Numerical tools for dam break risk assessment: validation and application to a large complex of dams

B. J. DEWALS, FNRS & University of Liege, Belgium
S. ERPICUM, University of Liege, Belgium
P. ARCHAMBEAU, University of Liege, Belgium
S. DETREMBLEUR, University of Liege, Belgium
M. PIROTTON, University of Liege, Liege, Belgium

SYNOPSIS. The present paper first describes briefly the hydrodynamic model WOLF 2D. Secondly, the simulation of the Malpasset dam break enables to highlight the effectiveness of WOLF 2D. Lastly, the model is applied to simulate the flood generated by the hypothetic collapse of a large concrete dam, which would induce three dam breaks in cascade.

INTRODUCTION

For more than ten years, the HACH (Applied Hydrodynamics and Hydraulic Constructions) research unit from the University of Liege has been developing numerical tools for simulating a wide range of free surface flows and transport phenomena. Those various computational models are interconnected and integrated within one single software package named WOLF. After a series of validation tests (benchmarking) and numerous comparisons with other internationally available models, the Belgian Ministry for Facility and Transport (MET) has selected WOLF for performing flood risk analysis on the main rivers in the South of Belgium and for conducting dam safety risk analysis in the country. The present paper focuses on the practical application of the model WOLF 2D for predicting the flow induced by dam breaks and for performing risk assessment.

The main features of WOLF 2D are first depicted. Then, the simulation of the Malpasset dam break is exploited to demonstrate the efficiency and accuracy of the model. Finally, the paper details the application of WOLF 2D to the simulation of the flood wave generated by the hypothetic instantaneous collapse of a large concrete dam. As this dam failure would occur upstream of a complex of five dams, it would induce three other dam breaks in cascade, including the gradual breaching of a 20-meter high rockfill dam. Those dam breaks in cascade are considered in the computation.

Improvements in reservoir construction, operation and maintenance. Thomas Telford, London, 2006

THE HYDRODYNAMIC MODEL WOLF 2D

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

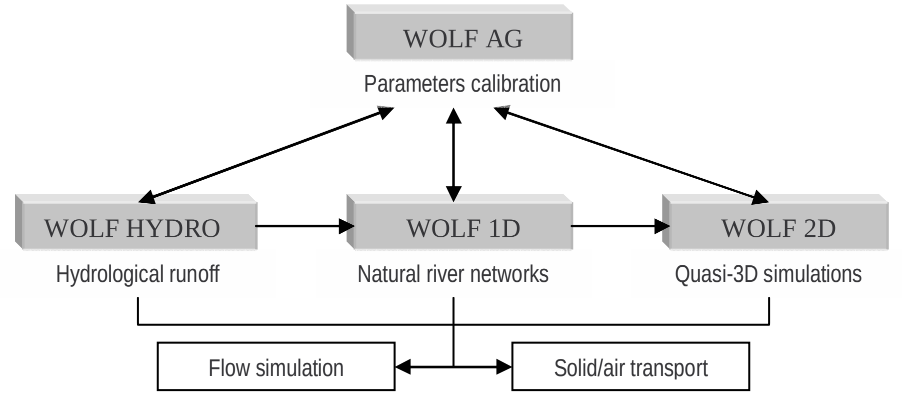

Figure 1: General layout of WOLF computation units.

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. It achieves fast computation performances while keeping a sufficiently broad generality with regard to flow regimes prevailing in natural rivers, including highly unsteady flows.

Physical system and conceptual 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 large majority of flows occurring in rivers, even highly transient flows such as those induced by dam breaks, can reasonably be seen as shallow everywhere, except in the vicinity of some singularities (e.g. wave front). The divergence form of the shallow-water equations includes the mass balance:

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

and the momentum balance:

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

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 specific discharge in direction i and S_{fi} is the friction slope.

Algorithmic implementation

The space discretization of the 2D conservative shallow-water equations is performed by a finite volume method. This ensures a proper mass and momentum conservation, which is a prerequisite for handling reliably discontinuous solutions such as moving hydraulic jumps. As a consequence no assumption is required as regards the smoothness of the unknowns.

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 according to the requirements of a Von Neumann stability analysis. Much care has been taken to handle properly the source terms representing topography gradients.

