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SUSTAINABLE RESERVOIR MANAGEMENT USING SEDIMENT BYPASS TUNNELS [1]

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1. INTRODUCTION

This paper summarizes the increasing problem of reservoir sedimentation and describes applicable countermeasures (chapter 1), addresses sediment bypass tunnels in detail (chapter 0) and describes a research project currently initiated by VAW (chapter 3). Finally, conclusions are drawn (chapter 4) and an outlook is given (chapter 5).

Reservoir sedimentation is an increasing problem affecting the majority of reservoirs not only in Switzerland but worldwide. As many dams are more than 50 years of age, this problem is becoming more and more serious nowadays. Mean annual sedimentation rates of 0.2 to 2% of the reservoir volume have led, and will lead to high aggradation in the near future [1], [2], [3], [4], [5]. Furthermore, sedimentation worldwide increases faster than new reservoir capacity is installed which will consequently result in a decrease of net capacity in the future (Fig. 1).

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[1] *Exploitation à long terme de retenues grâce au concours de galeries de dérivation de sédiments.*

Reservoir sedimentation causes various severe problems such as: (1) a decrease of the active reservoir volume leading to both loss of energy production and available water for water supply and irrigation; (2) a decrease of the retention volume in case of flood events; (3) endangerment of operating safety due to blockage of the outlet structures; and (4) increased turbine abrasion due to increased specific suspended load concentrations [6], [7], [8]. If no countermeasures are taken, reservoir sedimentation will progress and these problems will intensify eventually.

Decreasing sediment aggradation may be achieved by different sediment management techniques as shown, amongst others, in [2], [5], [8], [9] [10], [11], or [12]. According to [2], the type of measures can be divided into the following three methods: (1) sediment yield reduction; (2) sediment routing; and (3) sediment removal. [13] subdivided all common countermeasures into these three categories.

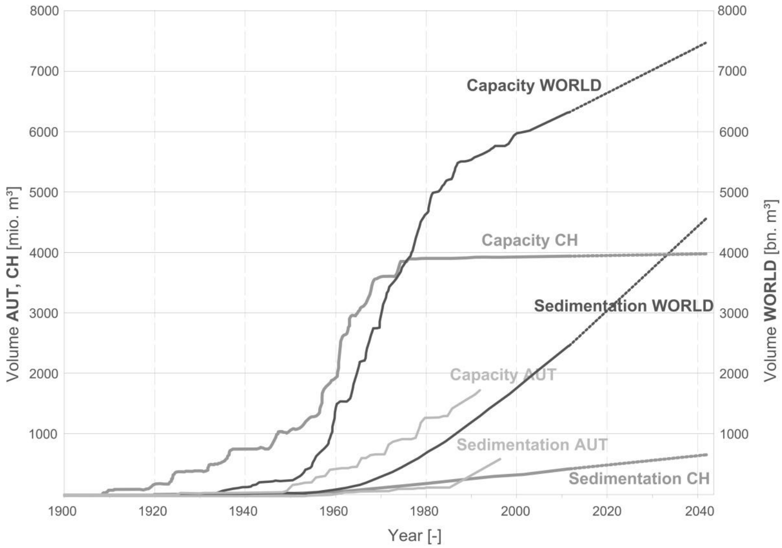

Fig. 1
Increase of reservoir capacity and sedimentation in Switzerland (CH), Austria (AUT) and worldwide; adapted from [3]
Augmentation de la capacité de retenue et de sédimentation en Suisse (CH), Autriche (AUT) et dans le monde entier; adapté de [3]

Fig. 2 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 of the dam, including three effective measures: (1) sluicing of sediments through the reservoir outlet structures by lowering the water level; (2) venting of 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 dredging of sediments during high reservoir levels, dry excavation of sediments during complete water level drawdown, or flushing of sediments 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 [13].

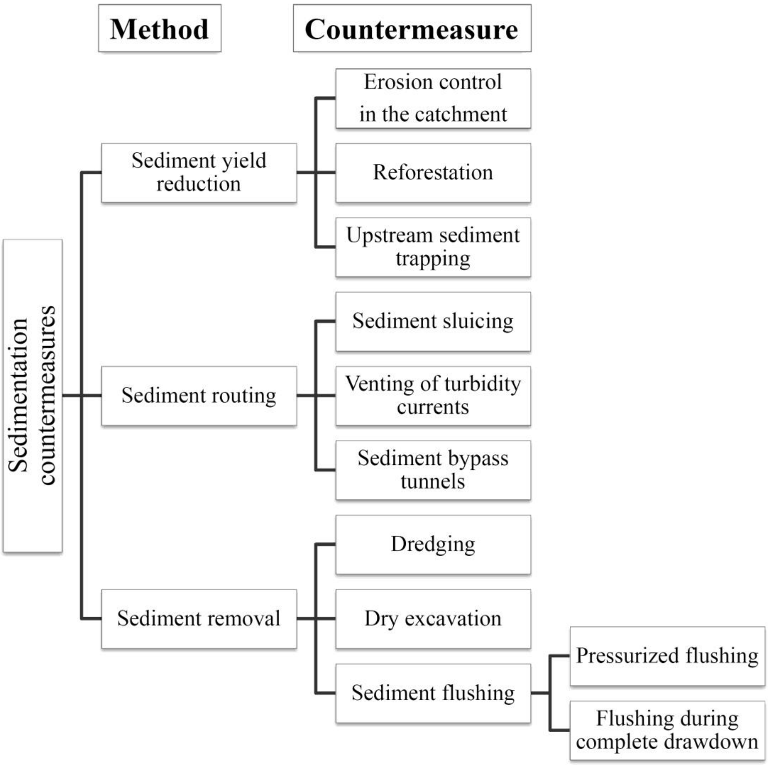

Fig. 2
Sedimentation countermeasures; adapted from [13]
Mesures contre la sédimentation; adapté de [13]

