SUMMARY

The present paper summarises recent experimental and numerical developments that focus on the geomorphic impacts of severe transient floods, such as those initiated by dam failures in erodible valleys. Future work, to be carried out in the framework of the IMPACT project of the European Commission, is also described, and preliminary results are presented. Rapid flood waves propagating over a loose sediment bed may trigger large-scale geomorphic changes. From a geomorphic point-of-view, impacts of the flow on the loose valley are in the present context divided in ‘near-field’ and ‘far-field’ features, depending on the scale and scope of the phenomena involved. These features are described, and their implications on the phenomenological assumptions and modelling approaches are reviewed. Recent extensions of shallow-water solvers to deal with strong erosional flows are presented. In the framework of IMPACT, additional research will be carried out at the Université catholique de Louvain, to advance knowledge in the field on geomorphic floods induced by catastrophic failures of flood-defence structures. This will be achieved through a combination of experimental work and numerical endeavours. The planning and objectives of this future work are presented and discussed.

1  INTRODUCTION

The propagation of rapid flood waves over a loose sediment bed may trigger large-scale geomorphic changes. Tremendous quantities of sediments, mobilised by the rushing waters, join the flow in the form of a heavier mixture of water and sediments. The rheology of this solid-liquid mixture, similar to debris-flows, can significantly affect the flow dynamics, in such a way that traditional, purely hydrodynamic flood routing schemes completely fail to reproduce the flow behaviour. Bulking of sediments into the flow comes with exchanges of mass and momentum across the evolving bed profile, which are usually not taken into account in classical morphodynamic approaches.

Natural hazards involving the movement of bulked solid-liquid mixtures are numerous. They differ in triggering mechanisms, flow characteristics and sediment properties. Examples range from stony debris surges in steep torrents (Iverson 1997), to mudflows and lahars (Waythomas 2001) or submarine landslides (Hampton et al. 1996). In the present research, we examine the case of geomorphic floods induced by the failure of a dam within erodible
valleys. Strong examples of well-documented recent catastrophes from dam failures include
the Lawn Lake failure along the Roaring River, Colorado (Jarrett and Costa 1993), the Lake
Ha!Ha! break-out flood in the Saguenay region of Quebec (Lapointe et al. 1998, Brooks &
Lawrence 1999), and the 1996 flood in the region of Biescas, Spain (Benito et al. 1998).

From a geomorphic point-of-view, impacts of the flow on the loose valley may be divided in
‘near-field’ and ‘far-field’ features, depending on the scale and scope of the phenomena
involved. Near-field flow behaviour refers to the initial bulking of sediments and complex
formation of the flood wave. At this stage, it is of crucial importance to account for sediment
inertia, debris-flow-like behaviour of the surge front, and vertical effects inducing non-
hydrostatic pressures. In addition, the failure can cause sediments accumulated in the dam
reservoir to be re-mobilized by the sudden emptying the reservoir, and transported
downstream. In the far-field, the flood wave progressively decreases in velocity; solid
transport remains very intense but its active role on the global flow dynamics decreases. In
addition, lateral effects come into action, causing bank failures and channel widening. All
these sources of sediments come into the flow and are transported in the downstream reaches,
where the decreasing flow velocities, combined with de-bulking of the solid-liquid sediment
mixture, often lead to overall deposition and over-aggradation.

In the framework of the EU IMPACT project, additional research will be carried out in order
to advance knowledge in the field on geomorphic floods induced by catastrophic failures of
flood-defence structures. This will be achieved through a combination of experimental work,
and theoretical and numerical endeavours. In this paper the guidelines of planned work in a
near future are presented.

The remainder of the paper is structured as follows: in section 2, a near-field approach is
adopted. The key mechanisms at play are described, and previous experimental work is
briefly presented. An original theoretical framework is described, extending the shallow water
solvers to cope with strongly transient geomorphic flows, along with its key strengths and
limitations. A more general framework, adopting less restricting assumptions on the flow
characteristics, is proposed. Future experimental work is described, including some
preliminary results of near-field dam-break wave simulations involving higher sediment
levels in the dam reservoir. In section 3, the difficult challenges associated with far-field dam-
break modelling are enlightened. Among them is the important aspect of channel widening
through bank failures; a simple bank failure criterion is proposed.

