Sediment bypass tunnel design – hydraulic model tests

C. Auel
Laboratory of Hydraulics, Hydrology
and Glaciology (VAW)
ETH Zurich
Gloriastrasse 37/39
8092 Zurich, Switzerland

R.M. Boes
Laboratory of Hydraulics, Hydrology
and Glaciology (VAW)
ETH Zurich
Gloriastrasse 37/39
8092 Zurich, Switzerland

Introduction

Reservoir sedimentation, a serious problem affecting the majority of reservoirs worldwide, was not systematically accounted for in the past. After 50 years of operation, a constantly decreasing reservoir volume becomes currently a serious challenge for reservoir owners, against which countermeasures have to be developed. This research focuses on sediment routing using a bypass tunnel to convey sediments past a dam.

By transporting sediments into the tailwater past a dam, their accumulation in the reservoir is reduced significantly. However, the global number of sediment bypass tunnels is limited primarily due to high investment and maintenance cost. The main problem of all bypass tunnels is the massive invert abrasion due to high flow velocities combined with high sediment transport rates. Therefore, VAW started two research projects to counter this problem. The main goal of the first project *Layout and design of sediment bypass tunnels* is to investigate the invert abrasion process by conducting hydraulic laboratory tests and to establish general design criteria for optimal flow conditions in which both sediment depositions in the tunnel are avoided and the resulting abrasion damages are kept at a minimum. The second project *Optimizing hydroabrasive-resistant materials at sediment bypass tunnels and hydraulic structures* investigates the hydraulic resistance of different tunnel invert materials, such as high performance concrete or cast basalt plates in prototype tests at the Solis bypass tunnel. The sediment transport measurement technique used in this project was optimized during preliminary model tests.

1 Background

Reservoir sedimentation is a problem with increasing importance affecting the majority of reservoirs not only in Switzerland but worldwide. As many dams are in operation for more than 50 years, this problem becomes more and more serious. Mean annual sedimentation rates of 0.2 to 2% of the reservoir volume led, and will lead to high aggradation in the near future (Boes & Reindl 2006). As a global problem, sedimentation rates increase faster than the new reservoir capacity installed, resulting therefore in a decrease of net reservoir capacity in the future.

Reservoir sedimentation causes various severe problems such as (1) decrease of the active reservoir volume leading to less available water for energy production, drinking water supply and irrigation; (2) reduction of retention volume during floods; (3) endangerment of operating safety due to blockage of the outlet structures; and (4) increased turbine abrasion due to increased specific suspended load concentrations (Sumi *et al*. 2009). If no countermeasures are considered, then reservoir sedimentation will progress and the above mentioned problems will intensify.

Decreasing sediment aggradation may be achieved by different sediment management techniques as described by Sumi *et al*. (2004) or Kantoush & Sumi (2010). The type of measure can be divided into the following three methods: (1) sediment yield reduction; (2) sediment routing; and (3) sediment removal. Auel & Boes (2011) subdivided all common countermeasures into these three categories.

Fig. 1 shows the three methods and its subdivided countermeasures. The first category *sediment yield reduction* refers to measures reducing the sediment inflow into the reservoir as e.g. upstream sediment trapping or erosion control in the catchment area by means of reforestation. The second category *sediment routing* refers to measures that route sediments into the tailwater past the dam including three effective measures: (1) sluicing of sediments through the reservoir outlet structures by lowering the reservoir water level; (2) venting the turbidity currents; and (3) routing of sediments through a sediment bypass tunnel. The third category *sediment removal* refers to measures that remove accumulated sediments from the reservoir. Typical measures include sediment dredging during high reservoir levels, excavation of dry sediments during complete water level drawdown, or sediment flushing through the reservoir outlet structures either during high reservoir levels (pressurized flushing) or during a complete water level drawdown. A detailed classification of all countermeasures is given in Auel & Boes (2011).

Further research is needed on reservoir sedimentation. VAW started two research projects concerning the countermeasure of rerouting sediments through bypass tunnels past a reservoir. The sediment bypass tunnel design, the abrasion problems of the tunnel invert and the current research at VAW is presented in this paper.