Since the model is applied to transient flows and flood waves, the time integration is performed by means of a second order accurate and hardly dissipative explicit Runge-Kutta method.

Friction modelling

River and floodplain flows are mainly driven by topography gradients and by friction effects. The total friction includes three components: bottom friction (drag and roughness), wall friction and internal friction.

The bottom friction is classically modelled thanks to an empirical law, such as the Manning formula. The model enables the definition of a spatially distributed roughness coefficient. This parameter can thus easily be locally adjusted as a function of local soil properties, vegetation or sub-grid bed forms. An original evaluation of the real shear surfaces is realized and the friction along vertical boundaries, such as bank walls, is reproduced through a process-oriented model developed by the authors.

Multiblock grid and automatic grid adaptation

WOLF 2D deals with multiblock structured grids. This feature enables a mesh refinement close to interesting areas without leading to prohibitive CPU times. A grid adaptation technique restricts the simulation domain to the wet cells, thus achieving potentially drastic reductions in CPU times.

Besides, the model 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 prior to any evaluation of momentum balances, a correct mass conservation is ensured in the whole domain.

User interface

A user-friendly interface makes the pre- and post-processing operations very convenient and straightforward to control, including a wide range of graphic capabilities such as 2D and 3D views as well as animations.

VALIDATION: MALPASSET DAM BREAK

Located in a narrow gorge of the Reyran River in the Department of Var in France, the double curved 66.5 metres high Malpasset arch dam has been built for irrigation purpose and for drinking water storage. Its crest was 223 metres long and the maximum reservoir capacity was 55 millions m³.

Description of the accident and collected data

At 21:14 on 2 December 1959, during the first filling of the reservoir, the dam broke almost instantaneously, inducing the catastrophic sudden release of 48 millions cubic metres of water in the 12-kilometer long river valley down to the town of Frejus and the Mediterranean Sea. A total of 423 casualties were reported [4, 6]. Further investigations showed that key factors in the dam failure were ground water pressure and left bank rock nature. As this dramatic real dam break case has been well documented, it has also been extensively used as a benchmark for validation of numerical models. Indeed, estimations of propagation times are available, since the shut-down time of three electric transformers destroyed by the wave are known. Similarly, a survey conducted by the police enabled to determine the flood level marks on both riverbanks. Finally, a non-distorted 1/400-scale model was built in 1964 by EDF and was calibrated against field measurements. This model has thus provided the modellers with additional data of water level evolution and propagation times [4, 7].

Characteristics of the simulation

By means of a multiblock regular grid, the mesh is refined close to strategic areas (dam location, sharp river bends), without leading to prohibitive CPU times. 180,000 cells, with three unknowns, are used to simulate the reservoir emptying and the wave propagation down to the sea (Figure 2).

Because of the important changes in the topography after the accident, an old map (1/20,000 IGN map of Saint-Tropez n°3, dated 1931) has been used by EDF to generate the initial bottom elevation of the valley. 13,541 points have been digitised to cover the area of interest. These points have been interpolated to generate a finer Digital Elevation Model (DEM) on the 180,000 cells finite volume multiblock grid exploited for the numerical simulation with WOLF 2D (Figure 2). The elevation of the domain ranges from minus 20 metres ABS at the sea bottom to plus 100 metres ABS, which corresponds to the estimated initial free surface level in the reservoir (with an uncertainty of about 50 cm).

From physical scale model tests, the Strickler roughness coefficient K has been estimated to be in the range of 30 to 40 m$^{1/3}$/s. Four simulations have been carried out with K values of 20, 30, 35 and 40 m$^{1/3}$/s.

