Zeitschrift: Wasser Energie Luft = Eau énergie air = Acqua energia aria

Herausgeber: Schweizerischer Wasserwirtschaftsverband

Band: 115 (2023)

Heft: 3

Artikel: Contribution of the hydraulic laboratories of the Swiss Federal Institutes of Technology to dam safety

Autor: De Cesare, Giovanni / Evers, Frederic M. / Stocker, Barbara

DOI: https://doi.org/10.5169/seals-1050003

Contribution of the Hydraulic Laboratories of the Swiss Federal Institutes of Technology to Dam Safety

Giovanni De Cesare, Frederic M. Evers, Barbara Stocker, Samuel L. Vorlet, Azin Amini and Robert M. Boes

Zusammenfassung

Obwohl der Talsperrenbau im Allgemeinen und die Talsperrenhydraulik im Besonderen weit entwickelte Fachgebiete sind, rechtfertigt das mit Talsperren verbundene Risikopotenzial in den meisten Fällen die Prüfung und Optimierung des Entwurfs der zugehörigen Talsperren-Nebenanlagen in hydraulischen Modellversuchen. Darüber hinaus erfordern Sediment- und Schwemmholztransport sowie Mehrphasenströmungen an Stauanlagen und in Stauseen häufig gegenständliche Modellversuche, um die beteiligten physikalischen Prozesse besser zu erfassen und zu verstehen. Die bei der physikalischen Modellierung gewonnenen Daten sind wertvoll für die Kalibrierung und Validierung von numerischen Simulationswerkzeugen sowie für ingenieurtechnische Regelwerke. Die Forschung auf dem Gebiet der Talsperrenhydraulik und verwandter Stauanlagen betreffender Aspekte wie Stauraumverlandung und Naturgefahren ist nach wie vor von grossem Nutzen, um das Wissen im Talsperrenwesen zu erweitern und die Sicherheit und den Betrieb von Stauanlagen zu verbessern. Die Wasserbaulabore der Eidgenössischen Technischen Hochschulen in Lausanne und Zürich leisten seit ihrer Gründung einen Beitrag zu den Themen des Talsperreningenieurwesens in der Schweiz sowie im Ausland und unterstützen somit das Fachwissen der Schweizer Talsperrenexpert:innen. Neben der Bedeutung der wasserbaulichen Laboratorien für die Planungsindustrie, respektive für den sicheren und effizienten Betrieb von Talsperren und Nebenanlagen, gilt es auch deren Wichtigkeit für die Grundlagenforschung herauszustreichen. Gemäss der Beurteilung der Autor:innen, gründen die meisten wissenschaftlichen Publikationen in anerkannten Fachzeitschriften nach wie vor auf Daten, welche experimentell im physikalischen Modell erhoben wurden.

Résumé

Bien que la construction de barrages en général et l'hydraulique des barrages en particulier soient des domaines techniques très développés, le potentiel de risque associé aux barrages justifie dans la plupart des cas la vérification et l'optimisation de la conception des installations auxiliaires par des essais de modélisation hydraulique. En outre, le transport de sédiments et de bois flottants ainsi que les écoulements multiphasiques sur les barrages et dans les réservoirs nécessitent souvent des essais de modélisation en grandeur réelle afin de mieux appréhender et comprendre les processus physiques impliqués. Les données obtenues lors de la modélisation physique sont précieuses pour le calibrage et la validation des outils de simulation numérique ainsi que pour l'établissement de normes et règlements. La recherche dans le domaine de l'hydraulique des barrages et des aspects additionnels concernant les barrages, tels que l'alluvionnement des retenues et les dangers naturels, reste très utile pour élargir les connaissances dans le domaine des barrages et améliorer leur sécurité et exploitation. Depuis leur création, les laboratoires d'ingénierie hydraulique des écoles polytechniques fédérales de Lausanne et de Zurich contribuent aux thèmes de l'ingénierie des barrages en Suisse et à l'étranger et soutiennent ainsi les connaissances spécialisées des expertes et experts suisses en la matière. Au-delà de l'importance des laboratoires d'hydraulique dans la planification, ainsi que pour l'exploitation sûre et efficace de barrages et ouvrages annexes, il convient également de souligner leur importance pour la recherche fondamentale. Selon la perception des auteurs, la plupart des publications scientifiques dans des revues spécialisées reconnues se basent toujours sur des données expérimentales collectées sur modèle physique.

1. Introduction

The two hydraulic laboratories at EPFL and ETH Zurich were founded in 1928 and 1930, respectively. Since the beginning, they have been involved in dam projects in Switzerland and abroad. Typically, model tests are carried out to check and optimize the layout of spillways, intake and outlet structures, as well as energy dissipators, i.e. the so-called appurtenant dam structures. These structures play a vital role in operational aspects and dam safety. Their malfunction may lead to severe dam safety problems, as exemplified in 2017 at the US American Oroville Dam in Northern California. Its service spillway failure and the erosion at the toe of the emergency spillway weir led to the evacuation of 190'000 people downstream of the dam, as a dam breach was imminent. In addition to appurtenant structures, reservoir sedimentation management techniques were and are regularly studied to find measures that help counter the gradual filling up of reservoirs by sediments.

In this article, three topics related to dam safety and reservoir operation which are researched at the laboratories in Lausanne (Plateforme de Constructions Hydrauliques PL-LCH) and/or Zurich (Versuchsanstalt für Wasserbau VAW) are presented: blockage of spillway overflow weirs by floating debris like large wood, impulse waves resulting from mass wasting like landslides and snow avalanches into reservoirs, and the sedimentation of reservoirs. All these may threaten dam safety when blocking outlets and intakes and/or leading to the overtopping of dams by the reservoir water level and waves, respectively. In addition to safety and operational aspects, the retention and trapping of wood and sediments have also negative consequences on aquatic and terrestrial ecosystems downstream of dams, as both are components of healthy natural rivers systems. To counteract reservoir sedimentation is thus a win-win situation both from a dam operational and ecological perspective.

