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OUTBURST FLOODS TRIGGERED BY IMPULSE WAVES:
INSIGHTS FROM HYDRAULIC EXPERIMENTATION

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ABSTRACT

Outburst floods represent a serious hazard in mountainous regions. A major trigger for these events are impulse waves generated by mass wasting into the water bodies including artificial reservoirs for hydropower generation, lakes impounded by a landslide dam, or moraine dammed proglacial lakes. After a short propagation distance, these impulse waves overtop the dam and erode its top. If the erosion is substantial enough, a dam breach is initiated. The stages leading to an outburst flood were represented by three different hydraulic model setups: impulse wave generation and spatial propagation in a wave basin, wave overtopping in a 2D wave channel, and spatial dam breach in a 1 m wide flume. Selected experiments are presented and the characteristic hydraulic features as well as governing parameters are discussed. The results support an improved hazard assessment and are useful to further develop existing numerical schemes.

Keywords: dam breach, hydraulic experimentation, impulse wave, outburst flood, wave overtopping

1 INTRODUCTION

Outburst floods are characterized by a sudden water release from a standing water body to downstream regions with a lower geodetic elevation. Potential water bodies include e.g. artificial reservoirs for hydropower generation, lakes impounded by a landslide dam, or moraine dammed proglacial lakes. Water masses overtopping the dam crest are a major load for the downstream dam face, eventually causing a complete failure of the structure due to erosion. The transport of water mass over the dam structure is initiated either by a water level rise exceeding the dam crest elevation, or by wave impact. While the former process is gradual and allows for monitoring and a temporal estimation of the instant of overtopping, the latter is subject to larger uncertainty. Impulse waves generated by substantial mass wasting into the water body pose a particular threat to the stability of embankment dams, even under conditions of a sufficient freeboard to withstand the load of wind waves.

Wave generation and propagation

Wave overtopping

Dam incision

Dam breach

Outburst flood

Figure 1. Three stages of outburst flood event triggered by impulse waves

From a hydraulician’s point of view, the chain of events leading to an impulse wave triggered outburst flood is divided into three significant stages (Fig. 1): (1) Mass wasting event such as a rockslide or an ice avalanche generating an impulse wave as a function of the governing sliding mass parameters including slide velocity, slide mass, and slide thickness. A wave train propagates radially from the impact location across the water body. During propagation, the wave characteristics (e.g. wave height, wave length) are subject to transformation due to wave decay and shoaling effects. (2) Impulse waves overtop the dam structure, thereby eroding its top and forming an incision. The overtopping volume itself might already create severe downstream flooding. If the
dam crest is eroded enough, a self-increasing spatial dam breach is induced as stage (3). Depending on the
dam geometry, its material, and the shape of the upstream water body, the released outburst flood features a
characteristic hydrograph.

Westoby et al. (2014) classify impulse wave generation by landslides or avalanches as a major triggering
mechanism for outburst floods from moraine-dammed lakes. Investigations retracing past events and hazard
assessment on possible occurrences in the future back up this statement (e.g. Klimeš et al., 2016, Clague and
Evans, 2000). While numerical approaches are the method of choice for flood modelling in complex
topographies of the valley downstream, the breach initiation and formation processes, which act as upper
boundary condition in numerical models, lack adequate integration (Westoby et al., 2014). To overcome these
limitations, the application of physical models provides a better understanding of the underlying processes and
means for quantitative estimations. Awal et al. (2010) show wave profiles, dam shape evolution profiles and
outflow hydrographs for an integrative experimental setup and describe the effect of selected parameters on
the overall outburst flood process. Balmforth et al. (2009, 2008) focus on the wave overtopping and incision
stage, and present experiments as a starting point for the development of a numerical approach. However,
these studies provide a primarily qualitative analysis but overlook possible scale effects.

Three self-contained experimental setups were installed and operated with the objective of gaining detailed
insight into the underlying physics of the stages shown in Figure 1. Impulse wave and dam breach tests were
conducted in 3D setups, while a 2D channel was employed for wave overtopping tests. Given the complex
hydraulic processes involving multi-phase flow and spatial test configurations, the requirements regarding
measurement techniques are demanding. The following sections present the respective setups and provide
descriptions of relevant hydraulic features for selected experiments as well as their main governing parameters.

![Figure 2](image-url)
2 IMPULSE WAVES

The stage of impulse wave generation and spatial propagation was modeled in an 8 m by 4.5 m wave basin. A deformable mesh-packed granular slide on an inclined plane was used for wave generation whereas a videometric measurement system was employed for tracking a grid projection on an opaque water surface as shown in Figure 2 (Evers and Hager 2016). Compared with conventional wave gauges, this approach allows for a high spatial resolution with up to 6,000 measurement positions at an acquisition rate of 24 Hz in a measuring field of approximately 14 m² (Evers and Hager, 2017).

