GLOBAL DESIGN OF HYDRAULIC STRUCTURES OPTIMISED WITH PHYSICALLY BASED FLOW SOLVERS ON MULTIBLOCK STRUCTURED GRIDS

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Abstract: This paper presents the numerical studies lead by the Laboratory of Applied Hydrodynamics and Hydraulic Constructions of the University of Liège (HACH) for the rehabilitation of the 21-meter high Nisramont dam in Belgium. After determination of the up-to-date 1000-year return flood using the hydrological runoff model WOLFHYDRO on the global 74,000 ha watershed real topography coupled with statistical analyzes, and after validation on the existing situation and for extreme observed events, the 2D finite volume multiblock flow solver WOLF2D has been applied to the design of the new stilling basin and to the bottom outlet rehabilitation impact study. The multiblock solver possibilities allow mesh refinement close to interesting areas, such as dam spillway and stilling pool, without leading to prohibitive CPU times, while suitable shallow water equations formulation allows the computation of the flows on the strongly vertically curved bottom of the spillway. In the described simulation, 270,000 structured finite volumes, from .25 to 1 meters long, are used to simulate as a whole the flows in the upstream reservoir, dam, spillway, stilling basin and downstream river, this on a real topography.

Keywords: Numerical modeling, shallow water equations, finite volume, structured grid, multiblock

1. INTRODUCTION

In the global framework of climate change, hydraulic structures rehabilitation is an up-to-date subject requiring appropriate design and impact studies. Suitable numerical models, coupled with contemporary computational possibilities, allow engineers to forecast the complex situations induced on real structures by extreme events with a great reliability. In this field, WOLF software, a physically based free surface flows computation package completely set up by the HACH, has proved its efficiency and reliability for years by numerous real applications (Archambeau & al., 2001, 2003).

In this paper, the rehabilitation study of the Nisramont dam is presented. Located on the Ourthe river in Belgium, this 21-meter high dam was built in 1958 and in a first time was dedicated to be used as a cofferdam during the construction of a large dam downstream. But this second dam was never built and Nisramont became a definitive reservoir of 3 hm³ assuming the drinking water supply of a large part of the population of the south of Belgium and producing hydro-electricity, while supporting low-water level discharges of the Ourthe river. Due to its temporary primary tasks, the stilling basin downstream of the three 12.5 meters large bays of the crest spillway has been designed for a temporary use. In order to complete the structure and following climate change observations, the Ministère wallon de l’Equipement et des Transport (MET) - Direction des barrages de l’Est (D. 241), entrusted the

HACH with evaluating up to date critical flood discharges and with designing a new stilling basin able to deal with these probable floods.

After validation on the existing situation and for extreme observed events, the WOLF package has been used to design a new stilling basin.

Fig. 1 Downstream view of the Nisramont dam © HACH

2. THE WOLF PACKAGE

2.1 General presentation

The WOLF free surface flows computation package includes in the same development environment the resolutions of the 1D Saint-Venant equations, the 2D shallow-water (SWE) equations as well as a physically based hydrological model and powerful optimisation capabilities. By this way, WOLF deals with hydraulic phenomena from hydrological runoff and river propagation to extreme erosive flows on realistic mobile topography, such as gradual dam breaching processes, using finite volume method on multiblock structured grid (Dewals & al., 2002, Erpicum & al., 2004). All pre- and post-processing operations are easily controlled through a unique interface, with generation of 3D videos, and integrated optimization tools based on the Genetic Algorithms technique are available within all the solvers (Erpicum & al., 2003). Figure 2 shows a general overview of WOLF computation units.

