamma_e\,\pi\,d^2\,u^2}{8\,g} \quad (7)$$

where *k* is a particles shape dependant factor.

The resistance force of the motionless sediments is a function of their weight and is given by:

$$P = \frac{\pi\,d^3\left(\gamma_s - \gamma_e\right)}{6} \quad (8)$$

where $\gamma_s$ is the density of the sediments.

The conservation of the ratio between these two forces, by taking into account (6), leads to the following scale for relative specific gravity $\rho$ of the sediments, if it is assumed that the real and on model materials have the same shape characteristics :

$$\left(\gamma_s^* - \gamma_e^*\right) = \frac{d^*}{u^{*2}} = 1 \rightarrow \boxed{\Delta\rho^* = 1} \quad (9)$$

According to these similarity laws, silt, i.e. particles with diameter from 7 to 120 µm, have been used in the scale model to represent the sand treated in the prototype, i.e. particles with diameter from 125 µm to 2 mm, when entrainment effects had to be studied.

As regards to the cohesion of the sediments, it seems to be overvalued on the model in comparison with the prototype. Indeed, the dimensions of the sediments are greatly reduced on the model compared with prototype. Adsorption effects (capillary tensions) and electrostatic surface tensions are then increased though the particles used on the model are of the same nature than the ones on the prototype.

*2) Sedimentation effects*

On another hand, the sedimentation of particles in suspension in a liquid is a function of the value of the particles carrying velocity, considered equal to the flow velocity, and of the particles fall velocity $v_s$ , given by the Stokes law:

$$v_s = \sqrt{\frac{4}{3}\frac{d\,g}{C_D}\frac{\Delta\rho}{\rho_f}} \qquad (10)$$

where $\Delta\rho = \rho_{solid} - \rho_{fluid}$ is the relative specific gravity of solid particles, $C_D$ is the particles drag coefficient, a function of their Reynolds number, $\rho_f$ is the specific gravity of the fluid.

In a diagram, the sedimentation effect is represented as:

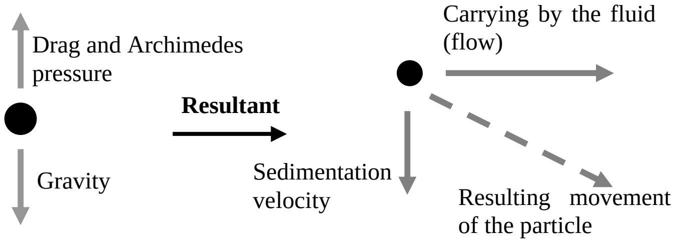


Fig. 11. Main effects involved in particle sedimentation

As flows with sedimentation effects in a preferentially vertical level have to be studied, the conservation of the non-dimensional numbers of Froude and of the ratio between flow and sedimentation velocities have been forced. Thus, on a first approach, it has been imposed to the scale model to work in a horizontal hydrodynamic fluid – sedimentary interaction in the same way on the model and in the reality:

$$\frac{\frac{v_{sm}}{u_m}}{\frac{v_{sr}}{u_r}} = 1 \Rightarrow \frac{v_{sm}}{v_{sr}} = \frac{u_m}{u_r} = \sqrt{L^*} \qquad (11)$$

where the settling velocity is evaluated with the Stokes law.

By expressing in the Stokes relation the drag coefficient for the model and the reality, we have at our disposal an additional degree of freedom which has been used to force the conservation of the sediments drag coefficient:

$$\frac{C_{Dm}}{C_{Dr}} \div \frac{\mathrm{Re}_{p,m}}{\mathrm{Re}_{p,r}} = 1 \Rightarrow \frac{\frac{\rho_{f,m}u_m d_m}{\mu_m}}{\frac{\rho_{f,r}u_r d_r}{\mu_r}} = 1 \qquad (12)$$

Now, the fluid specific gravity $\rho_f$ and its dynamic viscosity $\mu$ are similar, as water is used both for the scale model and the prototype. (12) leads then to the following relation :

$$\frac{d_m}{d_r} = \frac{u_r}{u_m} \Rightarrow \boxed{\frac{d_m}{d_r} = \frac{1}{\sqrt{L^*}}} \qquad (13)$$

By introducing in (10) the expression (11) of the sedimentation velocity, there is

$$\left(\frac{v_{sm}}{v_{sr}}\right)^2 = \frac{d_m}{d_r}\frac{C_{Dr}}{C_{Dm}}\frac{\Delta\rho_m}{\Delta\rho_r}\frac{\rho_{f,r}}{\rho_{f,m}} \Rightarrow L^* = \frac{1}{\sqrt{L^*}}\frac{\Delta\rho_m}{\Delta\rho_r} \qquad (14)$$

and

$$\boxed{\frac{\Delta\rho_m}{\Delta\rho_r} = L^{*3/2}} \qquad (15)$$

Calibrated sawdust saturated with water has been used to model the sediments. Due to their physical nature, these materials are not subject to surface tensions phenomena as strong as the ones observed for example with plastic particles. After 48 hours in water, sawdust density is constant and in good adequation with the needed value from similarity laws developed hereabove.

