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SEDIMENT BYPASS TUNNELS: SWISS EXPERIENCE WITH BYPASS EFFICIENCY AND ABRASION-RESISTANT INVERT MATERIALS*

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SUMMARY

In this paper typical bypass efficiencies of sediment bypass tunnels (SBTs) used to counter reservoir sedimentation are described, distinguishing between two layouts of the tunnel intake. It results that SBTs are an effective measure to

* *Galeries de dérivation de sédiments : expérience suisse sur l'efficacité de la dérivation et les matériaux de radier résistant à l'abrasion*

reduce the sedimentation of dam reservoirs, particularly of type (A) with intake at the reservoir head. The hydroabrasive wear of tunnel inverts is significant and has to be mitigated by using adequate invert liners. The invert abrasion can be estimated based on an abrasion model where a correct input value of the bed material resistance coefficient is paramount to limit model uncertainties. Based on abrasion measurements at prototype SBTs typical values of the material resistance coefficient are recommended for high-strength concrete, natural stones and steel liners. The field experiences gathered so far and the comparison of various invert materials suggest granite pavers as a promising lining material for severe abrasion conditions.

Keywords: Erosion, sedimentation, tunnel, wear, Asahi, Mud Mountain, Nunobiki, Pfaffensprung, Runcahez, Solis.

RÉSUMÉ

Dans cet article, l'efficacité typique de galeries de dérivation de sédiments (SBTs) destinées à combattre l'alluvionnement des réservoirs est présentée. Deux positions de la prise d'eau de telles galeries sont considérées. Les SBTs sont efficaces pour diminuer l'alluvionnement, particulièrement celles du type (A) avec prise d'eau située en amont de la courbe de remous de la retenue. L'usure du radier de la galerie est marquée et doit être atténuée en utilisant des revêtements adéquats. L'abrasion du radier peut être estimée en utilisant un modèle d'abrasion dans lequel la valeur du coefficient de résistance est décisive pour diminuer l'incertitude du modèle. Basées sur de nouvelles mesures d'abrasion dans des prototypes de galeries de dérivation, des valeurs typiques du coefficient de résistance sont proposées pour du béton à haute performance, la pierre naturelle et un revêtement en acier. Les expériences acquises sur les prototypes et la comparaison des divers matériaux indiquent que le granite semble être un revêtement prometteur pour des conditions d'abrasion sévères.

Mots-clés: Alluvionnement, érosion, galerie, sédimentation, usure, Asahi, Mud Mountain, Nunobiki, Pfaffensprung, Runcahez, Solis.

1. INTRODUCTION

To counteract reservoir sedimentation, different techniques may be implemented at dam sites, which can be grouped into three main categories: i) sediment yield reduction, ii) sediment routing, and iii) sediment removal. Sediment routing techniques have been proven to have positive effects both in reducing reservoir sedimentation and maintaining or re-establishing sediment continuity similar to pre-dam conditions. Among the techniques used to route sediments around dams, sediment bypass tunnels (SBTs) are built with the twofold aim of reducing reservoir sedimentation and maintaining/restoring sediment and water regimes in the downstream river reach.

Due to high bed load transport at supercritical flow conditions, many SBTs suffer from severe hydroabrasive invert wear (Fig. 1), significantly increasing maintenance and refurbishment costs. In a long-term research project conducted at the Laboratory of Hydraulics, Hydrology and Glaciology of ETH Zurich, various invert materials have been implemented in the three Swiss SBTs Solis, Pfaffensprung and Runcahez. Abrasion patterns and depths have been monitored and materials have been analyzed in detail as to their resistance against hydroabrasion. The materials range from high-performance concretes, cast-basalt tiles and granite pavement to steel lining.

This paper reports (1) the bypass efficiencies of two Swiss SBTs based on bed load and suspended sediment load estimates, (2) an invert abrasion prediction model to estimate abrasion rates at SBTs and other hydraulic structures, (3) abrasion-resistant lining materials, and (4) results on their cross-comparison.

