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SEDIMENT BYPASSING – A SUSTAINABLE AND ECO-FRIENDLY STRATEGY AGAINST RESERVOIR SEDIMENTATION*

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SUMMARY

Without adequate measures, reservoirs are not sustainable, neither the reservoir itself due to continuous sedimentation, nor the downstream ecosystem due to altered sediment continuity. Appropriate actions are inevitable and require a systematic sedimentation management. Sediment bypassing constitutes one effective strategy that routes sediment load around reservoirs during floods. A sediment bypass system has the advantage that only newly entrained sediment is diverted from the upstream to the downstream reach thereby re-establishing sediment connectivity. Hence, such a system contributes to a sustainable water resources management while taking the downstream environment into consideration. This paper gives a state-of-the-art overview encompassing design, bypass efficiency, hydraulics, challenges due to abrasion, positive effects on both downstream morphology and ecology, and makes design recommendations.

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* *La dérivation des sédiments – une stratégie durable et écologique contre l'alluvionnement des réservoirs*

RÉSUMÉ

Sans mesures adéquates, les réservoirs ne sont pas durablement viables, ni le réservoir en tant que tel du fait de l'alluvionnement continuel, ni l'écosystème à l'aval du fait de l'altération de la continuité sédimentaire. Des actions appropriées sont incontournables et demandent une gestion systématique de la sédimentation. Les by-pass sédimentaires constituent une stratégie efficace pour dériver l'apport sédimentaire vers l'aval des réservoirs durant les épisodes de crue. Un système de by-pass sédimentaire présente l'avantage de ne dériver que les nouveaux apports sédimentaires depuis l'amont vers l'aval, rétablissant ainsi la continuité sédimentaire. De ce fait, un tel système contribue à une gestion durable des ressources en eau qui prend en considération l'environnement aval du barrage. Le présent article donne une vision d'ensemble de l'état des connaissances sur les SBT comprenant la conception, l'efficacité, les considérations hydrauliques, les contraintes dues à l'abrasion, les effets positifs à la fois sur la morphologie et l'écologie du système aval, et dresse quelques recommandations pour leur conception.

1. INTRODUCTION

Worldwide, water availability in rivers varies both seasonally and annually. During droughts, not enough water is available to meet the demand for drinking and irrigation water, while during high flow periods, more water is available than can be used [1].

On the one hand, this varying availability requires the construction of dams and reservoirs. In addition to balancing the water availability, the stored water can be used as a renewable energy resource. Hence, dams and reservoirs are important for the prosperity of mankind by providing storage capacity for drinking and irrigation water, flood control and hydropower. However, the combined effect of a decrease in dam construction around the globe and reservoir sedimentation results in a net storage volume loss (Fig. 1). Together with an increasing world population, this will lead to both water scarcity and a decrease of renewable energy production.

On the other hand, dam construction has altered river systems across the globe. A reservoir traps the incoming sediments and leads to sediment starving conditions and degradation downstream. The natural flow and continuous sediment transport is interrupted, resulting in changes in downstream flow regime, bed morphology and ecosystem [2], [3].

Fig. 1
Population growth, reservoir gross storage (due to dam construction), and net storage (due to sedimentation) as a function of time (adopted from [1]).
Croissance démographique, capacité de stockage brute des réservoirs (due à construction de barrages), capacité nette (du fait de la sédimentation) en fonction du temps (d'après [1])

Hence, reservoirs are not sustainable, neither the reservoirs themselves due to continuous sedimentation, nor the downstream ecosystem due to sediment and biota discontinuity. Appropriate actions to prevent sedimentation and to restore reservoir capacity while enhancing sediment continuity are indispensable and require a systematic sedimentation management. Such a management encompasses a number of strategies: (1) reducing sediment yield, (2) routing sediments around or through a reservoir, and (3) recovering volume by removing sediment or heightening a dam [1], [3], [4], [5].

Sediment Bypass tunnels (SBTs) form part of the second strategy and permit routing the incoming sediment load around reservoirs during floods. A SBT has the advantage that only newly entrained sediment is diverted from the upstream to the downstream reach thereby re-establishing sediment connectivity. Therefore, a SBT contributes to a sustainable water resources management while taking the downstream environment into consideration.

This paper aims to give a state-of-the-art overview of this sedimentation countermeasure encompassing SBT design, bypass effectiveness, hydraulics, challenges due to abrasion, and the tunnel's positive effects on both downstream morphology and ecology.