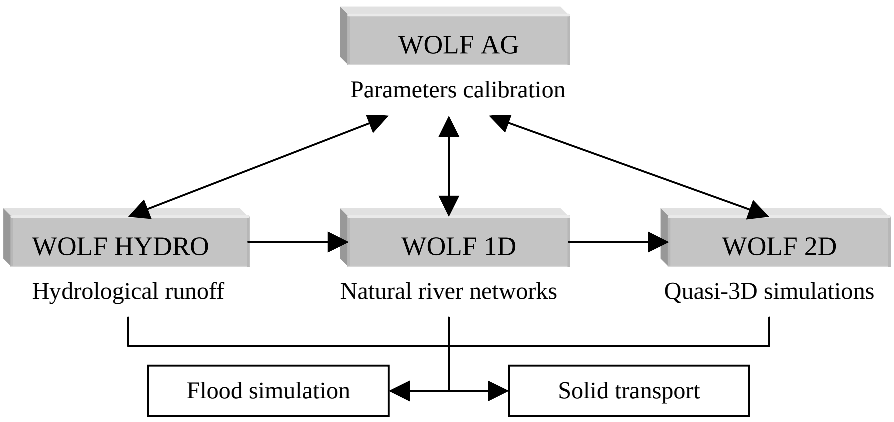

Fig. 2 General organization of WOLF computation units

2.2 WOLFHYDRO

The present version of the hydrological software, WOLFHYDRO, solves the conservative equations of 2-D diffusive wave model with a finite volume method for three specific vertically distributed layers. Different roughness laws (Manning, Darcy-Weissbach, Bathurst,…) are implemented to take into account the macroscopic roughness of the hydrological propagation and various flow regimes.

Originating from the well-known Saint Venant equations describing the flows, the diffusion approach can be obtained by ignoring the inertial terms compared with the gravitational terms, friction and pressure heads. SWE can then be replaced by the following system of parabolic differential equations:

$$\left(S_{fx} + \frac{\partial H}{\partial x} \right) = 0 \tag{1}$$

$$\left(S_{fy} + \frac{\partial H}{\partial y} \right) = 0 \tag{2}$$

where $H(x,y,t)$ is the water surface elevation above an horizontal datum, x, y are horizontal Cartesian coordinates and $S_{fx}(x,y,t)$, $S_{fy}(x,y,t)$ are friction slopes in x and y directions.

In addition and for example, applying the Manning-Strickler law to the description of the friction slopes that appear in the above equations, the relation between the velocity and water depth components can be obtained as

$$S_{fx} = \frac{n_x^2}{h^{\frac{4}{3}}} |w| u = \frac{n_x^2}{h^{\frac{4}{3}}} u \sqrt{\left(u^2 + v^2\right)} \tag{3}$$

$$S_{fy} = \frac{n_y^2}{h^{\frac{4}{3}}} |w| v = \frac{n_y^2}{h^{\frac{4}{3}}} v \sqrt{\left(u^2 + v^2\right)} \tag{4}$$

where $h(x,y,t)$ is the local water depth, $u(x,y,t)$, $v(x,y,t)$ are depth averaged flows velocities in x and y directions, $w = \sqrt{u^2 + v^2}$ is the velocity vector, n_x, n_y are the Manning roughness coefficients in the directions x and y, respectively, and therefore

$$|w|^2 = u^2 + v^2 = h^{\frac{4}{3}} \sqrt{\frac{S_{fx}^2}{n_x^4} + \frac{S_{fy}^2}{n_y^4}} \tag{5}$$

Lastly, using the above relation in the expressions (3) and (4) for S_{fx} and S_{fy} determines the following expressions for the components of the velocity vector :

$$u = -\frac{\partial H}{\partial x} \frac{h^{\frac{2}{3}}}{n_x^2} \frac{1}{\left[\left(\frac{\partial H}{\partial x} \right)^2 \frac{1}{n_x^4} + \left(\frac{\partial H}{\partial y} \right)^2 \frac{1}{n_y^4} \right]^{\frac{1}{4}}} \tag{6}$$

$$v = -\frac{\partial H}{\partial y} \frac{h^{\frac{2}{3}}}{n_y^2} \frac{1}{\left[\left(\frac{\partial H}{\partial x} \right)^2 \frac{1}{n_x^4} + \left(\frac{\partial H}{\partial y} \right)^2 \frac{1}{n_y^4} \right]^{\frac{1}{4}}} \tag{7}$$

As other main features, the model has three bunk layers to simulate respectively the thin runoff, the hypodermic propagation and the transfer to the groundwater. It handles the rainfall propagation, spatially and temporally variable according to the cloudy fronts, on the DEM, and a complete 1D model propagates the lateral floods components in the drainage path. The unsteady infiltration law permits the reforming of the soil capacity after the rain has stopped, and thus the calculation of long periods is possible without stopping the software (Archambeau & al., 2001).

