Suspended Sediment and Bed Load Transport Monitoring Techniques

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ABSRACT Continuous monitoring of suspended sediment and bed load is important for a better understanding and management of sediment related processes in rivers and hydraulic facilities such as reservoirs and hydropower plants. Selected results from recent real-time in-situ measurements of bed load and suspended sediment at two sites in the Swiss Alps using geophones as well as turbidimeters, an acoustic method and a laser diffractometer, respectively, are presented and the measuring capabilities of these techniques are evaluated.

Keywords: Bed load, suspended sediment, real-time monitoring, geophone, laser diffractometer, LISST, turbidimeter, acoustic

1 Introduction

Sediment yield in the Alpine region tends to increase due to glacier retreat under the strong impact of climate change. With respect to the sustainable use of hydropower, this adds to the challenges in terms of reservoir sedimentation and wear of turbines and steel hydraulics parts of hydropower plants (HPPs) and other hydraulic structures.

As an effective and sustainable measure against reservoir sedimentation, sediment bypass tunnels (SBTs) also restore the natural sediment continuity in the river system by diverting sediment-laden discharges (Sumi *et al.* 2012, Facchini *et al.* 2015). A major problem affecting nearly all SBTs is severe hydro-abrasion on tunnel inverts due to the high flow velocities and the large amount of coarse sediment transport (Auel and Boes 2011). Depending on site-specific operating conditions and sediment properties, i.e. size, hardness and shape, invert abrasion can cause considerable refurbishment costs.

Even with well-designed sand traps, desilting facilities or flushable reservoirs, mineral particles cannot be completely removed from the water which passes the turbines. At high- and medium-head HPPs substantial turbine wear may occur which leads to significant maintenance cost and negative impact on power generation and revenues (Felix *et al*. 2013b).

For optimized design and operation of HPPs with respect to sustainable sediment management and cost efficiency, there is an increasing need for continuous real-time monitoring of both suspended sediment and bed load transport.

This paper presents measuring techniques employed in two on-going sediment transport monitoring studies at HPPs in the Swiss Alps. One study deals with suspended sediment in the penstock of a high-head HPP and the other focusses on bed load transport in a SBT. From the studies, the experimental set-ups and selected recent results are presented and the measuring capabilities of the techniques are evaluated.

2 Measuring techniques and devices

2.1 Suspended sediment concentration

Overview

Suspended sediment mass concentration (SSC, in g/l) of mineral particles can be determined by gravimetric laboratory analysis of bottle samples (discontinuous, non-real-time) or using mainly acoustic or optical instruments (continuous, real or non-real-time). A general overview on suspended sediment measurements for field applications is given by Wren *et al.* (2000).

Bottle samples

Bottle sampling can be manually or automatically made and is a direct, widely used and reliable technique. However, it has many disadvantages such as time-consuming laboratory analysis of the samples, effort of transporting bottles from the study sites to the laboratory, having poor temporal resolution and giving results not in real-time (Wren *et al.* 2000).

Turbidimeters

As an optical technique, turbidimeters are relatively inexpensive and widely used for suspended sediment monitoring (SSM) at rivers (e.g. Spraefico *et al.* 2005). These devices measure either the scattering (also called optical backscatter probes) or the absorption (transmission) of near infrared or laser light. Output values are given in optical units (e.g. Formazine Nephelometric Unit, FNU). For conversion to SSC, a calibration based on the particle properties (size, shape, colour and composition) is required. In general, a linear calibration curve (conversion factor) is assumed.

Laser Diffractometers

Devices based on laser diffraction such as Laser in-situ Scattering and Transmissiometry (LISST, Sequoia Scientific, USA) have become available for SSM (Agrawal and Pottsmith 2000). The working principle of a LISST is based on the mathematical inversion of the measured scattering pattern and transmission. SSC obtained from LISST have the advantage of being not or less dependent from temporally variable particle size, since particle size is considered. However, with highly non-spherical particles, a site-specific SSC-correction factor should be applied (Felix *et al.* 2013c).

Acoustic techniques

Furthermore, acoustic techniques can be employed for SSM. Among many possibilities such as using active sensors like Acoustic Doppler Current Profiler (ADCP, e.g. Haught *et al.* 2014) the method of measuring the attenuation of ultrasonic pulses sent through the sediment-laden water in penstocks or channels lends itself particularly in cases where installations for acoustic discharge measurement (ADM) already exist. Such facilities can be upgraded to be used for SSM. Similar to turbidimeters, the attenuation of the ultrasonic signal is correlated with SSC (Costa *et al.* 2012, Felix *et al.* 2013a).

2.2 Suspended sediment particle size distribution

Besides SSC, particle size distribution (PSD) is an important parameter for sediment dynamics and hydro-abrasive wear. The primary method to obtain PSDs is by sieve analysis of dried particles. Especially for smaller particles, laser diffraction has been used in laboratories for decades. However, as mentioned above, analysing collected samples in the laboratory has many disadvantages and limitations. With LISST, practical real-time monitoring devices for both SSC and PSD in field studies have become available.

2.3 Bed load transport monitoring

Overview

Bed load transport can be monitored either directly by sediment trapping, collecting moving particles and using tracer particles or indirectly by active and passive sensors. Active sensors are typically ADCP, radar and sonar. Passive sensors do not emit any signal but only register acoustic, magnetic or seismic signals (Bogen and Møen 2001, Gottesfeld and Tunnicliffe 2003, Møen *et al.* 2010). Such techniques are hydrophone, geophone or vibrational sensors (Rickenmann and McArdell 2007). Direct methods can provide accurate data during the sampling time but are often laborious and risky, whereas indirect methods allow continuous and real-time monitoring but require calibration.

Swiss plate geophone system

An indirect method using a passive sensor is implemented in the so called Swiss plate geophone (Rickenmann and McArdell 2007, Rickenmann *et al.* 2012, & 2014). It is a robust, submersible device developed at the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL). The device consists of an elastically bedded steel plate installed flush to the channel bottom. A geophone sensor (GS-*20DX*) is mounted beneath the plate in a waterproof aluminium casing and registers the oscillations caused by gravel grains and stones impinging on the plate (Figure 1).

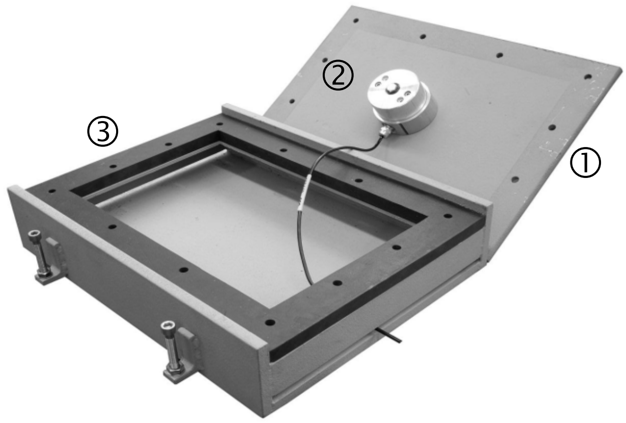

Figure 1: Swiss plate geophone system with steel plate ① (before assembly), geophone sensor ② and elastomer bearing ③ on the aluminum casing (VAW)

The number of impulses, defined as the signal exceeding a threshold, correlates linearly with the bed load volume (Rickenmann 1997, Rickenmann *et al.* 2012). The relation between impulses and bed load volume depends on site specific conditions like flow velocity, grain size and shape. A laboratory study demonstrated that smaller and a larger number of grains can be detected by inclining the geophone plate by 10 °against the bottom slope (Morach 2011). Recent investigations reveal that also the grain size distribution can be estimated based on the amplitude of the geophone signal (Wyss *et al.* 2014).

3 Methodology and set-up of field investigations

3.1 HPP Fieschertal

HPP Fieschertal is a high-head scheme located in Valais, Switzerland, at a tributary of the upper Rhone river in a highly glaciated area with relatively high yield of fine sediments. The HPP is equipped with gravel and sand traps at the intake to remove particles > 0.3 mm.

In this study, two in-line turbidimeters are used and relevant with respect to the results shown in this paper: (1) *AquaScat* from Sigrist Photometer, Switzerland, measuring light scattering at an angle of 90° at a free-falling jet and (2) *TF16-N* from Optek Danulat, Germany, measuring light attenuation over a path length of 10 mm in pressurized flow. The turbidimeters were installed in a valve chamber at the upstream end of the penstock in summer 2012 to quantify the suspended sediment load. They are fed from the penstock by a sampling pipe (d_i = 20 mm). The *LISST-100X* was installed in a bucket at the end of the sampling pipe. It has a nominal particle size measuring range from 2 to 380 µm in the calculation mode for so called ‘random shaped’ particles (Agrawal *et al.* 2008). Practically, particle sizes ≥ 5 µm can be measured. Furthermore, to extend the range of SSC, its optical path length was reduced from 50 to 5 mm with a glass cylinder.

Bottle samples were pumped from the bucket using an automatic sampler *Isco 3700*. The sampler was controlled by a program developed at VAW to take 0.5 liter samples every three days and more frequently if turbidity exceeded predefined threshold values.

Additionally, the existing ADM (from Rittmeyer) at the top of the penstock with four acoustic paths (each 2.27 m long) operating at 1 MHz was used for SSM.

Data from the turbidimeters and the acoustic method were recorded at 1 Hz, while the LISST was set to work at 1/60 Hz. The SSC time series in Figure 2 were obtained by calibrating the devices’ output signals to the gravimetrically determined SSC from bottle samples.

3.2 SBT Solis

The Solis reservoir located in Grisons in the Swiss Alps lies in a gorge and has a length of about 2.7 km. To maintain the active storage, a SBT was constructed and has been commissioned in 2012. Its intake is located 500 m upstream of the dam. The design discharge of the SBT is 170 m^3/s, corresponding to a 5-year-flood.

As part of a research study dealing with the abrasion resistance of various invert materials, suspended sediment and bed load transport in Solis SBT are monitored using two submersible turbidimeter probes *TurbiMax W CUS41* (Endress+Hauser) installed in the right and left tunnel walls 0.22 m above the invert, and eight Swiss plate geophones installed at the outlet of the SBT, respectively. The geophones are placed across the whole tunnel width of 4.40 m and have an inclination of 10° against the invert slope. Furthermore, the water levels in the reservoir and in the tunnel as well as the tunnel intake gate position are monitored. Data recording is triggered by the opening of the intake gate. The sampling rates are 1/60 Hz in general and 10 kHz for the geophone system.

