Dam-break hazard assessment with geomorphic flow computation, using WOLF 2D hydrodynamic software

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Abstract

WOLF 2D software solves the 2D shallow-water equations on any evolutive grid, dealing with natural topography and mobile bed. WOLF 2D is part of WOLF free surface flows computation package, which has been completely developed at the University of Liege. A mass balance for bed load sediments is coupled to the hydrodynamic model. Solid discharges are estimated by means of reliable transport laws. Side slope stability analysis are systematically performed to take gravity induced solid discharges into account.

The same finite volume technique in each computer code solves the equations, formulated in a conservative form to ensure exact mass and momentum balance, even across moving hydraulic jumps. An original splitting of the convective terms has been specifically developed for the model, in order to handle properly transient discontinuities. Its efficiency is highlighted through comparisons with analytical solutions.

WOLF 2D has been successfully applied to the simulation of the flooding triggered by an instantaneous and total failure of a large dam in Belgium (Eupen). This case study demonstrates the applicability of the solver to extreme erosive flows on any realistic mobile topography. By revealing severe visible geomorphic processes, the simulation also confirms the relevance of handling morphology changes in dam-break hazard assessment. Functional risk maps have been plotted to exhibit crucial practical information, like maximal water heights, in an incredibly convenient way to interpret. Such data reveals a major interest in the scope of prevention policies or protection plans for populations and goods.
1 Introduction

WOLF 2D is an efficient analysis and optimisation tool, which has been completely developed for several years in the Service of Applied Hydrodynamics and Hydraulic Constructions (HACH) at the University of Liege (http://www.ulg.ac.be/hach). WOLF 2D is part of WOLF free surface flows computation package, which includes in the same development environment the resolutions of the 1D and 2D depth-integrated Navier-Stokes equations as well as a physically based hydrological model [1], along with powerful graphical pre- and post-processing. Each code handles structured or unstructured grids, dealing with natural topography and mobile bed simultaneously [2], for any unsteady situation with mixed regimes (including moving hydraulic jumps). These very general computation capabilities have been successfully applied to the simulation of the flow induced by the instantaneous and total break of a dam (25 million m³ reservoir). This case study definitely demonstrates the applicability of the solver to extreme and highly erosive flows on any realistic mobile topography (see also [3] and [4]). By revealing severe visible geomorphic processes, the simulation also brings evidence for the relevance of handling morphology changes in dam-break hazard assessment.

Highly effective and helpful graphical display techniques are exploited throughout the post-processing analysis. Functional risk maps have been plotted to exhibit crucial practical information, like maximal water heights, in an incredibly convenient way to interpret [5].

2 Short description of the numerical model with mobile bed

2.1 Mathematical model

The governing equations for hydrodynamic free surface flows are the depth-integrated Navier-Stokes equations for an incompressible fluid:

\[
\frac{\partial h}{\partial t} + \frac{\partial}{\partial x_j} \left( h u_j \right) = 0
\]

\[
\frac{\partial u_i}{\partial t} + u_i \frac{\partial u_j}{\partial x_j} + g \frac{\partial h}{\partial x_i} \cos \theta_i + g n^2 \frac{u_j u_j}{h^2} u_i = g \sin \theta_i + \frac{\partial}{\partial x_j} \left( \nu \frac{\partial u_i}{\partial x_j} \right) + G_i
\]

where the Einstein notation has been used (sum over repeated subscripts). This system expresses the mass balance and the momentum balance along both space directions. The following symbols have been used: \( g \) (gravity acceleration), \( h \) (water height), \( n \) (Manning roughness coefficient), \( u_i \) (velocity components), \( t \) (time), \( x_i \) (space coordinates), \( \theta_i \) (bed slope), \( G_i \) (external forces), \( \rho \) (water density) and \( \nu \) (turbulent viscosity).

It must be outlined that no restrictive assumption is required for the bottom slope (see Pirotton [6] or [7]). In order to simulate flows on very steep topographies (as spillways or torrents for example), local references are defined with the x- and y-
axis following locally the mean bottom slope. This technique ensures the water depth to be orthogonal to the main flow direction. According to Exner equation, the mass balance for sediments can be stated as follows (see Fäh [8]):

\[
(1 - p) \frac{\partial z_b}{\partial t} + \frac{\partial q_{bx}}{\partial x} + \frac{\partial q_{by}}{\partial y} = 0.
\]

where \( z_b \) stands for the bed level, \( p \) is the porosity and \( q_{bx}, q_{by} \) represent the solid discharges in both horizontal directions. The bed load discharge is evaluated using the Meyer-Peter and Müller formula, known to be widely reliable (see for example [9], [10] or [11]):

\[
q_b = 8 \sqrt{(s-1)g d^2} \left[ \frac{R_h J}{(s-1) d} - 0.047 \right].
\]

\( s \) represents the relative density of the sediment particles, \( d \) is the mean grain diameter, \( J \) stands for the energy slope and \( R_h \) for the hydraulic radius. Several other solid discharge laws are available within the computation program and the user is free to choose any of them.