Fig. 1
Hydroabrasion at SBT inverts: (a) broken and partially eroded cast basalt tiles at Runcahez SBT, Switzerland (photo: M. Müller-Hagmann); (b) concrete lining abraded down to the steel bearing at Val d'Ambra SBT, Switzerland (courtesy of Azienda Elettrica Ticinese AET)
L'hydro-abrasion du radier des galeries de dérivation de sédiments: (a) dalles en basalte fondu brisées et partiellement érodées à Runcahez, Suisse (photo : M. Müller-Hagmann); (b) revêtement en béton abrasé jusqu'aux poutres en acier à Val d'Ambra, Suisse (avec l'autorisation de Azienda Elettrica Ticinese AET)

2. BYPASS EFFICIENCIES OF SEDIMENT BYPASS TUNNELS

2.1. GENERAL

SBTs have demonstrated to be an effective countermeasure against reservoir sedimentation. Whereas bed load deposition may be completely prevented with an

SBT, the deposition of fines in the reservoir depends on the design discharge of the tunnel and the operational regime. The higher the SBT design capacity and thus the flood recurrence interval to be bypassed, the higher is the share of the incoming suspended load to be conveyed through the tunnel and the smaller is the amount of fines entering the reservoir. Here, total sediment load *TL* is defined as the sum of bed load *BL* and suspended sediment load *SSL*, i.e. $TL = BL + SSL$. In the case without SBT, generally all *BL* and usually parts of the *SSL* deposit in a reservoir while the rest of *SSL* leaves the reservoir via the service outlets (such as power waterway for hydropower dams), spillways, bottom outlets, etc. The bypass efficiency *BE* of a reservoir is defined as the ratio of total sediment outflow to total sediment inflow:

$$BE\ [\text{-}] = TL_{out}/TL_{in}. \qquad [1]$$

The reservoir trap efficiency *TE* is a function of the sediment characteristics such as particle diameter and the mean resident time of water in the reservoir, expressed as the ratio of reservoir capacity (CAP) to mean annual runoff (MAR) entering the reservoir:

$$TE\ [\text{-}] = f\,(\text{sediment, CAP/MAR}) = 1 – BE. \qquad [2]$$

The reservoir lifetime *RL* is defined as the ratio of reservoir capacity to mean annual sediment load effectively depositing in the reservoir (MAS):

$$RL\ [\text{yr}] = CAP/MAS = CAP/(MAS_{in}\cdot(1\ BE)), \qquad [3]$$

where MAS_{in} = mean annual sediment inflow. The *RL* value represents the theoretical duration until the reservoir is completely filled with sediment.

The typical range of bypass efficiencies of reservoirs with type (A) SBTs (see section 2.2) is $BE > 0.60$ [1]. Two examples are the Asahi and Nunobiki reservoirs, both in Japan. Asahi SBT has greatly reduced the severe reservoir aggradation since its commissioning in 1998. During an exceptionally large flood due to a typhoon in 2011, the routing of sediments around the dam greatly helped to limit the sediment inflow into the reservoir. The mean annual bypass efficiencies amount to $BE = 0.77$ at Asahi and $BE = 0.94$ at Nunobiki reservoir, extending the respective *RL* by 450 and 1200 years, respectively [2].

2.2. SWISS EXAMPLES OF SEDIMENT BYPASS TUNNEL EFFICIENCIES

At a number of Swiss reservoirs equipped with an SBT, sedimentation data have been analyzed to evaluate their effectiveness [1]. Hereafter, the results of Runcahez and Solis SBTs are presented. Whereas the former is of type (A), i.e.

with intake at the reservoir head and free-flow conditions at the intake for fully-opened gate, the latter features a so-called type (B) system with pressurized inflow conditions due to its submerged intake structure located in the reservoir (Fig. 2, [3]).

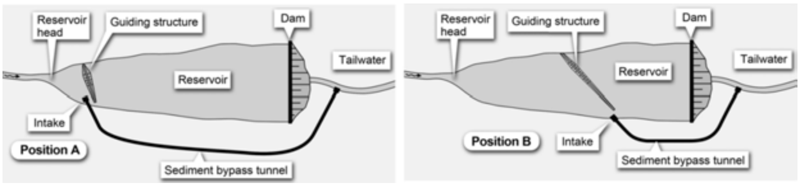

Fig. 2
Plan views of two different SBT systems relative to location of tunnel intake (a) free-surface inflow at reservoir head (position A), (b) pressurized inflow downstream of reservoir head (position B) (from [3])
Plans de deux galeries de dérivation de sédiments différentes quant à la position de la prise d'eau (a) écoulement à surface libre avec prise d'eau située en amont de la courbe de remous du barrage (b) écoulement en charge avec prise d'eau submergée située dans le réservoir (de [3])

2.2.1. Runcahez SBT

The Runcahez dam was erected in 1962, creating a reservoir that serves as a compensation basin between two hydropower plants of the Vorderrhein power scheme located in the Eastern Alps of Switzerland [4]. The total catchment area of the Runcahez reservoir spans 270 km^2, while the direct drainage area is 55.6 km^2, located between 1276 and 3164 m a.s.l. The original reservoir storage capacity was 0.44 million m^3, and the mean annual runoff of the direct catchment amounts to 72.5 million m^3/yr. In order to prevent reservoir sedimentation, a 572 m long type (A) SBT with a design discharge capacity of 110 m^3/s (free-flow conditions), representing a 2-year flood, was commissioned simultaneously with the dam in 1962.

