Reviewing research and experience on sediment bypass tunnels

WORKSHOP REPORT

M. Hagmann, I. Albayrak and R.M. Boes, ETH Zurich, Switzerland
C. Auel and T. Sumi, Kyoto University, Japan

The Laboratory of Hydraulics, Hydrology and Glaciology (VAW) of ETH Zurich, Switzerland, hosted the 1st International Workshop on Sediment Bypass Tunnels (SBT) in 2015. It was organized in collaboration with the Water Resources Research Center (WRRC), Disaster Prevention Research Institute (DPRI), Kyoto University, Japan, and the Electric Power Company of Zurich (ewz). Participants from 12 countries discussed research findings and experiences from the construction, operation and maintenance of SBTs.

Sediment bypass tunnels (SBTs) can reduce reservoir sedimentation, an increasing problem that impacts storage basins around the world. An SBT is an effective means to pass sediments around a dam to the tailwater reach, reducing sediment aggradation in the reservoir on the one hand, and allowing for re-establishing sediment continuity on the other.

Sediment continuity can bring ecological benefits, as riverbed erosion downstream of a dam may be stopped or at least significantly decelerated, and morphological variability can be increased. Sediments provided from the upstream river reaches are conveyed through an SBT, but generally no removal of accumulated sediments in the reservoir occurs. The sediment concentration in the tailwater of the dam is therefore not adversely affected by the reservoir or by natural flood characteristics.

Keynote addresses

At the Workshop in Zurich, three keynote lectures were presented. Dr. G. L. Morris (GLM Engineering- Coop, Puerto Rico) gave a comprehensive overview on sustainable sediment management, illustrated with a number of examples and case studies from around the world. He summarized a typical classification of sediment management strategies as follows:

• reduce sediment inflow from upstream;
• re-route sediments;
• remove sediment deposits; and,
• apply adaptive strategies, such as dam heightening or modifications to water intakes where sediments will not have to be manipulated.

Morris concluded that no feasible solution existed to preserve very large storage volumes. “Multiannual reservoirs can only be tackled with adaptive strategies”, he said.

Prof. T. Sumi (WRRC, DPRI, Kyoto University, Japan) described reservoir sedimentation countermeasures used in Japan, focusing on bypassing, flushing and sluicing on one hand, and on river restoration by flow and sediment management on the other. Regarding the latter, he said that sediment replenishment had been implemented downstream at a number of Japanese dams to counter riverbed erosion and to improve fish habitat conditions.

The oldest Japanese example of an SBT, he said, had been inaugurated in 1908 and was located near Kobe providing more than a century of operational experience. “To apply SBTs more widely, reducing construction costs by managing tunnel dimensions and length is important”, he concluded.

Prof. R. Boes, (VAW, ETH Zurich, Switzerland) spoke of the extent of sediment yield production in Switzerland, the recent increase in glacierized catchments, and how this affected Swiss reservoirs. He gave current examples for reservoir sedimentation countermeasures, ranging from landfill storage increases, by internal settling basins through sediment bypassing at water intakes based on real-time monitoring, to turbidity current venting through bottom outlets and reservoir drawdown flushing. This, he added, required permission from cantonal authorities, which typically prescribed suspended sediment concentration threshold values of 10 g/l.

Current research

Climate change and the retreat of permafrost may release large volumes of mobile sediment deposits, leading to an increase in sediment transport in the watershed and to an acceleration of sedimentation problems in reservoirs. This often affects energy generation, water supply, operating safety and flood protection issues. Dr. I. Albayrak (ETH Zurich, Switzerland) reported that research was being undertaken at VAW, ETH Zurich, to find solutions to these new questions. “First”, he said, “the hydropower potential, increased from glacier retreat, should be determined. Second, strategies for economic and sustainable sediment management should be found at the same time as enhancing the ecomorphology of the river system to pre-dam status, and thus natural-like conditions”. SBTs could fulfill these requirements, but their cost-effectiveness had often been limited because of hydro abrasive damage, Albayrak said.