2. SEDIMENT BYPASS TUNNELS

Sediment bypass tunnels are an effective measure to decrease or completely stop the reservoir sedimentation process. By routing the sediments around the reservoir into the tailwater during flood events, sediment accumulation in the reservoir can be significantly reduced. A second advantage gaining more and more in importance are the ecological and sustainable aspects of sediment routing. River bed erosion downstream of the dam can be decelerated significantly or even completely stopped resulting in an increase of morphological variability. Moreover, only sediments provided from the upstream river reach are conveyed through the bypass tunnel, while no removal of sediments that have already accumulated in the reservoir occurs. The sediment concentration in the tailwater of the dam is therefore not affected by the reservoir itself and keeps its natural character, which is advantageous regarding fish fauna aspects.

The number of realized sediment bypass tunnels in the world is small due to high investment and maintenance costs. Sediment bypass tunnels in operation are located mainly in Switzerland and Japan. According to [14], there are five tunnels in operation in Switzerland, namely Runcahez and Egschi in the canton of Grisons, Rempen (canton Schwyz), Pfaffensprung (canton Uri), and Palagnedra (canton Ticino). The Solis bypass tunnel in Grisons is currently under construction and is completed in 2012 [15], [16]. Bypass tunnels not especially used for sediment routing but for discharging floods with high sediment loads are located in the canton of Valais at the Serra reservoir and the Matter Vispa River next to Randa village. Another example is the bypass tunnel at the Grindelwald glacier in the canton of Berne, operating since 2010 and draining a proglacial lake [17]. To date, sediment bypass tunnels in Switzerland were only constructed at reservoirs with relatively small reservoir volumes varying between 0.15 and 4.3×10^6 m^3 with a mean value of 1.6×10^6 m^3.

Referring to [2] and present information there are three tunnels in operation in Japan, namely Nunobiki, Asahi and Miwa. Two tunnels are currently under construction (Matsukawa and Koshibu) and two are in planning (Yahagi and Sakuma). In contrast to Switzerland, sediment bypass tunnels in Japan are constructed also at larger reservoirs with volumes varying between 0.76 and 58.0×10^6 m^3 with a mean value of 22.3×10^6 m^3.

A detailed overview of the general sediment bypass tunnel design, the structural dimensions and the hydraulic parameters including inflow conditions of the tunnels mentioned above is given in [13].

2.1. INVERT ABRASION

A severe problem affecting nearly all sediment bypass tunnels is the hydro-abrasion of the tunnel invert due to the combination of high flow velocities along with a large amount of transported sediment [2], [11], [14], [18], [19], [20]. Fig. 3 shows selected hydraulic parameters for the six Swiss and the five Japanese bypass tunnels in operation or currently under construction, highlighting the supercritical flow and the high flow velocities in the sediment bypass tunnels. The values have been determined by a one-dimensional backwater curve calculation and are taken from [13]. The Froude Number Fr varies between 1.4 and 3.1 with a mean value of 2.1 (Fig. 3a), i.e. all tunnels are operated in supercritical flow conditions. The specific design discharge q_d varies between 13 and 67 m^2/s with a mean value of q_d = 41 m^2/s. The uniform flow velocity v_u varies between 7 m/s at low slopes of 1.3% and 15 m/s at high slopes of 4% with a mean value of 11.5 m/s (Fig. 3b). More detailed data are given in [13].

Depending on the geological conditions in the catchment and the hydraulic design of the bypass tunnel, the impact on the tunnel invert abrasion may differ significantly. Both high quartz content and high mean grain diameters contribute to high abrasion damages in the tunnel. In general, hard rock like granite and gneiss combined with a high quartz content leads to high abrasion damages at the tunnel invert.

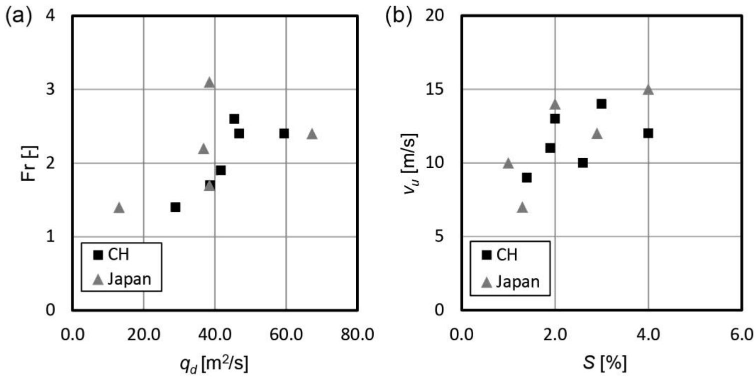

Fig. 3
a) Froude Number Fr versus specific design discharge q_d, and b) uniform flow velocity v_u versus tunnel slope S for 6 Swiss and 5 Japanese sediment bypass tunnels
a) Nombre de Froude Fr en fonction du débit spécifique de dimensionnement q_d, b) Vitesse d'écoulement uniforme v_u en fonction de la pente S de 6 galeries suisses de déviation de sédiments et de 5 galeries japonaises