### 2.2 Spatial discretisation and flux evaluation

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

Appropriate 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 two different upwind schemes. The first one uses an original flux-vector splitting technique developed for WOLF. The hydrodynamic and bed load fluxes are splitted according to the sign of the flow velocity. Indeed the stability of the numerical scheme has been extensively investigated by using Von Neumann analysis applied to a 1D linearized set of partial differential equations. This system is written out below, with \( - \) and \( + \) subscripts respectively indicating an upwinding towards upstream and downstream directions:

\[
\begin{align*}
\frac{\partial h}{\partial t} + \left[ \frac{\partial q}{\partial x} \right] &= 0, \\
\frac{\partial q}{\partial t} + \left[ \frac{\partial \left( \frac{q^2}{h} \right)}{\partial x} \right] + \left[ \frac{\partial \left( \frac{gh^2}{2} \right)}{\partial x} \right] + gh \left[ \frac{\partial z_b}{\partial x} \right] &= -\frac{\tau_{bx}}{\rho B}, \\
(1 - p) \frac{\partial z_b}{\partial t} + \left[ \frac{\partial q_b}{\partial x} \right] &= 0,
\end{align*}
\]

with \( q = hu \), \( \tau_{bx} \) is the bottom stress and \( B \) the channel width.
Efficiency, simplicity, optimal agreement with non-conservative terms and low computational cost are the main advantages of this original scheme. On the other side, the well-known approximate Riemann solver of Roe [12] has been introduced as a reference in the scope of numerical comparisons. Both methods showed their ability to simulate sharp transitions without excessive smearing.

Variable reconstructions are performed with a first or second order accuracy on regular grids. Classical limiters are applied to the linear variable reconstructions.

### 2.3 Time discretisation

As we are mostly interested in transient flows, an accurate and non-dissipative temporal scheme has to be chosen. It has been experienced in the Department that implicit schemes don't provide a substantial advantage for extremely transient free surface flows (e.g. dam-breaks) in comparison with the explicit ones. In this way, the explicit Runge-Kutta method is applied here to solve the ordinary differential equations obtained after spatial discretisation. Implicit time integration schemes are also available in WOLF in order to accelerate the convergence process for steady state solutions.

### 2.4 Other main features of WOLF 2D

The algorithm is designed to deal automatically with any moving boundary. It incorporates an original method to handle covered and uncovered cells (wet and dry cells). In addition an adaptative mesh generation technique achieves a drastic reduction in computation time, by restricting the simulation domain to the wet cells (and a surrounding narrow strip). The interactive user-interface, with high performance pre- and post-processing, allows monitoring 3-D large-scale runs graphically while they proceed. The solid transport includes not only flow-induced sediment discharges but also gravity-induced ones. These result for example of bank instabilities or embankment collapses. Therefore a competitive geotechnical model has been integrated in WOLF 2D (see [13] or [8]). This model is based on the concepts of limit slope angle and natural slope angle. An efficient optimisation tool (WOLF AG) is available within WOLF package. The algorithm is based on an innovating method and leads to an automatic and unbiased calibration of the Manning coefficient (Erpicum [14] and [1]).

### 3 Case study: Eupen dam

Important soil movements have been observed during floods from numerous dam failures in the world [15]. The quantity of entrained solid materials can even reach the same order of magnitude as the volume of water released from the reservoir. Furthermore even if a relatively small amount of sediments gets moved, bed-load transport by highly erosive flows can produce critical damages, especially in case of very localised effects.
For these reasons it is of paramount importance to deal with bed changes whenever dam failure induced flows must be simulated and related hazard assessed.

The robust and powerful computer code developed at the HACH has been successfully applied to the simulation of the flooding triggered by an instantaneous and total failure of Eupen dam (Belgium). The concrete gravity dam in Eupen is 66 meters high and 410 meters wide. The reservoir capacity is 25 millions cubic meters. Topographical information (with a spatial resolution of 10 m) was extracted from a Digital Elevation Model.

4 Results: risk maps

The final aim of this kind of simulations lies in the drawing of practical risk maps. These maps constitute a powerful way to summarize the numerous results produced by the unsteady and spatially distributed numerical simulations.