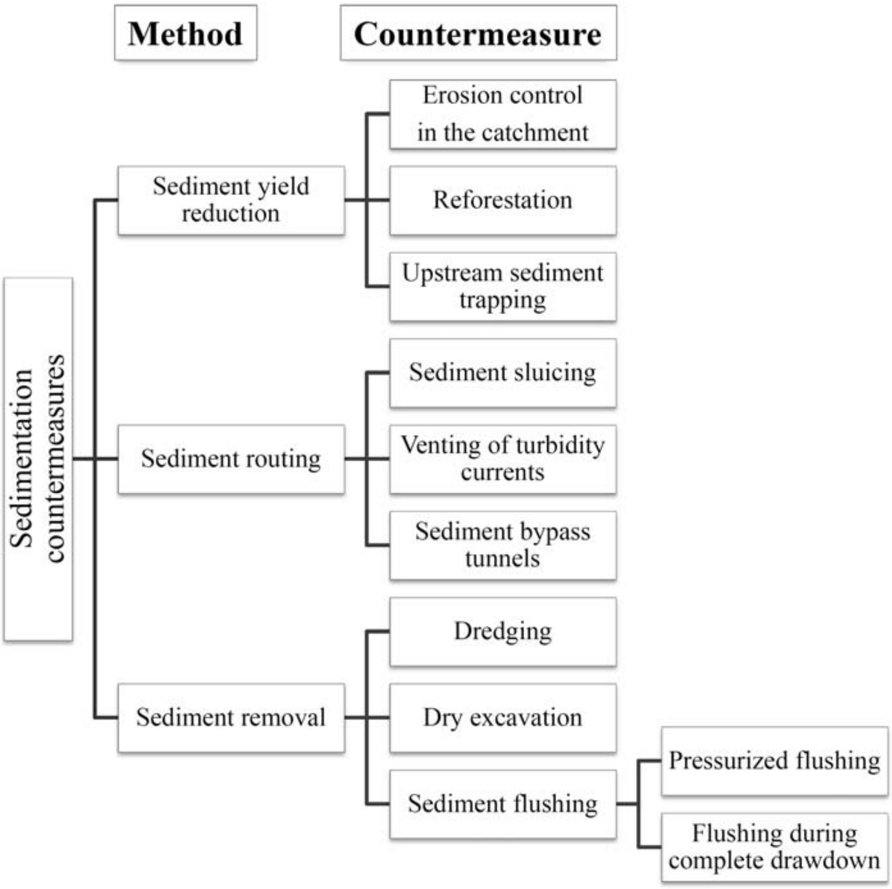

Fig. 1 Sedimentation countermeasures; adapted by Auel & Boes (2011).

2 Sediment bypass tunnels

Sediment bypass tunnels are an effective means to decrease or even stop the reservoir sedimentation process. By routing the sediments past the reservoir into the tailwater during flood events, sediment accumulation in the reservoir due to both bed-load and suspended-load can be minimized. The second advantage of sediment routing gaining importance is ecological sustainability. River bed erosion downstream of a dam is significantly reduced and the morphological variability increases. Only sediments supplied from the upstream river reach are transported through the bypass tunnel, so that sediments already accumulated in the reservoir are not removed. The sediment concentration in the tailwater of the dam is not affected by the reservoir itself and therefore of natural character.

The global number of realized sediment bypass tunnels is limited primarily due to high investment and maintenance cost. Mainly sediment bypass tunnels located in Switzerland and Japan are currently in operation. Referring to Vischer *et al*. (1997) the Swiss tunnels include Runcahez and Egschi (Canton Grisons), Rempen (Canton Schwyz), Pfaffensprung (Canton Uri), and Palagnedra (Canton Ticino). The Solis bypass tunnel in Grisons is currently under construction and planned to be completed in 2012 (Auel *et al*. 2011). Referring to Sumi *et al*. (2004) and present information there are three tunnels in operation in Japan, namely Nunobiki, Asahi and Miwa. Two tunnels, Matsukawa and Koshibu, are currently under construction, and two further (Yahagi and Sakuma) are planned.

2.1 Sediment bypass tunnel design

A sediment bypass tunnel generally consists of a guiding structure in the reservoir, an intake structure including a gate, a short and steeply-sloping acceleration section, a long and gently-sloping bypass tunnel section, and finally an outlet structure into the tailwater (Fig. 2). The discharge enters the tunnel as a free surface flow if the intake is located at the reservoir head (Fig. 2a). For this intake type the tunnel invert level is located at the river bed level. To generate supercritical flow conditions downstream of the gate, the discharge has to be accelerated by a short and steep acceleration section (Fig. 2a). The discharge enters the tunnel intake in pressurized flow conditions, if the intake is located further downstream in the reservoir (Fig. 2b). The tunnel invert level is then located below the river bed resulting in a certain excess energy head, so that free surface flow occurs downstream of the gate. Due to the relatively high energy head the flow velocity beyond the gate is high and no acceleration section is required. Currently just the Solis sediment bypass tunnel is operated under these conditions (Auel *et al.* 2010).

The discharge is conducted under supercritical flow conditions to ensure both a sufficient sediment transport capacity and an economic tunnel cross-section. The design of the invert slope involves two contrary challenges: on the one hand the slope has to be steep enough to generate sufficient shear stress at minimum discharge to transport all inflow sediments into the tailwater without sedimentation in the bypass tunnel. On the other hand, the steeper the slope, the higher are the flow velocities and consequently the stronger the abrasion damages at the tunnel invert (chapter 2.2).