2. SEDIMENT BYPASS

Sediment bypass systems route sediments around reservoirs commonly via a tunnel. However, depending on the topography, channels may also be used. A SBT has the advantage that only newly entrained sediment is diverted from the upstream to the downstream reach. Already accumulated sediments in the reservoir are normally not mobilized. The sediment pulse is therefore of natural character, and sediment connectivity is re-established during floods improving the downstream ecological system.

SBTs are located mostly in mountainous regions at small to medium-size reservoirs. River bed slopes are steep and transport a considerable amount of coarse material. Most SBTs are located in Switzerland and Japan, with 10 and six tunnels, respectively, while three are under construction in Taiwan (Table 1) [6], [7]. The oldest bypass in the world is a tunnel with a connected channel at Karasuhara reservoir, Japan, commissioned in 1905 followed shortly after by the Nunobiki dam in 1908 [8]. The first tunnel in Switzerland was the Pfaffensprung SBT commissioned in 1922. At these pioneering structures the responsible engineers already planned the reservoirs in a sustainable way, having in mind that without diversion, the reservoir would quickly fill up with sediments.

Flood bypass tunnels may also transport considerable sediment loads and hence show similar characteristics to SBTs. Examples are the diversions of the Rovana River and the Matter Vispa River as well as the Grindelwald proglacial lake relief tunnel in Switzerland, or the bypass tunnel at the Mud Mountain dam, a dry dam in Washington, USA [9].

Table 1
Examples of SBTs around the world ([6], [7], [10], [11], [12])

COUNTRY	RESERVOIR/ DAM NAME	SBT COM-MISSION	DAM COM-MISSION	DIS-CHARGE	LENGTH	SLOPE	RESER-VOIR VOLUME	CATCH-MENT
				[m^3/s]	[m]	[%]	[106 m^3]	[km^2]
Swiss	Pfaffensprung	1922	1922	220	282	3.0	0.15	390
Swiss	Serra	1952	1952	40	425	1.6	0.18	34
Swiss	Runcahez	1962	1961	110	572	1.4	0.48	50
Swiss	Ual da Mulin	1962	1962	145	268	4.3	0.06	25
Swiss	Val d’Ambra	1967	1965	85	512	2.0	0.4	24
Swiss	Egschi	1976	1949	50	360	2.6	0.4	108
Swiss	Palagnedra	1978	1952	220	1,760	2.0	4.26	140

Swiss	Rempen	1986	1924	80	450	4.0	0.5	43
Swiss	Hintersand	2001		38	1050	1.2	0.11	35
Swiss	Solis	2012	1986	170	968	1.9	4.1	900
Japan	Karasuhara/ Tachigahata	1905	1905		333 (channel) 139 (tunnel)	1.3	1.24	19
Japan	Nunobiki	1908	1900	39	258	1.3	0.76	10
Japan	Asahi	1998	1978	140	2,384	2.9	15.47	39
Japan	Miwa	2004	1959	300	4,300	1.0	29.95	311
Japan	Matsukawa	2016	1974	200	1,417	4.0	7.4	60
Japan	Koshibu	2016	1969	370	3,982	2.0	58.0	288
Taiwan	Nanhua	Presum. 2018	1994	1000	1287	1.85	144.0	108
Taiwan	Shimen	In planning	1964	600	3702	2.89	310	760
Taiwan	Tsengwen (also Zengwen)	2017	1973	995	1235	5.32		481
Pakistan	Patrind	2017	2017	650	140	1.12	6.0	2400
France	Rizzanese	2012	2012	100	133	6.9	1.2	

2.1. Construction design

To accurately design a SBT, the design discharge, the cross-sectional dimensions or at least the tunnel width, and the tunnel invert slope must be defined. Furthermore, knowledge of the river width and slope as well as the sediment particle size distribution present in the catchment upstream of the considered tunnel intake location is indispensable.

Two different locations are generally possible for the bypass intake, both affecting the entire design and the reservoir operation during sediment bypassing. The most common location for the bypass intake is at the reservoir head (Fig. 2a). Another suitable intake location is further downstream closer to the dam (Fig. 2b). The advantages of an intake at the reservoir head are: (I) the entire reservoir is kept free from sediments, and (II) the reservoir level during bypass operation is independent from the upstream river reach and can be kept at full supply level. Disadvantages are, depending on the topography, the long distance from the reservoir head to the tailwater causing high tunnel construction costs, and the free surface flow conditions at the tunnel intake requiring a steep acceleration section. The position further downstream has the following advantages: (I) The distance between the tunnel intake and the tailwater is short, reducing construction costs, and (II) the intake inflow is pressurized and an acceleration section can be neglected. As a major drawback, only the reservoir section downstream from the intake is kept free from sediment accumulation. Furthermore, the reservoir level must be lowered to a certain level to sustain sufficient sediment transport capacity in the upstream reservoir reach.