Furthermore, the mode of sediment transport in the tunnel is of major importance, as the impact 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. As saltating sediment conveys more impact energy on the tunnel invert compared to rolling or sliding sediment, therefore leading to higher abrasion rates [21]. A second important factor is the so-called tools and cover effect [21], [22]. At low sediment supply rates, sediment transport is dominated by saltating grains acting like a hammer on the tunnel invert (tools effect). At higher sediment supply rates, invert abrasion is limited due to the partial sediment deposition on the invert that prevents direct impact of saltating grains (cover effect). Therefore, the maximum abrasion rate is expected when the tunnel routes a moderate supply rate compared to its transport capacity. The sediment transport mode and its impact on the invert abrasion are currently investigated at VAW. Details of this research project are presented in chapter 3.

Besides the sediment transport mode, the type of invert material is another important factor influencing the abrasion. Several sediment bypass tunnels in Japan and Switzerland are designed with a concrete invert, mostly consisting of high performance concrete [16], [23]. Other tunnel inverts in Switzerland are designed with cast basalt plates. Both types are generally suitable. However, whereas cast basalt plates are highly resistant against rolling and sliding impact, the impact of saltating grains leads to a fast cracking. On the other hand, as the resistance of high performance concrete seems to be better regarding saltating bedload, rolling or sliding impact may lead to high invert abrasion as well. Typical Swiss examples of invert failures of both concrete and basalt plates are presented in chapter 2.2. To analyze the abrasive resistance of various invert material, another research project on sediment bypass tunnels is carried out at VAW, see chapter 5.

2.2. FAILURE EXAMPLES

2.2.1. Palagnedra bypass tunnel

Fig. 4 shows two photographs of the Palagnedra sediment bypass tunnel taken in February 2011. The tunnel, built in 1978, is 1760 m long, the design discharge is Q_d = 220 m^3/s for free surface inflow conditions and 250 m^3/s for pressurized inflow conditions, respectively. The tunnel invert was originally constructed with a 0.20 m thick BH 300 concrete layer, corresponding to a modern C20/25 concrete [24]. Fig. 4a shows a steep incision channel 1 to 2 m wide with an average depth of about 1 m up to a maximum of 4 m in several sections. The intensive invert abrasion started in August 1978 caused by an extreme flood with a peak discharge between 2000 and 3500 m^3/s [25]. During that event, the reservoir was completely filled with sediments, and the intake and outlet structures were totally blocked. In the reservoir rehabilitation period, the bypass tunnel was in operation for more than ten months. Additionally, during the flood event sediment accumulated at the reservoir head up to 8 m over the original river bed. This sediment aggradation was eroded successively during the permanent tunnel operation, therefore consequently leading to a high continuous sediment supply [25], [26].

The tunnel was rehabilitated to some extent from 1980 to 1988. However, some sections were never repaired during the last thirty years as shown in Fig 4a. As the tunnel was still in operation two to five times a year, the operator started repair works at the lower tunnel section in 2011 to counteract the continuing abrasion process and prevent a structural collapse (Fig. 4b). The bottom of the incision channel was filled with gravel followed by a 1 m thick layer of standard concrete and topped off by a 0.30 m thick layer of high performance concrete C50/60.

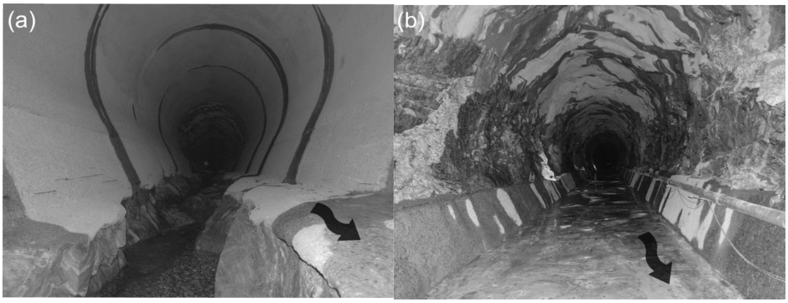

Fig. 4
Palagnedra sediment bypass tunnel. a) Incision channel, 1 to 2 m wide, 1 to 4 m deep. b) Lower tunnel section after replenishing
Galerie de déviation de sédiments de Palagnedra. a) Incision du lit, large de 1 à 2 m, profonde de 1 à 4 m. b) Section inférieure de la galerie après les travaux de remplissage

2.2.2. Pfaffensprung bypass tunnel

Fig. 5 shows two photographs of the Pfaffensprung sediment bypass tunnel taken in July 2011 after a five year flood event of about 120 m^3/s. The tunnel, built in 1922, is 282 m long, the design discharge is Q_d = 220 m^3/s for free surface inflow conditions. The current tunnel invert consists of 50 mm thick 20 x 20 cm cast basalt plates placed on a cement mortar sublayer. Fig. 5a and 5b show failures of the tunnel invert where basalt plates were broken presumably by saltating bedrock. Fig. 5a depicts that mostly entire plates are ripped out. Once the erosion process starts, more and more plates are ripped out from the sublayer leading to a broad area of missing plates as seen in Fig. 5b.