At Runcahez reservoir and SBT there is no information about the sediment accumulation in the reservoir due to a lack of a monitoring system. Therefore, the bypass efficiency *BE* of the reservoir was determined based on the estimated sediment masses transported in the river and through the SBT. The estimated annual bed load and suspended sediment load supplied by the river are $BL = 10.6 \cdot 10^3$ to/yr and $SSL = 10.6 \cdot 10^3$ to/yr, respectively (see Table 1). The trap efficiency of the suspended sediment TE_{SSL} was determined based on the criteria of [5], resulting in $TE_{SSL} = (1 - BE_{SSL}) = 0.33$. Applying this value and a 100% trap efficiency of bed load, i.e. $TL_{BL} = (1 - BE_{BL}) = 1.0$, to the estimated *SSL and BL* in the river leads to an annual total deposition volume in the reservoir of 14'100 to/yr. As of 2016, after 55 years of operation, the reservoir volume for the hypothetical case without SBT would thus be expected to be about *CAP* = 9'000 m^3 assuming a bulk density of 1.8 to/m^3. The total bypass efficiency without SBT would accordingly results in *BE* ≈ 0.33.

For the sake of simplicity the bypass efficiencies of the suspend sediment with and without the SBT were assumed to be equal, which is rather conservative as *SSL* are bypassed to a great extent during SBT operation, so that the *SSL* potentially depositing in the reservoir is decreased. The bed load transport mass can be assumed to be bypassed by 100%, since the bed load particles are hindered to enter the reservoir because of the high guiding structure at the intake. The resulting bypass efficiency with SBT is then *BE* = 0.83. This value lies within the typical range for reservoirs with a type (A) SBT in operation (see section 2.1) and is therefore assumed to be reasonable. Based on these estimations, the lifetime of the Runcahez reservoir is prolonged by the SBT by 4 times from 56 years to 226 years.

Table 1
Mean annual sediment volumes into and out of the Runcahez reservoir
and corresponding bypass efficiencies without and with SBT
Valeurs moyennes des volumes annuels de sédiments entrant et sortant du réservoir de Runcahez et efficacité de la dérivation sans et avec galerie
de dérivation de sédiments

	1962-2016	**1962-2016 (HYPOTHETICAL WITHOUT SBT)**			**1962-2016 (REAL WITH SBT)**		
	INFLOW [10^3 TO/A]	**OUTFLOW [10^3 TO/A]**	**DEPOSITION [10^3 TO/A]**	**BE [%]**	**OUTFLOW [10^3 TO/A]**	**DEPOSITION [10^3 TO/A]**	**BE [%]**
SSL	10.6	7.1	3.5	*67*	7.1	3.5	*67*
BL	10.6	0	10.6	*0*	10.6	0	*100*
TL	21.2	7.1	14.1	33	17.7	3.5	83

2.2.2. SBT solis

Solis reservoir is located on the Albula river with a catchment area of 900 km^2. Initially, in 1986, the total storage volume was 4.07 million m^3 with an active volume of 1.46 million m^3. After 25 years of operation the total sedimentation amounted to about 50% of the total storage volume, so that a SBT was commissioned in 2012 to counter the severe sedimentation problem. The estimated mean net sedimentation in the reservoir without SBT was some 91'000 m^3 despite gravel mining at the reservoir head. This value was validated based on bathymetric surveys.

The bed load and suspended load transport rates flowing into the Solis reservoir were estimated based on numerical bed load transport simulations; the mean annual bed load supply from the Albula river was calculated to vary between

40’000 and 55’000 m³ [6], [7]. Approx. 31’000 m³ of the bed load were excavated on average between 1987 and 2016, so that the effective bed load inflow to the reservoir varies between 9’000 and 24’000 m³.The bed load and suspended load rates conveyed through the SBT were measured using a Swiss plate geophone system and turbidimeters, respectively, whereas suspended sediments conveyed via the power waterways were additionally measured using turbidimeters. Moreover, rare suspended load outflows via the dam bottom outlet and dam spillway were estimated based on the suspended sediment concentrations measured in the power waterway and the SBT. From balancing the in- and outflows, the bypass efficiencies *BE* were obtained (Table 2).