2 NEAR-FIELD APPROACH

2.1 Key aspects for near-field modelling

The initial flow pattern formed after the sudden collapse of a dam over a loose sediment
substrate is rather complex, and poses tough challenges for modelling that go far beyond the
traditional shallow-water framework: intense scouring of the sediment bed, bulking of
sediments into the flow, re-mobilization of sediments trapped in the reservoir, important
vertical velocities and pressures that depart notably from the hydrostatic equilibrium, etc.

Traditional alluvial models are far from encountering these challenges: they usually rely on
classical sediment transport predictors, in which sediment movement is barely seen as a
passive response to the eroding power of the flow, whose resistance is mainly due to frictional effects. This is precisely why they completely fail to reproduce the observed behaviour. Rather than frictional resistance, the flow in the near-field is mostly governed by inertial effects: bulking of sediments into the flow comes with transfers of mass and momentum from the motionless bed into the moving sediment layer.

To account for inertia while still adopting simple assumptions, Capart (2000) has proposed to tackle the problem by using an extended shallow-water description: the flow is divided in three separate layers, namely a pure-water layer, a transport layer of finite thickness formed by a mixture of water and sediments, and a motionless sediment substrate. The layers are separated by sharp interfaces, and the erosion of the sediment bed is viewed as a phase change of the bed material, undergoing a transition from solid-like to fluid-like behaviour as it is entrained by the flow.

This concept of interfacial geomorphic flow is at the core of the recent advances in the modelling of transient sediment-laden currents, and has been adopted for a variety of situations ranging from coarse debris flows to cohesive mudflows. Based on this view, many things are possible. In the next section, we will briefly discuss a set of simple governing equations, along with some tracks for possible improvements. For a phenomenological description of the flow and for validation of numerical models, setting up experiments of geomorphic dam-breaks is of precious value: this is the purpose of section 2.3.

2.2 Theoretical framework

2.2.1 Idealised extended shallow-water description

The decomposition of the flow according to the original formulation of Capart (2000) is illustrated in Figure 1a, and relies on four essential assumptions: 1) shallow water: the interfaces separating the three layers are nearly horizontal, and their interdistance is small compared to the horizontal scale of interest; 2) the moving sediment layer behaves as a coherent mixture with no slip between solid and liquid phases, and moves at a constant speed equal to that of the pure-water layer; 3) the solid fraction throughout the moving sediment layer is assumed constant and equal to that of the underlying static bed; 4) grain-grain interactions within the transport layer are responsible for augmented mixture pressures, assumed as hydrostatic, with a supplement due to the increased mixture density.

Figure 1. Idealisation of the flow: (a) definition sketch of the layered flow structure and assumptions on velocities, concentrations and pressures; (b) control volume for the derivation of balance equations.
Under the above hypotheses, performing balances for the total volume of flowing material, the volume of flowing sediment material, and the momentum of the flowing mixture (Fig. 1b), yields the following vertically-averaged governing equations (Capart 2000):

\[
\frac{\partial}{\partial t} (z_b + h_m) + \frac{\partial}{\partial x} (h_m u_m) = 0, \quad \frac{\partial}{\partial t} (z_b + h_s) + \frac{\partial}{\partial x} (h_s u_m) = 0, \tag{1-a-b}
\]

\[
\frac{\partial}{\partial t} ((h_m + rh_s) u_m) + \frac{\partial}{\partial x} \left( (h_m + rh_s) u_m^2 + \frac{1}{2} gh_m^2 + \frac{1}{2} rgh_s^2 \right) + g(h_m + rh_s) \frac{\partial z_b}{\partial x} = (1 + r) \frac{e}{2} u_m - \frac{\tau_b}{\rho_w} \tag{1-c}
\]

where \( e = - \frac{z_b}{t} \) is the erosion rate, \( \tau_b \) is the bed shear stress, \( g \) represents the gravitational acceleration, and \( r = c_b \left( \frac{\rho_s}{\rho_w} - 1 \right) \) is the density supplement due to the presence of the sediment load at volume concentration \( c_b \). The other variables are explicitated on Fig 1a.

The last term in the right-hand side term of (1-c) has to do with the non-reciprocity of momentum transfers in case of erosion or deposition: deposition is associated with a net loss of momentum within the control volume, whereas erosion is not. The evolution of the morphodynamic bed interface is governed for example by a semi-empirical closure relation

\[
e = - \frac{\partial z_b}{\partial t} = \frac{1}{t_r} (m u_m^2 - h_s) \tag{2}
\]

where \( m \) is a sediment mobility coefficient and \( t_r \) is a relaxation time for a non-equilibrium formulation.