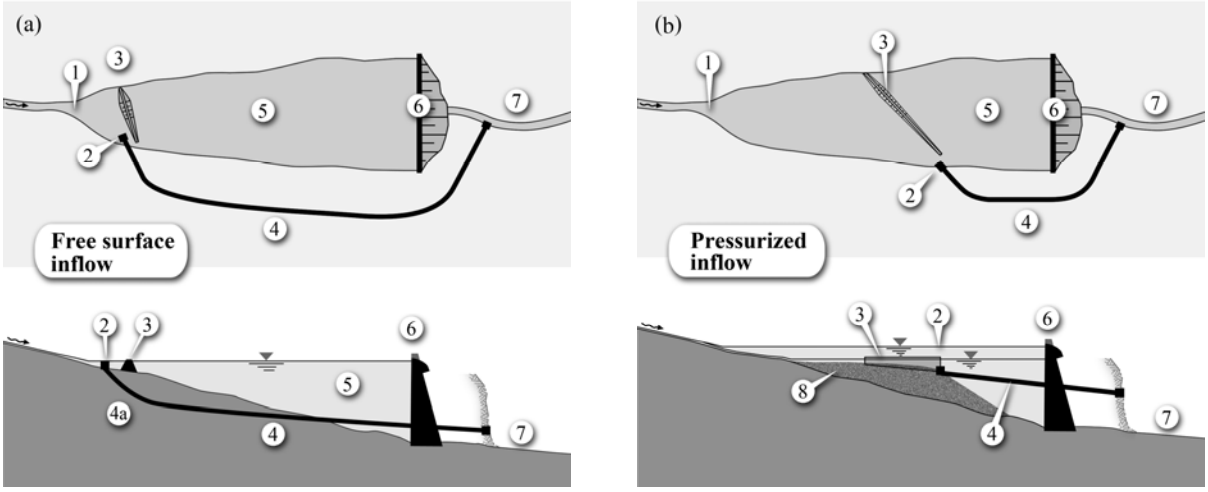

Fig. 2 Scheme of two different sediment bypass tunnel systems (a) Free surface inflow, location of tunnel intake at reservoir head; (b) Pressurized inflow, location of the tunnel intake downstream of reservoir head. 1) Reservoir head. 2) Intake. 3) Guiding structure. 4) Sediment bypass tunnel. 4a) Acceleration section. 5) Reservoir. 6) Dam. 7) Tailwater. 8) Aggradation body.

Sediment bypass tunnels in Switzerland are considered at reservoirs with relatively small volumes varying between 0.15 and 4.3×10^6 m^3 and a mean value of 1.6×10^6 m^3. Contrary to Switzerland, the sediment bypass tunnels in Japan are designed also at larger reservoirs with volumes between 0.76 and 58.0×10^6 m^3, resulting in a mean value of 22.3×10^6 m^3. Typical lengths of sediment bypass tunnel vary between 250 and 4,300 m, with invert slopes between 1 and 4%. The cross-sectional shape of most bypass tunnels is archway or horseshoe. A detailed review of sediment bypass tunnel design, structural dimensions and the hydraulic parameters of all Swiss and Japanese tunnels give Auel & Boes (2011).

2.2 Abrasion problem

A severe problem affecting all sediment bypass tunnels is the hydro-abrasion of the tunnel invert due to the combination of high flow velocities and a high sediment transport. Depending on the geological conditions of the catchment and the hydraulic design of the bypass tunnel, the abrasion effect on the tunnel invert differs. High quartz content and large mean grain diameters contribute to high abrasion damages. Further, the mode of sediment transport in the tunnel is of relevance, as the design on the tunnel invert differs for various transport modes. Depending on the tunnel slope and the amount of transported sediment, single grains may saltate, roll or slide over the tunnel invert. The sediment transport modes and its effect on the invert abrasion are currently investigated at Laboratory of Hydraulics, Hydrology and Glaciology (VAW). Details of the research project are presented in chapter 3.1.

The invert material type influences the abrasion besides the sediment transport mode. Most sediment bypass tunnels in Japan and some in Switzerland are designed with a concrete invert, consisting of high performance concrete (Jacobs *et al*. 2001). Other tunnel inverts in Switzerland are designed with cast basalt plates. Both types are generally suitable. Whereas cast basalt plates are highly resistant against the rolling and sliding impacts, an impact of saltating grains leads to a fast plate cracking. As the resistance of high performance concrete seems to be better regarding saltating bedload, rolling or sliding impacts may lead to high invert abrasion. Fig. 3 shows two examples of invert abrasion at the Palagnedra and Pfaffensprung sediment bypass tunnels. Fig. 3a relates to the concrete-lined Palagnedra sediment bypass tunnel with a steep incision channel 1 to 2 m wide and about 1 m deep, but at specific sections up to 4 m deep. Fig. 3b shows multiple failures of the cast basalt plates-lined tunnel invert of Pfaffensprung bypass tunnel. Some plates were broken presumably by saltating bedrock. Once the cracking process started, more and more plates failed leading to areas without plates. The second VAW research project aims to analyse the resistance of different types of invert lining, as presented in 3.2.