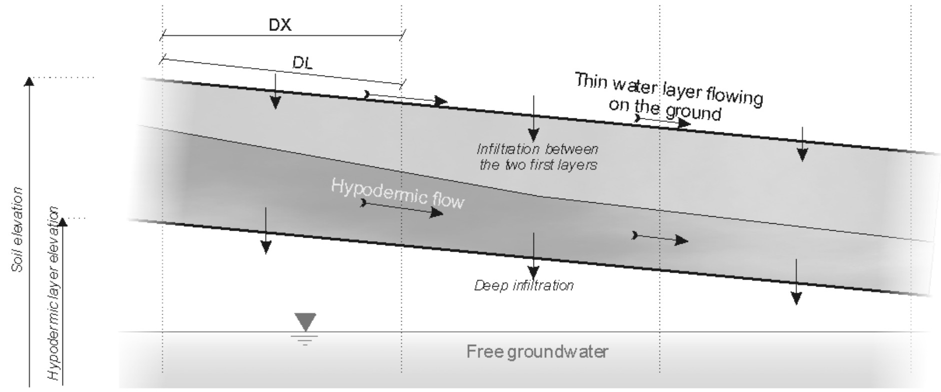

Fig. 3 Three flow layers computed in WOLFHYDRO

2.3 WOLF2D

2.3.1 Equations

The equations governing the movement of a liquid are based on the mass and momentum balances. After integration over the water height, the mass conservation equation for an incompressible open-channel flow states:

$$\frac{\partial h}{\partial t}+\frac{\partial uh}{\partial x}+\frac{\partial vh}{\partial y}=0 \tag{8}$$

If the vertical velocities are weak enough in comparison with the horizontal ones, so that the square of their ratio may be neglected, then the shallow-water equations can be used in the conservative form :

$$\frac{\partial}{\partial t}(hu)+\frac{\partial}{\partial x}\left(\rho_{xx}hu^2+\frac{gh^2}{2}\right)+\frac{\partial}{\partial y}\left(\rho_{xy}huv\right)+gh\frac{\partial z_b}{\partial x}=-\frac{\tau_{bx}}{\rho}+\frac{1}{\rho}\left(S_{xx}+S_{xy}\right) \tag{9}$$

$$\frac{\partial}{\partial t}(hv)+\frac{\partial}{\partial y}\left(\rho_{yy}hv^2+\frac{gh^2}{2}\right)+\frac{\partial}{\partial x}\left(\rho_{yx}huv\right)+gh\frac{\partial z_b}{\partial y}=-\frac{\tau_{by}}{\rho}+\frac{1}{\rho}\left(S_{yy}+S_{yx}\right) \tag{10}$$

where g is the gravity acceleration, t the time, ρ_{ij} the coefficients of uneven velocity profile, z_b the bed elevation, S_{ij} the diffusive terms (viscous and turbulent), ρ the water density and τ_{bx} and τ_{by} the shear stress components.

It must be outlined that no restrictive assumption is needed for the bottom slope, as shown by Pirotton (1994).

2.3.2 Spatial and temporal discretisation

The spatial discretisation of the 2D conservative shallow-water equations is performed by a finite volume method. This ensures the mass and momentum properties to be conserved, even across discontinuities such as hydraulic jumps.

Designing a stable flux computation has always been a challenging and tough issue in computing fluid dynamics, especially if discontinuous solutions are expected. Flux treatment is here based on an original flux-vector splitting technique developed for WOLF. The hydrodynamic fluxes are split and evaluated partly downstream and partly upstream according to the requirements of a Von Neumann stability analysis. Special care is done for consistent bottom slope evaluation. Optimal agreement with non-conservative and source terms as well as low computational cost are the main advantages of this original scheme.