To address this issue, Dr. C. Auel (Kyoto University, Japan, formerly with VAW, ETH Zurich) had used a physical laboratory model to investigate the flow and sediment transport characteristics (see Fig. 1) as well as the temporal and spatial evolution of the abrasion pattern at supercritical flow conditions. Based on these results, an easily applicable abrasion prediction model had been developed.
M. Hagmann (VAW, ETH Zurich, Switzerland) described prototype experiments to determine both the most resistant and cost-effective material for field applications. Preliminary results indicated that abrasion was mainly caused by bedload, whereas the effect of suspended sediment was insignificant. In the 1990s similar experiments at SBT Runcalvez (Switzerland) had been conducted, and additional measurements were reported to have been taken in 2014.

Dr. F. Jacobs (TBF AG, Switzerland) explained that high strength characteristics promote abrasion resistance of the invert material. However, implementation and curing was as important as the material choice itself, he said, because discontinuities and vulnerabilities created initial harm locations, which could increase, causing major damage.

It was reported that the impact of SBTs on the environment was currently being investigated in a research project at Solis SBT. M. Facchini (VAW, ETH Zurich, Switzerland) discussed the eco-morphological effects of an SBT to the downstream river system. Preliminary results had indicated that flood events with SBT operation could cause changes in the river morphology and in the grain size distribution of the bed material. The goal of this project, Facchini said, was to determine the effect of SBT operation on hydraulics, river morphology and finally on the quality of the river ecology, based on a field calibrated numerical model.

The ecological field analysis, it was reported, is being conducted by E. Martin (Erwag, Switzerland). His investigations had shown that the habitat quality of the river was affected by both the spillway and the SBT operation and that the extent of disturbance increased with the event intensity. Compared with a multi-year frequency of such events, the recovery duration was relatively short and in the order of several weeks to months. Further investigations were needed, he said, to quantify and assess the differences of these processes, in comparison with the ones in natural rivers without dams.

**Review of existing sediment bypass tunnels**

Seven existing SBTs located in Switzerland, Japan and France were described. The Swiss Pfaffensprung SBT, operated by the Swiss Federal Railways (SBF), was discussed by B. Müller (BBP, Switzerland). This 282 m-long tunnel operates from early April until the end of October; it acts to bypass the sediment-laden flows of the Reuss river, she said. The large-sized bedload, in combination with the high flow velocities, have been causing severe invert abrasion and corresponding high rehabilitation costs since the inauguration of the SBT in 1922. Recently, the operator had decided to fit 1 m³ granite blocks on the invert to minimize abrasion, Müller said.

The Swiss Palagoneda SBT, commissioned in 1977, was described jointly by A. Baumer and R. Radognia (OFIMA, Switzerland). The 1760 m-long tunnel is operated by OFIMA and diverts floods of the Melezza river. As a result of a very large flood event in 1978, the reservoir had filled completely and the tunnel had had to be operated continuously for several months during the rehabilitation works at the reservoir. This had caused severe invert abrasion of up to 4.8 m. However, over the past 30 years, the SBT had operated about five times a year without serious operational problems. From 2011 to 2013, 20 per cent of the tunnel invert had been restored to ensure stability.

The Swiss Solis SBT, operated by the Electric Power Company of Zurich (ewz) and inaugurated in 2012, was described by C. Oertli (ewz, Switzerland). He noted that the tunnel intake at this project was not located at the reservoir head, but only 450 m upstream of the dam. This had led to challenging operating procedures, he continued, as the intake was operated in pressurized conditions. A partial drawdown prior to the flood event was required to ensure sufficient sediment transport capacity at the upstream reservoir reach. Oertli emphasized the necessity of accurate weather forecasts to operate the tunnel successfully. The tunnel invert was lined with high performance concrete and showed almost no abrasion after three years of operation, he said.

The Asahi SBT in Japan, operated by Kansai Electric, was described by H. Nakajima (Kansai Electric, Japan). He reported that since its inauguration in 1998, about 80 per cent of the incoming sediments had been bypassed through the tunnel, demonstrating the high efficiency of this sedimentation countermeasure. Because of the high bedload transport, the tunnel had shown high invert abrasion, which required periodic rehabilitation works. "The tunnel has been repaired", Nakajima said, "with high performance concrete as this has the lowest life cycle costs in comparison to other possible invert materials".