The bypass efficiency of the Solis Reservoir without the SBT was 15%, increasing to 31% by the SBT. This value is relatively low compared to other reservoirs with a SBT in operation with $BE \approx 0.60\text{-}0.90$ (see section 2.1), due to the deviating intake location and different SBT operation durations and regimes. Most SBTs are of type (A) with an intake at the reservoir head, from where the inflowing sediments are directly conveyed past the dam. In contrast, type (B) SBTs such as in Solis exhibit an intake within the reservoir allowing for intermediate deposition of sediments between the reservoir head and the SBT intake, which negatively affects the overall bypass efficiency as long as an equilibrium topset slope of the aggradation body has not been reached. Moreover, type (B) SBTs are generally operated only during high flood discharge peaks. As a result, the annual operation duration of the Solis SBT was only 21.3 hours on average, which is significantly lower than typical operation duration of type (A) SBTs. Overall, the SBT allowed to double the *BE*, thereby prolonging the theoretical remaining Solis reservoir lifetime by 23% from 22 years to 27 years. Both *BE* and *RL* are expected to be raised significantly in the future by enhancing the operating regime, i.e. by sufficiently lowering the reservoir level prior to a flood, and by prolonging the operation duration. This will ensure high bed shear stresses on the aggradation body to increase sediment transport towards the SBT intake.

Table 2
Mean annual sediment volumes into and out of the Solis Reservoir and corresponding bypass efficiencies without and with SBT from 2012
Valeurs moyennes des volumes annuels de sédiments entrant et sortant du réservoir de Solis et efficacité de la dérivation sans et avec galerie de dérivation de sédiments depuis 2012

	1987-2016	1987-2016 (WITHOUT SBT)			1987-2016 (WITH SBT FROM 2012)		
	INFLOW [10^3 M³/A]	OUTFLOW [10^3 M³/A]	DEPOSITION [10^3 M³/A]	BE [%]	OUTFLOW [10^3 M³/A]	DEPOSITION [10^3 M³/A]	BE [%]
SSL	90.7	16.3	74.4	*18*	32.9	57.8	*36*
BL	16.8	0	16.8	*0*	0.4	16.4	*2*
TL	107.5	16.3	91.2	15	33.3	74.2	31

3. INVERT ABRASION

3.1. PHENOMENON

Hydroabrasion is defined as continuous material loss on the surface of a solid body caused by mechanical stress due to contact of solid particles transported in the flow [8]. Depending on particle properties and hydraulic conditions, the energy transferred to the bed and thus the particle harming potential vary. Due to viscous damping effects the kinetic energy of a particle can be completely dissipated, so that no abrasion occurs [9]. Field investigations revealed that this effect is negligible for supercritical flows with bed load transport [10], [11]. Hydroabrasion is a self-intensifying process triggered by irregularities. The material loss grows in streamwise, lateral and vertical directions, causing irregular bed forms like incision channels or pot holes. It can also result in a breakoff of an invert fragment.

Hydroabrasion is generally induced by particles in sliding, rolling or saltating motions, depending on the flow conditions. Since sediment grain sizes are typically rather widely distributed (from sub-millimeters – to several decimeters and more), the transport is generally a combination of the mentioned types of particle motion. Depending on the latter, the particles cause grinding, rolling or impinging impact stresses on the bed, respectively. Usually, saltation is the main process causing abrasion and incision of bedrock rivers [12], while sliding or rolling play a minor role [13]. Based on an evaluation of detailed abrasion data from SBT Asahi in Japan, it was proposed to neglect the grinding stresses by rolling and sliding particles compared to the impinging impact stresses by saltating particles [14].