The turbidimeter data were converted to SSC based on gravimetrically determined SSCs of bottle samples taken from the river at an existing gauging station1 km upstream of the reservoir. The geophone system was calibrated in the laboratory using natural stones with grain sizes similar to the field conditions.

4 Results and Discussion

4.1 HPP Fieschertal

From the suspended sediment measurements in the turbine water of HPP Fieschertal recorded from 2012 to 2014, an extract of four days is presented in Figure 2. The median particle size d_{50} stands for the diameter of graded particles, of which 50% by mass are smaller.

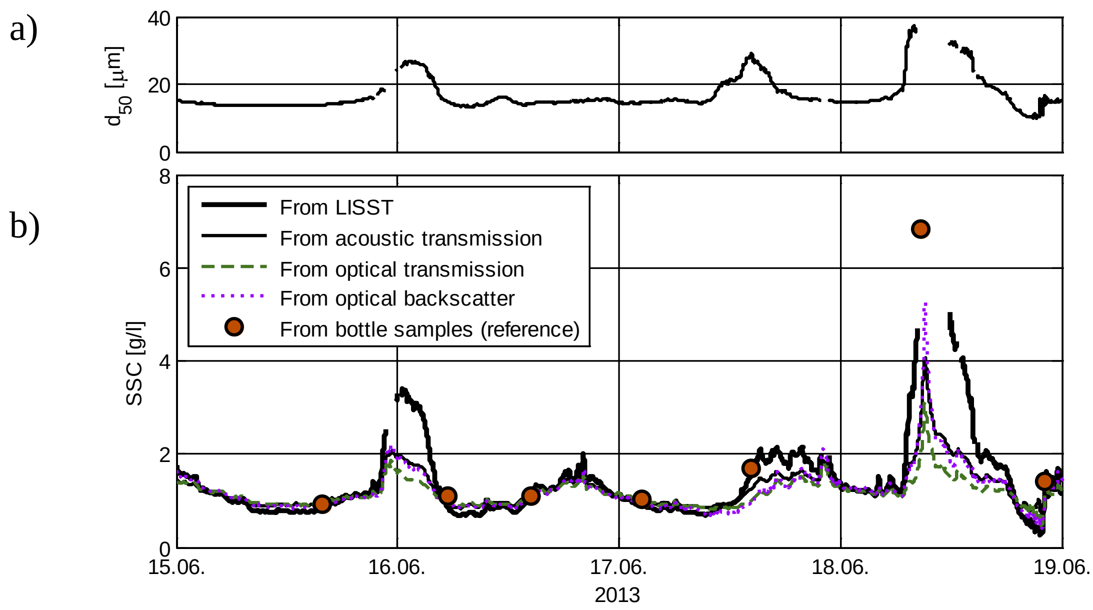

Figure 2: Time series of a) d_{50} from LISST and b) SSCs obtained from various methods after calibrating to bottle samples, measured in the turbine water of HPP Fieschertal

During these days in early summer 2013, the SSC occasionally rose to several g/l within a few hours. When the SSC was above 5 g/l, as captured by a bottle sample, no LISST results were available as the optical transmission was too low. The median particle size d_{50} had a base level of about 15 µm and rose up to approx. 35 µm at high SSCs. In many such events, the maximum d_{50} occurred after the SSC peak (time lag).

In periods of usual SSCs all devices yielded similar SSC values. During high SSCs, however, the acoustic method and the turbidimeters underestimated the

SSCs. This is attributed to temporal changes in particle size. When particles are coarser than the normally prevailing ones, less damping or scattering occurs. This was also observed in laboratory investigations prior to the field study by Felix *et al.* (2013c).

4.2 SBT Solis

Since its commissioning in 2012, the Solis SBT was in operation four times during 11 hours on average and diverted sediment volumes between 20’000 and 80’000 m^3. The operating conditions varied from event to event and within one single run. Figure 3 shows the normalized spanwise distribution of bed load transport across the eight geophones. It is seen that bed load transport was concentrated on the orographic right side of the tunnel. This is related to a horizontal curve in the tunnel layout located 100 m upstream of the geophones. The bend induces secondary currents transporting bed load at the inner side.

Figure 4 shows time series of volumetric suspended and bed load transport rates in the tunnel and the reservoir level during the largest flood event since the commissioning of the SBT. Monitoring data show that the lower the reservoir level, the coarser sediment material is transported into and through the tunnel. The geophone data revealed that during the drawdown, three peaks in bed load transport occurred at certain reservoir elevations (see arrows in Fig.4).Turbidity data showed a similar behavior for the suspended sediment transport rate, but the peaks occurred before those of the bed load (Fig. 4). In addition, suspended sediment transport in the tunnel occurred prior to the drawdown of the reservoir level.

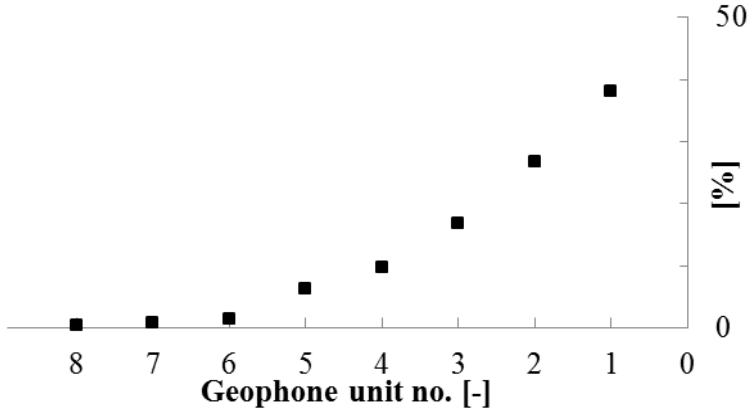

Figure 3: Distribution of the bed load transport in Solis SBT across the tunnel width, registered by the geophone units 1 to 8 at the outlet on 13th of August 2014

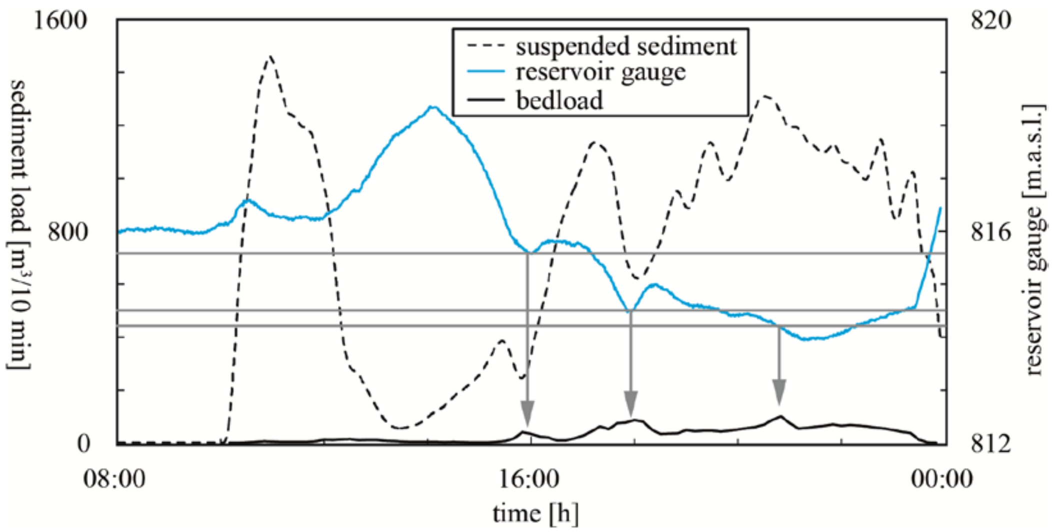

Figure 4: Time series of suspended and bed load transport in the Solis SBT as well as the reservoir level during the flood event on 13th of August 2014

5 Conclusion and Outlook

Selected state-of-the-art monitoring techniques and exemplary field data on suspended and bed load transport measurements were presented. The measuring capabilities of the devices during sediment transport events were evaluated.

In case of temporal variations in PSD, SSCs obtained from turbidimeters or single-frequency acoustic methods are less accurate than those from a calibrated LISST. In dynamic environments it is recommended to measure both SSC and PSD, and to combine continuous indirect measurements with automatic bottle sampling for calibration. In order to extend the SSC measuring range of LISST, devices with automatic dilution are an option (Agrawal *et al.* 2012).

As bed load transport may vary significantly in spanwise channel direction due to secondary currents, it is recommended to measure bed load across the channel width in such situations. Since suspended and bed load transports exhibit different temporal behaviors, it is recommended to measure both suspended and bed load to quantify total sediment transport in rivers and hydraulic schemes.

Measurements and data evaluation at both study sites are continued.

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Field research: Invert material resistance and sediment transport measurements

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Abstract

Reservoir sedimentation is a global issue affecting water supply, energy production and flood protection. For a sustainable and safe reservoir operation sediment management is mandatory. Sediment Bypass Tunnels (SBTs) are an efficient and ecological favorable measure by diverting sediment-laden inflows around reservoirs. They may prevent reservoir sedimentation and restore the downstream river reach suffering from sediment deficit. However, high flow velocities and high sediment loads cause substantial hydroabrasion wear. In the project presented herein, the abrasion resistance of different materials is investigated under field operating conditions and compared to life cycle costs by means of *in-situ* experiments. Furthermore, supplementary laboratory experiments are conducted to determine abrasion resistance of investigated materials under controlled conditions and to check and investigate upscaling from laboratory results to field applications. The abrasion resistance of materials increases with their strength. However, since hydroabrasion is a self-intensifying process starting at vulnerabilities and irregularities, implementation and curing is as important as the choice of the material itself.

1 Introduction

SBTs are an effective measure against reservoir sedimentation and contribute to a sustainable use of storage capacity for water supply, energy production and flood control. They divert sediment-laden inflows around dams and thus may restore the natural sediment continuity that is disturbed by dam construction. Due to climate change and population growth sustainable sediment management at reservoirs gained increasing importance and SBTs have recently attracted growing attention, especially in mountainous regions in Asia and South America. However, SBTs are subjected to strong abrasion due to high flow velocities and sediment transport rates causing high annual maintenance expenses in the range of 1% of the investment costs (Auel 2014). An impressive example showing massive damages is the Palagnedra SBT in southern Switzerland (Vischer *et al.* 1997). After a flood event in 1978 the corresponding hydropower plant was shut down and the Melazza River was diverted through the SBT during the refurbishment period of 10 months (Delley 1988). The concrete invert was destroyed and the incision channel depth reached up to 2.7 m into the bedrock (Figure

1). In order to enhance the cost-effectiveness of SBTs suitable invert materials are indispensable.