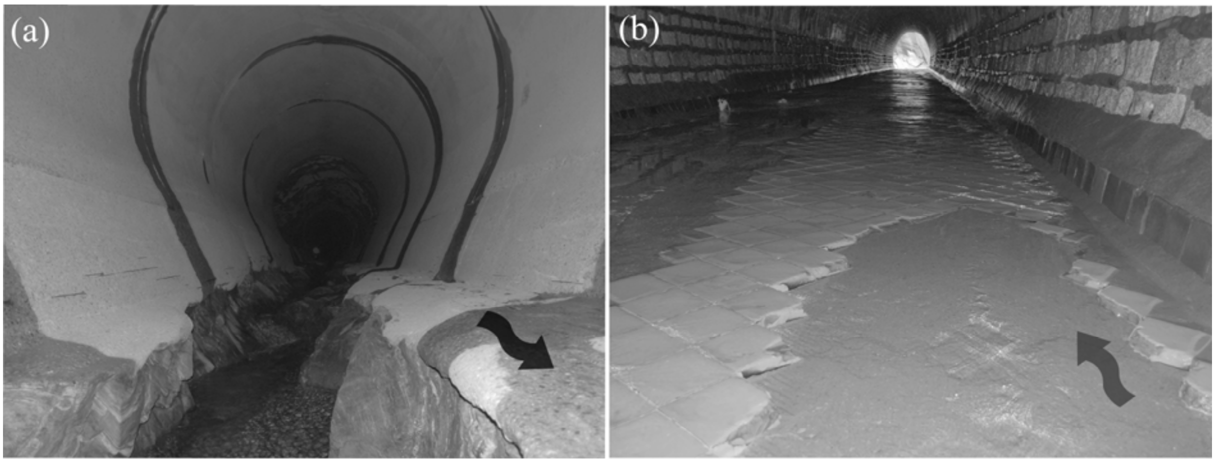

Fig. 3 *Invert abrasion examples (a) Palagnedra sediment bypass tunnel with incision channel, 1 to 2 m wide, 1 to 4 m deep; (b) Pfaffensprung sediment bypass tunnel, with broken and ripped out cast areas of cast basalt plates.*

3 Current research at VAW

In early 2011 the research project *Layout and design of sediment bypass* tunnels was initiated at VAW. In chapter 3.1 this project is briefly summarized. A second VAW research project *Optimizing hydroabrasive-resistant materials at sediment bypass tunnels and hydraulic structures* will start in spring 2012. First issues of the latter project were analysed within a master thesis and are presented in 3.2.

3.1 Project 1: "Layout and design of sediment bypass tunnels"

This project focusses on the optimization of the hydraulic conditions in the sediment bypass tunnel by conducting hydraulic model tests at VAW. The basic hydraulic design neglecting the effect of sediment transport is determined analytically and by numerical simulations, respectively, but there is a major lack of knowledge when both sediment transport and abrasion are taken into account. The governing parameters to be investigated are the tunnel invert slope S, the water discharge Q_w, the sediment supply rate Q_s and the mode of sediment transport.
The experiments will be conducted in a 14 m long and 0.30 m wide glass-sided model flume (Fig. 4). The maximum discharge capacity is 250 l/s. The flume slope varies between 1 to 4%. All tests are conducted in steady-state, free surface approach flow conditions. With gravity as the dominating force, Froude similitude applies. The prototype concrete invert is modelled by a brittle synthetic concrete with high ratios of sand to Portland cement from 10/1 to 15/1. Similar substrates were used e.g. by Finnegan *et al*. (2007) and Johnson & Whipple (2007, 2010) to simulate bedrock incision of rivers. Considering all existing sediment bypass tunnels mentioned in Auel & Boes (2011), the average dimensions of e.g. the mean tunnel width, tunnel height, flow depth or discharge can be determined. This leads to a scaling factor of approximately $\lambda = 15$ for the model flume.
The first goal of the research is to measure the abrasion depth after each model test. The invert incision is scanned by a laser to obtain a 3D scan of the developed invert topography. Measured abrasion depths are compared with each other as well as with prototype data of the Solis sediment bypass tunnel (compare 3.2). The second goal is to investigate the sediment transport process. Single grain movement i.e. saltating, rolling and sliding of grains is recorded by a high-speed camera through the glass-sided flume wall.