The Miwa SBT in Japan has been operated since 2004 by the Ministry of Land, Infrastructure, Transport and Tourism. T. Sakurai (Public Works Research Institute, Japan) reported that, in contrast to most other existing SBTs, the approximately 4 km-long tunnel diverted only the suspended load, whereas the bedload was captured and dredged in an upstream check dam.

The most recent Japanese SBT is Koshibu, which will begin operation in 2016. J. Kashiwai (Japan Dam Engineering Centre, Japan) reported that construction was in the final stage. He noted that major progress had been achieved with the hydraulic structure based on optimization tests done using hydraulic modelling.

A 133 m-long tunnel, on the Mediterranean island of Corsica, was described by E. Laperrousaz (EDF, France). At this project, the diversion tunnel used during dam construction had been remodelled to divert sediments. Because of project site restrictions, the gate was located in the downstream part of the tunnel, he explained, rather than at the intake. This had led to changing flows, varying from free surface to pressurized flows, depending on the operation regime, he added.

Many reservoirs in Taiwan, such as Shihmen, Wushe, Tsengwen and Nanhu, suffer from reservoir sedimentation. Dr. J.-S. Lai (National Taiwan University, Taiwan), gave an overview of sedimentation problems in these reservoirs, focusing on the planned countermeasures for the multipurpose Shihmen reservoir affected by Typhoon Aere in 2004. One of two penstocks at the powerhouse had been modified in 2012 to improve the sluicing capacity by venting turbid water. In addition, four SBT locations had been proposed. Dr. Lai reported that he had investigated the sediment sluicing efficiency of the modified penstock. For two of the proposed SBTS, physical model investigations had been conducted, and their downstream impacts for the flow conditions of Typhoon Aere had been numerically modelled, he reported.
Dr C-S. Kung (Simotech, Taiwan), presented the findings and outlined a number of challenges. With the impact of Typhoon Kalmegi (in 2008) and Typhoon Morakot (in 2009), Nanhua reservoir located in the south of Taiwan had lost 38 per cent of its storage volume as a result of siltation. A comparatively large SBT had been designed to discharge 1000 m$^3$/s of sediment-laden flow. The SBT design had been validated and optimized using hydraulic and numerical model tests. Another planned SBT is located in Ecuador on the Guayllabamba river and is an integral part of sediment management at the Chespi-Palma Real project. The SBT will divert 158 m$^3$/s of sediment-laden flow around the dam. Dr C. Grimaldi (Lombardi Engineering, Switzerland) gave a project overview and details of the SBT design for this scheme. Dr G. De Cesare (EPFL, Switzerland) then presented the results of the physical model tests. In these tests, he said, the preliminary design had been validated and the SBT structures and operational concept had been optimized to reach 100 per cent of bed load bypassing efficiency in frequent floods.

The 150 MW Patrinid hydropower project facility is located between the Kunhar and Jhelum rivers in northern Pakistan. The hydraulic design and sediment management concept of the project are currently being tested on a physical model. C. Beck (VAW, ETH Zurich, Switzerland) presented the proposed concept, to convey coarse particles through an SBT with a design discharge of 650 m$^3$/s during flood events, and to flush finer particles settled in the reservoir area between the weir and the cofferdam annually.

Lessons learned
Several outcomes were achieved during the conference and the organizers presented the following key concluding messages.

Reservoir sedimentation in general
It was agreed that there is a wide variety of measures to address sedimentation and the selection of the most appropriate one is very site-specific. The initial selection should be based on the capacity-inflow ratio (CIR). This is the ratio between reservoir volume and mean annual water inflow volume, and the reservoir life value (the ratio between reservoir volume and mean annual sediment inflow volume). Sustainable sediment management usually requires a combination of different measures. Whenever possible, the risk of sedimentation should be minimized from the beginning, by careful selection of the location and layout of reservoirs and dams. Off-stream reservoirs, filled mainly from water intakes with desilting facilities, may be feasible options for areas with high sediment yields.

Role of SBTs to counter reservoir sedimentation
SBTs are most effective for low CIR and reservoir life values. They may be used instead of reservoir flushing, or represent a complementary measure when used in combination with drawdown flushing. If an SBT is operated during natural flood events, sediment will be discharged downstream with minimal adverse environmental impacts.