Nearly every year the operator conducts maintenance works to replenish the missing plates. In the past decade, different tunnel invert material was tested in the sediment bypass tunnel such as concrete, steel plates and rectangular or square basalt plates arranged orthogonal or diagonal to the flow direction. Nevertheless, no satisfying durable solution has been found so far.

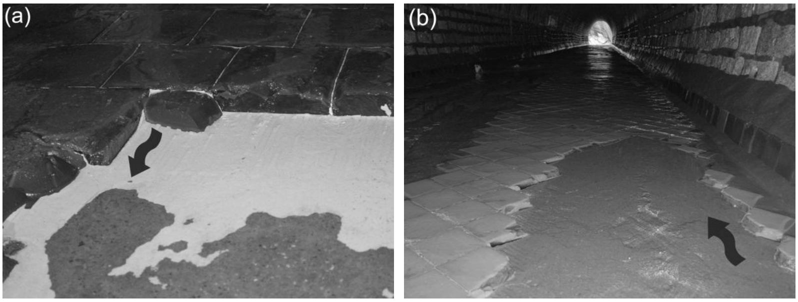

Fig. 5
Pfaffensprung sediment bypass tunnel. a) Broken and ripped out cast basalt plates. b) Area of ripped out cast basalt plates
Galerie de déviation de sédiments de Pfaffensprung. a) Plaques de basalte cassées et détachées. b) Région avec des plaques de basalte détachées

2.2.3. Runcahez bypass tunnel

Fig. 6 shows four photographs of the Runcahez sediment bypass tunnel taken in April 2011. The tunnel, built in 1962, is 572 m long, the design discharge is Q_d = 110 m^3/s for free surface inflow conditions, and 180 m^3/s for pressurized inflow conditions, respectively. The tunnel invert consists of both a concrete section as shown in Fig. 6a and 6c and 50 mm thick 20 x 20 cm cast basalt plates, see Fig. 6b and 6d. According to [23] the standard concrete section was designed with a C45/55 concrete.

In 1987 an extreme flood event occurred with a maximum discharge of about 400 m^3/s. In several sections, abrasion depths of about 1.20 m were measured [23]. Some sections of the tunnel were rehabilitated after the flood event, some with minor damages and lower incision channels were left unmodified (Fig. 6a). In Fig. 6b, an area of missing cast basalt plates can be seen comparable to the failures in the Pfaffensprung bypass tunnel shown in Fig. 5.

From 1996 to 1999 an extensive research project was conducted in the Runcahez sediment bypass tunnel to investigate the concrete resistance against hydro-abrasive wear [23]. Five different concrete test fields were implemented: microsilica-concrete, rolled concrete, high performance concrete, steel fiber concrete and polymer concrete. The aggregate for all five concrete types was always basalt. Fig 6c shows the steel fiber and the polymer concrete test fields and Fig. 6d shows the standard section of cast basalt plates and the microsilica-concrete test field. The sediment load during the four test years was moderate resulting in a mean annual wear of 0.5 - 1 mm/a. The maximum annual wear of local damages was 3 - 5 mm/a [23].

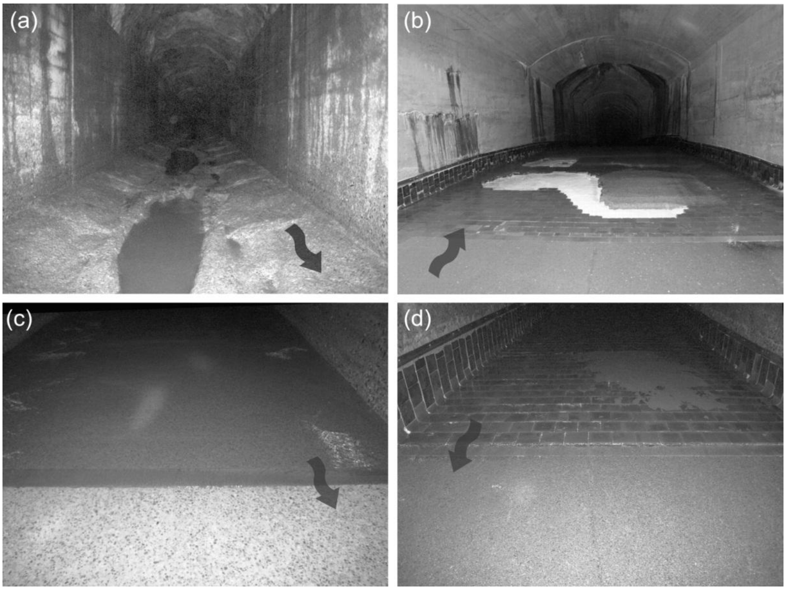

Fig. 6
Runcahez sediment bypass tunnel. a) Abrasion damages at the standard concrete section. b) Ripped out area of cast basalt plates at the acceleration section. c) Steel fiber and polymer concrete test fields (in flow direction). d) cast basalt plates and microsilica-concrete test field (in flow direction)
Galerie de déviation de sédiments de Runcahez. a) Dégâts dus à l'abrasion dans une section en béton standard. b) Région avec des plaques de basalte détachées à la section d'accélération. c) Travée d'essais pour fibre d'acier et béton de polymère (en direction de l'écoulement). d) Travée d'essais pour plaques de basalte et béton de microsilice (en direction de l'écoulement)

3. RESEARCH PROJECT

In early 2011, VAW started a research project on the "*Layout and design of sediment bypass tunnels"* to counteract the severe invert abrasion damages observed in every bypass tunnel. The project focuses on the optimization of the hydraulic conditions in the sediment bypass tunnel by conducting systematical scale hydraulic model tests at VAW.