Therefore a research project was initiated at the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) of ETH Zurich (Hagmann *et al.* 2012, Boes *et al.* 2014, Hagmann *et al.* 2014). The main objectives are to quantify the correlations between the hydraulic operation conditions, sediment load, invert material properties and measured hydroabrasion. To achieve this goal, *in-situ* experiments in Solis, Pfaffensprung and Runcahez SBTs are conducted.

Figure 1: Invert damages at the Palagnedra SBT (Canton Ticino, Switzerland) after an exceptional flood event in 1978 (IM Maggia Engineering AG)

Furthermore, the transferability of laboratory results to field scale is investigated in collaboration with the Institute of Construction Materials of TU Dresden, Germany. Therefore specimens of invert materials from Solis and Pfaffensprung SBTs have been tested in the laboratory and compared to their *in-situ* performance (Bellmann and Mechtcherine 2012, Mechtcherine *et al.* 2012). Finally, outputs of this project together with results of a precedent study on sediment transport and abrasion processes in SBTs (Auel 2014) will help operators of hydraulic systems facing abrasion problems by giving recommendations of SBT design, economical invert materials and their implementation. Herein, the experimental setups, the sediment transport monitoring system, and the recently obtained results are presented.

2 Instrumentation

2.1 Monitoring of hydraulic conditions

To adequately estimate the discharge in the tunnel, precise knowledge of the flow velocity and flow depth is needed. Pressure sensors are popular, competitive and robust devices for the determination of water depth under subcritical flow conditions. However, under the supercritical flow conditions prevailing in SBT, it is difficult to soundly mount these devices in tunnels without disturbing the measurements.

Another commonly used method for continuous and real-time monitoring of hydraulic operating conditions is the radar technique. This is a contact-free technique applicable also under supercritical flow conditions. It determines water levels by measuring time between sent and received pulses. Furthermore, it also measures surface flow velocity using the Doppler Effect. Finally, the discharge is determined based on the continuity equation and a site specific conversion factor adapted from water depth, cross section and surface flow velocity.

2.2 Sediment monitoring

Sediment load is divided into bed load and suspended load. For bedload monitoring there are various techniques available (Bogen and Møen 2001, Gottesfeld and Tunnicliffe 2003, Rickenmann and McArdell 2007, Møen *et al.* 2010). For the present research project, a robust, accurate and continuous real-time measurement technique is needed to monitor sediment load in SBTs. The Swiss plate geophone developed at the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) fulfills these requirements (Rickenmann and McArdell 2007, Rickenmann *et al.* 2012, Wyss *et al.* 2014). The device consist of an elastically bedded (elastic polymer type "CR/SBR Standard 65±5", manufactured by Angst + Pfister, Zurich, Switzerland) steel plate (S235; l=492 mm, w=358 mm, t=15 mm) mounted by a steel profile (S235, UPE400) flush to the channel invert (Figure 3). Bedload particles impinging the plate cause oscillations which are registered by a geophone sensor (Geospace GS-20DX, manufactured by Geospace Technologies, Houston, Texas) attached on the rear side of the plate within a waterproof casing. The sampling rate is 10 kHz and thus allows sampling of the plate oscillations.

When the signal voltage exceeds a certain threshold value corresponding to vibrations due to clear water background noise, an impulse is registered. The number of impulses correlates linearly with the sediment transport rate whereas the grain size distribution can be estimated based on the maximal amplitude value (Rickenmann *et al.* 2012, Wyss *et al.* 2014). However, correlation between registered signals and sediment transport rate, is strongly site-dependent. Hydraulic flow conditions, particle size distribution and particle shape affect the measurement signal. Therefore a calibration, in best case *in-situ*, is required for every single geophone system. Under controlled laboratory conditions (mean flow velocity of 4 m/s, water depth of 10 cm) the threshold for detected grain was determined being between 2 and 3 cm for the horizontal arrangement of a geophone system. Furthermore, threshold grain size was significantly lowered by inclining the geophone 10° against the channel bottom slope (Morach 2011).

Turbidimeters are a popular and commonly used optical device for suspended sediment measurements at rivers, lakes, desilting basins and power plants (Grasso *et al.* 2005, Habersack *et al.* 2008). The devices register either the backscatter or the transmission of the emitted visible or infrared light. The signal output is turbidity and has to be converted to suspended sediment concentration using a calibration curve. Therefore, bottle samples are taken regularly from the river. Their calibration is affected by particle shape, size and color (Felix *et al.* 2013). Depending on particle properties the measurement range varies from several milligram per liter up to hundred grams per liter (Black and Rosenberg 1994, Wren *et al.* 2000).

2.3 Abrasion measurement

Abrasion can be measured either by hand using a leveling rule or by use of 3D-laser-technique. Jacobs *et al.* (2001) used the former to measure the abrasion in the Runcahez SBT. Also the abrasion at Asahi SBT, Japan and the abrasion in the Runcahez SBT is measured similarly (Jacobs and Hagmann 2015, Nakajima *et al.* 2015).

However, the advantage of a 3D-laser technique is the provision of high resolution surface maps. Furthermore the measurement process is much less time consuming compared to the leveling rule method. Maps obtained at different stages are used to evaluate temporal and spatial development of abrasion occurring on the surface. Depending on the specifications, 3D–lasers are applicable up to 100 m distance measurements with measurement errors around ± 2 mm. In order to obtain a surface map with high resolution and minimal errors around ± 1 mm, the measurements distance is kept in the range of 1.5 to 10 m.

3 Experimental setups and methodology

3.1 Solis SBT

The Solis SBT located in the Swiss Alps was commissioned in 2012 (Oertli 2009, Auel *et al.* 2011, Oertli and Auel 2015). The SBT intake is located 804.5 m asl. For SBT operation the reservoir level partially lowered (active storage volume: 823.75 and 816 m asl, target SBT operation level: 816 and 814.5 m asl) resulting in pressurized flow conditions at the intake. After the intake flow conditions change to supercritical free surface flow with flow velocities up to 11 m/s.

The SBT houses six test fields, each 10 m long, with different abrasion-resistant materials. Four concretes with different compressive strengths and mixtures, cast basalt tiles and steel plates were implemented directly upstream of the right bend (Hagmann *et* *al.* 2012) (Figure 2). In combination with the high-performance concrete invert of Solis SBT, a total of seven different invert materials are tested. For separation of the single trial fields and for proper implementation, steel beams were installed at the end of every field.

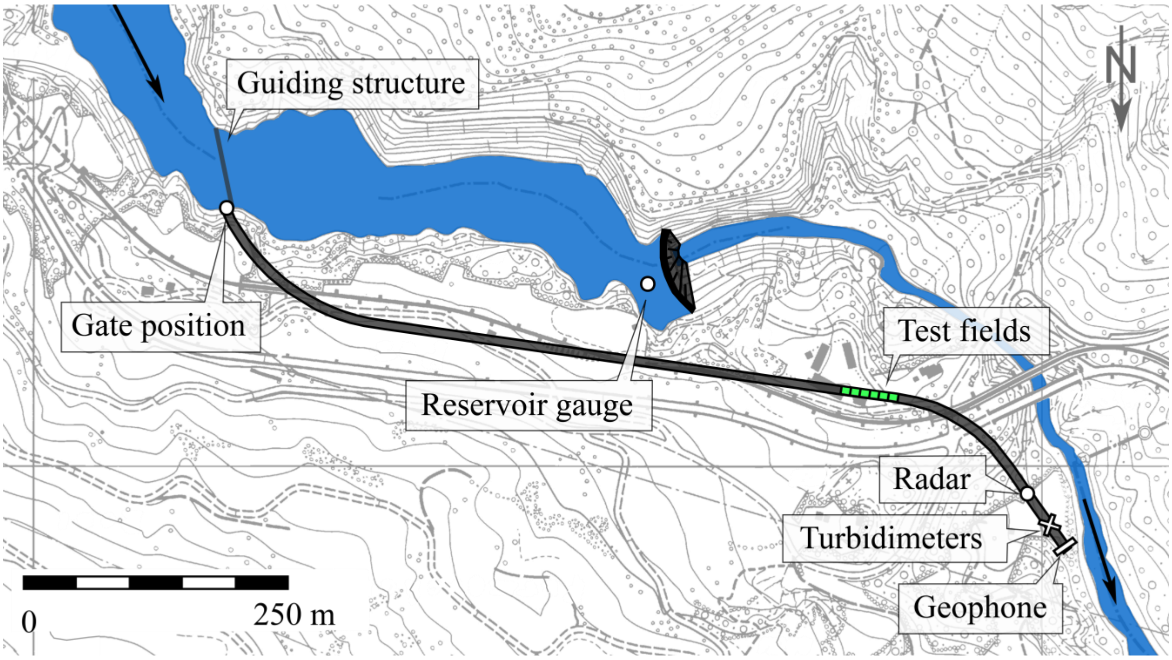

Figure 2: Overview of the Solis SBT with test fields and the instrumentation

Hydraulic conditions in the tunnel and reservoir are monitored using a radar system mounted on the tunnel ceiling (RQ-30, manufactured by Sommer Messtechnik, Koblach, Austria), two pressure sensors installed at both tunnel walls (Probe 26 W, manufactured by Keller AG, Winterthur, Switzerland), and a pressure transmitter measuring the reservoir level (MPA, manufactured by Rittmeyer, Baar, Switzerland), respectively. Furthermore, the position of the intake gate is observed by displacement transducers.

Both, the gate position and the reservoir water level are used in combination with hydraulic model test results (Auel *et al.* 2011) to estimate the discharge. These results can be compared to the measurements using the radar and pressure sensors in the tunnel. The sediment transport is monitored by two turbidimeters installed next to the pressure sensors in the side wall recesses (TubiMax W CUS41, manufactured by Endress+Hauser, Reinach, Switzerland) and by an in-house-constructed geophone system consisting of eight units at the SBT outlet (Figure 3). Generally, the sampling rate is 1/60 Hz, except for the geophones, where it is 10 kHz. The data acquisition is triggered by the SBT intake gate opening.

