Dam-break induced floods and sediment movement – State of the art and need for research

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SUMMARY
Floods from dam or dike failures may induce severe soil movements in various forms. The volume of sediment material that can be moved by such flows can reach the same order of magnitude as the initial volume of water released from the failed dam. Open-channel hydraulics deals reasonably well with two types of flow: slowly evolving alluvial flows, on the one hand, and transient flows in rigid geometries on the other hand. Dam-break induced geomorphic flows combine the difficulties of these two types of flow.

In the near field, a rapid and intense erosion accompanies the development of the dam-break wave, resulting in an intense transient debris flow, presenting some particular features: vertical component of the movement, inertial effects and bulking of the sediments. In the far field, the solid transport remains intense but the dynamic role of the sediments decreases. Dramatic geomorphic changes occur in the valley due to bank erosion, sediment de-bulking and deposition. For both cases, the understanding of involved physical phenomena is not achieved and corresponding numerical modelling still needs further developments. Some recent theoretical developments are promising but they have to be faced and validated against laboratory and field data. The aim of the IMPACT work packages devoted to sediment movements is precisely to explore and to improve these developments, in such a way that engineers and decision makers could take advantage of better assumptions, description and validation in numerical simulation of near- and far-field response to dam-break wave.

1 INTRODUCTION
In a number of ancient and recent catastrophes, floods from dam or dike failures have induced severe soil movements in various forms: debris flows, mud flows, lahars, floating debris and sediment-laden currents (Costa and Schuster, 1988). Other natural hazards also induce such phenomena: glacial-lake outburst floods and landslides resulting in an impulse wave in the dam reservoir or in the formation of natural dams subject to major failure risk.

Figure 1 presents some estimates of the volume of sediment material moved by such flows, gathered from published cases studies (Capart, 2000; Capart, Young and Zech, 2001). In some cases, the volume of entrained material can reach the same order of magnitude (up to millions of cubic metres) as the initial volume of water released from the failed dam.
Even when they involve comparatively small volumes of material, geomorphic interactions can lead to severe consequences because of localised changes or adverse secondary effects. In India, for instance, the Chandora river dam-break flow of 1991 stripped a 2 m thick layer of soil from the reaches immediately downstream of the dam (Kale et al., 1994). In the 1980 Pollalie Creek event, Oregon, the material entrained by a debris flow deposited in a downstream reach, forming a temporary dam that ultimately failed and caused severe flooding (Gallino and Pierson, 1985). Another cascade of events was that of the 1996 Biescas flood, Spain, where a series of flood-control dams failed (Benito et al., 1998).

The recent advances in open-channel hydraulics allow to deal reasonably well with two types of flow: alluvial flows, on the one hand, and transient flows in rigid geometries on the other. Alluvial geomorphic flows are such that the bed geometry evolves under the flow action, but with a sediment load small enough to play no dynamic role. The transported sediment can be treated as a passive tracer, and it is sufficient to handle the relation between solid transport and pure water hydrodynamics. Studies of this type are currently restricted to slowly evolving flows. On the other hand, it is now possible to deal with rapid transients involving water, dry grains, or liquid-granular mixtures as long as these flows take place in fixed geometries.

The problem with dam-break induced geomorphic flows is that they combine the difficulties of these two types of flow. They involve such rapid changes and intense rates of transport that the granular component plays an active role in the flow dynamics, and that inertia exchanges between the bed and the flow become important (Capart, 2000).

The present paper aims to present the issues and the scope of the IMPACT research project in the field of dam-break induced geomorphic flows, to give an overview of the state of the art, including some former studies by the IMPACT participants, and to describe briefly the research programme.
2 RESEARCH ISSUES AND SCOPE

Dam-break induced geomorphic flows generate intense erosion and solid transport, resulting in dramatic and rapid evolution of the valley geometry. In counterpart, this change in geometry strongly affects the wave behaviour and thus the arrival time and the maximum water level, which are the main characteristics to evaluate for risk assessment and alert organisation. A better understanding of such geomorphic flows and their consequences on the dam-break wave are the main goal of the “Sediment movement” work package.