Hydraulic design of SBTs
Free-surface flow is preferred, but pressurized flow for the design discharge is also possible, depending on the location of the gates that determine the control section. For free-surface flow tunnels, chocking should be avoided, to achieve safe operating conditions with a sufficient cross-section for aeration. Regarding flow velocities, there is a trade-off. While they must be sufficiently high to avoid sediment deposition, the maximum velocities should be as low as possible to minimize shear stresses and to control the extent of invert abrasion. Keeping flowing debris away from an SBT intake is usually advisable, to prevent the clogging of logs or root stocks at the control gate or elsewhere in the tunnel. However, in some cases, logs are allowed to pass the tunnel without having created problems. Racks, consisting of vertical piles, should be applied with care, as sediment transport may become interrupted if wooden debris is retained at these structures.

Selection of suitable bypassing capacity and frequency
The typical discharge capacity of SBTs in operation worldwide is equivalent to approximately 1 to 10 year flood event. The duration of operation ranges from a few days per year to more than 100 days per year, this depends on the local hydrology and reservoir size.

Target sediment granulometry
Most SBTs are designed and operated to pass all incoming sediment, from coarse bedload to suspended fines. However, in some cases, especially for long SBTs, the coarse material is trapped and dredged upstream, and only the suspended load is bypassed around the dam. However, for inflow discharges that are in exceedance of the SBT design discharge capacity, fine sediments may still enter the reservoir and accumulate there.

Tunnel invert lining
A large variety of materials may be used, including epoxy resin mortar and rubber plates on steel, but high-strength concrete is still the most widely used option. The minimum compressive strength should be around 50 to 70 MPa to guarantee sufficient resistance to hydro-abrasion. Natural stone material, such as cast basalt or granite is also used, and steel armouring in sections of high wear, such as in the acceleration section near the intake gate, have been applied successfully. For the selection of adequate material, both the initial investment and the total life-cycle costs should be considered and weighted. For this purpose, more research is required to predict abrasion depths and the service life of different materials more accurately.

Maintenance and rehabilitation
Maintaining SBTs in a functioning state may require significant effort and incur high costs. This should be considered from the outset by estimating the expected abrasion depths and by assessing life-cycle costs. Depending on the extent of invert abrasion and the endangerment of the tunnel stability, rehabilitation works at existing SBTs can be carried out through either a regular schedule during every low-flow season, or in irregular intervals after decades. Access to the inside of the tunnel should be well designed from the beginning.
**Instrumentation and monitoring techniques**

Modern SBTs should be equipped with instruments that can monitor their behaviour, including flow velocities and sediment transport. This allows for an analysis of flushing events to optimize operation. If real-time monitoring techniques are applied, the operation may even be adapted during the event to maximize the flushed sediment volume. 3D laser scanning can be effectively used for periodic monitoring of abrasion patterns.

**Ecological impacts and efficiency of SBT operation**

The downstream effects and the bypassing efficiency of SBT operations are becoming more and more important. The downstream morphology and ecology should be monitored to optimize SBT operation, both in terms of the downstream effects on fauna and flora and also the bypassing efficiency (the ratio of bypassed to incoming sediment volumes). The downstream situation should be compared with undisturbed river sections upstream of the reservoir, to assess the ecological effect of SBTs.

**Laboratory and field trip tour**

Delegates were invited on a tour of the new VAW laboratory commissioned in 2013, during which a number of physical model investigations were observed, see photo (a). The models included capacity examinations and optimization of the operating regime of the Patrnid SBT in Pakistan, capacity verification and layout optimizations of the bottom outlets of the Grand Ethiopian Renaissance Dam (GERD) in Ethiopia, and research projects about spatial and temporal behaviour of impulse waves and dyke breaches.

Three Swiss SBTs were visited on a post conference tour, including Solis in Grisons, Palagnedra in Ticino and Pfaffensprung in Uri. During these visits, delegates were given detailed information on the SBTs and an opportunity to walk through the entire tunnel at the Solis SBT, while full explanations about the intake and tunnel construction were given by the operator, see photo (b).

After an overnight stay in Tiefencastel, the group headed to Palagnedra where the dam and the SBT intake were also visited, see photo (c). The severe flood event in 1978 was described by the operator, and the challenging rehabilitation works were outlined. The last stop was at Pfaffensprung, the oldest Swiss SBT. Here, recent rehabilitation works of the entire tunnel invert were described and shown in detail, see photo (d).