As we are mostly interested in transient flows and flood waves, an accurate and non-dissipative explicit temporal scheme has been chosen for the time integration. In this way, the explicit Runge-Kutta method is applied here to solve the ordinary differential equations obtained after spatial discretisation.

However, implicit time integration schemes are also available in WOLF in order to accelerate the convergence process for steady state solutions.

2.3.4 Other main features of WOLF 2D

WOLF2D includes an efficient mesh generator and deals with multiblock structured grids. These features increase the size of potential problems to be solved and allow mesh refinement close to interesting areas without leading to prohibitive CPU times. Coordinates (x, y) of the simulation domain and of the different blocks, with their respective mesh sizes, are the only data needed to automatically define the computational grid.

The fluxes at blocks interfaces are built on each border side, using linear reconstruction efficiently limited to ensure a proper order of precision, by the way of ghost points, the unknowns values of which are adequately evaluated from subjacent real cells data. Moreover, to be conservative through adjacent blocks and to compute accurate mass and momentum balances, fluxes interesting larger boundary meshes are taken into account at the level of the smaller ones.

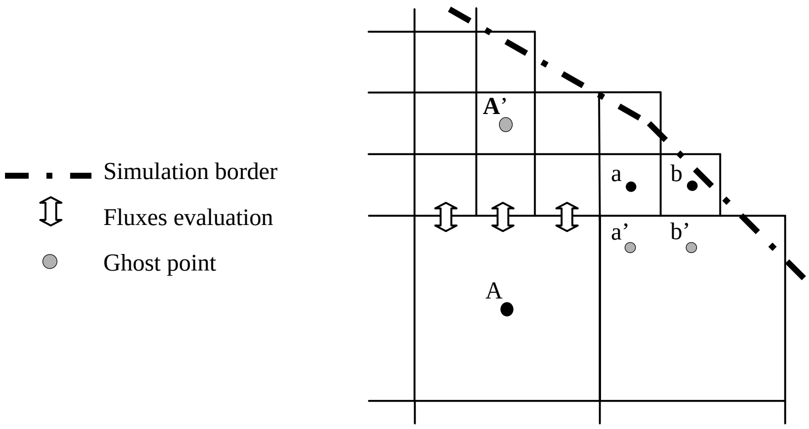

Fig. 4 Ghost points and fluxes evaluation level description

The algorithm is designed to deal automatically with any moving boundary. It incorporates an original method to handle covered and uncovered (wet and dry) cells. Thanks to an efficient iterative resolution of the continuity equation at each time step, based on a correction of the discharge fluxes before any evaluation of momentum balances, the conservation of the hydrodynamic properties is ensured in the whole simulation. In addition, an adaptative grid extension technique achieves a drastic reduction in computation time, by restricting the simulation domain to the wet cells and a surrounding narrow strip.

In order to adequately compute friction terms on a steep topography, an original evaluation of the friction areas is realized. Moreover, friction side edges are taken into account where a boundary between dry and wet cells is detected.

3. HYDROLOGICAL STUDY

The first part of the Nisramont dam rehabilitation study consisted in evaluating up-to-date critical flood discharges for the watershed. Indeed, the statistical analysis of the discharges values for the period 1959-2001 showed a sligth increase of the maximum floods, which one coupled with today climate change considerations rises the question of the adequation of initial old project flood.

Using all the available data along time, probable flood values have been computed using classical statistical laws. The WOLFHYDRO solver has in a second time been used to validate the order of magnitude of these floods in comparison with intensity - duration - frequency rain curves. 74,418 finite volumes 100 x 100 meters have been used for the hydrological computation on the whole dam watershed, with topographic informations from the DEM of the Wallonia Region.

Finally, values of 340 m³/s and 200 m³/s have been assumed as respectively 1000-years and 50-year flood. The 1000-year flood has been chosen as design flood.