2. Large Wood Blockage at Dam Overflow Weirs

Large wood (LW) carried along during floods can lead to security issues at dams when clogging of intake weir structures of spillways occurs. In particular, the accumulation of LW at the weir piers may significantly reduce the discharge capacity and cause unacceptably high water levels in the reservoir, so that the required freeboard may no longer be guaranteed *(Schmocker & Boes 2018)*. At both PL-LCH of EPFL and VAW of ETH Zurich, numerous site-specific model tests have been performed in the past to study weir and spillway flows. Often, the risk of blockage by LW was also tested within these investigations. The results referred to the particular cases, however, and could not easily be generalized. Therefore, more recently, model tests have been carried out at both laboratories to study the clogging risk and backwater rise effects at bridge piers and decks, dams and weirs in a more systematic way *(Pfister et al., 2013; Schmocker & Weitbrecht, 2013; Schmocker, 2017; Schalko et al., 2018, 2020; Furlan et al., 2019, 2020; Bénet et al., 2021, 2022; Stocker et al., 2022; Boes et al., 2023a,b)*. Herein, systematic model tests carried out recently at ETH Zurich for the Swiss Federal Office of Energy (SFOE), dam surveillance group, on multi-span, unregulated ogee weirs of dam spillways with frontal approach flow are described and results on blocking probability and backwater rise are given. To make the research studies listed above more accessible to practitioners, the results were included in a bulletin of the International Commission on Large Dams *(ICOLD, 2023)*.

2.1 State of the art

The currently, valid SFOE guideline *(SFOE, 2017)* regarding minimum weir bay dimensions for a safe passage of driftwood have been taken from the Norwegian recommendations, which are based on only one model investigation by *Godtland & Tesaker (1994)*. The database for determining the minimum required weir bay opening dimensions is therefore very limited *(SwissCOD, 2017)*. If driftwood cannot be passed, it must be retained in areas of low flow velocities at a sufficient distance from the spillway *(SFOE, 2017)*. An extensive state of the art on large wood issues at dam spillways can be found in *SwissCOD (2017)*. A systematic investigation of the required distance for large wood retention cannot be found in existing literature.

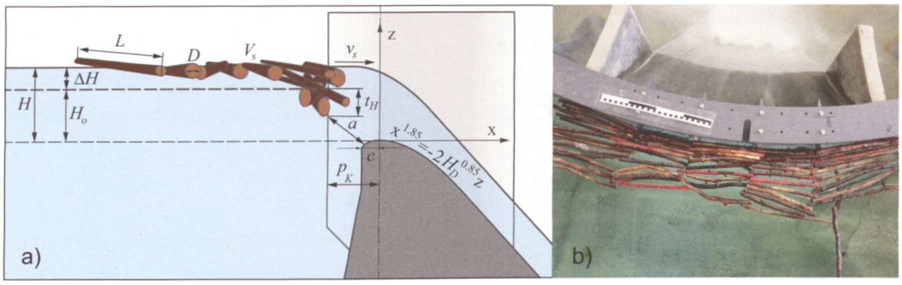

Figure 2.1: a) Definition sketch of all relevant parameters for a standard profile according to USACE (1987) with H = overflow depth with LW, ΔH = backwater rise, H_o = overflow depth without LW, L = log length, D = log diameter, v_s = surface velocity, t_H = immersion depth of LW accumulation, p_K = pier protrusion, a = free cross-sectional flow area, H_D = 2 m with x and z as coordinates, and $c = 0.28 \cdot H_D$. b) LW accumulation at the end of an experiment for p_K = 0.98 m and H_o = 3 m after systematic LW addition.

2.2 Blocking of LW at weir piers and backwater effect

VAW conducted experiments on the relation of trapped vs. added wood when LW approaches the spillway in large groups, as well as the potential rise of the reservoir level due to spillway blocking in relation of the distance of the LW-accumulation to the weir crest (parameter p_K in *Figure 2.1*). *Figure 2.1 a)* shows the definition sketch of the experiments, *b)* shows the formed accumulation body during an exemplary experiment. The applied methodology for the experimental investigations can be found in *VAW (2022)*, or partly in *Stocker et al. (2022)* and *Boes et al. (2023a, b)*.

Wood passage over weir bays

The results on the blocking ratio of large LW groups have shown that, by following the guidelines on minimum weir bay width equal to 80% of the relevant log length, a main part of the LW transported in groups will be blocked and thus cannot be safely passed through. Furthermore, they provide information on the relevant log length in heterogeneous length distributions. Accordingly, the 90% percentile is preferable to the median and the mean value of the length distribution as the relevant stem length, as one or a few long logs usually trigger an accumulation. These results show that the current state of the art does not provide safe passage when wood approaches a spillway weir in a big group. More detailed information can be found in *VAW (2022)*.

Wood retention at protruding weir piers

Figure 2.2 shows the measured discharge reduction η at a standard ogee weir profile due to LW blockage as a function of relative weir pier protrusion P_K, which is a measure for the distance from the blockage to the weir crest. It shows good agreement with data collected by *Hartlieb (2015)* and *Bénet et al. (2021)*.

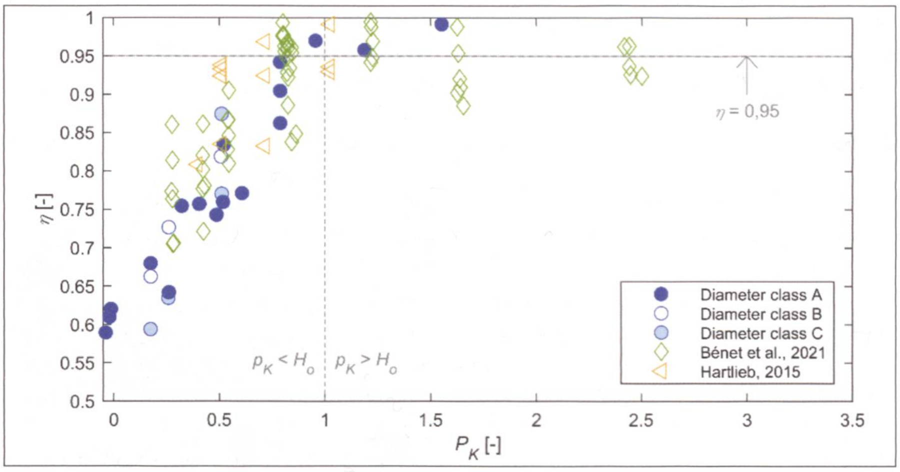

Figure 2.2: Relative discharge reduction $\eta = C_{dH}/C_d$ at standard ogee weir profile due to LW blockage as a function of relative weir pier overhang $P_K = p_K/H_o$ for data from this study with log diameter classes A (0.37 m), B (0.2 m), and C (0.54 m) as well as from Hartlieb (2015) and Bénet et al. (2021).