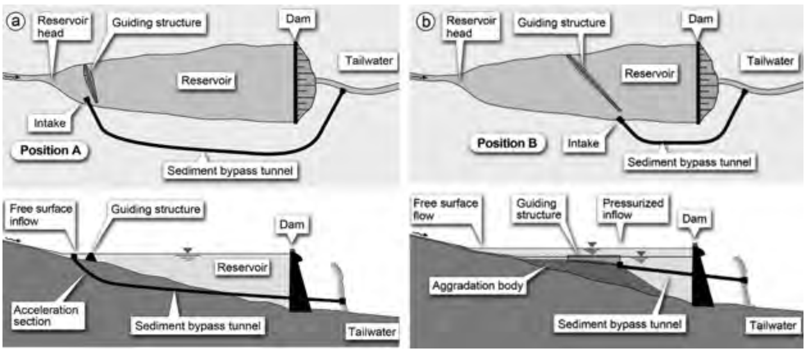

Fig. 2
Sketches of two SBT systems. a) Location of the tunnel intake at the reservoir head. Inflow under free surface conditions. b) Location of the tunnel intake downstream of the reservoir head. Inflow in pressurized conditions [12].
Schémas de deux systèmes SBT. a) Prise du tunnel de dérivation située en tête de réservoir. Prise en régime à surface libre. b) Prise du tunnel de dérivation située en aval de la tête du réservoir. Prise en charge [12].

Some tunnels (e.g. Koshibu) use upstream check dams to capture the largest bedload fractions. These sediments are often used as a construction material. Other check dams or guiding structures divert the sediment-laden flow directly towards the bypass intake (e.g. Asahi, Solis, Matsukawa, Nanhua). They span the entire reservoir from the opposite shore towards the tunnel intake [6], [7], [13], [14], [15]. The following must be kept in mind during design: The guiding structure should not be overtopped during SBT operation to avoid sediment accumulation in the reservoir. However, if the flood event exceeds the tunnel design discharge, the guiding structure must be securely overtopped, or openings are to be designed to lead the surplus flow towards the dam outlets.

Some tunnels (e.g. Koshibu, Nanhua) have vertical racks installed in front of the intake to prevent debris from entering the tunnel. Such a rack, however, might also support sediment deposition and must be designed properly. Another solution is a skimmer wall to divert the debris away from the intake (e.g. Solis).

The SBT intake consists of an intake trumpet followed by a gate. During regular reservoir operation, the gate is closed. In case of flood events the gate is opened and the sediment-laden flow is routed. The design of the intake directly depends on the selection of the intake location. If the intake is located at the reservoir head, the discharge is conveyed in free surface flow and the intake invert is constructed at the same level as the river bed. Downstream of the gate, the discharge accelerates to generate supercritical flow conditions. This is achieved by a steep acceleration section. If the intake is located further downstream the tunnel invert level can be situated lower than the river bed or the surrounding aggradation body, respectively. The resulting energy head leads to pressurized inflow conditions, but downstream of the gate, supercritical open channel flow occurs and an acceleration section can be neglected.

The tunnel cross section of most SBTs is of archway/hood or horseshoe shape. Circular shapes are rare as the sediment transport is concentrated at the lower invert section. Another disadvantage is the challenging trafficability during construction and maintenance due to a non-planar bed. The slope should be steep enough to generate sufficient bed shear stress to transport all incoming sediments into the tailwater without depositing any material.

The outlet structure conveys the sediment to the tailwater downstream of the dam. A sufficient transport capacity in the downstream river reach must be secured to avoid sedimentation and bed aggradation in the outlet vicinity and further downstream. In most cases, this should be no problem as the sediment transport process in the entire river system is revitalized to its original condition before dam construction. However, a sudden sediment pulse from the tunnel operation may temporarily exceed the natural transport capacity. The tunnel outlet should not release any sediments in the vicinity of the dam to avoid sedimentation and backwater effects. Furthermore, a drop from the tunnel outlet to the river reach should be designed to avoid backward deposition in the tunnel itself. The angle between the tunnel centreline and the river thalweg should be kept small to reduce erosion impact on the opposite river shore. Scouring due to outlet jet impinging must also be considered.