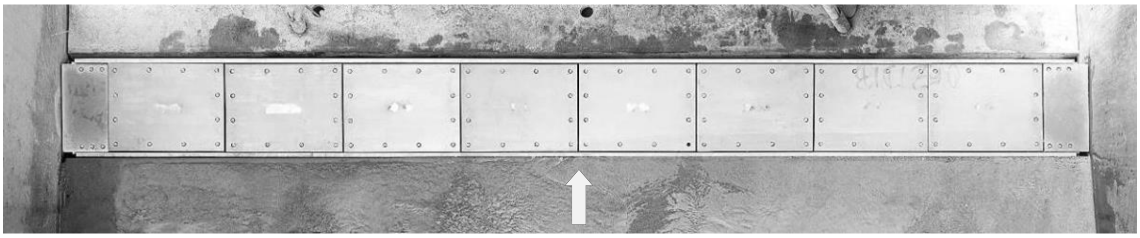

Figure 3: Picture of the geophone system consisting of eight units across the tunnel width, installed at the outlet of Solis SBT; flow direction from bottom to top

The surface of the tunnel invert is mapped by a laser scanner (FARO Focus 3D, manufactured by FARO, Lake Mary, United States). The first measurement was performed in 2012 after implementation. After every significant event provoking invert abrasion further scans are conducted.

3.2 Pfaffensprung SBT

The Pfaffensprung SBT located in the Swiss Alps was commissioned 1922 together with the Pfaffensprung reservoir erected for hydropower generation (SBZ 1943, Vischer *et al.* 1997, Müller 2015). The tunnel is in operation for over 100 days per year when the inflow exceeds the threshold discharge for bedload transport. The operating flow velocities lay between 15 and 17 m/s.

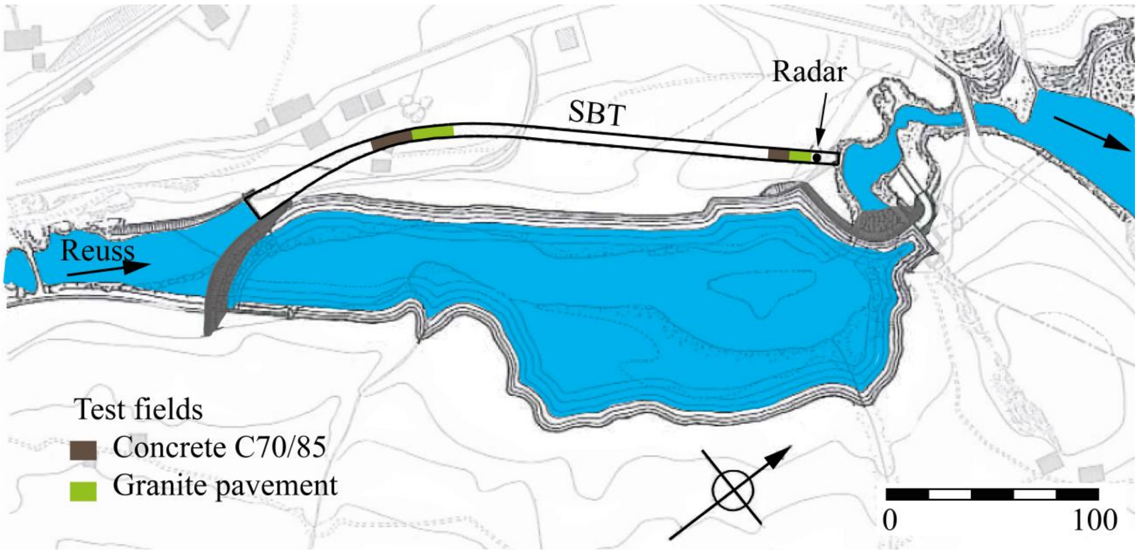

Figure 4: Overview of the Solis SBT with location of test fields and instrumentation

In the winter season 2011/12 and 2012/13 10 m long tests fields were implemented near the outlet and in the tunnel bend (Figure 4). They consist of a granite pavement and high-strength concrete with and without steel fibers. The original layer thickness was 30 cm. Compression strengths of granite and concretes are f_c = 180 MPa, 75 and 79 MPa, respectively. The hydraulic operating conditions are monitored by a radar mounted on the ceiling near the outlet (Vegaplus 54K, manufactured by Vega, Pfäffikon, Switzerland) while the invert abrasion is determined based on measurements taken every winter season by a 3D-laser scanner (Z+F Imager 5006h, manufactured by Zoller + Fröhlich, Wangen im Allgäu, Germany).

3.3 Laboratory tests

To simulate hydroabrasion in the laboratory at controllable conditions a rotating drum developed at the Technical University of Dresden is used (Bellmann 2012, Mechtcherine *et al.* 2012). It consists of an octagonal rotating drum, feed with an abrasive charge and equipped with slab shaped specimens (300 mm × 300 mm × 50 mm). By changing abrasive particle size and rotation velocity, different flow and sediment load regimes are simulated (Bellmann 2012, Mechtcherine *et al.* 2012). The abrasion is determined both by weighing and laser scans providing the parameters abrasion rate, mass loss, and abrasion depth, respectively.

4 Results

4.1 Solis SBT

Since the commissioning, the Solis SBT was in operation four times. It was found that the sediment transport rate changed as a function of the reservoir level, corresponding to an increasing energy head, and suspended sediment rate scattered larger than bed load (Figure 5a and Figure 5b). With increasing reservoir level the bed shear stress upstream of the intake decreases due to the low flow velocity, and reduces the sediment transport capacity leading to lower sediment transport rates in the reservoir and thus in bypass tunnel itself. Reasons for the fluctuations are assumed to be generated by local erosions of the aggradation body.

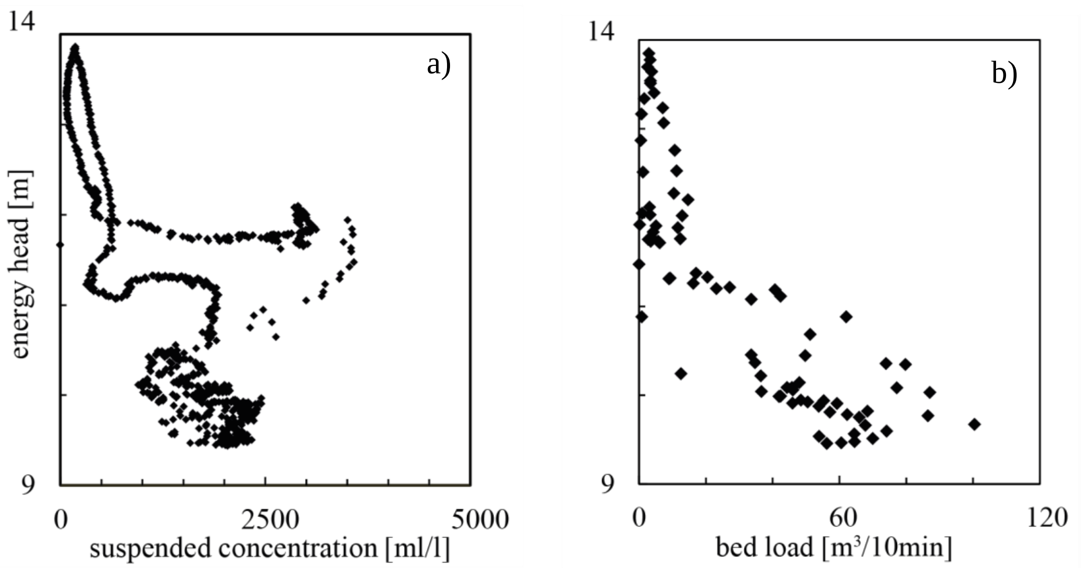

Figure 5: a) Suspended sediment concentration, and b) bed load transport rate depending on energy head during operation on 13th August 2014

Furthermore, the geophone system registered unevenly distributed bedload transport in the spanwise direction. Over 90% of the triggered bed load was transported on the orographic right tunnel side and showed an exponential distribution increasing towards the tunnel wall. This phenomenon resulted from the effect of the bend located 100 m upstream. It induces secondary flow currents causing sediment concentration at the inner side of the bend.

During the first three operations the measured bypassed sediment volume varied between 20’000 and 80’000 m^3, but the portion of bed load was insignificant. Consequently, no abrasion was observed. However, during the operation in August 2014 the suspended and the bed load transport mass were considerable and first abrasion traces were observed. Although an abrasion measurement is yet to be done, visual inspections already showed that cast basalt plates suffered from abrasion at the upstream edges while the concrete fields generally experienced comprehensive abrasion following an undulating pattern. However, at the test fields equipped with high alumina cement concrete and ultra-high-performance fiber-reinforced concrete no abrasions were visible.

4.2 Pfaffensprung SBT

In 2012 and 2013 the Pfaffensprung SBT was in operation for 113 and 131 days, respectively and let all test fields suffer from hydroabrasion. Due to the tunnel bend, abrasion occurred more intensely on the orographic right side, especially for the older concrete near the outlet. Furthermore, comparison of the abrasion topography between 2012 and 2013 revealed that the abrasion pattern stayed similar but amplified and damages grew in streamwise direction (Figure 6a and Figure 6b).

The abrasion on the concrete test fields showed an undulating pattern, whereas the abrasion on the granite test fields were concentrated at the lateral joints and upstream edges of the tiles (Hagmann *et al.* 2014). The mean abrasion rates were 2 mm and 14 mm per year while the maximal abrasion rates were 15 and 35 mm per year for granite and concrete, respectively. Note that the maximal abrasion rates are decisive for SBB to define the refurbishment intervals.