During the experiments, flow velocities, the forming accumulation body, and the resulting water level rise were investigated. The following procedure to estimate water level rise in case of driftwood blocking was proposed and can be applied at spillway structures of high dams similar to a standard weir profile:

i. Estimate normalized surface flow velocity v_{sn} without LW at the point, where wood will get blocked (e.g. at upstream pier noses, rack structure…) using

$$v_{sn} = \frac{v_s}{\sqrt{2 \cdot g \cdot H_o}} = 0.5 \cdot e^{-\frac{2}{3} \cdot p_K}$$

ii. Estimate the resulting immersion depth t_H of the forming LW accumulation body as follows:

$$\frac{t_H}{H_o} = T_H = 1.82 \cdot v_{sn} = 0.91 \cdot e^{-\frac{2}{3} p_K}$$

iii. Calculate the clear distance a between the weir profile and the lower edge of the accumulation body. For a standard profile ogee weir *(USACE, 1987)*, the clear distance a can be calculated as follows:

$$a = \sqrt{\left(p_K - \frac{2}{3}k\right)^2 + \left(H_o - t_H + \frac{c - \sqrt{c^2 - \frac{4}{9}k^2}}{2}\right)^2} \quad \text{for } k \geq 0$$

with $k = p_K$ for $0 \leq p_K \leq c$ and $k = c$ for $p_K > c$

iv. Estimate maximum water level rise ΔH_{max} using

$$\frac{\Delta H_{max}}{H_o} = 1.5 \cdot e^{-4.2 \frac{a}{H_o}} \quad \text{for } a / H_o \geq 0.3$$

2.3 Summary

Experiments have shown, that safe passage of LW via the weir can be hard to assure, as a few long logs can cause clogging of a significant amount of LW at the weir structure. In contrast, retention of the LW at a sufficient distance from the weir crest keeps the reservoir level rise low, even in the case of a prominent LW obstruction. The following basic characteristics regarding LW blockage at piers of dam spillway weirs can be derived from the present study:

- If LW is retained in an area with surface velocities $v_s < 1$ m/s, a loose log carpet is formed without the formation of a vertically extending LW obstruction body.
- For a clear distance below the obstruction body of $a > 0.7 \cdot H_o$, the relative backwater rise $\Delta H_{max}/H_o$ is < 0.1.
- For a pier overhang of $p_K \geq H_o$, the relative water level rise $\Delta H_{max}/H_o$ is < 0.1 because the discharge coefficient C_d is only slightly reduced (< 5%) *(Figure 2.2)*.
- Weir piers whose upstream ends are flush with the weir crest (i.e. do not project into the reservoir) cause an uncontrolled backwater effect in the event of a blockage and should be avoided if the safe passage of the LW via the weir and spillway cannot be assured or proven.

Further information and how to conduct a sensitivity analysis for accumulation bodies with less porosity than the ones examined can be found in *VAW (2022)*.

3. Impulse Waves In Reservoirs

3.1 From applied to fundamental research

Rockslides, avalanches, and glacier collapses are extremely rapid, gravity-driven mass wasting events occurring in Alpine environments that may generate large water waves upon impacting a large body of water including reservoirs. The characteristics of these so-called impulse waves and their destructive potential at the shore are similar to earthquake induced tsunamis in the ocean. In confined water bodies, the run-up height of impulse waves may locally even exceed the one of ocean tsunamis by an order of magnitude. This was, e.g., the case for the Lituya Bay event in Alaska, where in 1958 a rockslide generated waves that ran-up more than 500 m at the opposite shore. This event drew the attention of the international research community towards this type of hazard *(Hager & Evers 2020)*. For the dam engineering community, it was primarily the event at Vajont dam, Italy, in 1963 that brought the topic of impulse waves into focus. However, already the earlier events at Fedaia and Pontesei reservoirs, both Italy, in 1958 and 1959 demonstrated the associated risk for dams and reservoirs. In Switzerland, impulse waves were, e.g., generated in Räterichsbodensee by a snow avalanche in 1962. All these events fall into a period when reservoir development in Switzerland was soaring. In this context, site-specific hydraulic laboratory experiments that included an assessment of hazards related to impulse waves were conducted at VAW, e.g., for Mauvoisin and Ferden reservoirs *(Figure 3.1)*.

The site-specific studies showed the necessity for a better understanding of the fundamental hydraulic processes related to impulse waves, namely wave generation and propagation as well as wave-shore/structure interaction. This led to a series of dissertation research studies at VAW:

- *Huber, Andreas (1980)*. Schwallwellen in Seen als Folge von Felsstürzen [Impulse waves in lakes resulting from rockslides].
- *Sander, Johannes (1990)*. Weakly nonlinear unidirectional shallow water waves generated by a moving boundary.
- *Müller, Dieter R. (1995)*. Auflaufen und Überschwappen von Impulswellen an Talsperren [Runup and overtopping of impulse waves at dams].
- *Fritz, Hermann M. (2002)*. Initial phase of landslide generated impulse waves.
- *Zweifel, Andreas (2004)*. Impulswellen: Effekte der Rutschdichte und der Wassertiefe [Impulse waves: Effects of slide density and water depth].
- *Heller, Valentin (2007)*. Landslide generated impulse waves: Prediction of near field characteristics.
- *Fuchs, Helge (2013)*. Solitary impulse wave run-up and overland flow.
- *Evers, Frederic M. (2017)*. Spatial propagation of landslide generated impulse waves.

3.2 Impulse wave manual

To make the fundamental research studies listed above more accessible to practitioners, the results were compiled in a manual, first published in German in 2008 and translated to English in 2009. In addition to providing an overview of the state of research, the impulse wave manual (IWM) combined empirical equations derived from laboratory experiments into an integrated

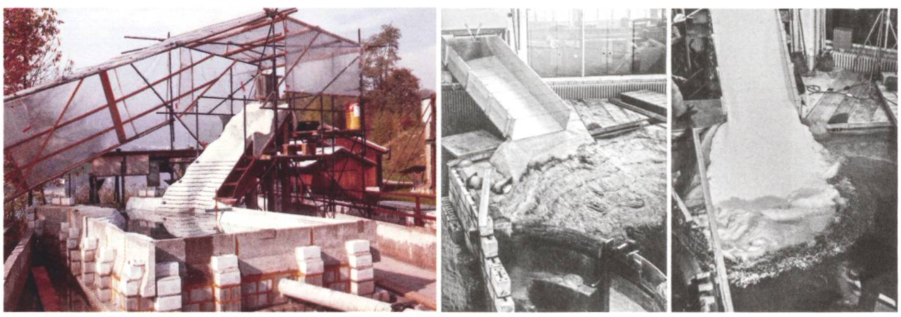

Figure 3.1: Applied impulse wave research at VAW with scale models of prototype sites in Switzerland: Lac de Mauvoisin (VAW 1972, left) and Ferden compensating reservoir (VAW 1973, center and right).