2.2. Design discharge

The design discharge depends on an economic tunnel diameter and the given hydrological conditions in the catchment. Design discharges typically vary from less than a one-year flood event to 25-year flood events [16]. However, particularly for reservoirs with small catchments impounded by embankment dams, a higher recurrence interval of up to 100 years may be preferable to complement the service spillway capacity [17]. New tunnels tend to be designed with higher discharges (e.g. Nanhua, Tsengwen) compared to the older ones.

When determining the design discharge, one must consider that the surplus flow exceeding the design capacity must be conveyed either to the downstream reservoir section or through the tunnel itself, causing pressurized flow conditions. Thus, a routing of all incoming sediments at free surface flow conditions is achieved only up to the SBT design discharge. Sediment transported within the surplus flow accumulates to some extent in the downstream reservoir section.

2.3. OPERATION

Depending on the tunnel intake location, the reservoir operation during sediment bypassing varies. If the intake is located at the reservoir head, the gate is opened in flood events and the incoming sediment-laden flow is routed in free surface flow conditions through the tunnel. Operation is relatively simple as a partial level drawdown is not required.

Operation is more challenging, if the intake is located downstream of the reservoir head. The reservoir level must be lowered prior to a flood event depending on the distance of the reservoir head from the tunnel intake. It has to be ensured that the reservoir reach upstream of the intake is subjected to surface flow conditions to force the incoming sediment-laden flow towards the intake. The reservoir should be kept at a certain level during bypass operation to avoid interruption of the sediment transport.

A reliable weather and runoff forecast combined with a decision support system is crucial for a successful operation. Fig. 3 shows reservoir operation at Solis, Switzerland [18]. A flood forecast of about 16 hours is needed to draw down the reservoir to the desired elevation. This is done via both the turbines and the bottom outlets if needed. The tunnel is opened for 15 hours, diverting the flood and its incoming sediments. Energy production continues if the reservoir level permits.

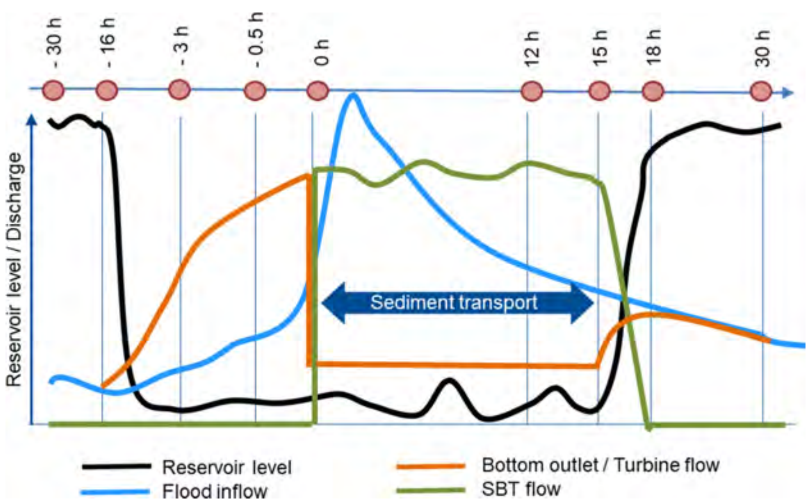

Fig. 3
SBT operation at Solis reservoir, Switzerland (adapted from [18])
Exemple d'opération d'un SBT au Réservoir de Solis, Suisse (d'après [18])

3. BYPASS EFFICIENCY

Research on the two Japanese SBTs Asahi and Nunobiki showed that bypassing during flood events is a very efficient strategy extending reservoir life considerably. On average 77% and 94% of the incoming sediments were diverted to the downstream river reach, extending the estimated reservoir life to 450 and 1,200 years respectively [5]. The expected reservoir life span is a useful parameter to express the SBT efficiency before and after implementation. It can be expressed as the ratio of reservoir capacity (CAP) to the mean annual sediment yield (MAS). The ratio CAP/MAS can be plotted as a function of the water turnover rate (CAP/MAR) (ICOLD 1999). These ratios are shown for two SBTs in Japan revealing their effectiveness by increasing the reservoir life (Fig. 4). The reservoir life of Nunobiki dam is extended by SBT operation from 60 to 1264 years. that is a 21-fold increase. The lifespan of the Asahi reservoir is extended 3.3 times due to SBT routing, i.e. from 198 to 644 years [5].