3.2. ABRASION PREDICTION MODELS

Several mechanistic models exist to predict abrasion rates. While models for the prediction of bedrock incision focus on typical flow conditions in river systems in the sub- and low supercritical flow regimes (e.g. [13]), models for the estimation of invert abrasion at hydraulic structures such as flushing channels and SBTs must account for highly supercritical flows. Depending on the invert material used at the latter, two basically different models are currently proposed for practical applications of abrasion prediction. The Ishibashi model is limited to concrete and steel inverts [14], [15], whereas the Auel model can be additionally applied to natural rock material such as granite [11]. Due to its wide application range, both for fixed planar bed of various material and for bedrock river incision, the latter is focused and summarized hereafter [11]. The magnitude of abrasion expressed as vertical abrasion rate A_r [m/s] follows

$$A_r = \frac{Y_M}{k_v f_t^2} \cdot \frac{(s-1)g}{230} q_s \left(1 - \frac{q_s}{q_s^*}\right) \text{ [m/s]} \qquad [4]$$

where Y_M [Pa] = Young's modulus of elasticity of the bed material, f_t [Pa] = splitting tensile strength of the bed material, k_v [-] = bed material resistance coefficient encompassing both the particle and bed material characteristics, $s = r_s/r_w$ = ratio of sediment (subscript s) to water (subscript w) densities, g = gravitational acceleration, q_s [kg/(sm)] = specific gravimetric bed load rate, and q_s^* [kg/(sm)] = specific gravimetric bed load transport capacity. The last term on the right hand side of Eq. [4] is related to the cover effect accounting for bed load partly covering the bed, resulting in reduced impact energy [12], [16]. Eq. [4] holds for supercritical open channel flow over a planar bed of low relative roughness height $k_s << d$, with k_s = equivalent sand roughness height and d = sediment particle diameter. For sediment mixtures, $d = d_{50}$ is typically applied, with d_{50} = mean particle diameter.

Interestingly, A_r from Eq. [4] only scales with the specific gravimetric bed load rate q_s, while the flow velocity does not affect A_r. Eq. [4] does not account for the transport mode shift from saltation to suspension, which might have to be included if suspended load is dominant in the total sediment transport.

To apply the saltation-abrasion model for hydraulic structures where concrete is the most common lining material, the material property parameters have to be adapted. The decisive parameter describing the concrete material strength is compression, as concrete bears only little tension without reinforcement [17]. Hence, for concrete abrasion, the compression strength is typically used [8]. A common correlation between the splitting tensile f_t and the cylindrical compression strength f_c follows [17]

$$f_t = 0.387 f_c^{0.63} \quad \text{for } 4 < f_c < 120 \text{ MPa} \qquad [5]$$

The Young's modulus Y_M for concrete is determined with ρ_c [kg/m^3] as concrete density as [18]

$$Y_M = k_1 k_2 \cdot 3.35 \times 10^4 \left(\frac{f_c}{60}\right)^{1/3} \left(\frac{\rho_c}{2400}\right)^2 \quad \text{for } 40 < f_c < 160 \text{ MPa} \qquad [6]$$

The correction factors k_1 and k_2 vary from 0.95 to 1.20 and account for the type of coarse aggregate and admixtures, respectively.

Eqs. [4] to [6] were applied to the measured abrasion at Pfaffensprung SBT based on estimated specific gravimetric bed load transport rates to calibrate the k_v value for both high-strength concrete and granite [19]. As a starting point for abrasion prediction modelling they propose to use $k_v = 1.9 \cdot 10^5$ and $2.4 \cdot 10^6$ for the former and latter, respectively. For steel being a ductile material, the fracture energy has to be accounted for. If Eq. [4] is applied, a value of $k_v = 8.1 \cdot 10^3$ is recommended for typical construction steel S235 with elongations at yield and of rupture of about 0.1% and 20%, respectively [1].

3.3. Abrasion-resistant lining materials

Although there is a large variety of materials used in SBTs, including particularly expensive ones such as epoxy resin mortar and rubber plates mounted on steel plates, medium- and high-strength concretes are still the most widely used. While the former concrete standard EN 206-1 defined high-strength concrete with a compressive strength class higher than C50/60 (in the current concrete standard EN 206 there is no more definition for high-strength concrete) and the American Concrete Institute (ACI) defines high-strength concrete as having a 28 day compressive strength of at least f_c = 55 MPa [20], so-called Ultra-High Performance Concrete (UHPC) features 150 MPa $\leq f_c \leq$ 250 MPa [21]. High performance concrete (HPC) and UHPC are defined as concrete meeting special combinations of performance and uniformity requirements not always achieved routinely using conventional constituents and normal mixing, placing, and curing practices (ACI 2013).