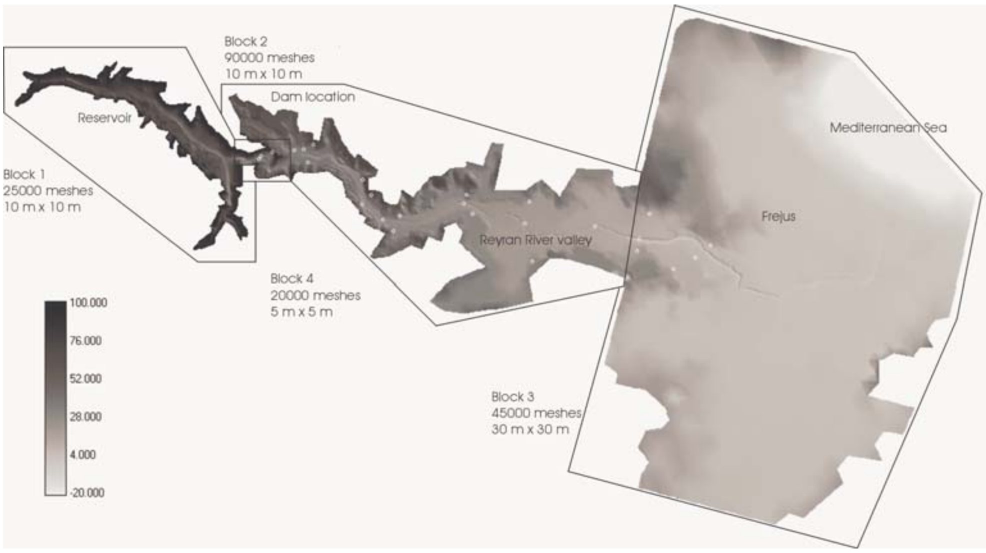

Figure 2. Shaded representation of the interpolated topography and definition of the blocks characteristics on the multiblock computation grid. Position of the field and laboratory measurement points.

Initially, the reservoir is at the level 100 metres ABS and, except in the reservoir as well as in the sea, the computation domain is totally dry, though in the reality a negligible but unknown base flow escaped from the dam. The simulations were run with a CFL number of 0.1 to maximize the accuracy.

Results

Figure 3 and Figure 4 enable to compare the computed results with the field and laboratory measurements, both in terms of wave arrival time and of maximum water levels. Indexes A to C refer the three electric transformers. Since transformer A is located in the bottom of the valley, its shutdown time corresponds indeed to the wave arrival time. For the two others, the shutdown time is assumed to be between wave arrival time and time of maximum water level. Therefore it is more relevant to compare the time interval between the two shutdowns (Figure 3). The computed arrival times are found to be in satisfactory agreement with the measurements. The value of $K = 35\ \mathrm{m}^{1/3}/\mathrm{s}$ appears to fit best reference data. This fact also corroborates the corresponding results from the physical tests performed by EDF.

Given the topography accuracy, the maximum water levels are found to be in good agreement with the measurement points, as shown by Figure 4. It must be outlined that the sensitivity of the results to the value of the roughness coefficient is particularly weak.

The user-interface of WOLF enables to easily produce and edit several risk maps, such as wave arrival time and highest water levels. These maps corroborate again the reliability of the simulation results, as shown by Figure 5 in terms of flood extension.

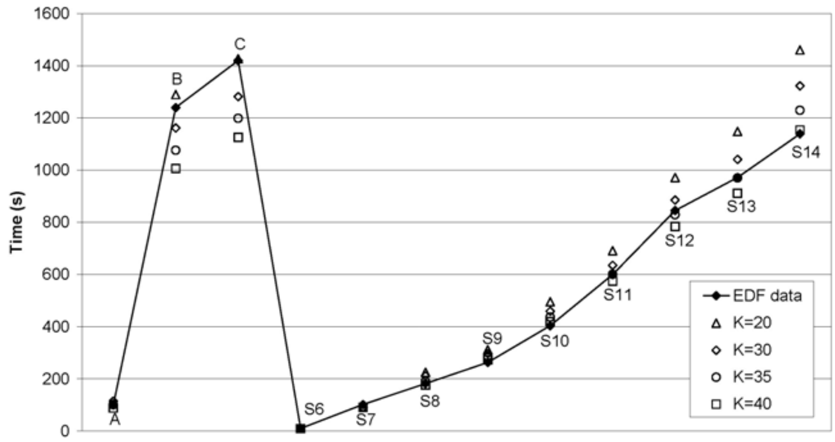

Figure 3. Wave arrival time to electric transformers (A to C) and to the gauges (S6 to S14) of the scale model.