4.1 Propagation time

Information of highest importance is the time elapsed between the moment of the dam fracture and the instant when a specified point is flooded. A first risk map (Figure 2) can be obtained by collecting this time at every point of the simulation domain.

If rigid bed is assumed, a threshold height of water (e.g. \( h > 50 \) cm) can be chosen as a correct criterion for determining whether a specified point is already submerged. However, in case of a mobile bed, the water front might be preceded by an important amount of moving sediments, which represent a real danger for any area even before it gets actually flooded by water. For this reason we choose to use a threshold value of the increase in the free surface level as a more general criterion (e.g. \( \zeta(t) - \zeta(0) > 50 \) cm, where \( \zeta \) stands for the free surface level). The software user can freely and easily modify the exact magnitude of this threshold parameter.
At the beginning of the process the water front moves much more slowly in case of a mobile bed than if the bed is assumed to be fixed. This feature is easy to understand since the water looses energy as it moves sediments. However, once the shape of the valley has been extensively modified, the water escaping from the reservoir at a later time meets a significantly lower resistance and thus keeps its energy to accelerate the propagating front. Hence the flooding model demonstrates that considering geomorphic processes may lead to more hazardous consequences of the dam fracture (see Figure 3).

Some very local characteristics of the bed level adaptation also contribute to the possibility of relative higher speed of the bore in an alluvial valley. For instance, it can be observed that in both cases a noteworthy fraction of the water climbs up into a tributary valley (Figure 4). Nevertheless simulations over an alluvial bed clearly reveal that the mouth of this tributary gets partly obstructed by an important sediments deposition. Since this obstruction doesn’t occur when the bed is alleged not to be moveable, additional water in this case is deviated from the main valley to the tributary and thus the main bore becomes less powerful.

Figure 3: Water depth (m) 840 s after the dam failure.
In any realistic application, the time required for the bore to reach a particular point must be reduced by proper safety coefficients and the maximal height of water increased by other safety coefficients (possibly legally planned).

4.2 Maximal increase in free surface level

A second way to characterize the hazard repartition is to observe the maximal increase in the free surface level during the whole unsteady process (Figure 5). In case of a rigid bed, the water depth can be simply used. Of first interest is to notice the time when this maximal increase in free surface level occurs at the confluence between the main valley and the tributary Helle. All the simulations have showed that water rushes into the tributary Helle valley, climbs upstream over about 800 m and then flows down again to the main channel. This phenomenon is so strong that the highest values of water depth at the confluence are observed not at the beginning of the flooding but at the time when the water flows down from the Helle valley.
4.3 Maximal erosion and deposition

Inspecting the topography on completion of the simulation brings only slight information regarding erosion and deposition processes during the whole unsteady riverbed evolution. Indeed it's likely that some local areas get first extensively eroded and that later substantial deposition occurs at these identical areas. That's why the maximal and minimal values of each cell elevation must be recorded throughout the whole computation. Two risk maps can then be plotted. As an illustration the following pictures point up the extreme erosion process taking place immediately downstream of the failed dam location. It can be noticed that the relief (10 m high) in the middle of the channel undergoes such severe erosion that it has practically disappeared once the reservoir is emptied (Figure 6).

Figure 6: 3D-view of the initial and final topographies immediately downstream the dam (not represented).
5 Conclusion

Strong aggradation areas and noticeable degradation zones have been highlighted in a very plausible way by the simulations carried out. Results also show that the bed load slows down the wave front during a short time following the accident. An interesting feature is that afterwards the flow on mobile bed becomes faster than its counterpart on a fixed bed. This has been justified by two physical explanations.

Further developments should focus on a more accurate computation of the momentum loss either induced by the bed friction or related to the energy transferred to the entrained sediments. The simulation results have been exploited to prepare maps clearly delineating the area which would be inundated in the event of a failure. Copies of the maps should be used in the development of a protection plan for the area which should be evacuated if there is evident danger of failure of the dam. Essential orders of magnitude have also been assessed. The speed of the wave front upstream of the town Eupen is as high as 70 km/h and 15 m water height can be observed in this residential area. The urban centre would be flooded already 200 seconds after the structure break. Immediately downstream of Eupen the wave front still moves at a speed of 50 km/h.

Moreover if different values of the friction coefficient had to be tested, the results would still more emphasize the hazard threatening Eupen town. This kind of study is of the utmost importance for establishing efficient people and goods protection policies. For instance, the results show that a short but fast movement is often enough to place the people in a safe area because of the hilly landscape all around Eupen. Insurance companies also demonstrate an obvious interest for this form of simulations.

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