2.1 Other EU research projects on natural hazards

The European Union strongly supports researches in the field of natural hazards in mountainous environment. Table 1 summarises some information about such recent projects.

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Scope</th>
<th>Start</th>
<th>Duration</th>
<th>Partners</th>
</tr>
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<tbody>
<tr>
<td><strong>Natural hazards</strong></td>
<td>Mitigation of climate induced natural hazards</td>
<td>Jan 2001</td>
<td>24 months</td>
<td>13</td>
</tr>
<tr>
<td>MITCH</td>
<td>Mitigation of climate induced natural hazards</td>
<td>Jan 2001</td>
<td>24 months</td>
<td>13</td>
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<tr>
<td><strong>Torrents and sediments</strong></td>
<td>Torrent hazard control in the European Alps. Practical tools and methodologies for hazard assessment and risk mitigation</td>
<td>Jul 2000</td>
<td>30 months</td>
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<tr>
<td>THARMIT</td>
<td>Torrent hazard control in the European Alps. Practical tools and methodologies for hazard assessment and risk mitigation</td>
<td>Jul 2000</td>
<td>30 months</td>
<td>11</td>
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<tr>
<td>EROSLOPE II</td>
<td>Dynamics of sediments and water in alpine catchments - processes and prediction</td>
<td>Jun 1996</td>
<td>36 months</td>
<td>10</td>
</tr>
<tr>
<td><strong>Debris</strong></td>
<td>Debrisfall assessment in mountain catchment for local end-users</td>
<td>Mar 2000</td>
<td>36 months</td>
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<tr>
<td>DAMOCLES</td>
<td>Debrisfall assessment in mountain catchment for local end-users</td>
<td>Mar 2000</td>
<td>36 months</td>
<td>6</td>
</tr>
<tr>
<td>DEBRIS-FLOW-RISK</td>
<td>Debris flow management and risk assessment in the Alpine region</td>
<td>Oct 1996</td>
<td>30 months</td>
<td>9</td>
</tr>
<tr>
<td><strong>Glaciological hazards</strong></td>
<td>Survey and prevention of extreme glaciological hazards in European mountainous regions</td>
<td>Jan 2001</td>
<td>36 months</td>
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<tr>
<td>GLACIORISK</td>
<td>Survey and prevention of extreme glaciological hazards in European mountainous regions</td>
<td>Jan 2001</td>
<td>36 months</td>
<td>11</td>
</tr>
<tr>
<td><strong>Avalanches and landslides</strong></td>
<td>Catastrophic avalanches: defence structures and zoning in Europe</td>
<td>Apr 2000</td>
<td>30 months</td>
<td>10</td>
</tr>
<tr>
<td>CADZIE</td>
<td>Catastrophic avalanches: defence structures and zoning in Europe</td>
<td>Apr 2000</td>
<td>30 months</td>
<td>10</td>
</tr>
<tr>
<td>ALERT</td>
<td>Avalanche and landslip early reporting technology</td>
<td>Dec 1997</td>
<td>4 months</td>
<td>2</td>
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<tr>
<td>–</td>
<td>Concerted action on forecasting prevention and reduction of landslide and avalanche risks</td>
<td>Jan 1998</td>
<td>30 months</td>
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</tr>
<tr>
<td>–</td>
<td>Major risk from rapid, large-volume landslides in Europe: the design and testing of new techniques for hazard assessment and mitigation</td>
<td>Jan 1998</td>
<td>24 months</td>
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<td>–</td>
<td>Mechanisms of catastrophic landslides</td>
<td>Jan 1998</td>
<td>24 months</td>
<td>6</td>
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<tr>
<td>–</td>
<td>New technologies for landslide hazard assessment and management in Europe</td>
<td>Jul 1996</td>
<td>24 months</td>
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Although none of the above projects aims to study specifically dam-break induced geomorphic flows, it appears that information can be gained for the understanding of some related aspects.

2.2 Problems to be solved
Depending on the distance to the broken dam and on the time elapsed since the dam break, two types of behaviour may be described and have to be understood and modelled.