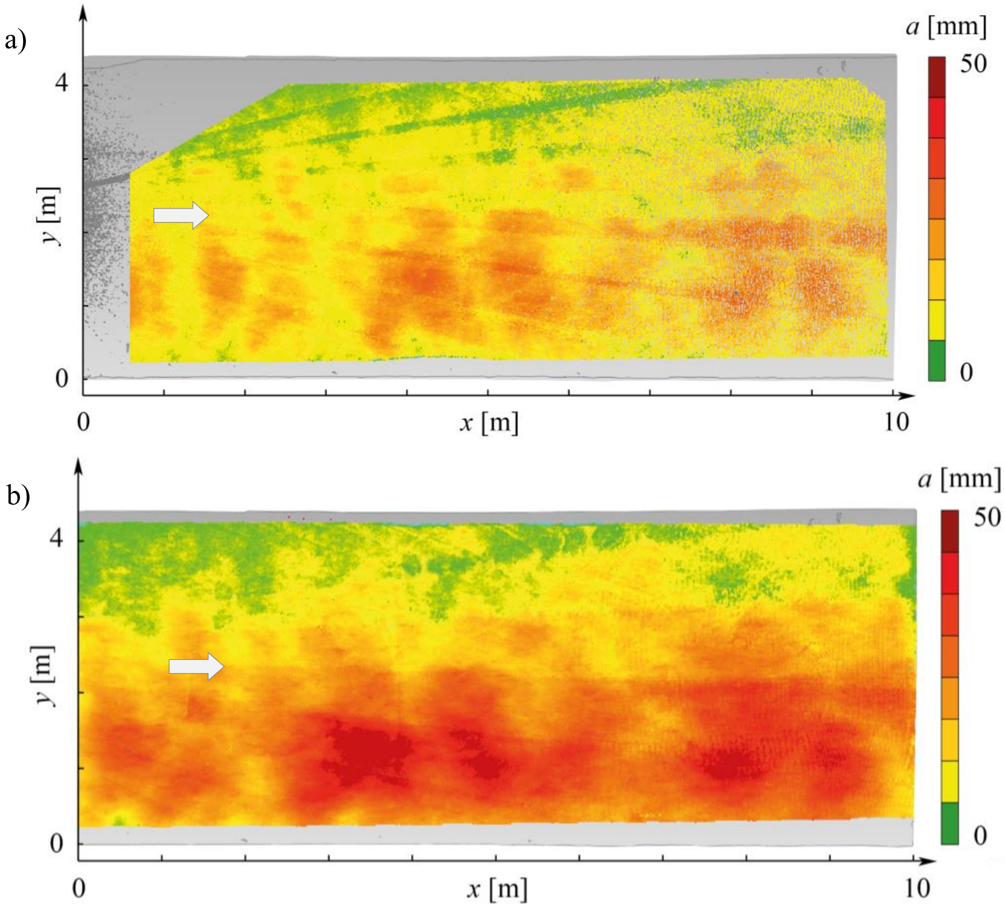

Figure 6: Abrasion of a high strength concrete test field in the Pfaffensprung SBT, a) after one year and b) after two year of operation, flow direction from left to right

4.3 Hydroabrasion drum

The concrete specimens taken from Pfaffensprung SBT were tested using the test drum described in Section 3.3. The tests were done using a mixture of 10 kg of water and 10 kg of steel spheres with a mean diameter of 5 mm. The rotation speed was 17 rotations per minute. Thereby the samples were stressed for 0.5454 s per rotation. The test duration was 58.8 h and the stress duration per sample was 9.09 h causing an abrasion rate of 1.1 mm/h (Figure 7). During the laboratory test a linear correlation between abrasion depth and stress duration was observed confirming former results (Auel 2014). Since the field abrasion was 14 mm per year, this laboratory test was able to reproduce the *in-situ* abrasion depth of a whole season in fast motion within less than 59 hours. Thus this testing procedure seems to be suitable for cross-comparison and determination of hydroabrasion resistance of different materials in respect of future applications. However, this promising result must be confirmed by further investigations.

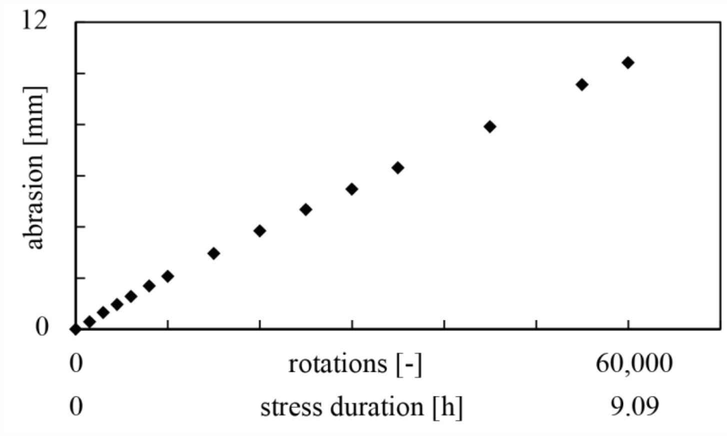

Figure 7: Hydroabrasion drum test results of high-strength concrete implemented in Pfaffensprung SBT; Abrasion as a function of both, stress duration and total number of rotations

5 Design recommendations

Since hydroabrasion is a self-intensifying process, invert irregularities and vulnerabilities or imprecise uneven invert implementation should be avoided or at least minimized in the design and implementation stages. Curves in plan-view should be avoided as sediment transport always occurs on the inner side of the curve due to the development of additional secondary currents. If they are inevitable, invert strengthening along the inner curve should be considered to cope with the increased specific sediment transport rates. Additionally, proper implementation and curing are preconditions for high resistant invert materials. At most sites the grain size distribution covers a large range resulting in a combination of two different particle size-dependent abrasion processes, grinding or impinging. Therefore, it is not possible to equip a facility with an optimum material persisting all operating conditions. Whenever damages appear and surface shows highly irregular pattern and protruding edges, refurbishment should be conducted in order to hinder fast growing damages. Further recommendations may be found in Boes *et al.* (2014).

6 Conclusions

Although hydroabrasion is an omnipresent issue in hydraulic engineering, only few standards or guidelines are available. The operators of facilities facing hydroabrasion wear often test the performance of different materials *in-situ*. However, in many cases even after decades of testing, the optimum lining material is not found. Recent investigations show that laboratory tests using a hydroabrasion drum are suitable to determine the hydroabrasion resistance of lining materials. These results confirm findings of other scientists (Jacobs *et al.* 2001, Kryžanowski *et al.* 2012). However, only a few investigations have been done, thus leaving a knowledge gap concerning the correct simulation of field conditions as well as the transferability of laboratory results to field scale. This requires further experiments.

The present field investigations reveal that monolithic materials exhibit undulating abrasion pattern which sometimes lead to incision channels or pot holes whereas modular materials have weak spots at the joints suffering the highest abrasion rates. Further it is found that hard materials persist suspended sediment. If the dominating abrasion process is caused by saltating particles, materials with high tensile strengths perform better than hard materials prone to brittle fracturing by absorbing the kinetic energy of the impacts. However, force-locked mounting and higher board thickness reduces the risk of fracturing significantly.

Acknowledgement

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Sediment bypass tunnel Runcahez: Invert abrasion 1995-2014

Frank Jacobs, Michelle Hagmann

Abstract

In 1962 the Sediment Bypass Tunnel (SBT) at the compensation basin Runcahez, located in the Canton of Grisons in the Swiss Alps, went into operation. The invert of the SBT was made partly out of concrete and partly remained the bedrock. Already after a few years the tunnel invert has been severely abraded by the relatively coarse bed load requiring repair work nearly every year. In 1993 a research project was started to evaluate suitable types of concrete for the rehabilitation of the invert. In 1995 five types of special concrete were cast in test fields of 10 m length. The abrasion depths were measured by geodetic measurements and the conditions of the test fields were surveyed by visual inspections. The results showed that suitable types of concrete were abraded approx. 1 mm/year during 20 years.

1 Introduction

The SBT Runcahez is situated in the Canton of Grisons in the Swiss Alps in the valley of the river Somvixer Rhine (Figure 1). The Runcahez compensation basin is part of the Vorderrhein hydropower scheme/cascade operated by *Kraftwerke Vorderrhein AG*. The SBT was constructed at the beginning of the 1960s and went into operation in 1962.

In the inlet section invert was made of normal and special concrete (unreinforced). In the remaining downstream part of the tunnel the excavated rock forms the invert. According to core samples taken in 1995 the cube compressive strength was approx. 70 MPa for the normal and approx. 80 MPa for the special concrete (both approx. 30 years old). The first damages were reported in the late 1960s.The damages continuously occurred and almost yearly repair works were necessary and carried out. During refurbishment works in 1994 and 1995 a part of the tunnel invert, between the intake and the test fields, is paved with cast basalt tiles (Fig. 1).

The Runcahez SBT was on average put in operation 2.3 times per year and the yearly operation duration is approx. 12.3 h (mean data for the period 1962 – 1999). The diameters of the bed load components are typically d_{50} = 0.16 m, d_{mean} = 0.23 m, d_{90} = 0.53 m and d_{max} = 1.20 m. This SBT is an outstanding example with relatively short annual operation times and large sizes of bed load material resulting in severe invert abrasion.

2 Concrete test fields placed in 1995

A research work was launched in 1993 to investigate the process of abrasion and suitable materials for various types of hydraulic structures (e.g. weirs, channels, SBTs). The project was funded by the Swiss Association of Producers of Electricity (PSEL, currently called swisselectric) and the Association of the Swiss Cement Manufacturers (VSZKGF, currently called cemsuisse). The work was carried out by TFB (Technik und Forschung im Betonbau, Switzerland) and VAW (Laboratory of Hydraulics, Hydrology and Glaciology of ETH Zurich). The research work comprised mainly in-situ tests at Runcahez SBT and was completed in 2001 with the publication of the report by Jacobs *et al.* (2001).