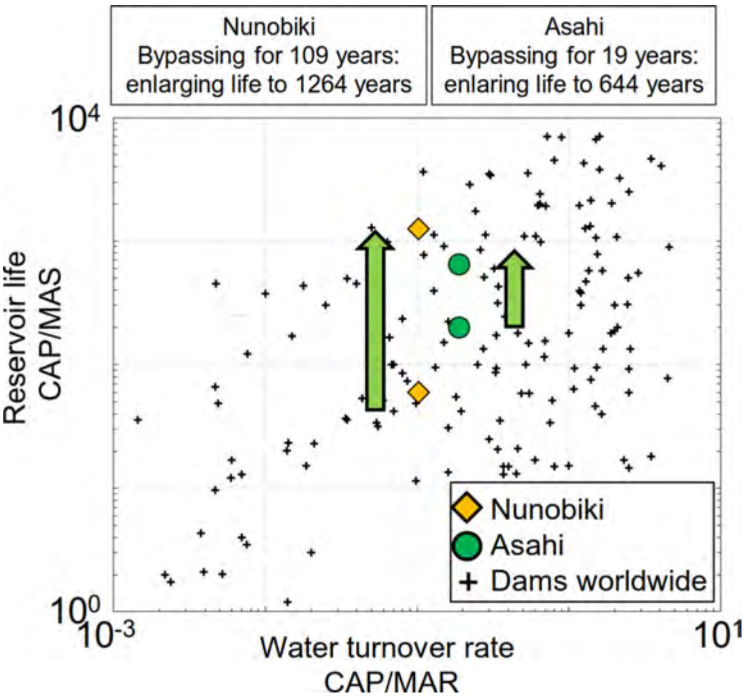

Fig. 4
Reservoir life (CAP/MAS) versus water turnover rate (CAP/MAR) with and without implementation of sedimentation strategies [5].
Durée de vie du réservoir (CAP/MAS) en fonction du taux de renouvelle-ment de l'eau (CAP/MAR) avec et sans mise en œuvre de stratégies sédimen-taires [5].

4. ABRASION

SBTs are generally operated in supercritical open channel flow conditions to avoid choking and transition to pressurized flow. Hydraulic jumps, pulsations or depressions may negatively affect the stability of hydraulic structures (e.g. [19]). Supercritical flow ensures both a sufficient sediment transport capacity and an economic tunnel cross section. However, if the design discharge is exceeded, pressurized flow is permitted for a limited time in some tunnels (e.g. Asahi, Palagnedra).

Besides the considerable construction cost, the main limiting factor inhibiting the application of SBTs are periodical maintenance costs due to severe invert abrasion caused by intense bedload sediment transport. Many existing SBTs are exposed to severe hydro-abrasion damages to the tunnel invert. As a striking example the Palagnedra SBT in the canton of Ticino, Switzerland, is shown in Fig. 5, where a vast flood event occurred in 1978 causing an about 2 to 4 m deep incision channel destroying the invert along the entire tunnel length and endangering the tunnel foundation [20].

Fig. 5
Invert damage in Palagnedra SBT, Switzerland. Horseshoe tunnel cross section with 2 to 4 m deep abrasion channel (courtesy C. Auel).
Dégâts du radier de la galerie de dérivation de sédiments de Palagnedra, Suisse. Une partie du tunnel présente un canal d'abrasion de 2 à 4 m de profondeur.

Abrasion is defined as progressive material loss due to hard particles forced against or moving along a solid surface controlled by kinetic energy due the vertical component of a saltating particle impact (deformation wear), and by friction due to grinding stress (cutting wear) caused by the horizontal component [21], [22]. Abrasion may occur in any system where bedload sediment is transported over an exposed bed, e.g. in bedrock rivers as well as at hydraulic structures such as SBTs, spillways, weirs and flushing channels. Saltating bedload impacts are considered as the driving factor for abrasion (e.g., [23], [24]).

4.1. Abrasion prediction models

Several mechanistic models exist to predict abrasion. Models for the prediction of bedrock incision focus on typical flow conditions in river systems in sub- and low supercritical flow regimes (e.g. [23]). Other models for the prediction of abrasion on concrete surfaces must account for highly supercritical flows (e.g. [25], [26], [27]). All models take the physical process of particle impact into account and are based on experimental research on particle motion characteristics, i.e. the analysis of particle impacts, velocities and saltation trajectories.