The assumptions leading to this set of equations may appear rather restricting. Indeed, at the very initiation of the motion, vertical effects induce upwards and downwards velocities as well as non-hydrostatic pressures that depart notably from the shallow water assumption. At later moments, the assumption of equal velocities within the transport layer and water layer becomes less and less justified as the solid transport decreases in intensity. Also, collisional interparticle contacts in the transport layer certainly lead to reduced solid fractions in comparison to the static bed packing, as experimentally observed by Spinewine et al. (2002) for mature debris flows.

Quite perplexing however, this simple model is seen to quite accurately reproduce the propagation of near-field dam-break waves observed in the laboratory. Figure 2 shows the comparison of numerical and experimental results after Capart (2000).

Providing the sediment mobility coefficient \( m \) and relaxation time \( t_r \) in (2) can be linked to material properties such as grain size and density, a great advantage of the formulation is that the model is not bound to lots of empirically-adjusted calibration coefficient.
2.2.2 Directions for improvement

The upper described formulation forms a basis for further developments and improvements.

At first, it is desirable to replace the semi-empirical erosion rate (2) by a more rigorous relation grounded on the underlying mechanisms of force equilibrium in the bed region. Instead of (2), Fraccarollo and Capart (2002) go somewhat further and propose a physically-based alternative for this relation, based on an imbalance between bed shear stresses experienced on both sides of the bed interface:

\[ e_b = \frac{1}{\rho_w (1 + r) u_m} (\tau_s - \tau_b) \]  

(3)

where \( \tau_s \) and \( \tau_b \) are the bed shear stresses experienced above and below the bed interface, respectively. \( \tau_s \) is given by a Chezy-type relation, and \( \tau_b \) derives from a Coulomb yield criterion written in terms of Terzaghi’s effective normal stress exerted on the bed interface.

A second restricting assumption highlighted above is the locked-phases description, whereby the pure water and transport layers are enforced to flow at a single average velocity. In order to be more realistic, it is necessary to let the phases flow at different – linked but not locked – velocities. This has been implemented by Capart and Young (2002), and compared by Spinewine et al. (2002) to a set of geomorphic dam-break experiments. A fourth equation for momentum balance in the transport layer is added to the previous set of evolution equations, and an additional closure relation is required to specify the shear stresses at the interface between pure water and transport layers. The flow structure is defined as in Figure 3. The set of evolution equations is now (note here that \( \rho_s = \rho_w (1 + r) \) is the density of the water-sediment mixture and not the density of the sediment constituents):

\[
\frac{\partial h_{w}}{\partial t} + \frac{\partial}{\partial x} \left( h_{w} u_{w} \right) = 0, \quad \frac{\partial h_{s}}{\partial t} + \frac{\partial}{\partial x} \left( h_{s} u_{s} \right) = e_{b}, \quad \frac{\partial \tau_{b}}{\partial t} = -e_{b} \tag{4 a-c}
\]

\[
\frac{\partial (h_{w} u_{w})}{\partial t} + \frac{\partial}{\partial x} \left( h_{w} u_{w}^{2} + \frac{1}{2} g h_{w}^{2} \right) + g h_{w} \frac{\partial}{\partial x} \left( \tau_{b} + h_{i} \right) = -\frac{\tau_{w}}{\rho_{w}} \tag{4 d}
\]

\[
\frac{\partial (h_{s} u_{s})}{\partial t} + \frac{\partial}{\partial x} \left( h_{s} u_{s}^{2} + \frac{1}{2} g h_{s}^{2} \right) + g h_{s} \frac{\partial}{\partial x} \frac{\tau_{b}}{\rho_{s}} + \frac{\rho_{w}}{\rho_{s}} g h_{s} \frac{\partial h_{w}}{\partial x} = \frac{\tau_{w}}{\rho_{w}} - \frac{\tau_{b}}{\rho_{s}} \tag{4 e}
\]
along with morphodynamic and closure relations

\[
e_b = \frac{1}{\rho_s u_s} (\tau_s - \tau_b), \quad \tau_w = \rho_w C_{fw} |u_w - u_s| (u_w - u_s),
\]

(5 a-b)

\[
\tau_s = \rho_s C_{fs} |u_s| u_s, \quad \tau_b = \tan \theta \sigma \frac{u_s}{|u_s|}.
\]

(5 c-d)

Figure 3. Flow structure with unlocked velocities

The above extensions, while allowing to go much further, are nevertheless inherently limited by the basic shallow-water assumptions. In the near-field, fluid filaments are not perfectly parallel, nor flowing horizontally, and the water pressures can depart notably from the hydrostatic distribution. Vertical velocities are far from being negligible at the initiation of the movement, when the water body collapses and sediments are pushed upwards. When the topography is locally very abrupt, sudden changes of flow directions are associated with an increased solicitation of the sediment bed. This is notably the case for a dike breach, and the deep scour hole that results downstream of breaches is such an example for the need of models that go beyond shallow-water assumptions.