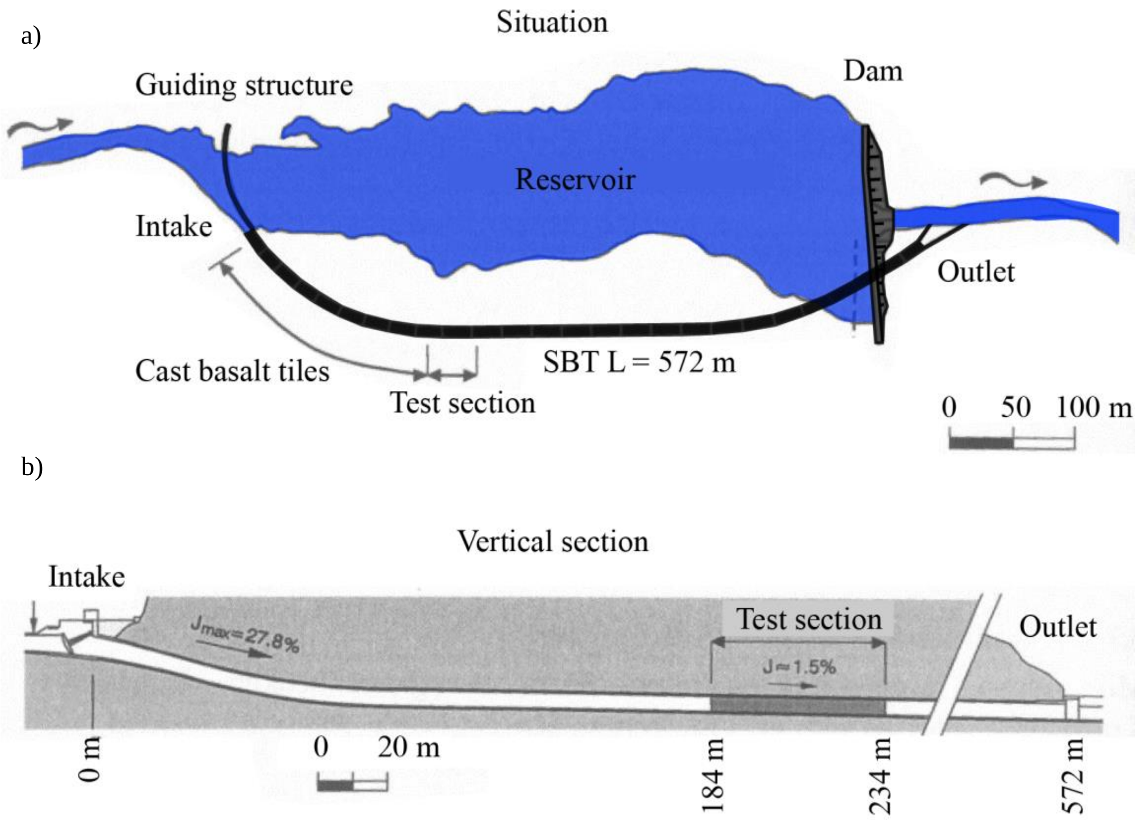

Figure 1: a) Layout and b) vertical section of the SBT Runcahez and location of the test fields (test section) in the bypass tunnel, after Jacobs et al. (2001)

In 1994 it was decided to test several types of concrete in the Runcahez SBT (Table 1). At this time it was not clear which process is the most damaging for the invert:

- Fracturing and breaking of brittle material due to impacting boulders saltating and rolling on the invert
- Abrasion of material with low resistance against grinding (when bed load components slide on the invert)

Therefore, the goal was to investigate the performance of different materials (Table 1). The concrete properties were tested on separately manufactured specimens. It is seen in Table 2 that the target properties were achieved. The roller compacted concrete (RCC) showed as expected generally the largest variability in the properties. This is attributed to the placement and compaction processes.

Table 1: Description and composition of tested types of concrete in the SBT Runcahez, from Jacobs *et al.* (2001); *three component polymer; **rounded river gravel

Concrete type	Concrete containing silica fume	High performance concrete	Steel fiber concrete	Roller compacted concrete	Polymer concrete EMACO APS T 2040
Abbreviation	SC	HPC	SFC	RCC	PC
Target properties	Very high strength, high modulus of elasticity	High strength, not too high modulus of elasticity	Very high strength, high modulus of elasticity, fibres for bridging cracks	Mean strength and modulus of elasticity, for convenient placing on large areas	Mean strength and low modulus of elasticity
Cement [kg/m^3]	450	500	480	400	1060*
Water/cement ratio	0.32	0.30	0.30	0.32	-
Additions [kg/m^3]	Silica fume: 40	-	Silica fume: 24 Steel fibers: 45	-	
River sand 0/4 mm [kg/m^3]	563	565	559	656	250
Basaltic gravel 3/15 mm [kg/m^3]	1505	1432	1405	1452	1250**

Table 2: Properties of the tested types of concrete in the SBT Runcahez; the properties are given for an age of 90 days, from Jacobs *et al.* (2001)

Concrete type	Concrete containing silica fume	High performance concrete	Steel fiber concrete	Roller compacted concrete	Polymer concrete EMACO APS T 2040
Cube compressive strength [N/mm^2]	109 ± 4	94 ± 3	114 ± 2	68 ± 12	68 ± 4
Modulus of elasticity [kN/mm^2]	57 ± 1	56 ± 1	58 ± 1	51 ± 4	13 ± 2
Splitting tensile strength [N/mm^2]	12 ± 1	10 ± 1	12 ± 2	9 ± 2	14 ± 1
Fracture energy [J/m^2]	210 ± 35	209 ± 35	1019 ± 412	143 ± 64	867 ± 93
Density [kg/m^3]	2683 ± 18	2655 ± 58	2726 ± 6	2568 ± 39	2360 ± 17

Each type of concrete was cast in a field of 10 m length and 3.8 m width. Between every test field a steel beam was placed with the intention of limiting the damage propagation from one field to the next. Before casting the concrete, an even underground was prepared (Figure 2): part of the old concrete was removed and the erosion channel in the middle of the tunnel width was levelled out with a normal concrete (approx. 45 MPa cube compressive strength at 28 days). In each field the concrete was cast in a thickness of 30 cm except for the polymer concrete. Due to its high price a thickness of 20 cm was chosen.

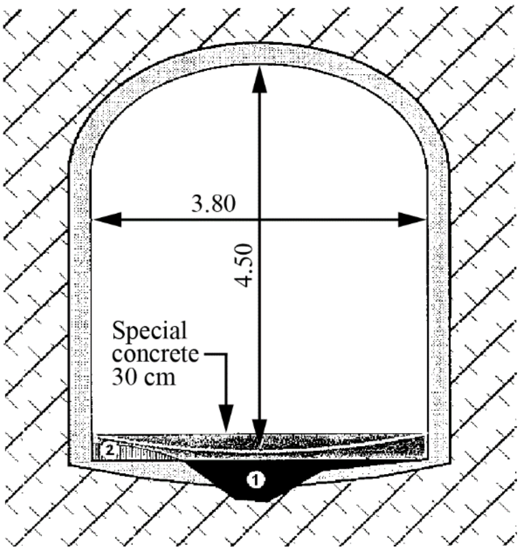

Figure 2: Cross section of the sediment bypass tunnel in Runcahez, ① casting of concrete to level out the underground ② removal of concrete, from Jacobs *et al.* (2001)

After the placement of concrete all fields were visually inspected. In every field cracks were observed (Figure 3). The cracks run more or less perpendicular to the flow direction and had in general widths of maximum 0.1 mm, except for the fields with silica fume containing concrete (up to 0.5 mm) and the polymer concrete (up to 2 mm). The cracks were mainly caused by the hydration heat under restrained conditions.

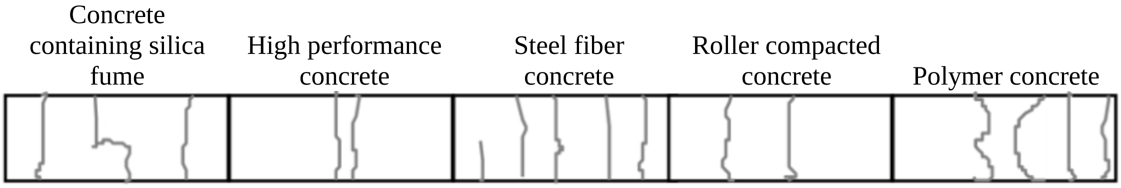

Figure 3: Cracks in the test fields visible some days after casting, the flow direction is from left to right (Jacobs *et al.* 2001)

3 Damages observed over 20 years

From 1995 to 1999, the surfaces of all five test fields were yearly monitored by geodetic measurements and visual inspections. A further inspection and further measurements were carried out by Hagmann in 2012 and 2014, respectively. The following figures, partially based on data from Jacobs *et al.* (2001) and from Hagmann.

Figure 4 shows the development of the abrasion depths, averaged over each field, for the various types of concrete over the last 20 years. The mean abrasion rate was approx. 1 mm/year, except for the RCC field with a much higher rate. In Figure 5 the same abrasion values are shown as a function of the estimated bed load mass. The mean abrasion rate was approx. 1 mm/10’000 tons of bed load, again except for the RCC. Since no bed load measurements are available at this site, the bed load mass was estimated. From 1995 to 1999 the discharge and operation duration were measured and enabled bed load estimation based on the approach of Smart and Jaeggi (1983) (Jacobs *et al.* 2001). After 1999 mean annual bed load volume determined from 1996 to 1999 is assumed.

In Figure 6 and Figure 7 the local maximum abrasion depth per test field is displayed. The local abrasions were in general twice as deep as the averages per test field except for the RCC. The deep local abrasion in the RCC field is mainly attributed to insufficient compacting near the tunnel walls. As it was not possible to use a road roller close to the tunnel walls, the RCC had been compacted with a hand-held device. After one year of service it was already visible that more material was lost in these areas.