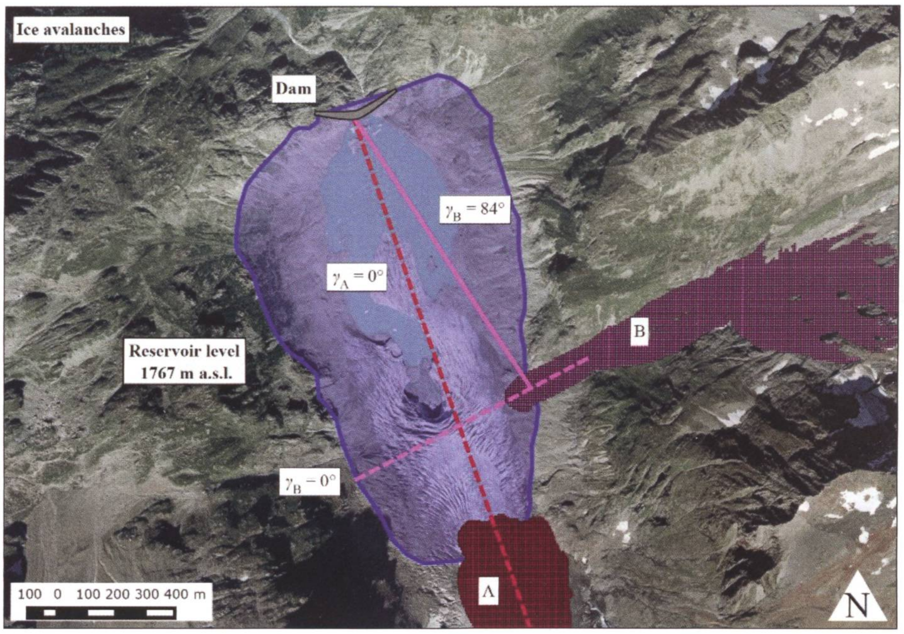

Figure 3.2: Ice avalanche scenarios and impulse wave propagation angles for future Trift Reservoir (KWO AG, in planning; background imagery: Federal Office of Topography).

and easy to apply computational procedure. Updating the IWM with latest research findings, a second edition was published in 2019 *(Evers et al., 2019)*. Over the years, the IWM's computational procedure has been widely applied by dam operators, engineering companies, dam safety agencies, and research groups around the world. To date, the bibliographic database Google Scholar counts more than 150 citations in total. In addition to an improved emergency planning for existing reservoirs, the IWM's computational procedure proved to be an inexpensive method to obtain a first indication of an impulse wave event's magnitude during the preliminary design phase of new reservoir projects. If a potential impulse wave risk is identified at an early stage of the design process, more extensive and prototype-specific methods including physical hydraulic modelling and numerical simulations can be conducted to develop mitigation measures *(Evers & Boes 2022)*. Moreover, in imminent emergency situations, the complementary spreadsheet-based computational tool allows for ad-hoc wave height and run-up estimations in quasi no time.

The impulse wave assessment conducted for the Trift Reservoir that is currently being planned by KWO AG illustrates the application of the IWM. Geotechnical investigations of the surrounding mountain flanks yielded no increased susceptibility to significant slope failures. However, snow avalanches in general and ice avalanches from the adjacent Trift Glacier in particular might generate impulse waves potentially posing a risk during the operation of the future reservoir. *Figure 3.2* shows two selected ice avalanche scenarios, which may affect the reservoir. Wave propagation along the main direction of the slide ($\gamma = 0°$) was assessed for both scenarios. For scenario B, also the almost perpendicular propagation angle towards the dam was investigated. Similarly, four snow avalanche scenarios were considered *(Evers et al., 2018)*. Mitigation measures against impulse waves generated by snow avalanches include preemptive avalanche blasting and lowering of the water level. Due to the high rate of glacier retreat, the risk of ice avalanches is continuously decreasing during the projected operation period of the reservoir.

3.3 Recent laboratory research

Following the IWM's second edition, further experiments on wave-structure-interaction were conducted in the impulse wave channel at VAW. *Kastinger et al. (2020)* investigated the run-up behavior of impulse wave trains. Especially during small impulse wave events, a series of waves, i.e. a wave train, is generated, where the leading wave is not necessarily the one reaching the maximum run-up height. Based on the equations derived from the experiments, a sufficient freeboard can be dimensioned or an adequate preemptive reservoir drawdown initiated. *Hess et al. (2023)* investigated the forces acting on dams when the available freeboard is not large enough and wave overtopping is induced *(Figure 3.3)*. It was found that for small freeboards, already small relative wave amplitudes may exert forces similar to those of earthquakes. The presented studies help to add relevant hydraulic processes to the IWM's computational procedure or to improve the application limits of already incorporated equations with extended experimental data sets. Another example for the latter is the just recently concluded research project on shallow impact angles funded by the Dam Safety Research Programme of the Swiss Federal Office of Energy that set the equation's lower parameter limitations for the slide impact angle from 30° to 15° *(Bross & Evers, 2023)*.

4. Reservoir Sedimentation

Reservoir sedimentation is one of the main challenges in the sustainable operation of large reservoirs as it causes volume loss, affecting hydropower production capacity, dam safety, and flood management. The construction of a dam alters the sediment inflow and outflow balance that is observed for natural conditions and the sediment flow continuity is interrupted, resulting in sedimentation *(Schleiss et al., 2016)*. On a global scale, storage capacity loss due to sedimentation is estimated to be between 1 and 2% annually. According to a recent UN University study *(Perera et al., 2023)*, it is forecasted that dams around

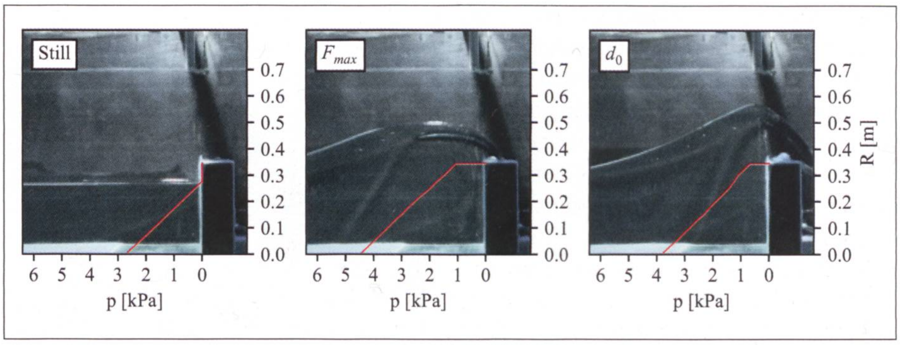

Figure 3.3: Solitary wave overtopping photos and measured water pressure distributions for still water conditions (left), the instant of maximum force (center), and the instant of maximum overflow depth (right) (Hess et al., 2023).