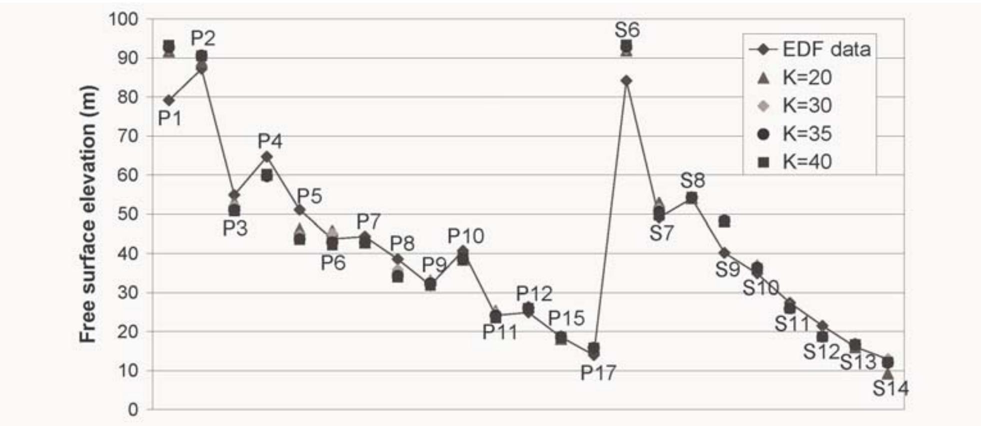

Figure 4. Maximum water level at police survey points (P1 to P17) and at the gauges (S6 to S14) of the scale model.

Figure 5. Map of highest water levels. Comparison of the flood extension with the police survey points.

APPLICATION: DAM BREAK ON A COMPLEX OF FIVE DAMS

The hydrodynamic model WOLF 2D has been applied in the framework of a complete risk assessment study of an important complex of dams.

The main dam (dam n°1), a 50 m-high concrete dam, is located upstream of a complex of five dams, including a 20-meter high rockfill embankment one (dam n°2). Figure 6 illustrates the global configuration of the complex of dams.

As a consequence of this layout of several dams, the hypothetical failure of the upstream concrete dam (dam n°1) is likely to induce other dam breaks in cascade. Therefore the risk analysis of such a complex must be performed globally and not simply for each dam individually.

In the following paragraphs, the failure scenario of dam n°1 is first detailed. Secondly, the propagation of the dam break wave is studied on the hydraulic plant itself and the potential breaching in cascade of other dams is analyzed. In a third step, the simulation of the propagation of the flood wave is performed in the whole downstream valley, taking into consideration the sudden collapse or the gradual breaching of the dams located downstream of the main one.