3.1. HYDRAULIC SCALE MODEL

The experiments are conducted in a glass-sided model flume. It is 0.30 m wide and 14 m long and has a maximum discharge capacity of 250 l/s (Fig. 7). The flume slope is adjustable between 1 to 4%. The inflow is regulated by a magnetic flow meter and discharged through a so-called jetbox, transferring the discharge from pressurized to supercritical free surface flow [27]. All experiments are conducted using a constant approach flow discharge to obtain simple boundary conditions.

Sediment transport is simulated using uniform grain material with diameters of 0.5, 1.0 and 2.0 cm. Sediment is added by a sediment dosing machine located right after the jetbox. The prototype concrete invert is modeled by a brittle synthetic concrete with high ratios of sand to Portland cement from 10/1 to 15/1. Similar substrates were used by [28], [29], and [30] to simulate bedrock incision of rivers.

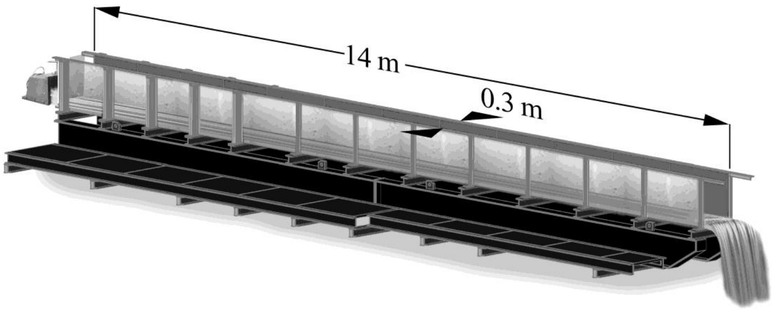

Fig. 7
Hydraulic model flume
Modèle hydraulique

All experiments are conducted under free surface flow conditions. All processes are therefore dominated by gravity and Froude similitude is applied. To respect the Froude (subscript F) similitude, $\lambda_F = 1$ is required, where λ_F is the scale ratio of the Froude number $Fr = v/(gL)^{0.5}$, with v = flow velocity, g = gravitational acceleration, and L = scaling length. The geometric scale ratio is given by the inverse of the scaling factor $\lambda = L_p/L_m$, where subscripts p and m refer to prototype and model, respectively. The scale ratios for velocity, time and discharge follow from the Froude similitude as $\lambda_V = \lambda^{0.5}$, $\lambda_t = \lambda^{0.5}$, $\lambda_Q = \lambda^{2.5}$, respectively. Considering all existing sediment bypass tunnels mentioned in [13], one can calculate the average dimensions, e.g. the mean tunnel width, tunnel height, flow depth or discharge. This leads to a typical scaling factor of $\lambda = 15$ for the hydraulic model.

Decisive model parameters are presented in Table 1. All parameters are presented in model scale dimensions and flow velocity v, flow depth h, Reynolds number Re and Froude number Fr are calculated by a one-dimensional backwater curve calculation at the flume end at chainage 14 m. The model discharge is varied between 100 and 200 l/s and the slope is varied between 1 and 4%, corresponding to the prototype slopes given in Fig. 3. The minimum flow depth h is 0.11 m and the lowest Reynolds number obtained in the model tests is Re = 6.6×10^5. No scale effects are to be expected for these model parameters [31].

Table 1
Hydraulic model parameters
Paramètres du modèle hydraulique

Q	***S***	v_u	h_u	**Re**	**Fr**
[l/s]	**[%]**	**[m/s]**	**[m]**	**[-]**	**[-]**
100	1	2.2	0.15	6.6×10^5	1.8
100	4	3.1	0.11	7.7×10^5	3.1
200	1	4.0	0.17	1.3×10^6	3.2
200	4	4.6	0.15	1.4×10^6	3.8

In Fig. 7 the model parameters, upscaled with $\lambda = 15$, are compared with the prototype data from the Swiss and Japanese sediment bypass tunnels presented in Fig. 3. Fig. 8a shows the Froude Numbers Fr and specific discharges q for model discharges of 100 and 200 l/s. Fig. 8b shows the flow velocities v at different slopes S. The upscaled model data fit well into the prototype data range. Upscaling the model discharge of 200 l/s and considering the flume width of 0.30 m leads to a specific discharge $q = 39$ m^2/s, corresponding to the mean specific discharge of all bypass tunnels of $q_d = 41$ m^2/s.