In the near field, rapid and intense erosion accompanies the development of the dam-break wave. The flow exhibits strong free surface features: wave breaking occurs at the centre (near the location of the dam), and a nearly vertical wall of water and debris overruns the sediment bed at the wave forefront (Capart, 2000), resulting in an intense transient debris flow (figure 2). Some difficult features have to be taken into account: vertical component of the movement, inertial effects and bulking of the sediments.

In the far field, the solid transport remains intense but the dynamic role of the sediments decreases. On the other hand dramatic geomorphic changes occur in the valley due to sediment de-bulking, bank erosion and debris deposition (figure 3).
3 FORMER STUDIES – BRIEF PRESENTATION OF THE STATE OF THE ART

3.1 Near-field geomorphic flow

The knowledge about near-field geomorphic flow relies on two types of experiments. The associated debris flow is studied through uniform debris-flow experiments while the severe transient aspects are considered by means of idealised dam-break experiments.

3.1.1 Debris flow

Iverson (1997) reports the current state of the art for the physics of debris flow and gives some interesting information about various debris-flow events in USA, Peru, Colombia and New Zealand. The main characteristics of this type of event are the involved volume, the runout distance (sometimes hundredths of kilometres), the descent height (till 6000 m in the quoted examples) and the origin of the debris flow (mainly landslides and volcanic events).

To investigate the vertical structure of free-surface liquid-granular flows, it is of particular interest to be able to materialise steady uniform flow conditions. For example, a re-circulating flume was designed and constructed for this purpose at the Università degli Studi di Trento, Italy. It consists in a tilting glass-walled channel linked with a conveyor belt, forming a closed loop for the circulation of both water and sediment (figure 4).

![Figure 4 – Trento re-circulating flume – Photograph and plane view](image)

From these experiments, it is possible to gather some information about the acting forces involved in such debris flow (Armanini et al., 2000). Also the main characteristics of the debris flow may be measured, such as velocity and concentration vertical distribution (figure...
5). Both can be measured by Voronoi imaging methods, using the grains themselves as tracers (Capart et al., 1999). The concentration along the wall is deduced from 3-dimensional Voronoi cells built by use of stereoscopic imaging (Spinewine et al., 2002).

![Figure 5 – Velocity and concentration distribution measured normally to the flume bottom for the case of a mature debris flow (Spinewine et al., 2002)](image)

The mechanisms of debris flow are relatively well known (see e.g. Takahashi, 1991 and Iverson, 1997). The momentum conservation equations are used for both particle phase and liquid phase. A constitutive relation has to be added, linking the shear stress to the inter-particle stress component normal to the bed. This relation is expressed as a function of the Bagnold number, which represents the ratio of grain-associated inertial force to viscous force. Theoretical vertical distributions may be deduced for different types of debris flow (stony or muddy, mature or not), sometimes in accordance with experiments (velocity), sometimes less (concentration).

Besides the rheological models of momentum transport (based either on viscoplasticity or on inertial grain flow) additional considerations about the energy distribution and the pore-fluid pressure linked to a granular temperature (the equivalent of turbulence intensity) can seriously improve the predictability of such models (Iverson, 1997).

An important approach is the determination of criteria, depending on the relative depths of water and sediment mixture and on the bottom slope, able to predict the flow regime and the stress distribution. Such criteria also aim to describe the liquefaction mechanism of landslide mass and the debris flow generation due to natural dam collapse (Takahashi, 1991).

A particular point concerns the floating debris. Experiments have been carried out by Khan et al. (2000) at the University of Alberta, Canada (figure 6). The surge speed is found to be decelerated by the friction induced by the debris accumulated near the surge front.
3.1.2 Dam-break induced geomorphic flow

Debris flow is only a part – in time and space – of a dam-break induced geomorphic flow. Other aspects due to the severe transient character of the flow are considered by means of idealised dam-break experiments. Typically, a horizontal bed composed of cohesionless sediments saturated with water extends on both sides of an idealised "dam". Upstream lies a motionless body of pure water, having infinite extent and constant depth $h_0$ above the sediment bed. An intense flow of water and eroded sediments is then released by the instantaneous dam collapse (figure 7).