Following the ideas of Sussman et al. (1998), very preliminary results were obtained by Capart and Spinewine by coupling a 2D-V Navier-Stokes solver with an interface-tracking model for the evolution of a three-phases medium: besides air and water, the sediment bed is idealised as a denser, very viscous fluid. In spite of this very crude approach, the collapse of the water mass on the left of Figure 4 is seen to erode the sediment bed and push it upwards, creating a front of sediments that precede the pure water wave. Future developments in this respect will concentrate on the behaviour of the sediment phase, that should be divided in a motionless solid-like assembly surmounted by a fluid-like slurry, with an adequate interface relation accounting for phase change.

Figure 4. Preliminary results from a 2D-V simulation. Gray levels indicate the three phases. Superimposed vector field indicates fluid velocities. Time \(t = 0.17\) s after gate opening.
2.3 Experimental work

2.3.1 Idealised dam-break experiments

To the knowledge of the authors, the first laboratory investigations of the geomorphic impacts induced by a dam-break wave over a loose bed are due to Chen and Simons (1979). Their experiments, however, were small-scaled and mostly qualitative.

Capart and Young (1998) have performed idealised experiments with the following configuration: a horizontal sediment bed channel, fully saturated with water, extends on both sides of an idealised dam. Upstream, a body of water initially at rest is suddenly released by removing the dam. The surge of water and eroded sediments was recorded by fast digital cameras. Tracking techniques (Capart et al. 2002) were used to follow each particle of the bed and obtain detailed measurements. Light pearls with a relative density \( s = 1.048 \) were used as bed material. Figure 5 shows the test set-up along with snapshots of the dam-break wave.

Figure 5. Idealized dam-break experiments with light pearls, relative density 1.048. Left: set-up and initial conditions; right: snapshots at \( t = 0.1 \) and \( 0.2 \) s (Capart & Young 1998).

Similar experiments have been performed at the Université catholique de Louvain by the authors with an upward-moving gate, and at the Universita degli studi di Trento with a downward-moving gate, using sand or heavier PVC pellets, with a density \( s = 1.54 \), in place of the light pearls. Figure 6 depicts some typical successive snapshots from the Louvain tests.

Figure 6. Image mosaics of the experiments conducted in Louvain with PVC pellets having a relative density of 1.54. Left: general view; right: snapshots at times \( t = 0, 0.25, 0.5, 0.75, 1.0 \) s
2.3.2 Future experimental work within IMPACT project

An aspect mentioned in the introduction and that has not been addressed by the above idealised experiments is the re-mobilization of sediments trapped in the dam reservoir. In reality, even when flushing gates are provided at the bottom of the dam, their efficiency has often a limited extent. The incorporation of those sediments in the flood wave can significantly alter its development. Also, the presence of a clear-water layer in the downstream channel may be regarded as important, as it is also the case for pure-water dam-break waves. The early experiments of Chen and Simons (1979) were performed with a higher sediment bed upstream of the gate section, and a clear-water layer above the downstream channel bed.

In the framework of the IMPACT project, a new series of tests will be performed in Louvain, exploring various water and sediment heights in the upstream and downstream channels. Such experiments have been carried out by Leal et al. (2001) using nearly uniform sand. The ambition of the new experiments is to investigate various materials, and in particular lighter materials to exacerbate the flow geomorphic action. The influence of the varying levels on the surge speed, front height, water levels and bed levels will be investigated. Preliminary experiments were performed in Louvain (Soler Salles 2000) in a small flume with a very basic gate mechanism. Sample images are given in Figure 7 for upstream water and sediment levels respectively 10 and 6 cm above the downstream bed level. They show that, besides their influence on the wave development, high sediment levels in the upstream reservoir are associated with rather complex phenomena, sometimes at the frontier between alluvial hydraulics and soil mechanics.