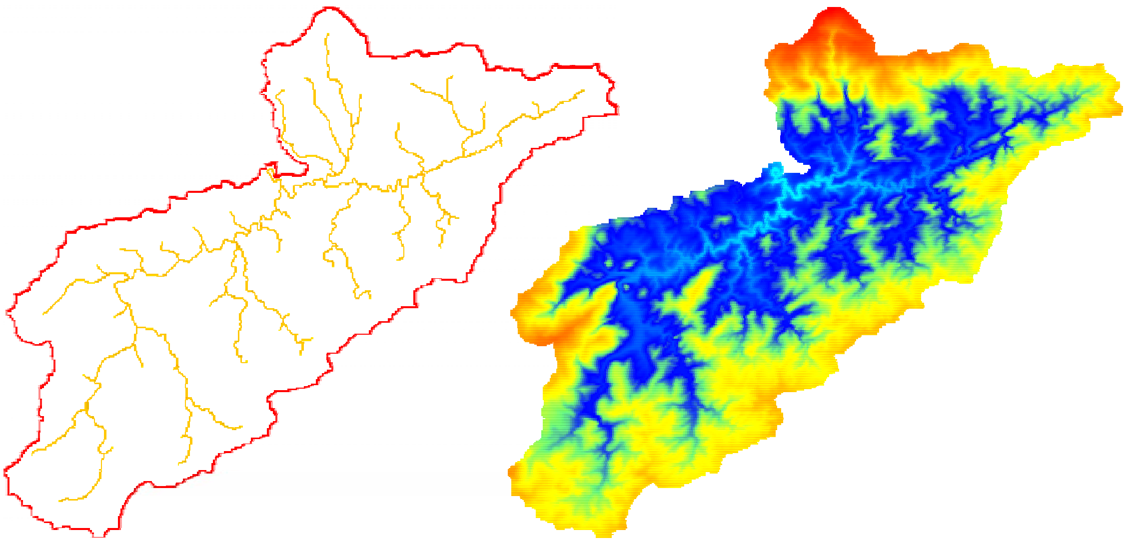

Fig. 5 River network (left) and topographic data (right) of the Nisramont watershed used in WOLFHYDRO

4. 2D SIMULATION FEATURES

The domain of simulation covered 700 meters of Ourthe river, 50 meters upstream and 650 downstream of the dam crest. Thanks to the new model, the whole structure has been computed in a single process.

Upstream discharge boundary conditions have been deduced from large scale simulation of the whole reservoir. Downstream, a limnimeter placed by the Hydrological Studies Service (SETHY) has been used as a water level boundary condition.

General topographic information was available on a 1 meter square grid and came from aerial laser measurements (MET). The main river bed topography has been interpolated by WOLF from cross section profiles available every 25 meters. This information has been integrated in WOLF and automatically interpolated on a regular 25 cm square grid. Then the geometry and the topography of the dam have been manually integrated from paper plans.

In order to minimize CPU time while keeping good accuracy in critical parts of the domain, four different blocks have been defined for the computation. The mesh size was 25 cm in the upstream reservoir, on the dam and stilling basin, while it was 1 meter on the downstream part, as explained on figure 6. A new and original model based on curvilinear coordinates has been used in block 2 for modelling the spillway, while classical SWE model of WOLF2D has been used in the other blocks.