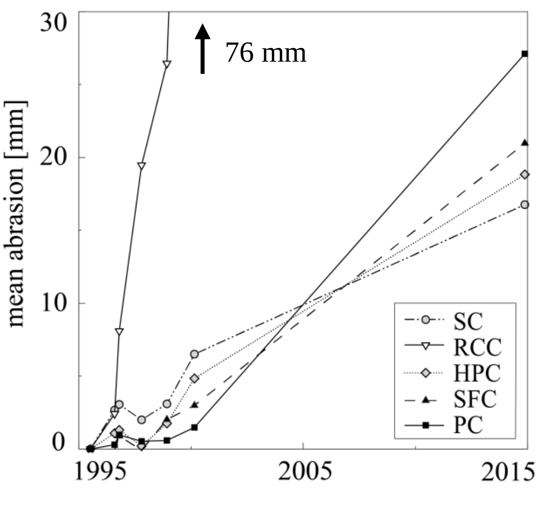

Figure 4: Mean abrasion depths (averaged in each test field) over time (years)

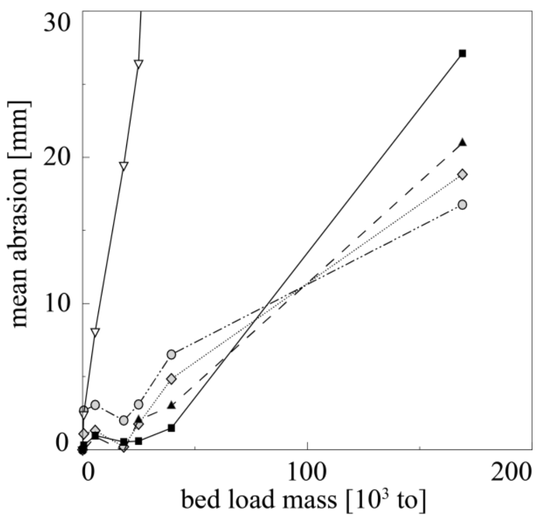

Figure 5: Mean abrasion depths (averaged in each test field) as a function of bed load mass

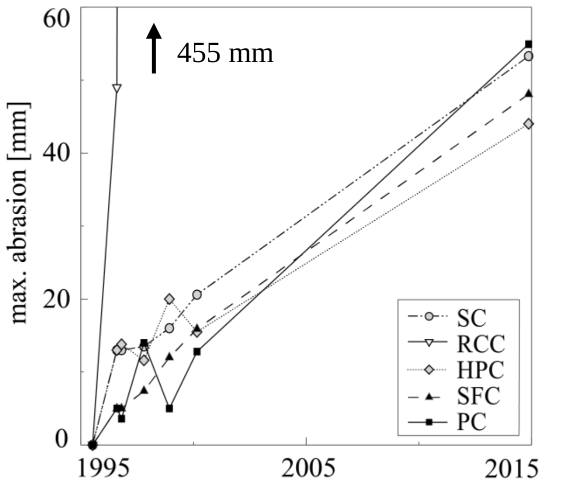

Figure 6: Local maximum abrasion depths (per test field) over time (years)

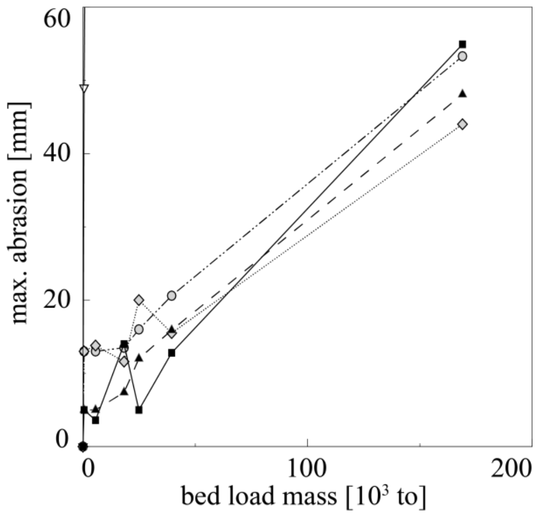

Figure 7: Local maximum abrasion depths (per test field) as a function of bed load mass

A map of erosion depth in the RCC test field 5 years after construction is shown in Figure 8. . The damage along the tunnel walls continuously spreads out. Such spreading of an initial damage is a typical and dangerous process which can also be observed with pavements.

Figure 9 and Figure 10 show the abrasion map in the test field made of silica fume concrete after 5 and 20 years, respectively. It can be seen that the abrasion patterns are similar but amplified. This is typical for a self-intensifying harming process.

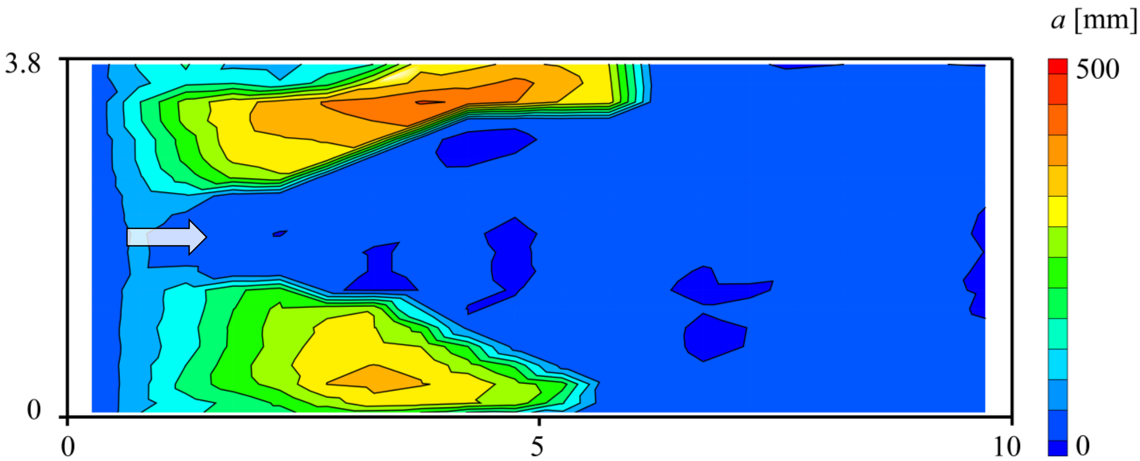

Figure 8: Top view on the RCC test field with erosion depth over 5 years (1995 to 1999), the arrow indicates the main flow direction

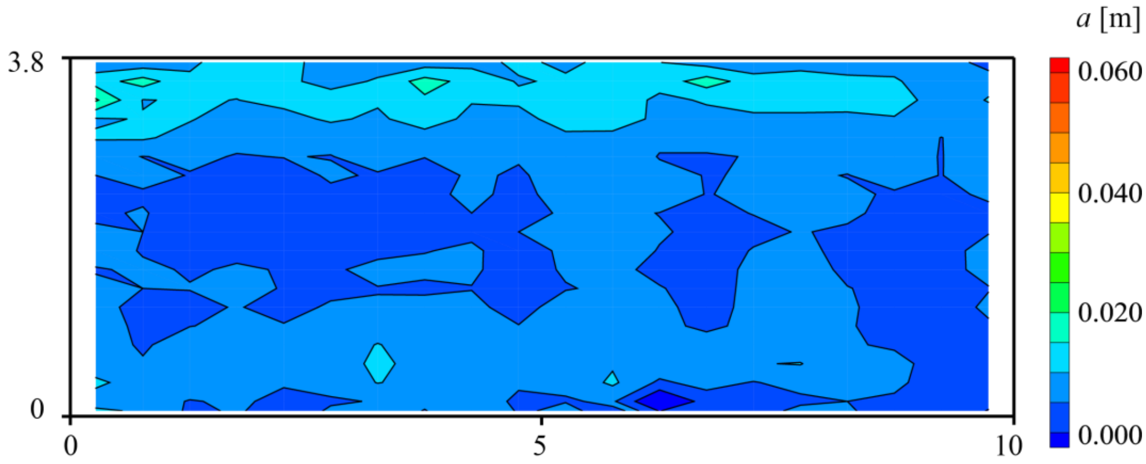

Figure 9: Top view on the test field made of silica fume concrete with abrasion depth over 5 years (1995 to 1999)

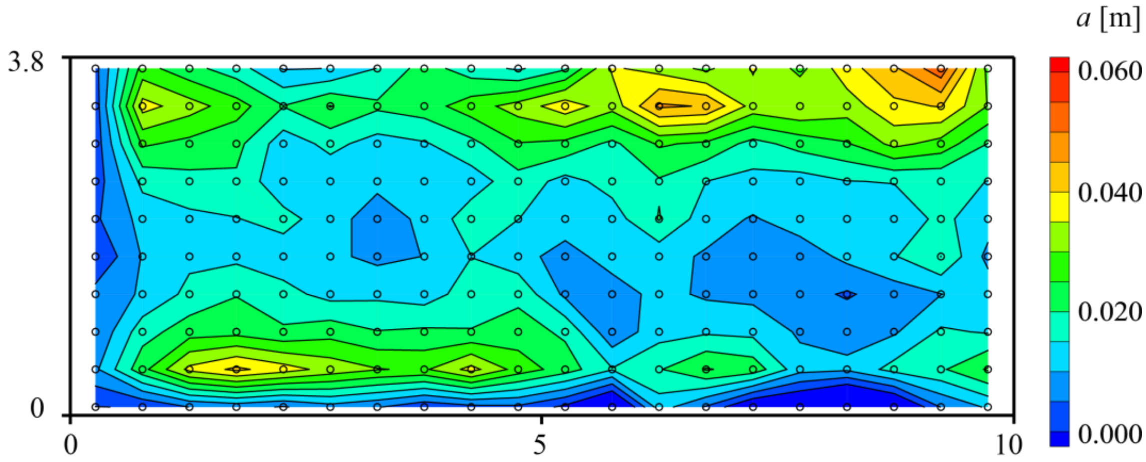

Figure 10: Top view on the test field made of silica fume concrete with abrasion depth over 20 years (1995 to 2014), circles represent measurement points

In 2012, no significant additional damages were observed along the (Figure 11). So far the cracks did not have any negative consequences. Moreover, uneven abrasion patterns on the inverts (Figure 10, Figure 12 and Figure 13) and a severe abrasion on the steel beams (Figure 14) were observed during many inspections.

Due their brittleness many cast basalt tiles got cracks by impacts of boulders (Figure 15). With further action of the bead load and the flow, the tiles fell apart and are swept away. From broken and missing tiles the destruction of the pavement propagates in flow direction.

It is interesting to note that the abrasion occurs mainly on the invert and only to a very small extent on the tunnel walls (Figure 16). At the lower part of the walls only a few millimeters of the normal type of concrete were abraded during 20 years.