![Figure 7. Dam-break experiments with upstream water and sediment levels respectively 10 and 6 cm above the downstream bed level. Snapshots at t = 0.0, 0.2, 0.4 s after gate opening.](image)

In addition, another type of flow involving fast water and sediment transients is also studied at the Université catholique de Louvain: dike breaching is a process quite similar to dam-break waves, and however different in nature. Catastrophic natural hazards of this type are listed in Wahl (1998).

Besides longitudinal erosion, lateral growing of the breach has also to be assessed in order to accurately model peak outflow discharges and attained water depths in downstream areas. This research is only at its premises, but very enriching experiences have been carried out very recently in the UCL Hydraulics Laboratory by student investigators (Riffon & Van Goethem 2002). Digital cameras were used to follow the breach development, and small tracers were spread at the free surface to obtain flow velocities. Breach stabilisation was achieved at the end of the tests. A scour hole developed at the downstream side of the dike. Figure 8 shows a photograph of the experiment, around 100 seconds after initiation of the breach.
3 FAR-FIELD APPROACH

3.1 Key aspects for far-field modelling

Dam-break floods can significantly rework the morphology of erodible valleys. The upper-described near-field approach was limited to experiments in straight, horizontal and laterally-constrained channels, and similarly to 1D numerical modelling. Actual dam-break floods, however, are bounded by natural valleys. They exert their geomorphic action not only on the bed of the valley, but also on its flanks: the bankline itself may retreat severely under the attack of surging waters. The overall impact of the flood is then determined by a strong interplay between in-channel and bank processes. In addition, a two-dimensional model is clearly desirable if we want to accurately reproduce the flow in natural valleys, through interactions with topographical features such as bends, local contractions or widenings, etc.

The ‘far-field’ flow behaviour is also characterized by progressive debulking of the moving sediment phase as the velocities decrease. Rather than inertial effects as for the near-field, the flow resistance is now mostly governed by frictional dissipation. The large amount of sediments carried away by the surge tends to settle in the downstream reaches when the valley enlarges, creating deposits that may take the form of large alluvial fans.

The dramatic effects of such interactions in actual valleys are documented in the field studies of Costa and Schuster (1988), and Brooks and Lawrence (1999). In some cases, the deposed sediments can block auxiliary valleys or create temporary dams, diverting the course of the river or its confluents, as for the Lawn Lake dam failure (Jarrett & Costa 1993).

The following sections describe past, present and future laboratory experiments reproducing schematic ‘far-field’ dam-break flows, and numerical models aimed at addressing the far-field challenges.
3.2 Experimental work

Erodible channel dam-break wave experiments were carried out in the Civil Engineering Laboratory of the Université catholique de Louvain. As shown in Figure 9, two different channel configurations were examined. The first configuration (Paquier & Poncin 2000) consists of a symmetric loose bed channel with two erodible banks placed downstream of a pure water reservoir barred by a narrow sluice gate. Results from these full-channel experiments were previously reported in Soares et al. (2001). The second configuration (Jonard & le Grelle 2001) consists of a half-channel with a single bank. The bank is rigid upstream of a sluice gate, and erodible downstream, with a loose bottom layer extending both upstream and downstream. An advantage of this configuration is that the flow can be observed both from the top and through the transparent sidewall opposite the erodible bank.

![Figure 9. Erodible channel dam-break wave experiments: (a) full-channel; (b) half-channel configuration.](image)

The wave released when the gate is suddenly opened is seen to heavily attack the channel banks. As illustrated in Figure 10a for the full-channel tests, dam-break induced bank recession is most severe in the immediate vicinity of the "dam". The observed pattern of water and sediment motion in this area is represented schematically on the photograph. Both near the dam and further downstream, bank recession occurs as a series of intermittent collapse events, as can be seen on Figure 10b for the half-channel tests. Rather than gradual lateral erosion, one can clearly observe successive cycles of block failure, rapid slumping into the channel, then gradual entrainment of the material accumulated at the toe before the next failure occurs.