the world will lose nearly a quarter of their storage capacity due to sedimentation by 2050. The evolution of storage capacity and of volume loss due to sedimentation is a substantial problem for sustainability, as the annual increase in storage volume due to construction of new reservoirs is close to 1% *(Müller, 2012)*. It has been estimated that Alpine reservoirs have a mean annual sedimentation rate of approximately 0.2% *(Beyer & Schleiss, 2000)*. This low sedimentation rate is mainly due to geological characteristics of the catchment areas. However, safe and sustainable operation of Alpine reservoirs, which are predominantly used for hydropower production, is threatened by the deposition of sediment after decades of operations. The accumulation of fine sediment in large reservoirs has negative impacts on hydropower production and can lead to serious issues, such as reduction of live storage, blockage of power intakes, turbine abrasion and dam safety in case of bottom outlet blockage *(Müller et al., 2014; Guillén Ludeña et al., 2018)*. In addition, downstream river reaches are negatively impacted by the decrease in sediment supply *(Mörtl & De Cesare, 2021)* or increased clogging *(Dubuis & De Cesare, 2023)*.

Figure 4.1: Räterichsboden power intake and bottom outlet (KWO, Switzerland); courtesy of Michael Müller.

Sedimentation is a serious issue for most Alpine reservoirs, as many of them were built in the second part of the last century and have been experiencing ongoing sedimentation for decades. In large seasonal storage reservoirs in partially glaciated catchments, sediment inflows are mostly fine-graded, supplied by glacier melt flows and moraine sediment transport during rainfall events in the summer and autumn months in the catchment area. Coarse-graded sediment is mainly deposited in the delta area, while fine-graded sediment is transported and deposited near the dam by turbidity currents *(De Cesare et al., 2001)*. These reservoirs are often part of hydropower plants composed of multiple reservoirs with a range of reservoir size and morphology, including pumped-storage facilities, facing new challenges with sedimentation.

In order to ensure the sustainability of large reservoirs by maintaining sediment flow continuity, it is essential to understand the mechanisms of sedimentation. The prediction of sediment deposition can enable adequate sediment management, including the design and implementation of prevention and mitigation measures. Several technical methods are now being used worldwide to combat sedimentation in large reservoirs. However, most of these methods have a considerable ecologic and/or economic impact. It is therefore paramount to develop new measures to ensure fine sediment transport through large reservoirs. This chapter presents innovative methods developed at the Hydraulic Constructions Platform (PL-LCH) of Ecole Polytechnique Fédérale de Lausanne (EPFL) for fine sediment management in reservoirs, and another related research project on fine sediment routing via power waterways conducted at the Laboratory of Hydraulics of ETH Zurich.

Numerous technical solutions have been developed in recent decades for sediment management in reservoirs. These measures are commonly distinguished between solutions in the catchment area (soil conservation, slope and banks protection, bypass structures, etc.), in the reservoir (flushing operations, controlling turbidity currents, etc.), at the dam (intake/bottom outlet heightening, etc.) or downstream *(Jenzer Althaus et al., 2010)*. However, these measures usually have a significant economic or ecological impact. In this context, innovative methods to combat the trapping of fine sediment by large reservoirs still need to be developed.

4.1 Fine sediment routing by stirring

Sediment routing is one innovative method that aims to keep fine sediment in suspension in large reservoirs for subsequent routing through power waterways, without additional water consumption or adverse impact on hydropower operations. Turbulence levels in the reservoir and close to the waterway intakes should be maintained above a minimum threshold level to ensure fine sediment transport for given particle sizes and physical properties. This can be achieved via operational stirring, where the level of turbulence is related to the hydropower operations and power intake structures, or via forced stirring, where the level of turbulence is controlled by an external device. Both methods help to keep fine sediment in suspension, and/or the mobilization of deposited sediment in specific conditions.

4.1.1 Operational stirring

Operational stirring makes use of hydrodynamics induced by inflows and outflows in large reservoirs *(Jenzer Althaus et al., 2015; De Cesare et al., 2019)*. The interplay between inflows and outflows helps to maintain a proper turbulence level in vicinity of these structures. In pumped-storage facilities, the water intake works in both flow directions. The hydrodynamics induced by the inflow and outflow sequences (and the turbulence maintained or increased by the cyclic flow exchanges) inhibit sediment settling *(Guillén Ludeña et al., 2018)*. Previous studies have shown that reservoir stratification and sediment transport dynamics are altered by pumped-storage operations, and that the settling of fine sediment can be considerably reduced near the outlet structures by inflow and outflow sequences *(Guillén Ludeña et al., 2017; Müller et al., 2017)*. Therefore, the assessment of reservoir hydrodynamics and turbulence levels, and the resulting sediment motion, is of paramount importance in selecting the most suitable location, orientation, and layout of the power intake and outlet structures. These elements can then be integrated into the design of new or expanding hydropower schemes.

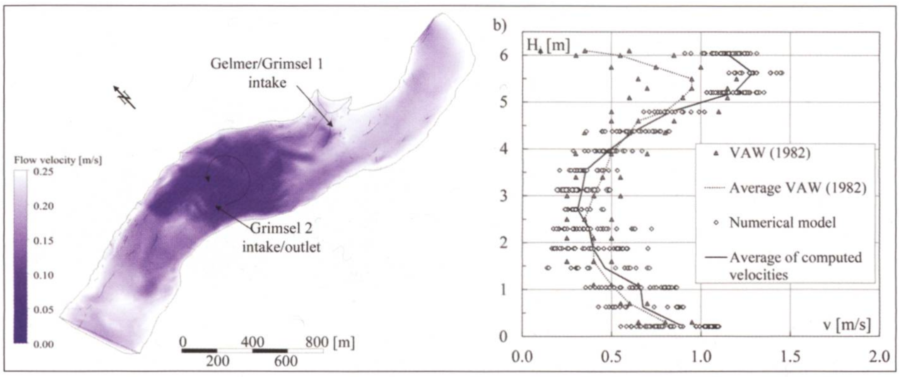

Figure 4.2: Volumetric distribution of flow velocity and computed flow velocities at the trash rack of Grimsel 2 intake/outlet structure for turbine operation (Müller et al., 2018).