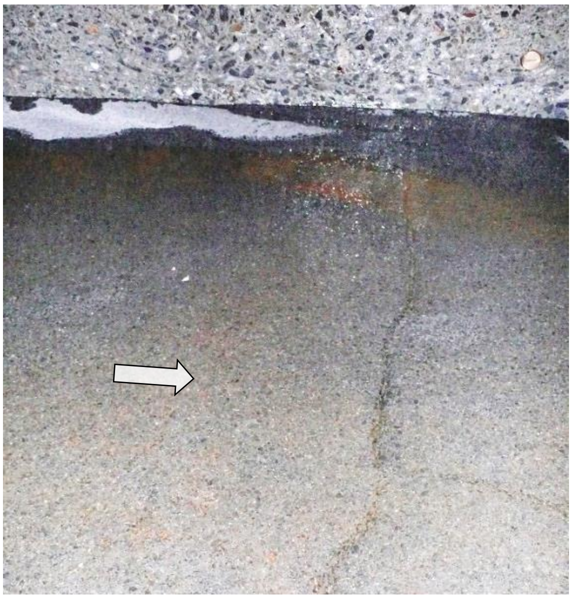

Figure 11: Crack in the HPC test field running perpendicular to the flow direction, picture taken 2012

Figure 12: Erosion channel on the normal tunnel lining, picture taken 2012

Figure 13: damage (uneven surface) in the HPC test field, picture taken 2012

Figure 14: Damage on the steel beam separating the HPC field (right) from the SFC field (left), basaltic aggregates (dark grains) are visible, picture taken 2012

Figure 15: Damage in an area with cast basalt tile paving, picture taken 2012

Figure 16: Minor damage due to abrasion in the PC test field and at the lower part of the wall (normal concrete), picture taken 2012

4 Conclusions

Five types of special concrete were tested on the invert of Runcahez SBT over the past 20 years. The SBT's annual operation time is relatively short, but the bed load components are relatively coarse. Abrasion depths were quantified by repeated geodetic surveys. Annual abrasion rates were calculated and abrasion rates with respect to the estimated transported bed load mass.

Excepting the RCC, for all types of special concretes, surface-averaged erosion rates of approx. 1 mm per year were determined. This corresponds to approx. 1 mm per 10'000 tons of bed load which were transported over the 3.8 m wide tunnel invert. These moderate abrasion rates result at this site in a tolerable maintenance effort and in a reasonable expected life time of a concrete invert with a usual thickness. The tests proved that adequate special concrete can be used under severe exposure conditions and maintain the stability of the tunnel invert as well as the tunnel itself.

For Runcahez SBT it is still not clear which property of the concrete is of utmost importance to reduce the abrasion and to characterize the abrasion resistance.

The proper implementation, especially the compaction of the concrete, is very important since small damages due to insufficient concrete compaction can rapidly spread out. The flatness of the concrete surface is also very important to avoid locally pronounced abrasion damages due to surface irregularities which could lead to larger damages.

It is expected that the invert concrete in this SBT with an original slab thickness of 30 cm will still be suitable for more than another decade if the size and/or quantity of the bed load is not significantly increased.

Acknowledgement

The authors thank swisselectric research and cemsuisse for supporting the research project in the 1990s. Additionally, M. Hagmann acknowledges the support of the current research project by swisselectric research, the Swiss Federal Office of Energy (SFOE), cemsuisse, the foundation Lombardi Ingegneria as well as ewz (Elekrizitätswerk der Stadt Zürich). Further thanks go to Kraftwerke Vorderrhein/Axpo, the operator of the Runcahez SBT and the SBB (Swiss Federal Railways), the operator of the Pfaffensprung SBT, for the good collaboration.

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Abstract

A sustainable use of reservoirs requires long-term solutions against reservoir sedimentation. Worldwide, sedimentation exceeds the reservoir capacity increase, revealing a net volume lack in the near future. The topic of reservoir sedimentation therefore attracts worldwide attention. Sediment bypass tunnels are an effective countermeasure to significantly reduce sediment accumulation, particularly for small to medium-sized reservoirs in the mountainous environment. During floods incoming sediment is routed around the dam into the tailwater. Besides the desilting effect, ecologically favorable aspects also arise due to reconnected up- and downstream river reaches, thereby reestablishing sediment continuity. However, high flow velocities and bedload transport cause severe hydroabrasion in these tunnels, requiring continuous maintenance works.

The Workshop deals with the optimization of the hydraulic conditions and a suitable selection of the invert lining material for sediment bypass tunnels. Many Swiss, Japanese but also worldwide tunnel operators are invited to present the lessons learnt from sediment bypass tunnel prototypes. Invited keynote speakers present sedimentation-related topics. Furthermore, current research achievements will be highlighted.

Workshop topics will encompass:

- Hydraulic design
- Selection of suitable bypassing capacity and frequency
- Target sediment granulometry
- Tunnel invert lining
- Maintenance
- Instrumentation and monitoring techniques
- Ecological impacts

Location

The Workshop takes place at:
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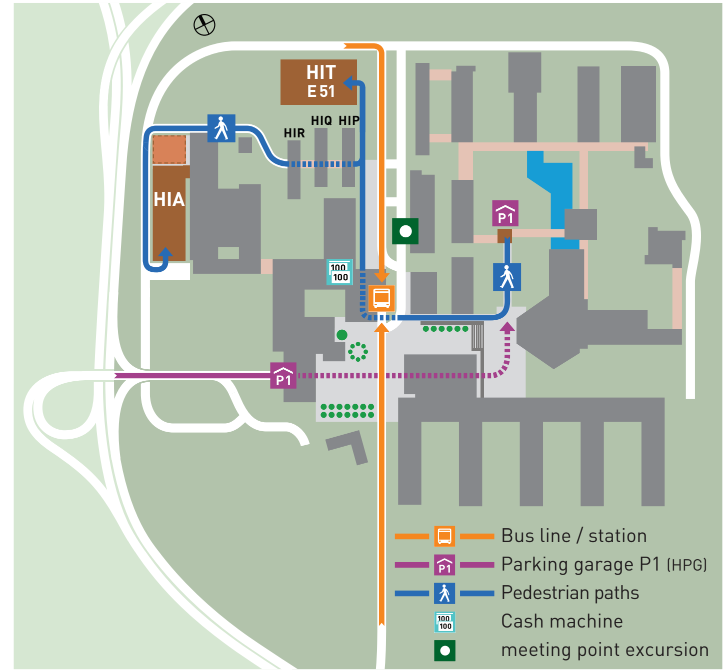

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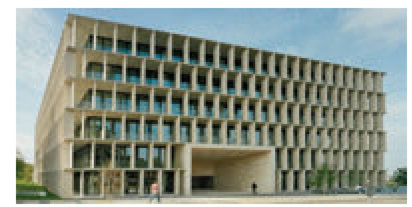

VAW Laboratory:
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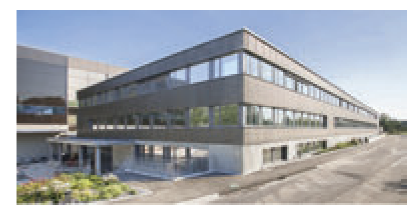

Program

Monday, April 27th

Registration 08:30

Welcome address and opening remarks 09:30
Prof. Dr. Robert M. Boes, VAW, ETH Zurich, Switzerland

Keynote 09:45

Sedimentation countermeasures in Japan
Prof. Dr. Tetsuya Sumi, WRRC, DPRI, Kyoto University, Japan

Coffee break 10:15

Sediment bypass tunnels in Japan *chaired by C. Auel* 10:45

Asahi
Hiroshi Nakajima, Kansai Electric Power Co., Inc., Japan

Miwa
Toshiyuki Sakurai, National Institute for Land and Infrastructure Management
Ministry of Land, Infrastructure, Transport and Tourism, Japan

Koshibu
Josuke Kashiwai, Japan Dam Engineering Center, Japan

Sediment bypass tunnels in the world *chaired by C. Auel* 11:45

Shihmen, *Taiwan*
Jihn-Sung Lai, Ph.D, National Taiwan University, Taiwan

Nanhua, *Taiwan*
Dr. Chen-Shan Kung, Sinotech Engineering Consultants Ltd., Taiwan

Lunch break and poster presentation 12:25

Sediment bypass tunnels in the world *chaired by G. Morris* 13:55

Chespí y Palma Real, *Ecuador*
Carmelo Grimaldi, Ph.D, Lombardi Engineering Ltd., Switzerland

Rizzanese, *France*
Eric Laperrousaz, Électricité de France, France

Research on sediment bypass tunnels *chaired by G. Morris* 14:35

Laboratory research: Sediment motion and invert abrasion
Dr. Christian Auel, WRRC, DPRI, Kyoto University, Japan,
formerly VAW, ETH Zurich

Field research: Material resistance and transport measurements
Michelle Hagmann, VAW, ETH Zurich, Switzerland

Coffee break 15:15

Research on sediment bypass tunnels *chaired by T. Sumi* 15:45

Numerical research: Downstream morphological impact
Matteo Facchini, VAW, ETH Zurich, Switzerland

Field research: Downstream ecological impact
Eduardo Martin, Eawag, Switzerland

Current sedimentation research at VAW
Dr. Ismail Albayrak, VAW, ETH Zurich, Switzerland

Laboratory research: Bedload guidance into Bypass inlet
Dr. Giovanni De Cesare, LCH, EPF Lausanne, Switzerland

Laboratory research: Patrind, *Pakistan*
Claudia Beck, VAW, ETH Zurich, Switzerland

Laboratory tour in the evening 17:40

Social dinner in the restaurant „Die Waid“ 19:30

Tuesday, April 28th

Keynotes *chaired by I. Albayrak* 09:00

Reservoir sedimentation
Gregory L. Morris, Ph.D, GLM Engineering, Puerto Rico

Sedimentation countermeasures in Switzerland
Prof. Dr. Robert M. Boes, VAW, ETH Zurich, Switzerland

Coffee break 10:00

Sediment bypass tunnels in Switzerland *chaired by I. Albayrak* 10:30

Runcahez
Dr. Frank Jacobs, Technik und Forschung im Betonbau, TFB, Switzerland

Solis
Christof Oertli, Electric Power Company of Zurich, ewz, Switzerland

Palagnedra
Andrea Baumer, Riccardo Radogna,
Le Officine Idroelettriche della Maggia, OFIMA, Switzerland

Pfaffensprung
Bärbel Müller, Swiss Federal Railways, SBB, Switzerland

Closure 11:50
Prof. Dr. Robert M. Boes, VAW, ETH Zurich, Switzerland

Excursion departure 12:15

from meeting point for excursion
a packed lunch will be distributed in the bus

Solis Sediment bypass tunnel 15:00

Departure to „Hotel Albula & Julier“ 17:30

Dinner in the hotel 19:30

Wednesday, April 29th

Breakfast 06:30

Departure to Palagnedra 07:00

Palagnedra Sediment bypass tunnel 11:15

Departure to Pfaffensprung 13:15

Pfaffensprung Sediment bypass tunnel 16:00

Departure to Zurich 17:30

Arrival in Zurich 19:15

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sbt-workshop@vaw.baug.ethz.ch
www.vaw.ethz.ch/sbt-workshop

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