Figure 2 shows a photo sequence of an experimental run for a slide with impact velocity \( V_s = 4.55 \text{ m/s} \), mass \( m_s = 20 \text{ kg} \), slide thickness \( s = 0.12 \text{ m} \), slide width \( b = 0.5 \text{ m} \), and impact angle \( \alpha = 60^\circ \) at a stillwater depth \( h = 0.3 \text{ m} \). At time \( t = 0 \text{ s} \), the grid projection on the water surface is undisturbed. The sliding mass impacts the water body at \( t = 0.3 \text{ s} \) creating a splash that has developed its maximum extent at \( t = 0.5 \text{ s} \). Later, the impact crater collapses as shown at \( t = 0.93 \text{ s} \). The collapse leads to wave run-up at the sliding plane (\( t = 1.27 \text{ s} \)). Simultaneously, the first wave detaches from the impact location featuring a long crest. At \( t = 1.65 \text{ s} \), the first crest is followed by a wave trough and a second wave crest is generated. A steeper second wave crest is fully developed at \( t = 2.23 \text{ s} \) with spilling features noted at its crest line. At \( t = 2.66 \text{ s} \), these spilling features have dissipated and a third wave crest has developed. The last photo at \( t = 2.66 \text{ s} \) shows succeeding waves of the wave train generated by the slide impact. Note that the length of the first wave is substantially longer than these succeeding waves.

Evers and Hager (2016) state that the height of the first wave is mainly governed by the same parameters as in 2D experiments; namely slide impact velocity \( V_s \), slide mass \( m_s \), slide thickness \( s \), and slide impact angle \( \alpha \) as well as the stillwater depth \( h \). The slide width \( b \) is identified as an additional governing parameter in spatial environments by Evers and Hager (2017). Only waves outgoing from the slide impact location were analyzed. However, a water body prone to create outburst floods is confined by a dam or a shoreline with expansive slopes. Outgoing waves are reflected, creating an irregular wave pattern with wave superposition or potentially a seiche. These processes cannot be experimentally accounted for in a general setup. To quantify the wave load for wave run-up or overtopping along the shore, an estimation of the decay rate of a wave envelope consisting of multiple impulse waves is required, whose envelope’s initial maximum wave at impact can be determined from experiments.

3 WAVE OVERTOPPING

The erosional processes of impulse wave overtopping were analyzed in a 2D wave channel. Solitary waves were generated with a piston-type wave maker and the overtopping process at a granular dam of uniform grain size was captured with a high-speed camera. A drainage system was installed at the downstream dam toe to avoid seepage flow. A detailed description of the experimental setup provides Huber et al. (2017).

Figure 3 shows an experimental run with dam height \( H = 0.18 \text{ m} \), freeboard \( f = 0.02 \text{ m} \), and solitary wave height \( H_f = 0.11 \text{ m} \) at a stillwater depth \( H_f = 0.18 \text{ m} \). The water surface is undisturbed and the freeboard intact at \( t = 0 \text{ s} \). At \( t = 0.9 \text{ s} \), the solitary wave has reached the dam crest and the overtopping process is initiated. The maximum overtopping depth \( d_0 \) is attained at \( t = 1.12 \text{ s} \) and sediment transport occurs both on the upstream side and on top of the dam. At \( t = 1.22 \text{ s} \) the overtopping water mass has reached the dam toe and the downstream portion of the dam is covered with a maximum water column. The water column above the dam crest has substantially dropped and a constant flow depth at the downstream side has formed at \( t = 1.3 \text{ s} \). In addition, air entrainment from the dam body into the water column is observed. At \( t = 1.6 \text{ s} \) the flow depth above the dam crest continues to drop and the flow on the downstream dam portion becomes highly turbulent. Only a slight flow depth remains at \( t = 2 \text{ s} \), while water is infiltrating the dam body. The overtopping process is completed at \( t = 2.42 \text{ s} \) along with a freeboard reduction to 50% of its initial extent.