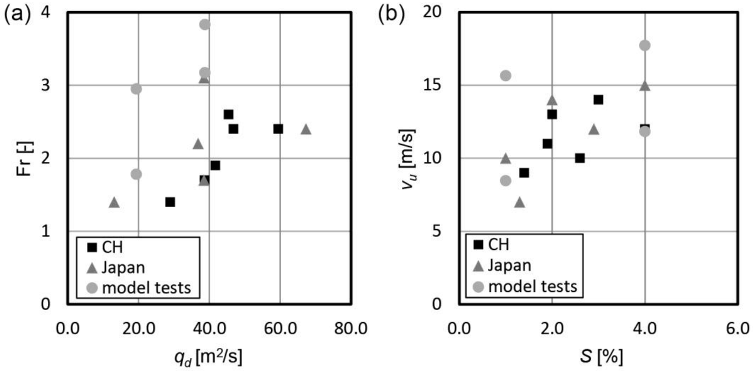

Fig. 8
a) Froude Number Fr versus specific design discharge q_d, and b) Uniform flow velocity v_u versus tunnel slope S for 6 Swiss and 5 Japanese sediment bypass tunnels and upscaled calculated model test data from Table 1 (scaling factor $\lambda = 15$)
a) Nombre de Froude Fr en fonction du débit spécifique de dimensionnement q_d, et b) Vitesse d'écoulement uniforme v_u en fonction de la pente S de 6 galeries suisses de déviation de sédiments, de 5 galeries japonaises et des données des essais du modèle mises à l'échelle de la Table 1 (facteur d'échelle $\lambda = 15$)

3.2. Research foci

The basic hydraulic design without the occurrence of sediment transport can be easily determined using analytical calculations or numerical simulations, but there is a major lack of knowledge when sediment transport and abrasion have to be taken into account. Therefore the governing parameters to be investigated in the laboratory model tests are the tunnel invert slope S, the hydraulic discharge Q and the sediment supply rate Q_s. Every parameter is varied systematically in the test runs. Another main objective is the detailed analysis of the sediment transport processes in the tunnel.

One main goal of the research project is the determination of the abrasion depth after every model test. The invert incision is scanned with a laser to obtain a 3D scan of the new invert topography. Measured abrasion depths are compared with each other and upscaled to prototype values using the investigations made by [32], where the authors measured the erosion rate of different materials in an abrasion mill, e.g. granite, quartzite or basalt rocks and the brittle synthetic concrete used herein to simulate the tunnel invert. They related the erosion rate to the tensile strength of the material allowing to upscale the abrasion depth of the brittle artificial concrete to prototype material values.

The second research goal focuses on the sediment transport processes as described in chapter 0. Single grain movement, i.e. saltating, rolling and sliding of grains, is recorded by a high-speed camera through the glass-sided flume wall. The main goal is to determine which type of movement and which hydraulic conditions result in the highest incision. In addition, the movement of entire sediment layers, i.e. the above described tools and cover effect, is recorded from above using CCD cameras.

4. CONCLUSIONS

This paper highlights the need for a sustainable reservoir management, and possible countermeasures are presented. One efficient and ecologically compatible countermeasure is the setup of a sediment bypass tunnel to route the incoming sediments around the reservoir into the tailwater. The major problem facing all bypass tunnels is the invert abrasion due to high flow velocities in combination with high sediment transport. Continuing invert abrasion leads to high maintenance costs, one crucial criterion for reservoir operators not to construct a sediment bypass tunnel.

To counteract this problem, VAW started a research project to investigate the invert abrasion process by conducting hydraulic scale tests in the laboratory. A 14 m long, 0.30 m wide flume with a discharge of up to 250 l/s is used to appropriately simulate the invert incision processes. The tunnel invert is modelled by a brittle synthetic concrete, and sediment movement processes are recorded by different video camera systems. The goal of this research project is to establish general design criteria for optimal flow conditions where both sediment depositions in the tunnel are avoided and the resulting abrasion damages are kept at a minimum.

5. OUTLOOK

The research project described above started in spring 2011 and will presumably be finished in early 2014.

A second ongoing research project at VAW regarding sediment bypass tunnels started in early 2012. Prototype tests at the Solis sediment bypass tunnel are conducted to investigate the abrasive resistance of different tunnel invert materials. The project is based on similar tests as conducted by [23] described in chapter 2.2. In total, seven different test fields are installed in the bypass tunnel: four concrete fields, one cast basalt field, one vulcanized rubber on steel field and one natural granite stone field. The test fields are scanned after every major flood event during the years 2012 to 2016. Additionally the test fields in the Runcahez sediment bypass tunnel are also scanned and compared to the data measured by [23].

Furthermore, sediment transport in the prototype tunnel of Solis reservoir is predicted with geophone sensors, a continuous measurement technique so far mainly used in rivers [33], [34]. Hydraulic model tests have already been conducted at the VAW laboratory to test and optimize the geophones at high flow velocities occurring in sediment bypass tunnels [35]. In addition, suspended load is measured in the tunnel as well as in the tributary Albula and the tailwater channel of the hydropower plant Sils by continuous suspended load sensors. The Solis reservoir bottom is surveyed every year to verify the effectiveness of the new sediment bypass tunnel and to calibrate the geophone sensors.

The scanned data from the test fields in combination with the sediment transport measurements will finally allow for a detailed comparison of the different invert materials tested in the two tunnels.