Such experiments have been carried out in various hydraulics laboratories, e.g. at the National Taiwan University (Capart and Young, 1998), at the Università degli Studi di Trento, Italy, at the Université catholique de Louvain (Capart, 2000) and at the Instituto Superior Técnico, Portugal (Ferreira and Leal, 1998). Various materials have been used for representing the sediments: light pearls with a density just greater than water, PVC pellets and sand, with uniform or graded grain-size distribution. Also measurement techniques were various: gauges,
interface imaging by simple cameras, particle tracking using tracers or the sediments themselves.

The near-field modelling generally relies on numerical methods, since analytical solutions (Fraccarollo and Capart, 2002), whilst clever, cannot take into consideration real-case geometries. Figure 8 illustrates a simplified but fruitful approach of the problem (Capart, 2000). Three zones are defined: the upper layer is clear water while the lower layers are composed of a mixture of water and sediments, the concentration of sediment being assumed to be constant. The upper part of this mixture is assumed to be in movement, on a depth $h_s$, with a the same uniform velocity $u$ as the clear-water layer. In the mixture layer, water and sediment move with the same velocity. In the frame of shallow-water approach, it is now possible to express the continuity of both the sediments and the mixture and also the momentum conservation with the additional assumption that the pressure is hydrostatically distributed in the moving layers, which implies that no vertical movement is taken into consideration. The set of equations is solved by a finite-volume technique, where the fluxes are computed using a Roe-type scheme. The solid transport is evaluated in a non-equilibrium frame: the erosion rate is assumed to be proportional to the difference between the actual solid transport and the potential transport corresponding to the hydraulic parameters.

![Figure 8 – Assumptions for mathematical description of near-field flow (Capart, 2000)](image)

As shown in figure 9, the comparison between measurements and numerical prediction is rather satisfactory, although some assumptions are not really in accordance with the observations: in the reality, the vertical component of the movement is not negligible at the beginning of the event, and the velocity distribution is not really uniform (see figure 5). Figure 10 gives some limitations – in time and space – arising from this simplified approach.

![Figure 9 – Comparison between measured and computed thickness and position of the water and mixture layers after 0.4 s (Capart, 2000)](image)
3.2 Channel alteration in the far field

The transition between near-field and far-field behaviour is not absolutely clear. The debris-flow front resulting from the early stage of dam-break forms a kind of obstacle, which is progressively subject to piping and overtopping. That means that a sediment de-bulking occurs and the solid transport evolves to a bed- and suspended-load transport with a particularly high concentration. The flow is highly transient and invades a part of the valley that was probably never inundated in the past. All the bank geotechnical equilibrium characteristics are ruined, in such a way that a dramatic channel metamorphosis may be expected. This corresponds to the so-called far-field behaviour.

A spectacular channel widening generally occurs due to bank scouring and collapse (see figure 3). This eroded material over-supplies the bed-load transport resulting in bed deposition (figure 11) and generation of natural dams in the downstream reaches, which may rapidly collapse.

Figure 10 – Limitations of simplified near-field approach (Capart, 2000)

Figure 11 – Dam-break consequences in the far field
Lake Ha!Ha! 1996 dam break (Brooks and Lawrence, 1999)
Laboratory scale models of rivers give interesting information about such phenomena but they are generally not used for sudden transients. Bank failure experiments are commonly carried out to study some fluvial mechanisms such as river meandering or braiding. Also channel-width adjustments during floods may be reproduced in laboratory (see e.g. Chang, 1992), but for cases where this evolution is relatively progressive.

Also experiments about breaching processes supply information about the widening of a channel under extreme flow conditions. For example, the figure 12 shows that after some time the breach shape is very similar to the cross section of a valley devastated by a dam-break wave (see figure 3). But this kind of experiment generally represents the erosion and deposition of the dike material only, the downstream valley often being modelled in the scale model with a fixed geometry. In a natural valley, the processes may be completely different, as the bank material is often undisturbed soil with a great heterogeneity.

Some experimental studies have been carried out in the past (Chen and Simons, 1979), which confirmed the above description, but the used scale (the flume was 2.40 m long and 0.12 m wide) was too small to gain quantitative information.