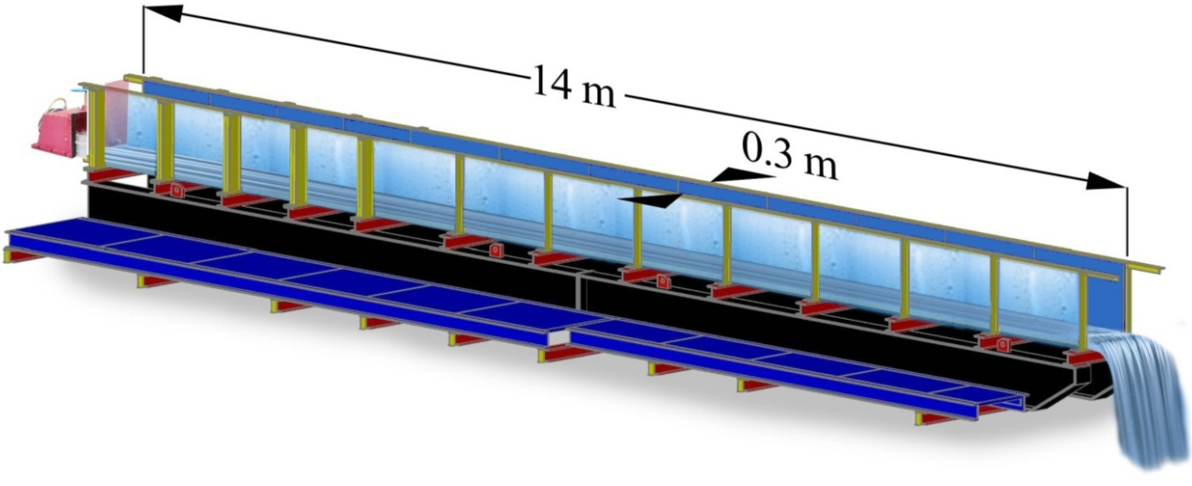

Fig. 4 *Glass-sided model flume.*

3.2 Project 2: "Optimizing hydroabrasive-resistant materials at sediment bypass tunnels and hydraulic structures"

With the completion of the Solis sediment bypass tunnel in spring 2012 prototype measurements will be conducted during the operation phases. Based on similar tests conducted by Jacobs *et al*. (2001) at the Runcahez sediment bypass tunnel, this project investigates the hydraulic resistance of various tunnel invert materials. A total of seven test sections will be equipped with: four different types of concrete, cast basalt, vulcanized rubber on steel and natural granite stones. The test fields of the Solis sediment bypass tunnel will be scanned following each major flood from 2012 to 2016. Additionally the test sections of the Runcahez sediment bypass tunnel are also scanned and compared with the data of Jacobs *et al*. (2001). The collected data in combination with continuous sediment transport measurements allow for a detailed comparison of the different invert materials tested in the two tunnels.

One scope of the tests is to continuously measure the sediment transported through the tunnel. Sediment transport can be measured e.g. using geophone sensors, a continuous measurement technique commonly used in rivers (Rickenmann & Mc Ardell 2007, 2008). Morach (2011) conducted hydraulic model tests at VAW to adapt and optimize the geophone system for high flow velocities as occur in sediment bypass tunnels. Selected results are presented below.

3.2.1 Experimental setup

Geophone systems are an indirect, non-intrusive measurement technique to record the sediment transport in gravel rivers, as currently used in rivers and mountainous streams in Switzerland and Austria. The system consists of the seismic sensor GS-20DX, Geospace Technologies, mounted below a 2 cm thick 36 cm × 49 cm a steel plate; the plate oscillation is damped by a 2 cm thick elastomeric strip (Fig. 5). In general, several geophones are installed in a circumferential U-profile, mounted orthogonally to the flow direction on the river bed. Detailed information about geophone implementation and functionality is given e.g. by Rickenmann & Fritschi (2010).

The experiments were conducted at VAW in a 6 m long and 0.50 m wide glass-sided model channel (Fig.6). The maximum discharge capacity was 250 l/s. The inflow was controlled by a magneto-inductive flow meter and regulated using a so-called jetbox (Fig.6a), transferring the discharge from pressurized pipe flow into supercritical free surface flow (Schwalt & Hager 1992). The geophone was implemented at the end of the channel upstream of a 0.30 m drop, preventing the sediment to accumulate next to the geophone (Fig.6b).

The tests were run in prototype dimensions, i.e. flow velocities, sediment grain sizes and geophone dimensions were similar to these at Solis sediment bypass tunnel. Due to facility restrictions, the flow depth was not modeled in prototype dimensions. The channel discharge capacity is limited to Q_w = 250 l/s, resulting in model flow depths between 0.05 to 0.15 m, whereas prototype flow depths vary between 1 to 3.50 m. Since the modeled flow velocities were kept equal to prototype values, the model Froude numbers Fr were overestimated as compared to the prototype. However, supercritical flow was attempted in both the sediment bypass tunnel and the hydraulic model.

Fig. 5 Geophone sensor, with cover plate removed for demonstration purposes. Seismic sensor GS-20DX mounted below a 2 cm thick 36 × 49 cm steel plate.

The main goal of these tests was to identify the detection rate of transported single grains at various flow velocities and to optimize this rate by inclining the geophone plate against the flow, if necessary. Up to date, geophones were never used for velocities higher than 2 to 3 m/s corresponding to typical flow velocities in mountainous rivers. The test runs were conducted with flow velocities $v = 2$, 4, 6 and 7.4 m/s, measured at the geophone. The geophone sensor was inclined against the flow by 0, 1, 2, 3, 4, 5, 7.5 and 10°, measured against the channel invert. Two principal test series were conducted, namely single-grain tests and multiple-grain tests including five sediment fractions (Tab. 1), resulting in a total of about 130 test runs. Every fraction consists of 50 single grains.