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REFERENCES

[1] SCHLEISS A., OEHY C. Verlandung von Stauseen und Nachhaltigkeit. *Wasser, Energie, Luft*, 94(7/8): 227-234, 2002 [in German].

[2] SUMI T., OKANO M., TAKATA, Y. Reservoir sedimentation management with bypass tunnels in Japan. *Proc. 9th International Symposium on River Sedimentation*. Yichang, China, 1036-1043, 2004.

[3] BOES R., REINDL R. Nachhaltige Maßnahmen gegen Stauraumverlandungen alpiner Speicher. *Proc. Symposium "Stauhaltungen und Speicher - von der Tradition zur Moderne"*, Bericht 46/1, TU Graz, Austria: 179-193, 2006 [in German].

[4] BASSON, G.R. Management of siltation in existing and new reservoirs. General Report Q. 89, *Proc. 23rd ICOLD Congress*. Brasilia, Brazil, 2009.

[5] SCHLEISS A., DE CESARE G., JENZER ALTHAUS J. Verlandung der Stauseen gefährdet die nachhaltige Nutzung der Wasserkraft. *Wasser Energie Luft*, 102(1): 31-40, 2010 [in German].

[6] VISCHER, D. (ED.) Int. Symposium: Verlandung von Stauhaltungen und Speicherseen im Alpenraum. *VAW-Mitteilung* No. 53, ETH Zurich, 1981 [in German].

[7] VISCHER, D. (ED.) Int. Symposium: Verlandung von Stauseen und Stauhaltungen, Sedimentprobleme in Leitungen und Kanälen. *VAW-Mitteilung* No. 142 & 143, ETH Zurich, 1996 [in German].

[8] SUMI T, KOBAYASHI K., YAMAGUCHI K., TAKATA Y. Study on the applicability of the asset management for reservoir sediment management. Q. 89 R. 4, *Proc. 23rd ICOLD Congress*. Brasilia, Brazil, 2009.

[9] ANNANDALE G.W. Reservoir sedimentation. *Developments in water science* No. 29. Elsevier Science Publishers B.V., The Netherlands, 1987.

[10] SLOFF C.J. Reservoir sedimentation: a literature survey. *Communications on hydraulic and geotechnical engineering* Report No 91-2, TU Delft, The Netherlands, 1991.

[11] SUMI T. Future perspective of dam reservoir sediment management. *Proc. of Int. Workshop on Reservoir Sedimentation Management*. 145-156, 2000.

[12] KANTOUSH S., SUMI T. River morphology and sediment management strategies for sustainable reservoir in Japan and Switzerland. *Annuals of Disaster Prevention Research Institute*, No. 53 B. Kyoto, Japan, 2010.

[13] AUEL C., BOES R. 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, 2011.

[14] VISCHER D., HAGER W.H., CASANOVA C., JOOS B., LIER P., MARTINI O. Bypass tunnels to prevent reservoir sedimentation. Q. 74 R. 37, *Proc. 19th ICOLD Congress*. Florence, Italy. 1997.

[15] AUEL C., BERCHTOLD T., BOES R. Sediment management in the Solis reservoir using a bypass tunnel. *Proc. of the 8th ICOLD European Club Symposium*. Innsbruck, Austria, 2010.

[16] AUEL C., BOES R., ZIEGLER T., OERTLI C. Design and construction of the sediment bypass tunnel at Solis. *Hydropower and Dams*. 18(3). Aqua-Media International Ltd: 62-66, 2011.

[17] WERDER M.A., BAUDER A., FUNK M., KEUSEN H.-R. Hazard assessment investigations in connection with the formation of a lake on the tongue of Unterer Grindelwaldgletscher, Bernese Alps, Switzerland. *Nat. Hazards Earth Syst. Sci*., 10, 227–237, 2010.

[18] SUMI T. Sediment flushing efficiency and selection of environmentally compatible reservoir sediment management measures. *Int. Symposium on Sediment Management and Dams, 2nd EADC Symposium*. Yokohama, Japan, 2005.