![Figure 10. Dam-break induced bank recession. (a) flow (thick arrows) and erosion (thin arrows) pattern for the full-channel experiments. (b) bank recession as a series of intermittent block failure and collapse (half-channel experiments).](image)
Beyond qualitative observations, imaging methods were used to extract quantitative measurements. For the full-channel tests, imaging is used to survey the entire channel topography after the flow has ended, by taking snapshots of a thin panel plunged into the channel bed at regular intervals. The detailed cross-sections could later be assembled into digital terrain models (DTMs) of the post-flood channel. For the half-channel tests, on the other hand, measurements were focused on the time evolution of the flow and banks. Digital cameras were used to simultaneously film the channel from the side and from the top. On the side images, one measures the water free-surface and sediment bed profiles, and, on the top images, the lateral position of the bankline. Some results of those two series of tests are presented in the next section, where they are also compared with numerical simulations.

3.3 Numerical modelling

3.3.1 1D decoupled scheme including a discrete bank failure model

A model (Soares et al. 2001, Spinewine et al. 2002) was developed in order to integrate a bank failure mechanism in the time-stepping loop of a morphodynamic one-dimensional scheme. It comprises a hydrodynamic finite-volume algorithm and a separate sediment transport routine.

In traditional bank erosion models, bank retreat is generally approached as a continuous process, in which the successive cycles of bank toe erosion and mass failure are averaged in time. In the simplest models, the rate of bank retreat is assumed proportional to the excess bank shear stress above some critical threshold value (Osman & Thorne 1988). While this hypothesis may be appropriate for slowly evolving flows, it is likely to break down for the sudden surges considered in the present work. In such cases, abrupt changes in water depth experienced upon arrival of dam-break wavefronts can destabilise banks independently of the steady erosional action of flow-induced shear stresses. To describe such destabilising effects, geotechnical considerations must be invoked.

Goncette and Spinewine (1998) proposed a simple bank failure model, which accounts for discrete mass failure events due to geotechnical instability. The mechanism strictly applies only to small-scale sand slopes, but constitutes a rough analogue of cohesive bank failures. Upon successive failures, the bank adopts the typical shape shown on Figure 11a: planar faces with a break of slope at the waterline and well-defined angles of repose above and below the surface. Failure is triggered whenever the channel profile exceeds the two angles of repose characterising the emerged and submerged regions, respectively (Fig. 11b). Material above the failure surface defined by these two angles then contributes a lateral influx of sediment into the channel. A key feature of this deceptively simple picture is that it predicts two possible failure modes: failure due to bank undercutting, occurring when bed material is eroded beneath the water surface; failure due to bank submergence, triggered when the water level rises and destabilises the previously emerged flank of the channel.

Two refinements of this simple picture (Spinewine et al. 2002) are possible. The first is to invoke a relaxation mechanism giving the destabilised bank some time to discharge its material into the stream. This is done by restricting the volume of bank material destabilised over a time-step to only a fraction of the volume that would result from strict application of the model. The second is to distinguish between critical and residual angles of failure (Duran 2000): failure is initiated when a representative critical angle is exceeded, and a residual angle is adopted after failure. Incorporating this refinement in the above model is done quite simply...
by defining four distinct angles of repose (Fig. 12): two for the submerged domain, and two for the emerged domain. It has to be noted that, although different in nature, those two refinement mechanisms achieve the same goal, and both should not be used at the same time.

The material from the failed banks enters the flow and is incorporated in the global sediment continuity equation of a 1D model with separate hydrodynamic and sediment transport routines (Soares et al. 2001, Spinewine et al. 2002). Corresponding deposits are simply spread uniformly over the wetted cross-section. Numerical simulations with this 1D model have been compared with the experiments described in previous section. Results are presented in section 3.3.3.

3.3.2 Preliminary coupled 2D model with 2-layers, 2-velocities

The bank erosion mechanism outlined above has been implemented in a fully two-dimensional model proposed by Capart and Young (2002). This model is based on a 2D extension of the set of equations given in (4 a-e), in which the pure water and slurry layers are allowed to flow at distinct velocities. Within a 2D view, they are also allowed to flow in different directions, an essential feature to cope with lateral flowslides plunging under water.
This framework may appear rather complex, but it has the great advantage of accommodating bank failure events in a very simple way. By allowing separate water and fluid-like slurry layers to flow independently (with their own depths $h_w, h_s$ and 2D velocities $u_w, v_w$ and $u_s, v_s$), the governing equations are fully equipped to deal with flowslides of bank material slumping into the water stream. Once failure has been triggered, the post-failure flow can be captured just like any other pattern of water and sediment motion!