The first mechanistic model to determine concrete and steel abrasion on hydraulic structure surfaces was published by Ishibashi [25]. The abraded invert volume V_a is calculated as:

$$V_a = C_1 E_k + C_2 W_f \quad [1]$$

where E_k = total particle kinetic energy of saltating particles, W_f = total friction work by grinding particles, and C_1 and C_2 = invert material property constants for either concrete or steel. The total kinetic energy E_k is given by:

$$E_k = 1.5 V_{ts} \sum E_i N_i n_i \text{ [kgf m]} \quad [2]$$

and the total friction work W_f by:

$$W_f = 5.513 \mu_s V_{ts} \sum \left(\frac{U_p}{W_{im}} \right) E_i N_i n_i \text{ [kgf m]} \quad [3]$$

where V_{ts} = amount of transported sediment [m^3], μ_s = dynamic friction coefficient, E_i = kinetic energy of a single particle, U_p = horizontal particle velocity, W_{im} = vertical particle impact velocity, $N_i = L/L_p$ = impact frequency, with L = total invert length and L_p = particle saltation length, and n_i = number of particles per sediment volume. Re-evaluation of Eq. (1) using long-term invert abrasion data of the Japanese SBT Asahi led to the conclusion that the second term in Eq. (1) (C_2W_f) should be dropped in case of concrete inverts [28]. A detailed systematic calculation procedure is presented in [28].

A widely applied model for bedrock incision by Sklar and Dietrich, in its general form, follows as [23]:

$$A_r = \frac{Y_M}{k_v f_t^2} \cdot \frac{W_{im}^2}{L_p} \cdot q_s \cdot \left(1 - \frac{q_s}{q_s^*}\right) \text{ [m/s]} \qquad [4]$$

where Y_M = Young's Modulus of elasticity of the bed material [Pa], f_t = splitting tensile strength of the bed material [Pa], $k_v = 10^6$ = non-dimensional abrasion coefficient encompassing both the particle and bed material characteristics, q_s = bedload mass transport rate per unit width [kg/(sm)], and q_s^* = bedload mass transport capacity per unit width [kg/(sm)]. The last term on the right of Eq. (4) is related to the cover effect accounting for bedload partly covering the bed [29]. Sklar and Dietrich [23] applied correlations of hop length, hop height and particle velocity for a wide data range to Eq. (4) and proposed the saltation abrasion model for bedrock river abrasion as:

$$A_r = 0.08g\left(s-1\right)\frac{Y_M}{k_v f_t^2} \cdot q_s \cdot \left(1 - \frac{q_s}{q_s^*}\right)\left(\frac{\theta}{\theta_c} - 1\right)^{-0.5}\left(1 - \left(\frac{U_*}{V_s}\right)^2\right)^{1.5} \text{ [m/s]} \qquad [5]$$

where $U_* = (gR_hS)^{0.5}$ = friction velocity, R_h = hydraulic radius, S = energy line slope for steady but gradually-varied flow, or bed slope for uniform flow, V_s = particle settling velocity, θ = Shields parameter calculated as $\theta = U^{*2}/[(s\text{-}1)gD]$, $s = \rho_s/\rho$ with ρ_s = particle density and ρ = fluid density, D = particle diameter, θ_c = critical Shields parameter. The last term in Eq. (5) accounts for the mode shift from saltation to suspension using a nonlinear function additionally increasing the hop length.

Auel [27] proposed a revised version based on Eq. (4) accounting for sub- and supercritical flows as well as fixed planar and alluvial beds:

$$A_r = \frac{Y_M}{k_v f_t^2} \cdot \frac{(s-1)g}{230} q_s \left(1 - \frac{q_s}{q_s^*}\right) \text{ [m/s]} \qquad [6]$$

Based on the similarity between bedrock and concrete (both being brittle materials), a material strength-dependent Young's modulus formulation and a correlation of compression to tensile strength were introduced [27]. Both the Young's modulus reformulation and new equations for vertical impact velocity and hop length have led to a variation of the abrasion coefficient with $k_v = 10^5$, an order of magnitude lower than the values used in [23].

4.2. Abrasion resistant invert materials

Inverts of SBTs are made of concrete, natural bedrock, steel or more recently epoxy resin, while medium- and high-strength concretes are still the most widely used materials. Table 2 lists invert materials and associated compression strengths, mean diameter of the transported sediment and mean annual abrasion depths of different SBTs.

To guarantee sufficient resistance to hydro-abrasion, the compression strengths of SBT linings should be higher than 70 MPa, while the fracture energy should be higher than 200 J/m^2 after 28 days [10]. Steel fibres might be added to improve resistance against tensile stress. However, their positive effect on abrasion reduction is limited and does not compensate for the higher material cost [10].