[19] CHERVET A., VISCHER D. Geschiebeumleitstollen bei Stauseen; Möglichkeiten und Grenzen. *Int. Symposium: Verlandung von Stauseen und Stauhaltungen, Sedimentprobleme in Leitungen und Kanälen,* VAW-Mitteilung No. 143, ETH Zurich, 25-43, 1996 [in German].
[20] INOUE M. Promotion of field-verified studies on sediment transport systems covering mountains, rivers, and coasts. *Science & Technology Foresight Center, NISTEP*. Quarterly Review No. 33. 89-107, 2009.
[21] SKLAR L.S., DIETRICH W.E., A mechanistic model for river incision into bedrock by saltating bed load. *Water Resources Research* 40(6), 2004.
[22] TUROWSKI J.M., RICKENMANN D. Tools and cover effects in bedload transport observations in the Pitzbach, Austria. *Earth Surface Processes And Landforms* 34(1): 26-37, 2009.
[23] JACOBS F., WINKLER K., HUNKELER F., VOLKART P. Betonabrasion im Wasserbau. *VAW-Mitteilung* No. 168, ed. H.-E. Minor, ETH Zurich, 2001 [in German].
[24] EUROCODE 2. BS EN 1992-1-1:2004 Design of concrete structures. General rules and rules for buildings.
[25] BRUSCHIN J., BAUER S., DELLEY P., TRUCCO G. The overtopping of the Palagnedra dam. *Water Power & Dam Construction*. 34(1), 1982.
[26] DELLEY P. Erosionsschäden im Spülstollen Palagnedra und deren Sanierung. *Int. Symposium - Erosion, Abrasion und Kavitation im Wasserbau*, VAW-Mitteilung No. 99, ed.: D. Vischer, ETH Zurich, 329-352, 1988 [in French].
[27] SCHWALT M., HAGER W.H. Die Strahlbox. *Schweizer Ingenieur und Architekt.* 110(27-28), 1992 [in German].
[28] FINNEGAN N.J., SKLAR L.S., FULLER T.K. 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), 2007.
[29] JOHNSON J.P., WHIPPLE K.X. Feedbacks between erosion and sediment transport in experimental bedrock channels. *Earth Surface Processes And Landforms* 32(7): 1048-1062, 2007.
[30] JOHNSON, J.P., WHIPPLE K.X. 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, 2010.
[31] HELLER V. Scale effects in physical hydraulic engineering models. *Journal of Hydraulic Research*, 49(3), 293 - 306, 2011.
[32] SKLAR L.S., DIETRICH W.E. Sediment and rock strength controls on river incision into bedrock. *Geology* 29(12): 1087-1090, 2001.
[33] RICKENMANN D., MC ARDELL B.W. Continuous measurement of sediment transport in the Erlenbach stream using piezoelectric bedload impact sensors. *Earth Surface Processes And Landforms* 32(9): 1362-1378, 2007.

[34] RICKENMANN D., MC ARDELL B.W. Calibration of piezoelectric bed-load impact sensors in the Pitzbach mountain stream. *Geodinamica Acta* 21(1-2): 35-51, 2008.

[35] AUEL C., BOES R.M. Sediment bypass tunnel design – hydraulic model tests. *Proc. Hydro 2011 “Practical Solutions for a Sustainable Future”*, 2011.

SUMMARY

Reservoir sedimentation is an increasing problem affecting the majority of reservoirs both in Switzerland and worldwide. As many dams are more than 50 years of age, this problem is becoming more and more serious nowadays. Reservoir sedimentation leads to various severe problems such as a decisive decrease of the active reservoir volume leading to both loss of energy production and water available for water supply and irrigation. These problems will intensify in the near future, because sediment supply tends to increase due to climate change. Therefore, countermeasures have to be developed. They can be divided into the three main categories sediment yield reduction, sediment routing and sediment removal. This paper focuses on the sediment routing using sediment bypass tunnels. Sediment bypass tunnels are an effective means to decrease the reservoir sedimentation process. By routing the sediments around the reservoir into the tailwater, sediment accumulation is reduced significantly. However, the number of sediment bypass tunnels in the world is limited primarily due to high investment and maintenance costs. The main problem of all bypass tunnels is the invert abrasion due to high velocities in combination with high sediment transport. Three Swiss bypass tunnel examples suffering invert abrasion are presented in this paper. Furthermore, VAW started a research project to investigate the invert abrasion process by conducting hydraulic scale tests in the laboratory. The goal of this research project is to establish general design criteria for optimal flow conditions where both sediment depositions in the tunnel are avoided and the resulting abrasion damages are kept at a minimum.

RÉSUMÉ

La sédimentation de retenue est un problème de plus en plus courant, affectant la majorité des retenues du monde entier. Beaucoup de barrages ayant aujourd’hui plus de 50 ans, ce problème est de plus en plus sérieux. La sédimentation de retenue entraîne différents inconvénients importants, comme une diminution marquée du volume utile de retenue, provoquant non seulement une perte de production d'énergie mais aussi une diminution des réserves disponibles pour l'approvisionnement en eau et pour l'irrigation. Ces problèmes s'intensifieront

dans un avenir proche, car les réserves de sédiments ont tendance à augmenter à cause du changement climatique. Des contre-mesures doivent donc être développées. Elles peuvent être divisées en trois catégories principales : réduction de la production de sédiments, dérivation des sédiments et enlèvement des sédiments. Cet article se concentre sur la déviation des sédiments grâce à l'utilisation de galeries de dérivation. Ces galeries sont un moyen efficace de lutter contre le processus de sédimentation des retenues. En déviant les sédiments autour de la retenue pour les conduire directement à l'aval, l'accumulation de sédiments est réduite de façon importante. Pourtant, le nombre de galeries de déviation de sédiments dans le monde est limité, essentiellement en raison de l'investissement élevé et des coûts d'entretien. Le problème principal de toutes les galeries de déviation est l'abrasion du radier due aux hautes vitesses combinées avec l'intense transport de sédiments. L'exemple de trois galeries suisses de déviation victimes d'une abrasion de radier est présenté dans cet article. Le VAW a par ailleurs commencé un projet de recherche pour étudier le processus d'abrasion de radier en laboratoire au moyen de modèles hydrauliques à échelle réduite. Le but de ce projet de recherche est d'établir des critères de dimensionnement généraux pour les conditions d'écoulement optimales, où les dépositions de sédiments dans la galerie sont évitées tout en réduisant au minimum les dégâts dus à l'abrasion.