The model tests were carried out as follows. The discharge and the flow depth were kept constant, and sediment grains were supplied manually one by one downstream of the jetbox. The geophone sensor measured the number of impulses, the maximum impulse and the squared integral below the voltage oscillation graph induced by the sediment grain impact. Detailed information of the geophone data analysis provide Rickenmann & Fritschi (2010) and Turowski & Rickenmann (2009, 2011).

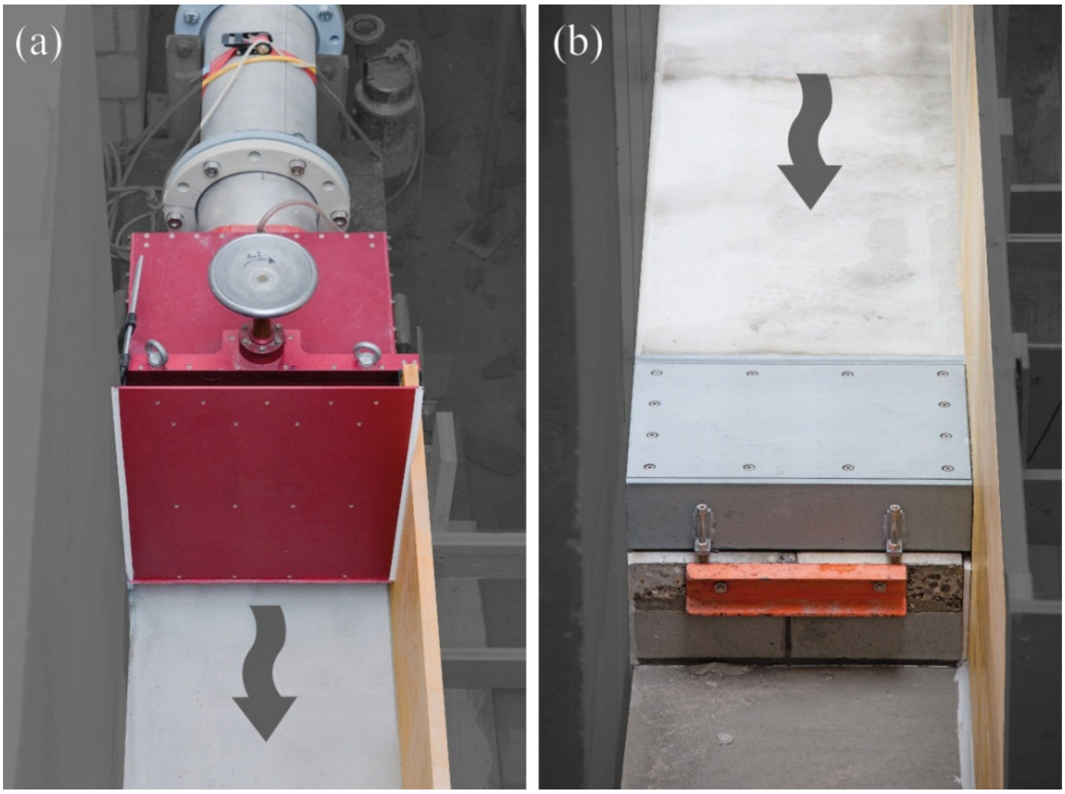

Fig.6 Prototype scale model channel. (a) Channel intake with jetbox, (b) Geophone system at channel end.

Tab. 1 Dimensions of sediment fractions used in tests.

Fraction	*b*-axis [cm]	Average weight [g]
1	2.3 – 3.2	31.4
2	3.2 – 4.5	85.7
3	4.5 – 6.3	221.6
4	6.3 – 8.0	489.9
5	8.0 – 11.2	1135.9

3.2.2 Results

Fig. 7 shows two typical plots of single grain tests series for flow velocities of $v = 2$ m/s and $v = 7.4$ m/s (Morach 2011). The detection rate, e.g. the rate of all 50 grains per fraction inducing an impulse, is plotted against the geophone inclination. Fig. 7a shows the detection rate plotted against the probe inclination for $v = 2$ m/s. Fraction 1 is almost never detected, whereas just every fifth grain is detected for fraction 2. For grains of fraction 3 and higher, the detection percentage is about 80% and higher. All lines are nearly horizontal, implying that the geophone inclination has no effect on the detection rate. As a result, the grain diameter of 3.2 cm describes the detection limit, independent of the probe angle for low velocities.

Fig. 7b shows the detection rate plotted against the probe inclination for $v = 7.4$ m/s. Detection rates for horizontal geophone inclinations are low, even for fractions 4 and 5. Just 40 to 50% of the grains hit the plate. Apparently the flow velocity is too high; the grains are transported above the plate without impacting it. However, all fraction curves increase with the probe inclination. Fraction 1 is not detected at a horizontal geophone inclination, but increases at angles from 4° and higher to nearly 40%. Fraction 2 increases from 20 to 80% at a 10° angle, fraction 3 from 30 to nearly 90%, and fractions 4 and 5 increase from 50 to nearly 100% detection rate.