4.1.2 Forced stirring

Depending on the reservoir morphology and operations management, the interplay between inflows and outflows might not be sufficient to maintain fine sediment in suspension and ensure fine sediment transport through the reservoir. In this case, additional tools are needed to locally generate an upward sediment motion at critical locations within the reservoir. One such tool is the innovative SEDMIX device, which uses thrusters to keep fine sediments near the dam in suspension and allows these sediments to be routed downstream. The SEDMIX device is composed of two parts: one floating and one close to the basin bottom holding a multi-thruster manifold frame. The thrusters induce a rotational flow which creates an upward motion and keeps fine sediments in suspension near the dam and water intakes. The sediment can then be continuously routed downstream through the power waterways at suitable concentrations, without additional water or energy loss. Once deployed, the thruster manifold frame is suspended from a floating platform and lowered underwater into position. As such, the system can be mobile and can be moved around the reservoir to find the position that provides optimal sediment evacuation.

4.2 Uptake of sediments by dredging and routing of fines via power waterways

At Bolgenach Reservoir in Austria, illwerke vkw currently operate a suction dredging system for the transfer or routing of fine sediments via the power waterways of the Langenegg hydropower plant (HPP). As the capacity of this existing system is not sufficient to stop the progressive sedimentation of the reservoir, an innovative scheme for sustainable sediment management, a new clamshell dredging system, is put into operation featuring a substantially larger conveying capacity. However, the associated increased concentration of suspended fine sediments in the waterways poses a challenge in terms of erosion of the Francis turbines. The commissioning of the new dredging and conveying facility offers the unique opportunity to study this sediment management approach with a scientific monitoring campaign and to evaluate its transferability to other reservoirs with similar sedimentation problems. While the IEC 62364 (2019) erosion model has already been adapted and calibrated by VAW for Pelton turbines based on measurements at Fieschertal HPP in Switzerland *(Felix 2017; Abgottspon et al., 2022)*, there is still limited in-depth knowledge of the erosion behaviour as a result of sediment impact for the Francis turbines. Therefore, the recently started project aims in particular at establishing an efficient routing strategy based on real-time monitoring data as well as the development of an enhanced erosion model for Francis turbines. A similar case study has been performed at Gübsensee, operated by St. Gallisch-Appenzellische Kraftwerke AG (SAK) at their Kubel powerhouse *(De Cesare et al., 2008)*.

4.3 Turbidity currents venting

In high-altitude reservoirs, turbidity currents are the main inflow process for sediment *(De Cesare et al., 2001)*. During floods, the density of river water usually increases due to an increase in the concentration of the suspended sediment that the river carries. Once the river enters the reservoir downstream of the root delta, the denser river water plunges underneath the free surface of the ambient clear water of the reservoir. After plunging, a turbidity current is triggered and travels along the reservoir's bottom and, in case of high enough concentrations, can reach the dam. This causes two main issues: increased sedimentation at the dam (decreasing the available storage volume for hydropower and flood control), as well as negatively impacting operation of the bottom outlets and/or water intakes.

Turbidity current venting involves the evacuation of sediment-laden flows through the bottom outlets during flood events *(Chamoun et al., 2016b, 2016a, 2018)*. This allows for the direct transport of turbidity currents and prevents the settling and sediment and subsequent blockage of the outlet structures *(De Cesare et al., 2019)*.

5. Conclusions

Although dam engineering in general and dam hydraulics in particular are mature disciplines, the risk potential related to dams mostly justifies to test and optimize the design of appurtenant dam structures in hydraulic model tests. Furthermore, sediment and driftwood transport as well as multi-phase flows at dams and in reservoirs often require hydraulic model tests to better grasp the physical processes involved. The data acquired in physical modelling are highly valuable for the calibration and validation of numerical simulation tools and engineering guidelines. Research on dam hydraulics and related fields like reservoir sedimentation and natural hazards affecting reservoirs remains of great benefit to further enhance the knowledge in dam engineering and to improve dam safety and operation. The hydraulic laboratories of the Swiss Federal Institutes of Technology in Lausanne and Zurich have been contributing since their foundation to dam engineering topics in Switzerland and abroad, supporting the expertise and advanced skills of Swiss dam engineers *(De Cesare et al., 2012)*.

Hydraulic modelling remains at high demand even almost 100 years after the founding of the two hydraulic laboratories of the Swiss Federal Institutes of Technology. Most of the major dams, hydropower plants or flood protection projects built today go through one or more phases of physical modelling as part of their design validation. For several decades already, this has been supported by numerical simulations, providing a second, complementary tool for understanding hydraulics. At the same time, hydraulic modelling, alike the entire design and planning process, is subject to constant evolution. In addition to the general time and cost pressure, new instruments and hydraulic scenarios are constantly finding their way into modelling and are more and more increasing the demands on the academic hydraulic institutes. Hybrid modelling has become the norm, and test engineers are increasingly also experts in computer science and digital tools.

In addition to the importance of hydraulic laboratories for the design engineer, as

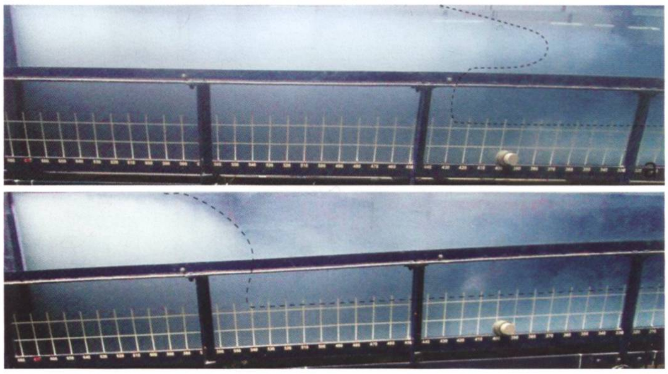

Figure 4.3: Experimental investigation on reflected turbidity currents with closed bottom outlet, original turbidity current flow from right to left (Chamoun et al., 2017).

well as for safe and efficient operation of hydraulic structures such as dams, it is also worthy to emphasize their importance for fundamental research as shown in this paper. According to the authors' knowledge, most scientific publications in recognized peer reviewed journals are still based on experimental laboratory data.