## E. Model of one hopper

From the initial state of a hopper filled with a certain amount of sediments and without flow in the chamber axis, the sediments flushing system has been tested on this first model: the gates of the emptying pipes were opened and the time to empty one hopper has been measured as well as the shape and volume of the residual deposits.

Due to pipes blocking risks and sediments deposits consolidation phenomena, a small but permanent discharge in the emptying system is necessary. Moreover, it seemed preferable, whatever the adopted solution, to avoid all pipes sections other than vertical between the bottom of the hopper and the principal collector, with a system of flushing short and of large diameter. If an intermittent flushing system is planed, the emptying operations have to be very frequent and of a frequency adapted to the quantity of materials to be evacuated. For example, a discharge of 1 $m^3$/s/hopper during 30 minutes has given a good satisfaction on the scale model for an initial not consolidated silting up rate of 12%.

## F. Model of one settling chamber

If the settling structure had a flat bottom, the theoretical required length to trap sediments of 250 µm would be about 100 m. Now, it is known that the settling structures with a bottom made up of hoppers have to be longer than those with flat bottom. In this case, the structure proposed is as long as 180 meters. The main goal of this part of the studies was to validate the length of the chambers in regards with their trap efficency.

Two kinds of tests have been realized on the scale model. First, sedimentation tests to verify the length of the settling structure. They were realized with discharges in the chamber of 56 and 70 $m^3$/s, corresponding respectively to the average equipment and probable maximum discharge rate. The upstream water level for these tests was fixed to min. or max. exploitation level. Sawdust was injected upstream of the model and the recovered quantities in each hopper were measured at the end of the test (fig. 12). The sawdust quantities which escaped of the model were not measured for it would be necessary to have a more effective settling structure than the one tested, and the needed space to its realization was not available.

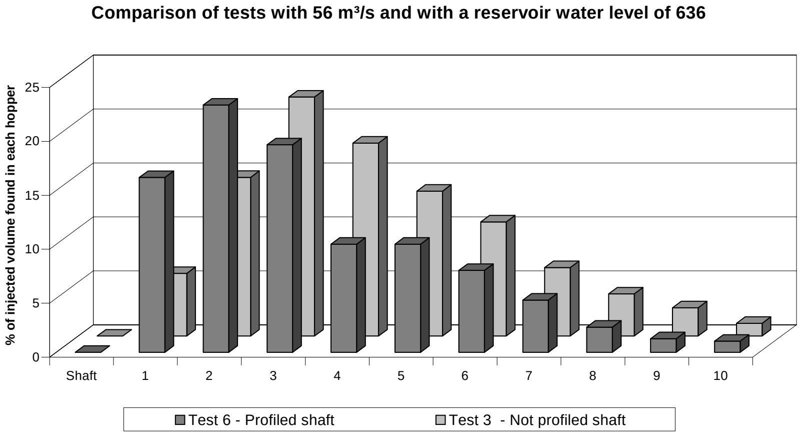



Fig. 12. Volumes of sediments recovered in each of the ten hoppers after a sedimentation test (left) and view of the chamber

The tests tend to confirm the trap efficiency of the settling structure with a cut off diameter of 250 µm for sandy materials and for maximum discharge values of 70m³/s and minimum reservoir water level, what was the worst working configuration. Moreover, as shown on figure 12, it seems possible to shorten the chambers length of 2 hoppers without significantly affecting their trap efficiency.

In a second time, tests for the validation of the continuous flushing system have been realized. These tests had to help validating the value of the discharge evacuated by each hopper during monsoon to verify that for the sediments probable maximum concentration at the entry of the chamber, the evacuation system would not get blocked.

Discontinuous flushing way, chosen after the tests on the desilting hopper alone, has also been validated for natural deposits of sediments which do not cling to the hoppers walls and are not subjected to too fast consolidation phenomena.

Finally, a profiling of the alimentation shaft foot has been proposed to better ensure sedimentation in the first hoppers and to guide the flow at the entry of the chambers. The beneficial effect of the profiling clearly appears on figure 12.

## V. Conclusions

The quasi-3D flow model WOLF2D has been used to analyse the silting processes and to assess the efficiency of flushing operations in a real large dam reservoir.

The simulations are based on the most sophisticated developments available for engineering purpose, both on the theoretical and the numerical levels, keeping in mind the heavy CPU time required.

Obviously the presented results demonstrate the ability of WOLF to treat complex flow phenomena interconnected with sediment entrainment transport and siltation. Further research is currently undertaken for investigating more carefully grain sorting effects and interactions between the transport rate and the turbulence characteristics.

On the other hand, using adapted and theoretically justified similarity laws coupled with realistic scales for physical models, the hydrodynamic behaviour and solid transport phenomena in a complex under pressure settling system have been studied. Special care has been taken to evaluate the trap efficiency and evacuation system working. Sawdust or very small sand particles have been used to model real 250 µm sediments, depending of the studied phenomena.

According to the results of the studies, the length of the structure has been shortened of up to 20 percents and best use instructions have been suggested for the sediment evacuation system.

All the experiments described in this paper, numerical as well as physical, allowed assessing sedimentation problems related to a practical case study, to set up efficient design changes in the structures and to suggest best use instructions to ensure safest and longest operating life of a real projected dam. They underline the advantages arising from a jointed experimental and numerical approach in engineering research.

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