Therefore, at a 10° inclination angle 80 to 100% of the sediments from fraction 2 and superior are detected. As a result of these results, geophones will be implemented at Solis bypass tunnel with an inclination angle of 10° toward the flow.

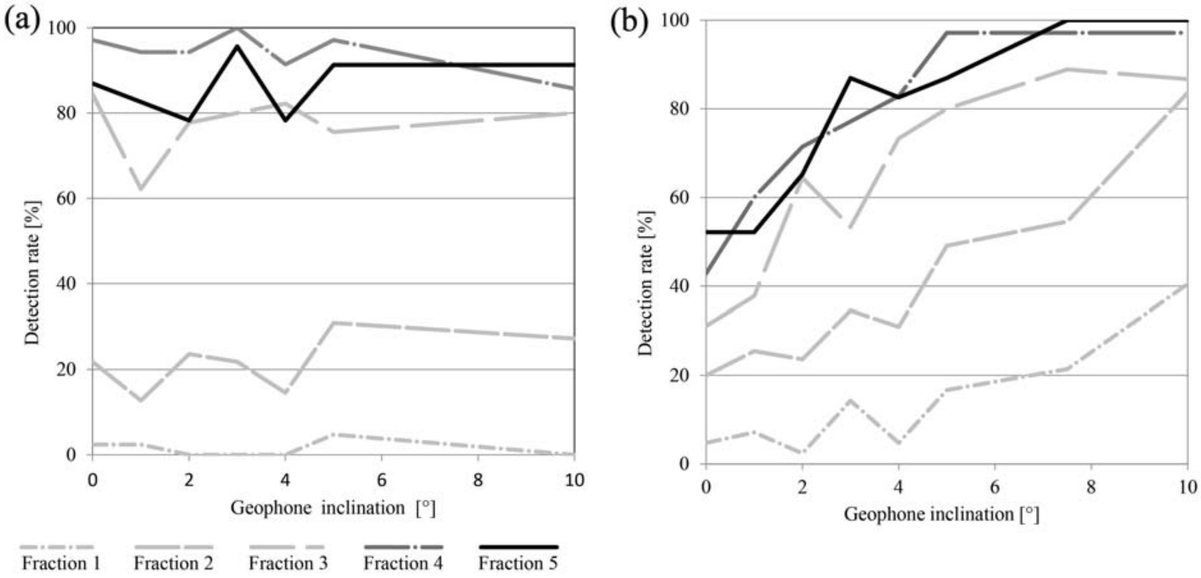

Fig. 7 Diagrams of single grain detection by geophone sensor. Detection rate against geophone inclination at (a) v = 2 m/s, (b) v = 7.4 m/s; adopted from Morach (2011).

4 Conclusions

This paper highlights the need for a sustainable reservoir management. One efficient and ecologically compatible countermeasure is the setup of a sediment bypass tunnel to reroute the incoming sediments past the reservoir into the tailwater. A major problem of all bypass tunnels is invert abrasion due to high flow velocities in combination with high sediment transport. Continuing invert abrasion leads to high maintenance cost, one crucial criterion for reservoir operators to avoid a sediment bypass tunnel.

To counteract this problem, VAW started the two research projects *Layout and design of sediment bypass tunnels* and *Optimizing hydroabrasive-resistant materials at sediment bypass tunnels and hydraulic structures* to investigate both the invert abrasion process and the resistance of invert materials by conducting scale hydraulic tests in the laboratory and prototype tests at Solis bypass tunnel, respectively. The first research project started in spring 2011 and will presumably be finished in early 2014. The second research project starts in spring 2012. Both projects are presented herein.

In the prototype tests at Solis, so-called geophones are used to measure the sediment transport in the bypass tunnel. Hydraulic model tests were conducted to investigate the geophone performance at high flow velocities up to 7.4 m/s. Currently, geophones are commonly used in gravel rivers of low flow velocities up to 2 m/s. The goal of the model tests was to identify the detection rate of transported grains at different flow velocities and to increase this rate by inclining the geophone against the flow. Selected results are presented. As a main issue, the detection rate of sediment transport increases significantly by increasing the inclination angle against the flow. A 10° geophone plate inclination increases the detection rate from 50 to nearly 100%, so that geophones will be implemented in the Solis bypass tunnel with this angle.

Acknowledgements

The authors would like to thank Stephanie Morach for conducting the geophone model tests during her master thesis. Furthermore the authors would like to thank swiss*electric* research and the Swiss Federal Office of Energy for their financial support.

References

1. **Auel C. and Boes R. 2011**. Sediment bypass tunnel design – review and outlook. *Proc. 79th Annual Meeting of ICOLD "Dams and Reservoirs under Changing Challenges"*. Lucerne, Switzerland. Taylor & Francis, London. 403-412.
2. **Auel C., Boes R. Ziegler T. and Oertli C. 2011.** Design and construction of the sediment bypass tunnel at Solis. *Hydropower and Dams*. 18(3). Aqua-Media International Ltd: 62-66.