![Figure 12 – Breaching experiment (Université catholique de Louvain)](image)

Finally, information about the consequences of sudden floods may be gained above all from real-case data. Some of such real cases are mentioned in figure 1. An extensive survey after the catastrophe generally allows to have an idea of the final stage and to deduce the approximate evolution of the valley feature. For instance, the above mentioned Lake Ha!Ha! dam break (Canada, 1996) is well-documented (Brooks and Lawrence, 1999) and could serve as comparison for modelling (see figures 3 and 11).

The mathematical modelling of fluvial processes is relatively well developed and some commercial codes include the possibility to manage some of them (see e.g. Chang, 1992). Using the same conservation equations as mentioned in the near-field description, applied as well for water as for water-sediment mixture, it is possible to predict the variation of the wetted area of the cross sections at each time step, taking into account the sediment routing. This variation can result in a width adjustment and a bed erosion/deposition. The classical approach relies on the trend of a natural river to equalise the spatial distribution of stream
power along the reach. An adjustment in width reflects the river’s adjustment in flow resistance, that is, in power expenditure.

However, such a description does not match the rapid changes associated with dam-break waves. In this latter case, bank failure is not due to progressive toe erosion inducing a downfall of the upper part of the bank. The whole bank is strongly eroded by the intense flow and the bank evolves rapidly to an equilibrium slope corresponding to the submerged condition. Due to the short time to adapt, the upper part of the bank may present rather sharp angle of repose, at least during the time the material remains humid.

It is thus more realistic to consider that the cross sections present a profile similar to figure 13, which was obtained from experiments with sand in rising water level (Soares et al., 2001). After a rapid water-level variation, the cross-section profile adapts, with a little delay, as illustrated in figure 14. The corresponding eroded mass is now entrained in the main flow, which generally become overloaded leading to subsequent deposition. This rather crude description is able to reproduce the main features of the observed behaviour, at least qualitatively.

![Figure 13 – Typical cross section under sudden water-level variation](Université catholique de Louvain (Soares et al., 2001))

![Figure 14 – Bank failure mechanism (Soares et al., 2001)](Some more sophisticated bank-failure mechanisms could be proposed, for example using vertical slides for describing the cross-section evolution, but the associated geometrical algorithms may become very complex.)
Another promising approach relies on two-dimensional description based on a multiple layer, sharp interface approach, with a bank failure operator nested in the time-stepping loop (Capart and Young, 2002). First comparisons with 1D model and experiments (Spinewine et al., 2002) clearly indicate the interest to deepen both approaches.

However, at the moment, some limitations arise in far-field modelling. The physical coupling between the hydrodynamics and the geomorphic evolution is very strong and it would be desirable to introduce this coupling also in the numerical model. Moreover the bank-failure mechanism features 2D and even 3D geometry and is closely linked to not completely known rheological aspects. Also the modelling should cover the suspended load and the re-suspension of bed material to better fit the reality. It is thus clear that further research, including basic aspects, is required to reach satisfactory modelling of far-field response to a dike- or dam-break wave.

4 The IMPACT research programme
In the IMPACT project, two work packages are devoted to the geomorphic response to dam-break floods: “Near-field sediment flow in dam-break flow conditions” (WP 4.1) and “Geomorphologic changes in a valley induced by dam-break flows (far field)” (WP 4.2).

4.1 Near-field sediment flow in dam-break flow conditions
The objective of this work package is to advance knowledge and understanding of the processes involved in the near field transport of sediments under extreme conditions like dam-break flow. Investigations will be carried out by means of experimental observations and mathematical modelling.

Three research teams are involved in this work package: the Université catholique de Louvain, Belgium (UCL), the Università degli Studi di Trento, Italy (UDT) and the Cemagref, Lyon, France.