References:

Abgottspon, A., Felix, D., Staubli, T., & Boes, R. M. (2022). Betriebs- und Unterhaltsoptimierung von beschichteten Peltonturbinen mit hydro-abrasivem Verschleiss – Erkenntnisse aus einem Forschungsprojekt am KW Fieschertal. Wasser Energie Luft 114(2): 114–117.

Bénet, L., De Cesare, G. & Pfister, M. 2021. Reservoir level rise under extreme driftwood blockage at ogee crest. J. Hydraul. Eng., 147(1), 04020086.

Bénet, L., De Cesare, G., & Pfister, M. (2022). Partial driftwood rack at gated ogee crest: Trapping rate and discharge efficiency. Journal of Hydraulic Engineering, 148(8), 06022008.

Beyer, N., & Schleiss, A. (Eds.). (2000). Bodenerosion in alpinen Einzugsgebieten in der Schweiz. Wasserwirtschaft, 90(3), 88–92.

Boes, R.M., Stocker, B. & Lais, A. 2023a. How to cope with floating debris at dam overflow spillways. Proc. 91st ICOLD Annual Meeting, Gothenburg.

Boes, R.M., Stocker, B. & Lais, A. 2023b. Schwemmholz an Talsperren: Abflusskapazität, Aufstau und Gegenmassnahmen. WasserWirtschaft 113(6): 84–87.

Bross, F., & Evers, F. M. (2023). Impulswellen bei flachen Eintauchwinkeln [Impulse waves at shallow impact angles]. Final Report, Swiss Federal Office of Energy, Bern.

Chamoun, S., De Cesare, G., & Schleiss, A. (Eds.). (2016a). Venting turbidity currents for the sustainable use of reservoirs. International Journal on Hydropower and Dams, 23(5), 64–69.

Chamoun, S., De Cesare, G., & Schleiss, A. J. (2016b). Managing reservoir sedimentation by venting turbidity currents: A review. International Journal of Sediment Research, 31(3), 195–204.

Chamoun, S., De Cesare, G., & Schleiss, A. J. (2017). Management of turbidity current venting in reservoirs under different bed slopes, Journal of Environmental Management, 204(1), 519–530.

Chamoun, S., De Cesare, G., & Schleiss, A. J. (2018). Influence of Operational Timing on the Efficiency of Venting Turbidity Currents. Journal of Hydraulic Engineering, 144(9), 04018062.

De Cesare, G., Baumann, R., Zuglian, R., & Binder, F. (2008). Sedimentausleitung aus dem Speicher Gübsensee über die Triebwasserleitung, Proc. of Internationales Symposium VAW ETH Zürich "Neue Anforderungen an den Wasserbau", 317–326 und Wasser, Energie, Luft, 101(3), 203–206.

De Cesare, G., Manso, P. A., Chamoun, S., Amini, A., & Schleiss, A. J. (2019). Innovative methods to release fine sediments from reservoirs developed at EPFL, Switzerland. Hydrolink, 2.

De Cesare, G., Pfister, M., Daneshvari, M., & Bieri, M. (2012). Herausforderungen des heutigen wasserbaulichen Versuchswesens mit drei Beispielen – Challenges of Current Hydraulic Modeling with three Examples, Wasserwirtschaft, 7–8, 71–75.

De Cesare, G., Schleiss, A., & Hermann, F. (2001). Impact of Turbidity Currents on Reservoir Sedimentation. Journal of Hydraulic Engineering, 127(1), 6–16.

Dubuis, R., & De Cesare, G. (2023). The clogging of riverbeds: A review of the physical processes. Earth-Science Reviews, 239, 104374.

Evers, Frederic M. (2017). Spatial propagation of landslide generated impulse waves. VAW-Mitteilung 244, ETH Zurich.

Evers, F. M., & Boes, R. M. (2022). Slide-induced Impulse Waves in the Context of Periglacial Hydropower Development. In: Twenty-Seventh International Congress on Large Dams. Vingt-Septième Congrès International des Grands Barrages (pp. 59–69). CRC Press.

Evers, F. M., Heller, V., Fuchs, H., Hager, W. H., & Boes, R. M. (2019). Landslide-generated Impulse Waves in Reservoirs: Basics and Computation. VAW-Mitteilung 254, ETH Zurich.

Evers, F. M., Schmocker, L., Fuchs, H., Schwegler, B., Fankhauser, A. U., & Boes, R. M. (2018). Landslide generated impulse waves: Assessment and mitigation of hydraulic hazards. In: Twenty-Sixth International Congress on Large Dams/Vingt-Sixième Congrès International des Grands Barrages (pp. 679–694). CRC Press.

Felix, D. (2017). Experimental investigation on suspended sediment, hydro-abrasive erosion and efficiency reductions of coated Pelton turbines. VAW-Mitteilung, 238, ETH Zurich.

Fritz, Hermann M. (2002). Initial phase of landslide generated impulse waves. VAW-Mitteilung 178, ETH Zurich.

Fuchs, Helge (2013). Solitary impulse wave run-up and overland flow. VAW-Mitteilung 221, ETH Zurich.

Furlan, P., Pfister, M., Matos, J., Amado, C., & Schleiss, A. J. (2019). Experimental repetitions and blockage of large stems at ogee crested spillways with piers. Journal of Hydraulic Research, 57(2), 250–262.

Furlan, P., Pfister, M., Matos, J., Amado, C., & Schleiss, A. J. (2020). Statistical accuracy for estimations of large wood blockage in a reservoir environment. Environmental Fluid Mechanics, 20, 579–592.

Godtland, K., Tesaker, E. 1994. Clogging of spillways by trash. Proc. 18th ICOLD Congress, Durban: 543–557.

Guillén Ludeña, S., Manso, P. A., & Schleiss, A. J. (2017). Fine sediment routing in a cascade of alpine reservoirs: Influence of the inlet angle on settling of fine sediments. Proc. Hydro 2017. Hydro 2017, Seville, Spain.

Guillén Ludeña, S., Manso, P. A., & Schleiss, A. J. (2018). Multidecadal Sediment Balance Modelling of a Cascade of Alpine Reservoirs and Perspectives Based on Climate Warming. Water, 10(12), 1759.

Hartlieb, A. (2015). Schwemmholz in Fließgewässern – Gefahren und Lösungsmöglichkeiten ('Driftwood in watercourses – danger and possibilities for mitigation'). Report 133 (P. Rutschmann, ed.), Lehrstuhl und Versuchsanstalt für Wasserbau und Wasserwirtschaft, Technical University of Munich, Germany.