3. **Auel C., Berchtold T. and Boes R. 2010.** Sediment management in the Solis reservoir using a bypass tunnel. *Proc. of the 8th ICOLD European Club Symposium*. Innsbruck, Austria.
4. **Boes R. and Reindl R. 2006.** Nachhaltige Maßnahmen gegen Stauraumverlandungen alpiner Speicher [in German]. *Proc. Symposium "Stauhaltungen und Speicher - von der Tradition zur Moderne"*, Bericht 46/1, TU Graz, Austria: 179-193.
5. **Finnegan N.J., Sklar L.S. and Fuller T.K. 2007.** Interplay of sediment supply, river incision, and channel morphology revealed by the transient evolution of an experimental bedrock channel. *Journal of Geophysical Research-Earth Surface* 112(F3).
6. **Jacobs F., Winkler K., Hunkeler F. and Volkart P. 2001.** Betonabrasion im Wasserbau [in German]. *VAW-Mitteilung* No. 168, ed. H.-E. Minor, ETH Zurich.
7. **Johnson J.P. and Whipple K.X. 2010.** Evaluating the controls of shear stress, sediment supply, alluvial cover, and channel morphology on experimental bedrock incision rate. *Journal of Geophysical Research-Earth Surface* 115.
8. **Johnson J.P. and Whipple K.X. 2007.** Feedbacks between erosion and sediment transport in experimental bedrock channels. *Earth Surface Processes And Landforms* 32(7): 1048-1062.
9. **Kantoush S. and Sumi T. 2010.** River morphology and sediment management strategies for sustainable reservoir in Japan and Switzerland. *Annuals of Disaster Prevention Research Institute*, No. 53 B. Kyoto, Japan.
10. **Morach S. 2011.** Geschiebemessungen mittels Geophonen bei hohen Fliessgeschwindigkeiten [in German]. Master thesis. Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich.
11. **Rickenmann D. and Fritschi B. 2010.** Bedload transport measurements using Piezoelectric impact sensors and geophones. In Bedload Surrogate Monitoring Techniques. Gray JR, Laronne JB, Marr JD (eds). USGS Scientific Investigation Report.
12. **Rickenmann D. and Mc Ardell B.W. 2008**. Calibration of piezoelectric bedload impact sensors in the Pitzbach mountain stream. *Geodinamica Acta* 21(1-2): 35-51.
13. **Rickenmann D. and Mc Ardell B.W. 2007.** Continuous measurement of sediment transport in the Erlenbach stream using piezoelectric bedload impact sensors. *Earth Surface Processes And Landforms* 32(9): 1362-1378.
14. **Schwalt M. and Hager W.H. 1992.** Die Strahlbox. *Schweizer Ingenieur und Architekt.* 110(27-28).
15. **Sumi T, Kobayashi K., Yamaguchi K. and Takata Y. 2009.** Study on the applicability of the asset management for reservoir sediment management. Q. 89 R. 4, *Proc. 23rd ICOLD Congress*. Brasilia, Brazil.
16. **Sumi T., Okano M., and Takata, Y. 2004.** Reservoir sedimentation management with bypass tunnels in Japan. *Proc. 9th International Symposium on River Sedimentation*. Yichang, China, 1036-1043.
17. **Turowski J.M. and Rickenmann D. 2009.** Tools and cover effects in bedload transport observations in the Pitzbach, Austria. *Earth Surface Processes And Landforms* 34(1): 26-37.
18. **Turowski J.M. and Rickenmann D. 2011.** Measuring the Statistics of Bed-Load Transport Using Indirect Sensors. Journal of Hydraulic Engineering, 137(1), 116-121.
19. **Vischer D., Hager W.H., Casanova C., Joos B., Lier P. and Martini O. 1997.** Bypass tunnels to prevent reservoir sedimentation. Q. 74 R. 37, *Proc. 19th ICOLD Congress*. Florence, Italy.

The Authors

Christian Auel studied civil engineering at the Technical University of Berlin (Germany), Universidad Politécnica de Valencia (Spain), and at RWTH Aachen University (Germany). After graduating in 2007 he started working as a scientific assistant and project engineer at the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) at ETH Zurich in Switzerland. Amongst others he conducted hydraulic model tests of the sediment bypass tunnel at Solis reservoir. His research interest is mainly related to sustainability of reservoirs and sedimentation management. In early 2011 he started his PhD on the *layout and design of sediment bypass tunnels*.

Robert M. Boes studied civil engineering at RWTH Aachen University (Germany), Ecole Nationale des Ponts et Chaussées in Paris (France), and at the Technical University of Munich (Germany), from where he graduated in 1996. He then became a research engineer at ETH Zurich in 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, where he was involved in various projects relating to hydropower schemes, hydraulics and flood protection and became head of the Dam Construction Group.
In 2009 he was appointed Professor for Hydraulic Structures at ETH Zurich, where he currently directs the Laboratory of Hydraulics, Hydrology and Glaciology (VAW). His research interest are mainly related to dam hydraulics, two-phase flow, reservoir sedimentation, impulse waves, suspended sediment transport and hydro-abrasive wear of hydraulic structures and machinery.