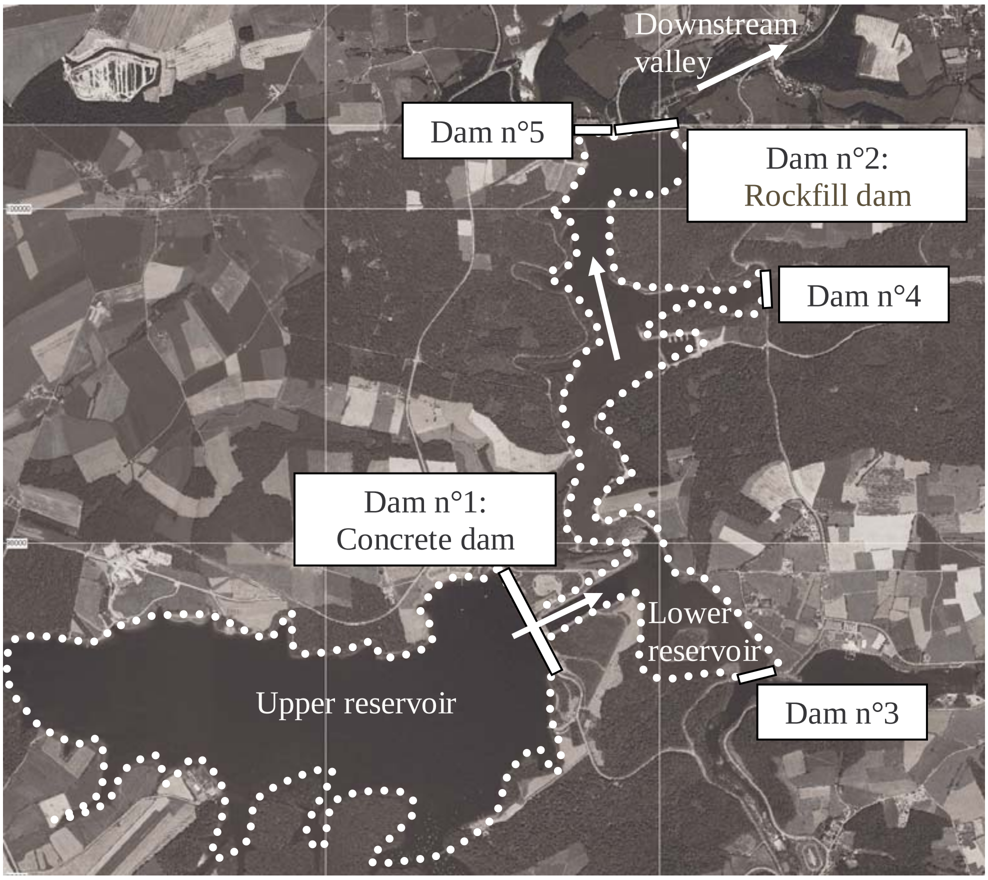

Figure 6: Global layout of the complex of five dams.

Dam break scenario

Defining the failure scenario requires to identify the proper breach formation time as well as the final breach size. According to ICOLD's recommendations, the failure of a concrete dam is supposed to be purely instantaneous. Regarding the final breach geometry in a concrete dam, the question is more complex. Indeed, the guidelines to select this parameter differ from one norm or legislation to another and there is no general rule. For this reason, a sensitivity analysis has been performed here by simulating the induced flow in the case of two different final breach widths: either a total collapse (width: 800 m) or a 200 m-wide breach (see Figure 7). The results of the computation reveal that the difference in the peak discharge value remains lower than 15 %. This can obviously be explained by the higher "efficiency" of the section of the valley in its centre (where the narrower breach is located). As a consequence the hypothesis of a total collapse of dam n°1 is selected, since it doesn't lead to an unrealistic overestimation of the flow.

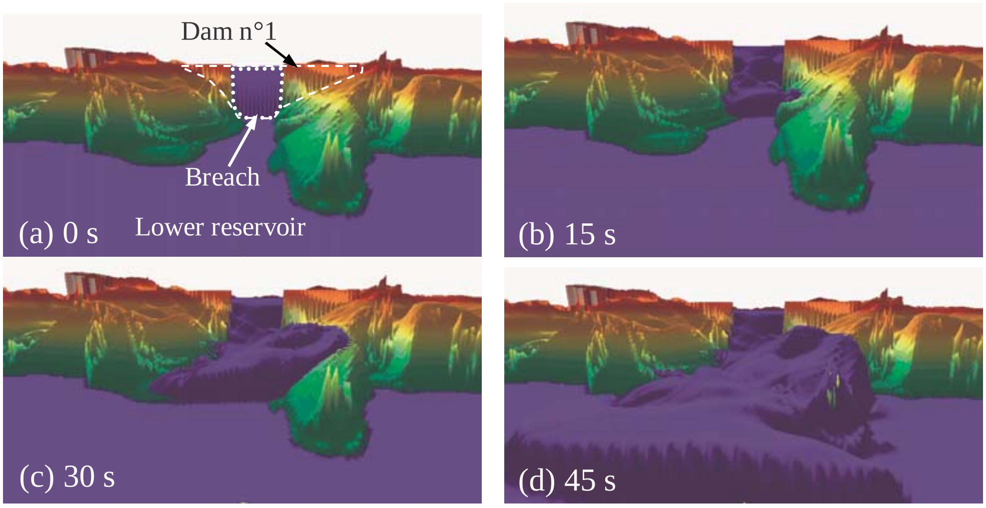

Figure 7: 3D view from downstream of the flow induced by a 200 m wide breach formed instantaneously in the concrete main dam (dam n°1).

Hydraulic and structural impact on the complex of dams

By means of a 2D numerical simulation with WOLF 2D, involving over 400,000 computation cells, the detailed propagation of the waves induced on the lower reservoir (see Figure 6) has been simulated.