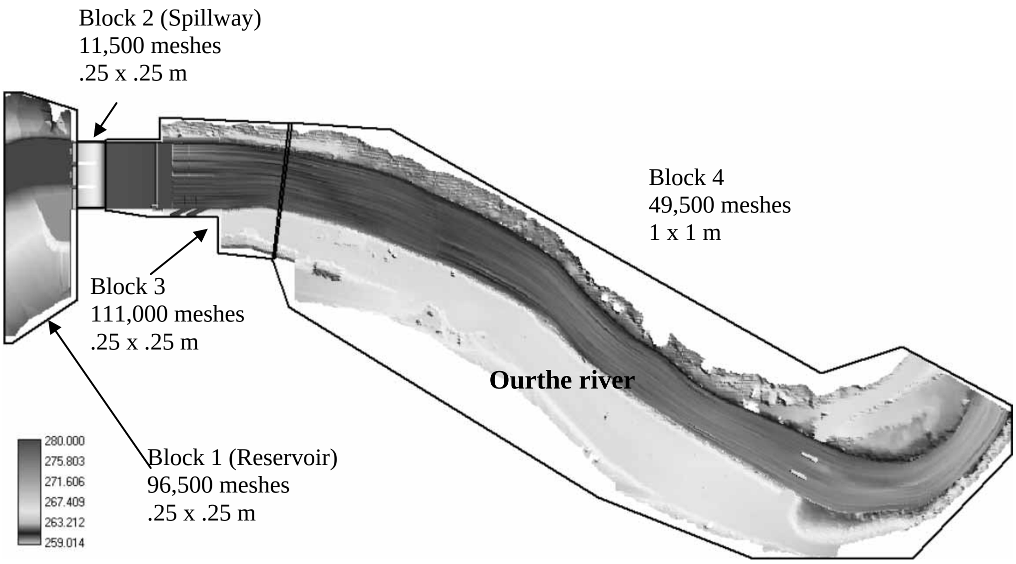

Fig. 6 Shaded view of the topography used for the 2D simulation

5. RESULTS

Simulation of the well documented 175 m³/s flood of January 3rd 2003 leads to very good agreement between numerical results and photos of the real event. For example, the position of the hydraulic jump at the downstream extremity of the stilling basin is reliable to make comparisons. Cross waves shape and length have also been compared, as well as dried areas at the spillway piles bottom. Moreover, water levels reached in the river downstream of the dam were in good agreement with those measured in reality.

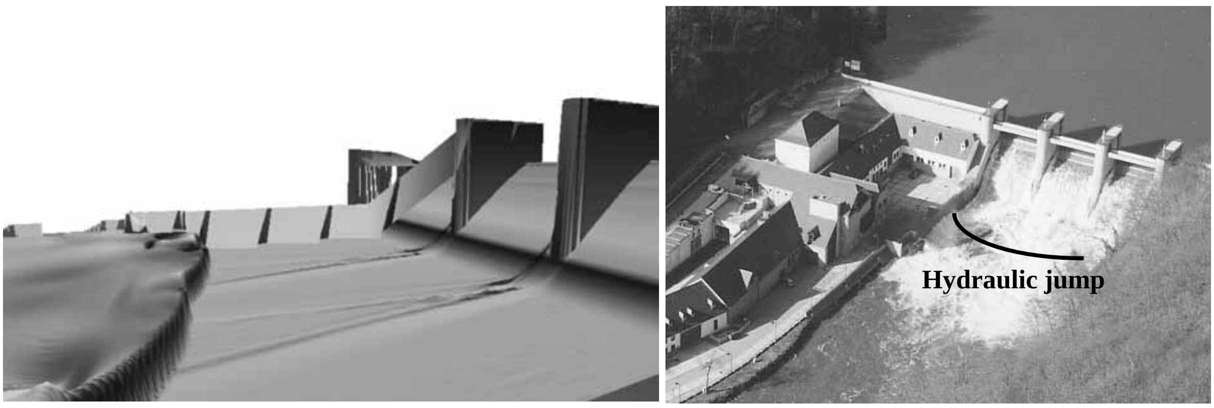

Fig. 7 175 m³/s flood on the spillway - 3D view of the numerical computation (left © HACH) and of the real situation (right © MET)

Following this first validation and calibration stage, at the end of which Manning's coefficient has been found equal to 0.014 and 0.037 respectively for concrete areas and natural river, the numerical model has been used to search for a new design of the stilling basin able to deal with the design flood of 340 m³/s. In the same time, solutions have been searched for the rehabilitation of the three bottom outlets of the dam.

Finally, this leads to a new design of the spillway structures, with a lenghtened stilling basin downstream and new cofferdam piers in the reservoir close to the spillway crest. Hydraulic consequences of these new structures have been numerically evaluated with the aim to find a solution inducing zero modification in comparison with the actual situation.