Natural rock, e.g. granite is an adequate material showing high resistance and durability. Besides Pfaffensprung, Serra, and Egschi SBTs in Switzerland, granite blocks were implemented recently at Mud Mountain bypass tunnel, USA [9], [30]. Further, cast basalt tiles are used in some tunnels, e.g. at Ual da Mulin, Rempen and earlier in Pfaffensprung. Their performance is limited primarily due to removal of entire tiles. Irregularities trigger or intensify abrasion, hence joints and offsets on the invert have to be avoided [30]. Therefore, large blocks (around 1 m^2) should preferably be used as compared to small tiles (of about 0.04 m^2).

For the selection of adequate material, not only the initial investment, but also the total life-cycle cost including maintenance and repair should be considered and weighed. For this purpose, more research is needed to better predict abrasion depths and service life of different materials.

Table 2
Invert linings of existing SBTs [10]

COUNTRY	RESERVOIR/ DAM NAME	MATERIAL	COMPRESSION STRENGTH	MEDIAN SEDIMENT DIAMETER	MEAN ABRASION
			[MPa]	[mm]	[mm/year]
Swiss	Pfaffensprung	Granite blocks	180	250	4.0
Swiss	Serra	Granite, concrete	160, unknown	50	0.5
Swiss	Runcahez	Concrete	30	230	< 1.5
Swiss	Ual da Mulin	Cast basalt tiles	450	40	< 2.0
Swiss	Val d'Ambra	Concrete	34-49	60	3.0
Swiss	Egschi	Granite	184	60	5.0
Swiss	Palagnedra	Concrete	30	74	
Swiss	Rempen	Cast basalt	450	60	1.0
Swiss	Hintersand	Rock, Concrete	Unknown, 33	20	1-4
Swiss	Solis	Concrete	101	60	<0.1
Japan	Nunobiki	Bedrock	-	-	-
Japan	Asahi	Concrete	70	50	23
Japan	Miwa	Concrete	22	Fines	-

Japan	Matsukawa	Concrete	60	-	-
Japan	Koshibu	Concrete	40	-	-
Taiwan	Nanhua	Epoxy resin	-	-	-
France	Rizzanese	Steel	-	-	-

5. SEDIMENT CONNECTIVITY

Sediments released downstream through a SBT lead to morphological changes in the river bed, with formerly degraded sections showing depositional trends again [31], [32]. In addition to the morphological changes, benthic habitats are likely to be affected by reservoir flushing or bypass operations [33], [34].

Invertebrate communities are known to change due to sediment supply in degraded channels. In Japan, invertebrate communities responded quickly to sediment replenishment, where 1,000 to 10,000 m^3 of sediment per year were excavated and placed downstream of the dam [35], [36]. Analysis of invertebrate communities after dam removal at eight rivers in the US showed large recovery in terms of species composition and richness in downstream river reaches compared to their natural up-stream reaches after three to seven years following removal [37].

The effects of sediment supply on the downstream environment were analysed based on up- to downstream differences in geomorphological and biological characteristics at four SBTs in Switzerland and Japan [38]. Sediment grain size distribution was monitored, and microhabitats and invertebrates were analysed in terms of richness and composition. Results showed that grain sizes were coarser down- than upstream at dams with newly established SBTs, while they were similar or finer for dams with long SBT operation. Analysis of biotic data revealed that microhabitat and invertebrate richness was low directly below the dam but increased further downstream the longer the SBT operation. Sedentary species dominated at locations where bed conditions were stable, e.g. directly downstream of the dam at Koshibu. Recovery of downstream environment with increasing SBT operation time was disclosed by the Bray-Curtis similarity index, which evaluated an overlap between up- and downstream reaches for both microhabitat composition and invertebrate communities. With increasing operation time, both indices increased, revealing the positive effects of long-term SBT operation.

6. MONITORING

Monitoring of both bypassed sediments and invert abrasion development is crucial to successfully operate and maintain an SBT. For real-time bedload transport monitoring, indirect measurements are suitable. These involve a microphone or an acceleration sensor placed on a metal device, that is a steel plate or hollow steel pipe mounted in the river bed, to register the impacts generated by sediment particle collisions as acoustic or acceleration data respectively [39]. Such systems are successfully adapted for high-speed flows and installed at Solis and Koshibu SBTs [40], [41], [42].