Input data

Let's emphasize that the accuracy of the simulation results depends widely on the quality of available topographic data. In the present case, the simulation is based on a highly accurate Digital Elevation Model with a horizontal resolution of 1 point per square metre and a vertical precision of 15 cm. The

Belgian Ministry of Facilities and Transport (MET-SETHY) have acquired this high quality set of data on most floodplains in the South of Belgium, by means of an airborne laser measurement technique. Specific features of the flow in urban areas, such as the macro-roughness effect of buildings, are thus directly reproduced in the topography and there is no need any more for an artificial increase of the roughness coefficient in urbanized areas [1].

Simulation results

The computation performed provides an estimation of the overtopping wave, induced by the total collapse of the upstream dam, over each downstream dam. The overtopping height on the downstream rockfill dam (dam n°2) has been evaluated at 5 m, with a maximum discharge of about 10,000 m³/s. Similarly, the overtopping wave on the three other dams (n°3 to 5) has been characterized: the dams are respectively submerged by waves of 15 m (dam n°3), 8 m (dam n°4) and 5 m (dam n°5), with maximum discharges of 35,000 m³/s, 5,480 m³/s and 720 m³/s respectively. The question of the stability of those dams under such severe solicitations naturally arises.

Stability of the downstream dams

For the concrete dams (n°3 and n°4), a comparison has been carried out between the forces normally acting on the dams and those acting on the dams during their overtopping. This comparison has shown that the resultant force and the resultant moment differ so significantly that the dams would most likely not remain stable once the hydrodynamic waves reach them. As a consequence, in the final simulation, dams n°3 and n°4 will be artificially removed from the simulation topography as soon as they are overtopped.

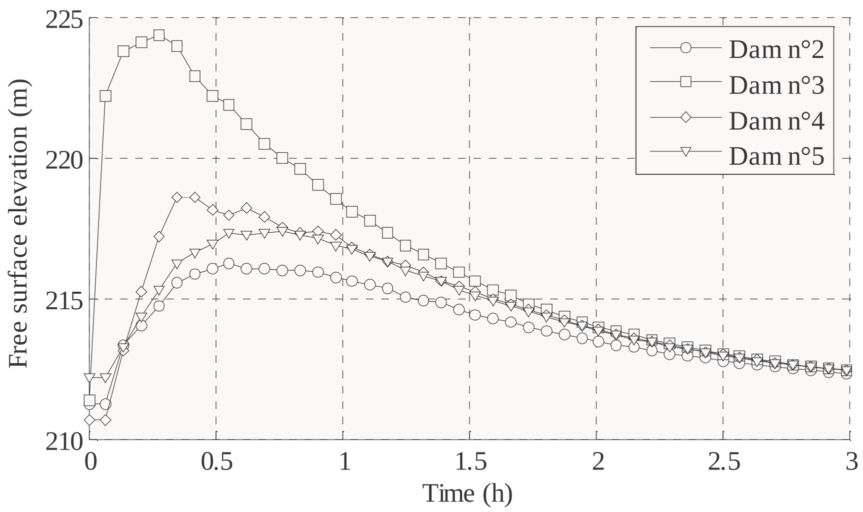

Figure 8: Free surface elevations in the reservoirs near the four downstream dams, after the instantaneous and total collapse of dam n°1.

On the contrary, the embankment dam n°5 is supposed not to be breached considering that its solicitation is significantly weaker than for dams n°3 and n°4. Moreover, the reservoir upstream of dam n°5 is smaller and would essentially act as a temporary storage area for the flood wave. Consequently, assuming that dam n°5 remains stable doesn't lead to an underestimation of the wave reaching the downstream valley.
Regarding the downstream rockfill dam (dam n°2), the challenge is more intricate because it will most probably be breached by the overtopping flow and the proper breach parameters have thus to be estimated. For this purpose, using a process-oriented computation approach was hardly possible because of the lack of reliable data concerning the embankment material. For this reason, the breach parameters have been evaluated on the basis of several empirical formulae [3]. Norms imposed in the regulation of several European and American countries or in national companies have also been considered to validate the selected breach parameters.

Modelling methodology
Afterwards, the breaching mechanism has been introduced in the DEM used for computation in the form of a transient topography. In other words, once the computation code detects that a dam is overtopped, it triggers a time evolution of the local bed elevation in the topography matrix, according to the breach parameters previously defined. This transient topography reproduces a very realistic breaching mechanism for embankment dams made of non-cohesive material (Figure 9 and Figure 10).
The progressive removal of the dam from the topography is defined by the instantaneous location of a virtual plan. This plan is initially tangent to the downstream face of the dam (plan α on Figure 9) and it progressively evolves towards upstream, rotating simultaneously until it coincides with the bottom natural topography at the bottom of the dam (plan β on Figure 9). For the two concrete secondary dams, which are assumed to break in cascade, the parameters correspond to a total collapse in two minutes, while the breach parameters selected for the rockfill dam (dam n°2) correspond to a total erosion in 30 minutes.