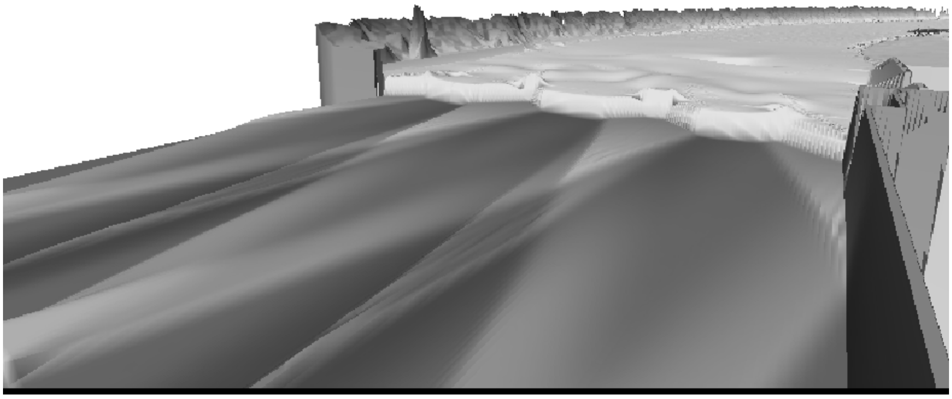

Fig. 8 Computation results of a 100-year flood in the new silting basin with working of the bottom outlets

6. CONCLUSIONS

In this paper, several components of the WOLF free surface flow computation package have been successfully used to assess in a whole the hydraulic behaviour of a dam complex. In particular, WOLF 2D multiblock flow solver has shown its ability to accurately compute in a single way the flow over a spillway, from upstream reservoir to downstream natural river with very good agreements in regards with on the spot data for extreme observed events.

Up to date critical floods have been evaluated, and, consequently, a new adequate design of the silting structures has been proposed, which has been carefully validated thanks to WOLF software.

Experimental modelling has been considered for decades as the single tool for the design of hydraulic structures. Whenever appropriate similitude laws are applied, scale models provide the modeller with reliable results. Though attractive for highly complex configurations (e.g. aerated or sediment-laden turbulent flows), such experimental tests suffer from their high cost and weak flexibility. This article aims to prove that today numerical models have become more attractive tools for predicting a wide scope of flow behaviours and can be considered as a credible alternative to classical scale models for a large set of applications.

REFERENCES

Archambeau, P., Erpicum, S., Mouzelard, Th., Pirotton, M., 2001, Experimental - numerical interaction: an example of a large dam in Laos, *in Water Resources Management 2001*, Progress in water resources, WIT Press, Southampton, Boston, pp. 365-374

Archambeau, P., Erpicum, S., Mouzelard, Th., Pirotton, M., 2001, Impact studies and water management with WOLFHYDRO : a new physically based hydrological solver, *International Symposium on Environmental Hydraulics*, Arizona State University, USA

Archambeau, P., Dewals, B., Erpicum, S., Detrembleur, S., Pirotton, M., 2003, A set of efficient numerical tools for floodplain modeling, *International Symposium on Shallow Flows*, IfH & TU Delft, The Netherland

Dewals, B., Archambeau, P., Erpicum, S., Mouzelard, Th., Pirotton, M., 2002, Coupled computations of highly erosive flows with WOLF software, *in 5th International Conference on Hydro -Science & -Engineering*, Warsaw University of Technology

Erpicum, S., Archambeau, P., Dewals, B., Mouzelard, Th., Pirotton, M., 2003, Optimising a cascade of hydroelectric power stations with the WOLF package, in *Water resources management*, Gran Canaria: W. I. T.

Erpicum, S., Archambeau, P., Dewals, B., Detrembleur, S., Fraikin, C., Pirotton, M., 2004, Computation of the Malpasset dam break with a 2D conservative flow solver on a multiblock structured grid, *in 6th International Conference on Hydroinformatics*, Liong, Phoon & Babovic, Singapore

Pirotton M., 1994, Modélisation des discontinuités en écoulement instationnaire à surface libre, PhD Thesis, LHCN, Liège, Belgium