The eroded crest depth \( h_c \) is defined by Huber et al. (2017) as the vertical distance between the initial dam crest and the highest dam elevation after a test. It is mainly governed by the freeboard, followed by wave height and dam shape. No effect of the grain size was found for the investigated range between 1.23 mm and 2.68 mm, including mixtures. Another important quantity is the overtopping volume \( V_f \). If the dam crest withstands wave loading and the entire structure is not subject to failure, small overtopping volumes can already create severe downstream flooding. Compared to rigid structures, overtopping volumes at granular dams are only slightly lower. As described in the previous section, not only solitary impulse waves will be generated by a landslide or avalanche, but also a wave train with multiple impulse waves including wave reflections impacting the granular dam. Although the impulse wave envelope at impact is subject to decay, repeated overtopping can erode the dam crest so strong, that its maximum elevation lies beneath the still water level and a constant outflow is initiated. Therefore, the vulnerability of a dam section to become the initial incision for a dam breach is affected by its distance to the slide impact location as well as its freeboard and geometry. It should also be borne in mind that the above-described research applies exclusively to 2D dam overtopping, so that additional 3D effects need to be carefully considered using detailed laboratory experimentation if the failure of the dam structure poses severe risks in the tailwater valley.
4 DAM BREACH

The dam breach experiments were conducted in a 1 m wide and 11.9 m long flume. A videometric measurement system was employed for tracking the spatial and temporal evolutions of the breach geometry during a test, taking into account refraction effects in the submerged breach portions due to the change of the refractive index between air and water (Frank and Hager, 2015). Figure 4 shows the grid projection onto the dam surface of the half-model test. The direction of view is from down- to upstream with the pilot channel at the glass wall on the right, necessary to initiate the spatial breach and representing an incision created by wave overtopping. To simulate the discharge characteristics for different reservoir sizes and shapes, a controller-based pump regulation scheme was applied to add a simulated reservoir volume to the physical reservoir of the laboratory channel (Frank, 2016).

Figure 4 shows a dam breach experiment of dam height $w = 0.3$ m, dam length $b = 1$ m and reservoir water surface area $A_R = 33.4$ m$^2$. At time $t = 0$ s, the granular dam is intact and water flows through the pilot channel. The initial small breach discharge mixes with the eroded sediment, so that the water-sediment mix flows slowly and deposits on the downstream dam face up to $t = 15$ s. The initial mainly vertical incision has extended to the downstream dam toe at $t = 21$ s and water continuously runs through the small channel of approximately constant width. At $t = 34$ s, increased side erosion leads to the characteristic so-called hourglass shape of the dam breach channel, while at the same time the base of the breach channel is still eroded vertically. Surface waves form in the downstream reach of the breach channel, inhibiting a clear view of the projected grid and
impeding the capturing of the submerged breach shapes, as described by Frank and Hager (2015). For \( t > 34 \) s, the breach channel widens, the reservoir water level drops and the breach discharge increases up to \( t = 200 \) s before reducing to zero at \( t = 647 \) s.

Frank (2016) conducted 45 laboratory tests with dams built of non-cohesive sediment. It was found that the peak breach discharge is mainly governed by the parameters maximum headwater level \( h_M \), reservoir water surface area \( A_R \), cross-sectional dam area \( A_D \), and inflow discharge \( Q_o \) if the drainage discharge is assumed to be negligible. The results indicate that \( A_R \) represents a more practical parameter to describe peak breach discharge as compared with the often-used reservoir volume. In addition, \( A_R \) is directly extracted from ortho-images so that no information of the reservoir bathymetry is needed for estimating the peak discharge. A satisfactory fit with peak breach discharge data of historical dam failures was obtained by introducing a fit parameter for the higher erosion resistance of prototype dike material. The results of Frank (2016) also include data on the spatial breach topographies as well as the breach hydrographs and allow for a quantification of erosion rates. Given that outburst floods commonly evolve into debris flows (Westoby et al., 2014), these two quantities are relevant as upper boundary condition in numerical simulations modelling downstream flood propagation.

![Figure 4. Photo sequence of dam breach experiment with a simulated reservoir volume](image)

5 CONCLUSIONS

Mass wasting into dammed water bodies is a major triggering mechanism for outburst floods. Related events have occurred in the past and pose a major future hazard in mountainous regions. The hydraulic features of the triggering processes were analyzed for three selected experimental setups. These setups represent the three stages of such an event, including impulse wave generation and propagation, wave overtopping and dam incision, and a dam breach with a characteristic hydrograph as the source for the outburst flood. Key hydraulic features were presented and discussed with photo sequences of selected experimental runs. To obtain quality measurement data of high spatial density and acquisition rate, a novel videometric measurement technique with versatile capabilities was applied. Although outburst flood events are simulated by means of numerical models,
the physical principles of the triggering processes are still lacking detailed understanding and are a source of substantial uncertainties. The experimental data are crucial to develop integrated numerical schemes covering all stages of an outburst flood event, offering the potential to model prototype settings including downstream reaches. In addition, model tests provide the basis for generally applicable equations serving for an overall hazard assessment as well as a prediction of hydrographs as the input parameter for numerical simulations of the tailwater flood impact.

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