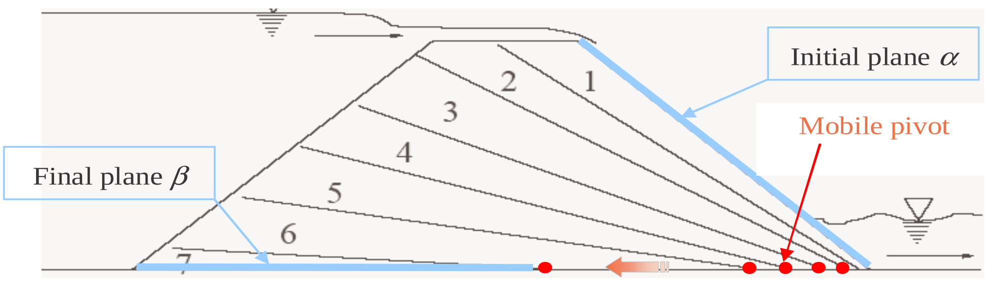

Figure 9: Schematic representation of the breach formation in a non cohesive embankment dam [5].

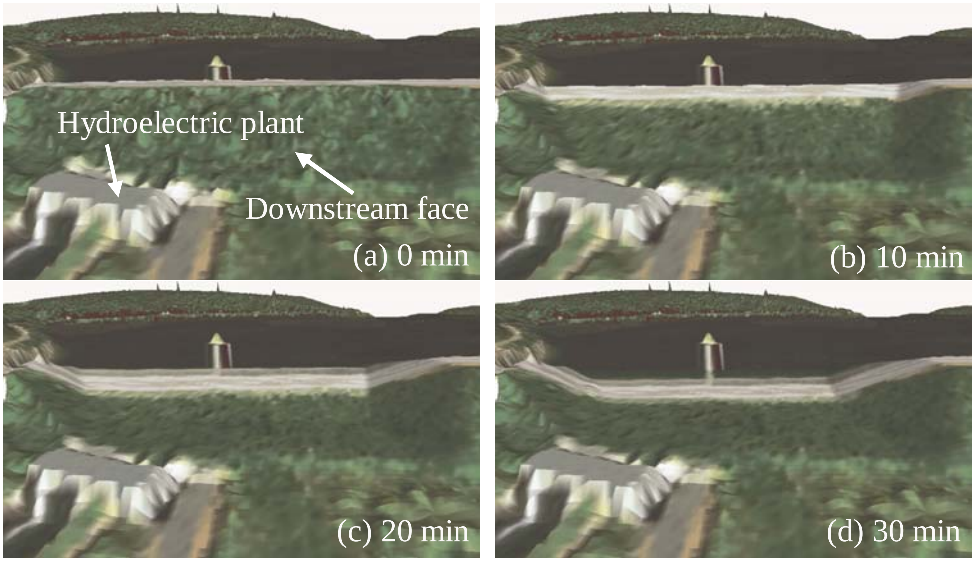

Figure 10: Breach formation process in the downstream rockfill dam (dam n°2), as reproduced in the DEM for hydrodynamic computation.