Based on a long-term field study at Runcahez SBT between 1995 and 2014 ([8], [22]) the decisive material characteristics of concrete as to its abrasion resistance are not completely known. The splitting tensile strength, and the fracture energy show a moderate correlation to abrasion. The compressive strength shows a weaker correlation. However, due to the fact that in most cases only compressive strength data are available, compressive strength is still often used as “characteristic” parameter. Note that the splitting tensile strength f_t is used in eq. [4], which can be calculated from f_c using eq. [5]. To guarantee sufficient resistance to hydroabrasion excluding very severe conditions (e.g. Runcahez and Solis SBTs), the compressive strengths of SBT linings should be f_c > 60 MPa, while the fracture energy should be > 200 J/m^2 at 28 days. Natural stone material such as cast basalt or granite can also be used, and steel armoring in reaches of high wear, e.g. in the acceleration section near the intake gate, have been applied successfully. 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.

3.4. Cross-comparison of abrasion-resistant materials

Results from *in-situ* tests at the Swiss SBTs Runcahez, Pfaffensprung and Solis indicate that the mean abrasion rates tend to increase with decreasing compressive and splitting tensile strengths of the invert concrete as expected [19], [22], [23]. One of the important findings from the Pfaffensprung SBT abrasion study is the significantly higher abrasion-resistance of granite compared to the implemented high-strength concrete invert ($f_c \approx$110 MPa) under very severe abrasion conditions. The results show that the mean abrasion rate of the granite plates is considerably smaller (by a factor of about 6 to 7) than that for the concrete invert [23], [24]. This may suggest that the used type of granite is a better choice as invert material over high-strength concrete for very severe abrasion conditions like in the Pfaffensprung SBT. For Runcahez and especially Solis SBTs invert materials with a lower abrasion resistance (e.g. high-performance concrete) are sufficient, however. By considering these results, a granite pavement was selected for the rehabilitation of the formerly steel-lined Mud Mountain bypass tunnel in the USA [15]. However, the quality and cost of granite should be carefully considered in the SBT design phase.

The results of the Pfaffensprung SBT study show that damages typically occur in the form of grooves along the joints of basalt and granite plates (Fig. 3a), while a wavy pattern of abrasion occurs on high-strength concrete (Fig. 3b). To further reduce the abrasion on granite, this result suggests that plates should not be placed in parallel to the main flow direction and a jointless tight installation between the plates should be achieved. It should be noted that the latter is challenging and requires for special knowledge and skills of the construction team, which are not always available. The joints between the granite plates and the SBT side walls should be as small as possible and filled with a high-abrasion resistant material such as a special mortar with basalt aggregates.

Whereas natural stone material, e.g. cast basalt plates, is supposed to have a high abrasion resistance against pure particle grinding action, their brittleness may favor fracturing by impinging particles for saltating sediments. The risk of fracturing largely depends on both the particle size determining the impact energy and the thickness of the invert liner. For particularly large saltating sediment particles in the multi-decimeter range, either steel or cementitious material such as high-strength concrete may show improved resistance. As steel linings are often too costly for abrasion protection of large areas such as in SBTs, high-strength concrete becomes an interesting and economical alternative [23].

Fig. 3
Abrasion patterns at Pfaffensprung SBT: (a) grooves forming along joints of granite plates, (b) undular invert at steel-fiber high-strength concrete test field with f_c > 70 MPa [1]
Dessins d'abrasion dans la galerie de dérivation de sédiments de Pfaffensprung: (a) rainures le long des joints de dalles en granite, (b) radier ondulé en béton à haute performance avec fibres en acier (f_c > 70 MPa) d'un champ d'essai [1]

4. CONCLUSIONS AND RECOMMENDATION

Sediment bypass tunnels (SBTs) have proven to be effective in reducing reservoir sedimentation and re-establishing or keeping sediment continuity past a reservoir dam. The degrees of efficiencies, i.e. the ratio between bypassed and inflowing sediment, amount to up to 90% or more for type (A) SBTs with the intake at the reservoir head. For type (B) SBTs with submerged intake in the reservoir the efficiencies seem to be lower, with some 30% for the Solis SBT in Switzerland, which can be potentially increased with optimized operation duration and operation regime.

Abrasion prediction is essential for the economical design of an invert liner. For SBTs with supercritical flow the Auel model is recommended herein, although its prediction uncertainty can be still significant. It is applicable for both brittle material such as concrete and natural stone, and ductile material like steel. The bed material resistance coefficient is crucial in terms of model uncertainty. From inverse modelling, values for high-strength concrete, granite and steel have been determined and are given herein as a first estimate. From current field experiments granite pavements seem to be promising in terms of abrasion resistance and from a life-cycle perspective for very severe abrasion conditions. However, various materials should be carefully evaluated to come up with the best option for each case study with its specific boundary conditions.

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