Experimental work will focus on two major themes: debris-flow characterisation in uniform condition (UDT) and dam-break experiments (UCL). In the UDT re-circulating flume it is foreseen to measure the flow resistance on the bottom interface and to derive the relation of its dependence on the flow dynamics under different flow conditions, as well for uniform material as for graded material. At UCL, experiments will consist in the sudden removal of a gate between two reaches with different water and sediment levels, as well for idealised material as for material closer to natural. The results of each series of tests will be documented as a validated set of benchmark data for the development and verification of mathematical models.

In parallel, UCL will develop methods to model the near-field processes by 1D and 2D-V finite-volume description, including the moving sediment layers and exploring new velocity-distribution assumptions. The three teams (UCL, UDT, Cemagref) will test their new or existing models against the benchmark data generated by the experimental work. The expected deliverable will consist in giving assumptions, description, validation and comments for the numerical simulation of near-field dam-break flow.
4.2 Geomorphologic changes in a valley induced by dam-break flows (far field)

The objective of this work package is to study the evolution from near-field behaviour to far-field geomorphologic changes in a valley induced by a dam-break flow. This includes the bank erosion, the important sediment deposition forming secondary dams with the risk of breaking up and the severe alterations of the initial river bed. The research will be undertaken by means of laboratory and field observation, which will contribute to the development of reliable mathematical models. The following problems will be addressed: (1) the bank failure mechanisms under rapidly changing flow conditions; (2) the evolution from the near-field behaviour (debris flow front, fully laden water and sediments mixture) to the far-field highly erosive flow inducing sudden bank failures; and (3) the deposition of important amounts of sediments eroded from the banks.

Four research teams are involved in this work package: the Université catholique de Louvain, Belgium (UCL), the Università degli Studi di Trento, Italy (UDT), the Cemagref, Lyon, France, and the Instituto Superior Técnico, Lisbon, Portugal (IST). For some experiments a fifth institute will be associated: the Laboratoire de Recherches Hydrauliques (LRH) of the Walloon Ministry of Equipment and Transport, Châtelet, Belgium.

The experimental programme will cover three topics: (1) tests of dam-break flow in an initially prismatic valley, with uniform and graded material (UCL); (2) similar tests in a large-scale facility to investigate scaling effects (LRH); and (3) large scale dam-break flow in an initially prismatic valley with sudden enlargement (LRH).

In parallel, field data will be collected from two sources: (1) the in situ dam-break tests foreseen in Norway by Statkraft Groner (WP2) whose observations will be used to investigate the initiation of the far-field behaviour at a "real life" scale by means of topographical surveys before and after the event; and (2) the above-mentioned lake-Ha!Ha! dam-break event (Canada), which presents severe geomorphic changes in the downstream valley. The experimental and field data will be documented as a validated benchmark.

The mathematical modelling research will consist in: (1) develop better bank-failure description; and (2) develop and extend existing 1D numerical techniques in 2D-H to include the bank failure mechanisms and consecutive sediment deposition (UCL). The four teams (UCL, UDT, Cemagref, IST) will test their new or existing models against the benchmark data generated by the experimental work. At the end of the research, it is expected to deliver assumptions, description and validation of a numerical simulation of far-field response to dam-break wave.

5 CONCLUSIONS

The problem with dam-break induced geomorphic flows is that they combine several difficulties. They involve such rapid changes and intense rates of transport that the granular component plays an active role in the flow dynamics, and that inertia exchanges between the bed and the flow become important. Dam-break induced geomorphic flows generate intense erosion and solid transport, resulting in dramatic and rapid evolution of the valley geometry. In return, this change in geometry strongly affects the wave behaviour and thus the arrival time and the maximum water level.
In the near field, rapid and intense erosion accompanies the development of the dam-break wave, leading to an intense transient debris flow. Some models exist, generally based on a shallow-water 1D description. To improve those models, some difficult features have to be considered: vertical component of the movement, inertial effects and bulking of the sediments. In the far field, dramatic geomorphic changes occur in the valley due to bank erosion, sediment de-bulking and deposition. The available models use 1D shallow-water approach with a crude bank-failure description. Improvements can be expected in order to better describe this failure mechanism and include 2D aspects.

This overview of the state of the art shows that many issues are not yet stated. The understanding and the modelling of the sediment movements induced by dam-break waves are thus really challenging and fascinating.

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