Hager, W. H., & Evers, F. M. (2020). Impulse waves in reservoirs: research up to 1990. Journal of Hydraulic Engineering, 146(10), 03120002.

Heller, V. (2007). Landslide generated impulse waves: Prediction of near field characteristics. VAW-Mitteilung 204, ETH Zurich.

Hess, F., Boes, R. M., & Evers, F. M. (2023). Forces on a vertical dam due to solitary impulse wave run-up and overtopping. Journal of Hydraulic Engineering, 149(7), 04023020.

Huber, A. (1980). Schwallwellen in Seen als Folge von Felsstürzen [Impulse waves in lakes resulting from rockslides]. VAW-Mitteilung 47, ETH Zurich.

ICOLD (2023). Blockage of reservoir outlet structures by floating debris. Bulletin 176, International Commission on Large Dams (ICOLD), in press.

IEC 62364 (2019). Hydraulic machines – Guide for dealing with hydro-abrasive erosion in Kaplan, Francis and Pelton turbines, Edition 2.0, International Electrotechnical Commission (IEC), Geneva, Switzerland.

Jenzer Althaus, J., De Cesare, G., & Schleiss, A. J. (2010). Verlandung der Stauseen gefährdet die nachhaltige Nutzung der Wasserkraft. Wasser Energie Luft – Eau énergie air, 102(1), 31–40. https://doi.org/10.5169/seals-941640

Jenzer Althaus, J., De Cesare, G., & Schleiss, A. J. (2015). Sediment Evacuation from Reservoirs through Intakes by Jet-Induced Flow. Journal of Hydraulic Engineering, 141(2), 04014078.

Kastinger, M. B., Evers, F. M., & Boes, R. M. (2020). Run-up of impulse wave trains on steep to vertical slopes. Journal of Hydraulic Engineering, 146(10), 04020072.

Mörtl, C., & De Cesare, G. (2021). Sediment Augmentation for River Rehabilitation and Management – A Review. Land, 10(12), Article 12.

Müller, D. R. (1995). Auflaufen und Überschwappen von Impulswellen an Talsperren [Run up and overtopping of impulse waves at dams]. VAW-Mitteilung 137, ETH Zurich.

Müller, M. (2012). Influence of in- and outflow sequences on flow patterns and suspended sediment behavior in reservoirs [Ecole Polytechnique Fédérale de Lausanne (EPFL)].

Müller, M., De Cesare, G., & Schleiss, A. J. (2014). Continuous Long-Term Observation of Suspended Sediment Transport between Two Pumped-Storage Reservoirs. Journal of Hydraulic Engineering, 140(5), 05014003.

Müller, M., De Cesare, G., & Schleiss, A. J. (2017). Experiments on the effect of inflow and outflow sequences on suspended sediment exchange rates. International Journal of Sediment Research, 32(2), 155–170.

Müller, M., De Cesare, G., & Schleiss A. J. (2018). Flow field in a pumped-storage reservoir – in situ measurement and numerical modeling, Journal of Applied Water Engineering and Research JAWER, 6(2), 109–124.

Perera, D., Williams, S., & Smakhtin, V. (2023). Present and Future Losses of Storage in Large Reservoirs Due to Sedimentation: A Country-Wise Global Assessment. Sustainability, 15(1), Article 1.

Pfister, M., Capobianco, D., Tullis, B., & Schleiss, A. J. (2013). Debrisblocking sensitivity of piano key weirs under reservoir-type approach flow. Journal of Hydraulic Engineering, 139(11), 1134–1141.

Sander, J. (1990). Weakly nonlinear unidirectional shallow water waves generated by a moving boundary. VAW-Mitteilung 105, ETH Zurich.

Schalko, I., Schmocker, L., Weitbrecht, V., & Boes, R. M. (2018). Backwater rise due to large wood accumulations. Journal of Hydraulic Engineering, 144(9), 04018056.

Schalko, I., Schmocker, L., Weitbrecht, V., & Boes, R. M. (2020). Risk reduction measures of large wood accumulations at bridges. Environmental Fluid Mechanics, 20, 485–502.

Schleiss, A. J., Franca, M. J., Juez, C., & De Cesare, G. (2016). Reservoir sedimentation. Journal of Hydraulic Research, 54(6), 595–614.

Schmocker, L. (2017). Floating debris retention racks at dam spillway. Proceedings of the 37th IAHR World Congress, Kuala Lumpur, Malaysia.

Schmocker, L. & Boes, R. (2018). Floating debris at dam spillways: hazard analysis and engineering measures. ICOLD Congress, Vienna, Austria: Q101–R15.

Schmocker, L. & Weitbrecht, V. (2013). Driftwood: Risk Analysis and Engineering Measures. Journal of Hydraulic Engineering, 139 (7).

SFOE (2017). Richtlinie über die Sicherheit der Stauanlagen – Teil C2: Hochwassersicherheit und Stauseeabsenkung. Guideline of the Swiss Federal Office of Energy, Switzerland, downloadable at https://www.bfe.admin.ch/bfe/de/home/versorgung/aufsicht-und-sicherheit/talsperren/richtlinien-und-hilfsmittel.html

Stocker, B., Lais, A., Schalko, I. & Boes, R.M. (2022). Backwater rise due to large wood accumulation at protruding piers of dam spillways. Proc. 39th IAHR World Congress, Granada, Spain, 2300–2306.

SwissCOD (2017). Floating debris at reservoir dam spillways. Report of the Swiss Committee on Dams, Switzerland, downloadable at https://www.swissdams.ch/de/publications/publications-csb/2017_Floating%20debris.pdf.

USACE (1987). Hydraulic Design Criteria. United States Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MI, USA.

VAW (1972). Stausee Mauvosin [Lac de Mauvoisin]. Technical Report 601, Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich.

VAW (1973). Ausgleichsbecken Ferden [Ferden compensating basin]. Technical Report 621, Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich.

VAW (2022). Schwemmholz am Mauerüberfall von Talsperren ('Driftwood at ogee crest weir spillways of reservoir dams'). Report, Laboratory of Hydraulics, Hydrology and Glaciology, ETH Zurich, Switzerland; downloadable at https://www.aramis.admin.ch/Texte/?ProjectID=47511.

Zweifel, A. (2004). Impulswellen: Effekte der Rutschdichte und der Wassertiefe [Impulse waves: Effects of slide density and water depth]. VAW-Mitteilung 186, ETH Zurich.

Corresponding author:

Giovanni De Cesare, Hydraulic Constructions Platform (PL-LCH), Ecole Polytechnique Fédérale de Lausanne (EPFL)