Suspended sediment load is monitored in real-time by acoustic or optical instruments such as turbidity meters [43], [44]. Their measuring principle is based either on backscattered or transmitted near infrared or laser light. Since light scattering depends on particle size, shape, colour and composition, a site-specific calibration is required with bottle samples. Further, ultrasonic measurements (Acoustic Discharge Measurements) or Acoustic Doppler Current Profilers can be used to estimate sediment concentration [43].

Periodical abrasion measurements are crucial to evaluate the abrasion progress. These can be done manually using a pendulum as performed annually at Asahi SBT. The entire measurement of the 2,384 m long tunnel takes three days and is done by ten workers. Other tunnels make use of laser scanning techniques, e.g. at Pfaffensprung and Solis SBTs, Switzerland, the material loss is monitored using a 3D laser scanner [10]. At Koshibu SBT, Japan, the 3984 m long tunnel will be measured by a digital laser mounted on a car.

7. DESIGN RECOMMENDATIONS

The following design recommendations should be kept in mind while designing a SBT [11], [30], [45]:

- Constant bed slope. Avoid slopes changes, if possible. Observations in SBTs with steep acceleration sections at the intake (e.g. Runcahez, Pfaffensprung, Palagnedra) show high abrasion directly downstream of the transition to the mild slope. Also changes from mild to steep slope presumably create sections with locally increased particle impacts in their downstream reach as the slope transition acts as a ramp forcing particles to bounce at the same location.
- Whenever possible, bends in plan view should be avoided to reduce shock waves and secondary currents, which cause locally high specific sediment transport rates and shear stress concentrations
- Select tunnel cross section with plane invert geometry, i.e. archway and horseshoe profiles with horizontal bed rather than circular ones, to avoid stress concentrations in the centre.
- Keep the bed slope as mild as possible without endangering sediment aggradation.
- Construction and invert lining placement have to be carried out with utmost caution as abrasion always starts at irregularities such as joints, gaps or

cracks. Hence horizontal joint widths should be minimized and vertical step joints avoided.

- Proper connection (bonding) of the upper layer, i.e. the lining material, with the lower layer/bedding has to be ensured in order to withstand both abrasion wear due to particle impact and hydraulic uplift forces, but also fatigue failure.
- For granite lining, measures against failure by uplift include (i) increasing the weight of the blocks, i.e. their size, (ii) proper fit and adequate filling of the lateral gaps between lateral blocks and side walls to enhance friction, (iii) decreasing the water pressure below the lining by drainage, and, if necessary, (iv) anchoring the blocks in the underlying bed rock.
- For steel lining, a failure caused by uplift is comparatively more likely due lower weight and hence measures (iii) and (iv) in addition to welding are recommended.
- For cast basalt tiles, measures (i) to (iii) are typically applied in addition to using adhesive to enhance bonding to the bedding layer.
- Avoid vertical steps, notches or sharp flow width changes at the intake section upstream of the gate.
- Blocks or plates of natural stone material should be embedded into a special mortar. In case of longitudinal joints, they should be staggered in order to avoid overlap of zones, prone to intense abrasion. The use of hexagonal plates is an option.
- Avoid hydraulic conditions where stable vortices might be generated, as bedload is captured in these vortices (glacier mill effect). Such areas are prone to high abrasion as the captured sediment is not transported downstream but constantly impinging the invert.
- A mineralogical analysis of the sediment (considering particularly the content of hard material such as quartz) and investigation of the sediment shape (angular or rounded) is recommended in order to estimate its abrasive potential.

8. CONCLUSIONS AND OUTLOOK

Without adequate measures, reservoirs are not sustainable, neither the reservoir itself due to continuous sedimentation, nor the downstream ecosystem due to discontinuity of sediment. Appropriate actions to prevent sedimentation and to restore reservoir capacity, while enhancing sediment continuity are inevitable and require a systematic sedimentation management. Sediment bypassing constitutes one effective strategy that routes sediment load around reservoirs during floods. An SBT has the advantage that only newly entrained sediment is diverted from the upstream to the downstream reach thereby re-establishing sediment connectivity. An SBT contributes to a sustainable water resources management while taking the downstream environment into consideration.

The ICOLD Committee J “Sedimentation of Reservoirs” is currently (2017 – 2020) working on a bulletin on sediment bypass systems. The bulletin aims to discuss the contents of this paper in more detail. It will give a state-of-the-art overview of sedimentation bypassing, encompassing design, bypass efficiency, hydraulics, challenges due to abrasion, economic analysis, positive effects on both downstream morphology and ecology, and will also provide design recommendations.

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