**Acknowledgement**

The financial and/or logistical support for this workshop and the field trip were provided by the Swiss Federal Office for the Environment (FOEN), the Swiss Association for Water Resources Management (SWV), the Swiss hydroelectric utilities cew, KWO and OFMA, the Swiss Federal Railways (SBB), Lombardi SA, and Kalesbörn and are greatly acknowledged. Further outcomes of the workshop are available free of charge at: http://www.vaw.ethz.ch/publications/vaw_reports/2010-2019.
Michelle Hagmann studied civil engineering at the Swiss Federal Institute of Technology in Zurich (ETH Zurich), Switzerland. After graduating in 2010 she began her career as a teaching assistant at the Institute of Structural Engineering (IBK) at ETH Zurich and as a project engineer at Jackcontrol AG, Switzerland. Besides hydropower projects, she has worked on structural and civil engineering projects. In 2012 she started her PhD study about sediment bypass tunnels and hydro-abrasion at the Laboratory of Hydraulic, Hydrology and Glaciology (VAW) at ETH Zurich and was workshop secretary of the First International Workshop on Sediment Bypass Tunnels, taking place in April 2015 at ETH Zurich.

Dr. Ismail Albayrak obtained his PhD in the field of environmental hydraulics at the Federal Institute of Technology in Lausanne (EPFL), Switzerland in 2008. He worked as a Research Fellow on the topic of eco-hydraulics for three years at Aberdeen University, UK. Since 2011 he has worked as a scientist and lecturer at the Laboratory of Hydraulic, Hydrology and Glaciology (VAW) at ETH Zurich. He is involved in various hydropower-related scientific projects. His principal research interests are in the fields of sediment transport, hydro-abrasive wear on hydraulic structures and turbines, reservoir sedimentation, fish migration, eco-hydraulics, fluid mechanics, turbulent open-channel flows and high-tech measurement techniques.

Prof. Dr. Robert M. Boes studied civil engineering at RWTH Aachen University, Germany, Ecole Nationale des Ponts et Chaussées in Paris, France, and the Technical University of Munich, Germany, from which he graduated in 1996. He then became a research engineer at ETH Zurich, Switzerland, obtaining a Doctorate in hydraulic engineering in 2000. After a post-doctoral research period at ETH Zurich, he joined the Hydro Engineering Department of the Tyrolean utility TIWAG in Innsbruck, Austria in 2002. He became head of the dam construction group at TIWAG. In 2009 he was appointed professor for Hydraulic Structures at ETH Zurich, where he currently directs the Laboratory of Hydraulics, Hydrology and Glaciology (VAW). He is involved as a consultant in dam and flood protection projects and is a board member of the Swiss Association of Water Resources Management and the Swiss Committee on Dams.

Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich, Switzerland.

Dr. Christian Auel studied civil engineering at the Technical University of Berlin (Germany), Universidad Politecnica de Valencia (Spain), and RWTH Aachen University (Germany). After graduating, he began his career as a research scientist and project engineer at the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) at ETH Zurich, Switzerland, where he obtained a Doctorate in the field of hydraulic engineering in 2014. His research interest is related to reservoir sustainability, sedimentation management and strategies, sediment bypass tunnels, sediment transport, hydro-abrasive wear and flow turbulence. Currently he works as a senior research scientist at Kyoto University, Japan, where he is involved in research projects related to reservoir sedimentation strategies and their ecological effects.

Prof. Dr. Tetsuya Suni is a Professor at the Water Resources Research Center, Disaster Prevention Research Institute, Kyoto University, Japan. He graduated in Civil Engineering from Kyoto University. After that, he worked for the Ministry of Construction of the Japanese Government. His specialties are hydraulic and dam engineering, with particular emphasis on integrated sediment management for reservoir sustainability and improvement of the environmental aspects of the river basins. He has contributed to several international associations and conferences such as IAHR, IRSIS and ISE. He has also contributed to ICOLD as Chairman of the scientific committee of the International Symposium at the ICOLD Annual Meeting in Kyoto 2012, and is currently a member of the technical committee on reservoir sedimentation.

Water Resources Research Center, Disaster Prevention Research Institute, Kyoto University, Japan.