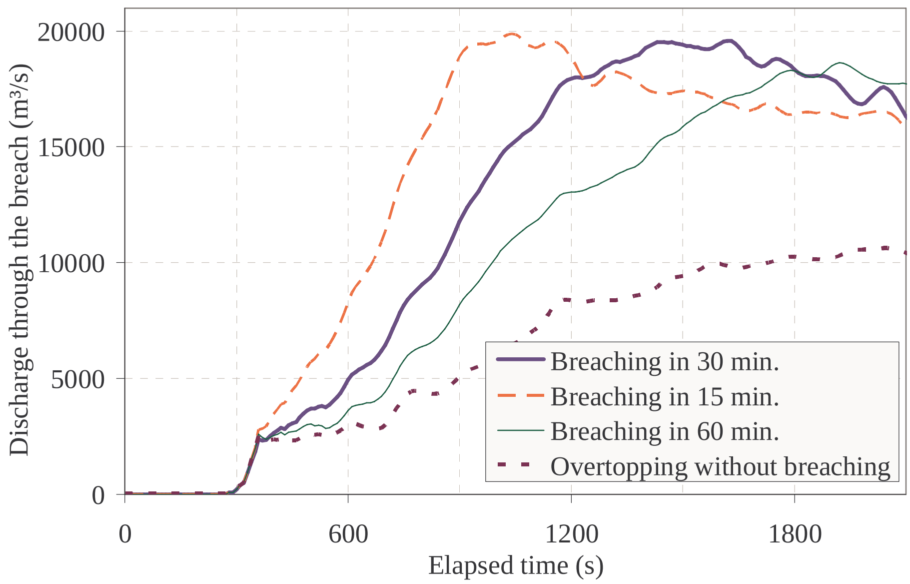

Figure 11: Hydrograph corresponding to the flow overtopping dam n°2 as a consequence of the total collapse of dam n°1.

Since uncertainties remain obviously regarding those parameters, an extensive sensitivity analysis has been carried out. In particular, Figure 11 represents the hydrographs obtained through the breach of dam n°2, depending on the formation time. For a breach formation time varying between 15 minutes and one hour, it appears that the peak discharge is only modified by a few percents. The sensitivity of the hydrodynamic results with regard to this breach parameter remains thus extremely weak.

Hydraulic impact in the downstream valley

Finally, a global 2D hydrodynamic computation has been carried out, coupling the flows in the reservoirs and in the whole downstream valley, and taking into consideration the transient topography (dam collapses in cascade). The simulation mesh is based on a grid of about 900,000 potential computation cells (8 m × 8 m). The obtained results enable to draw essential risk maps and to plot hydrographs or limnigraphs at numerous strategic points downstream of the dams (urbanized areas, bridges, …).

CONCLUSION

The hydrodynamic model WOLF 2D, based on a multiblock mesh, has shown its ability to accurately compute extreme wave propagation induced by the instantaneous or gradual collapse of dams. Very satisfactory agreements have been found between computed results and validation data in the case of the Malpasset accident. WOLF 2D has also been successfully applied to the simulation of a major dam break on a complex of dams, considering three additional dam breaks in cascade.

Further developments are currently undertaken. In particular, new simulations taking into account sediment movements under dam break flows have been performed. The first results already obtained by the authors [2] demonstrate that these phenomena strongly affect both the wave propagation time and the maximal water levels.

REFERENCES

[1] Dewals, B., *Une approche unifiée pour la modélisation d'écoulements à surface libre, de leur effet érosif sur une structure et de leur interaction avec divers constituants*. 2006, PhD thesis, University of Liege**:** 636 p (in French).

[2] Dewals, B., P. Archambeau, S. Erpicum, T. Mouzelard et M. Pirotton, *Dam-break hazard mitigation with geomorphic flow computation, using WOLF 2D hydrodynamic software*, in *Risk Analysis III*, C.A. Brebbia (ed). 2002, WIT Press. p. 59-68.

[3] Dewals, B.J., P. Archambeau, S. Erpicum, S. Detrembleur et M. Pirotton. *Comparative analysis of the predictive capacity of breaching models for an overtopped rockfill dam*. in *Proc. Int. Workshop "Stability and Breaching of Embankment Dams"*. 2004. Oslo, Norway.

[4] Goutal, N. *The Malpasset dam failure. An overview and test case definition*. in *Proc. of CADAM Zaragoza meeting*. 1999. Zaragoza.

[5] Hanson, G. *Soil parameter development for a breach headcut migration model based on experience from dam incidents and results from model tests*. in *Proc. Int. Workshop "Stability and Breaching of Embankment Dams"*. 2004. Oslo, Norway.

[6] Marche, C., *Barrages : crues de rupture et protection civile*. 2004: Presses Internationales Polytechniques, 388 p (in French).

[7] Soares Frazão, S., M. Morris et Y. Zech, *Concerted Action on Dam Break Modelling : Objectives, Project report, Test cases, Proceedings*. 2000, UCL, Belgium, CDRom.