According to figure 12, the upper-mentioned failure mechanism may be easily incorporated in this model. Triggering of a block failure event occurs whenever and wherever the local slope exceeds the critical slope of the relevant emerged or submerged region. An extended failure surface is then defined as a cone centred on the trigger location and sloping outwards at the corresponding residual slope. Considering emerged and submerged domains, each failure surface then becomes biconic, a shape which is qualitatively consistent with the “scalloped” bank crests observed in the experiments. Finally, sediment material above this biconic surface is assumed to instantaneously liquefy upon failure. Once liquefaction has occurred, the flow operator simply takes over.

This 2D model has been compared with the experiments described in section 3.2. Some results, taken from Spinewine et al. (2002), are presented here below.

3.3.3 Simulation results

Based on the 1D and 2D models presented above, numerical simulations have been compared with the experiments described in section 3.2. Figure 13 to 15, reproduced from Spinewine et al. (2002), offer quantitative comparisons between measured and simulated data. In Figure 13, the Digital Terrain Model for post-flood conditions of the full-channel tests is compared with 1D and 2D simulations. Figures 14 and 15 show longitudinal profiles of water and sediment levels and channel widths, at different times, for the half-channel experiments.

![Figure 13. Valley topography DTMs for the full-channel experiments: (a) initial conditions; (b) post-flood survey; (c) simulated 1D post-flood topography; (d) 2D simulation results. Dam location is at the top-left corner, marks are in m.](image-url)
The dominant feature illustrated by the DTMs of Figure 13 is the simultaneous channel widening and aggradation caused by the dam-break wave. Material from the failed banks has filled the channel bed, with only a moderate degree of longitudinal redistribution and entrainment out of the channel. This contrasts with a naïve picture which would require a lowering of the channel bed for banks to be undercut and destabilised. Here, the action of the flood wave is sufficient to attack the banks despite the concomitant rise of the channel bed. This effect is well-captured by both simulation techniques, with the best quantitative agreement being recorded for the 2D results. The same pattern of widening and aggradation has been observed in the field during the 1996 Ha! Ha! Lake break-out flood in the Saguenay region of Québec.

Figure 14. Water free-surface and sediment bed longitudinal profiles for the half-channel experiments: (×) measured data; (- - -) 1D computations; (——) 2D computations. Times $t = 0, 0.5, 1, 1.5, 2, 4$ s.; ticks on x-axis at 0, 0.5, 1, 1.5 m.

Figure 15. Width profiles for the half-channel experiments (symbols, times as in Fig. 14); ticks on y-axis at 0, 0.25, 0.5 m.

The evolution of the surge and its effects on the sediment bed and bankline are seen to be reasonably well captured by the 1D and 2D numerical schemes. Qualitatively, the 1D results seems in better agreement with the experiments. Not unexpectedly, the 2D results are more “grainy”, i.e. they exhibit stronger local fluctuations in space and time due to discrete slumping events. By contrast, the 1D results are smoother, reflecting the damping action of the relaxation treatments of sediment and bank motion, as well as the absence of lateral momentum effects.
4 CONCLUSIONS AND PERSPECTIVES

Geomorphic impacts of dam-break waves in erodible valleys have been divided in ‘near-field’ and ‘far-field’ features, depending on the scale and scope of the phenomena involved. Near-field flow behaviour refers to the initial bulking of sediments and complex formation of the flood wave: inertial effects, debris-flow rheology, vertical effects, resuspension of sediments, are some of the challenging problems of near-field modelling. In the far-field, the flood wave progressively decreases in velocity; solid transport remains very intense but its active role on the global flow dynamics decreases. Lateral effects come into action, causing bank failures and channel widening. All these sources of sediments usually lead to severe deposition in the downstream reaches.

The key aspects of near-field and far-field modelling have been highlighted. In the near-field, an extended shallow-water framework is described, which divides the flow in a pure water layer and a water/sediments mixture transport layer of finite thickness. With the ambition to go beyond the limitations inherent to shallow-water solvers, preliminary results of 2D-V simulations were presented. In the far-field, the description is extended to 2D-H for use in actual valleys having complex topography. In order to cope for lateral channel widening, a bank failure mechanism was proposed, and nested in the time-stepping loop of the models.

Both for near- and far-field scales, a range of various laboratory experiments were presented, and the observations were compared with numerical models, with good qualitative agreement. Despite all those developments and encouraging results, lots of further needs for development have been identified, and form the basis of the research programme for the incipient EU IMPACT project related to the modelling of sediment movements associated with extreme floods.

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