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Abrasion Damage in Sediment Bypass Tunnels

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ABSTRACT

Sediment bypass tunnels are an effective and sustainable strategy against reservoir sedimentation. Sediments are diverted into the downstream during floods without deposition in the reservoir, hence morphological and ecological variability increases. One major drawback of these tunnels is the severe invert abrasion due to a combination of high flow velocities and bedload sediment transport. The abrasion phenomena is briefly described, different abrasion prediction models are presented and their applicability for the estimation of concrete abrasion is discussed.

KEY WORDS: Abrasion prediction model; reservoir sedimentation; sediment bypass tunnel; wear

INTRODUCTION

Dam-regulated rivers interrupt continuous sediment transport along a river system and cause accumulation in the reservoir. Hence, a sustainable use of reservoirs implies the application of strategies to counteract sedimentation. Mean annual sedimentation rates vary from 0.2 to some 2 to 3% with a global annual average rate of about 1% and worldwide, increase in sedimentation volume exceeds increase in reservoir capacity revealing a gross storage loss in the near future (Schleiss and Oehy 2002, ICOLD 2009). Reservoir sedimentation causes various problems. Firstly, the volume decrease leads to a loss of energy production, water used for water supply and irrigation, and retention volume (Annandale 2013). Secondly, both an endangerment of operating safety due to blockage of outlet structures and an increased turbine abrasion due to increasing specific suspended load concentrations may result. Finally, a dam retains sediment causing downstream river incision and inhibiting its ecologic connectivity (ICOLD 2009, Kondolf et al. 2014).

Sediment management to minimize aggradation in reservoirs is achieved with a variety of techniques categorized in three main strategies (ICOLD 2009, Morris and Fan 1998, Annandale 2013, Auel and Boes 2011, Kondolf et al. 2014). Figure 1 shows an overview of these techniques and their corresponding strategies: (1) sediment yield reduction, (2) routing sediments around or through the reservoir, and (3) recover volume by sediment removal or dam heightening. Furthermore, two more strategies may be added: (4) dam removal and (5) no action.

Sediment routing is ecological favorable compared to other strategies as operation is conducted during high flows. River bed erosion downstream of the dam can be decelerated resulting in an increase of morphological variability (Fukuda et al. 2012, Facchini et al. 2015, Martín et al. 2015). Moreover, only sediments provided from the upstream river reach are conveyed, while hardly any 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 (ICOLD 2009).

SEDIMENT BYPASS TUNNELS

Sediment routing using a bypass tunnel (SBT) is a very effective strategy regarding both bed and suspended sediment load (Sumi et al. 2004, Auel et al. 2016a).

In general, all sediments are guided into the tunnel intake using guiding structures such as walls or weirs and the reservoir is kept free of sediments downstream of the intake. Only if the tunnel design discharge is exceeded, a partial flow is entering the reservoir leading to suspended load entrainment (Auel and Boes 2011).

The number of tunnels is still limited with about 30 facilities worldwide. Most SBT exist in Switzerland (Egschi, Hintersand, Palagnedra, Pfaffensprung, Rempen, Runcahez, Sera, Solis, Ual da Mulin, Val d’Ambra) and in Japan (Asahi, Koshibu, Matsukawa, Miwa, Nunobiki), some others in China and South Africa. Two SBT are under construction in Taiwan (Nanhua, Shimen). Additionally, a number of flood bypass tunnels exist showing similar flow characteristics to SBT. These are i.e. in Switzerland the Rovana, the Grindelwald glacier and the Matter Vispa downstream of Zermatt.

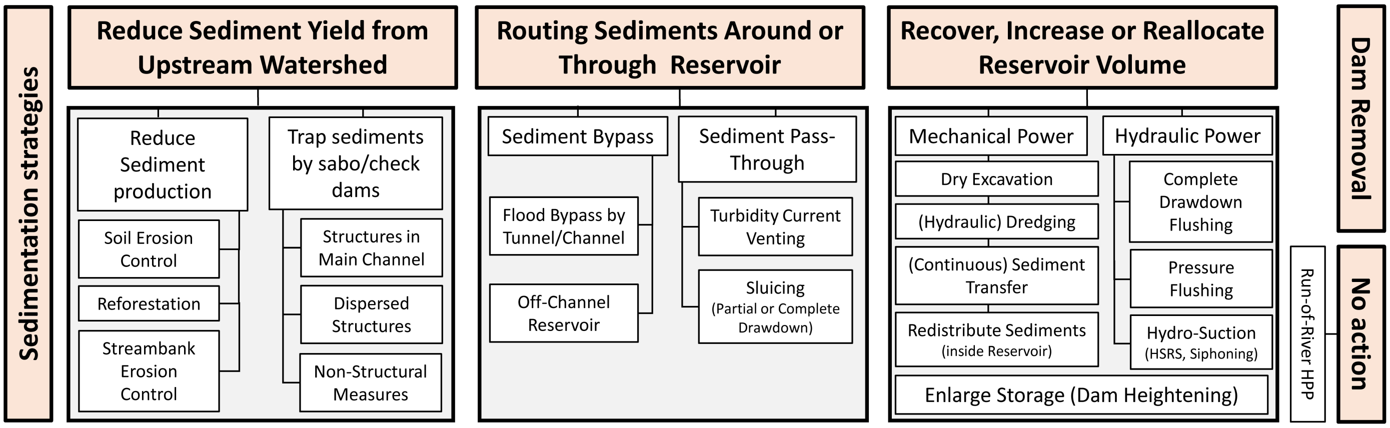

Fig. 1 Classification of strategies against reservoir sedimentation (adopted from Auel et al. 2016a).

In general, SBTs are operated in supercritical free surface flow conditions (Fig. 2), although some are operated in pressurized flow for a limited time period. The intake is located either at the (1) reservoir head or (2) inside the reservoir. The first location results in long tunnels, but operation is simple and the entire reservoir is kept free from sediment deposition. The second location allows for short tunnels, but both construction and operation are challenging. The reservoir has to be partially lowered prior a flood event to allow for sufficient transport capacity towards the tunnel intake.

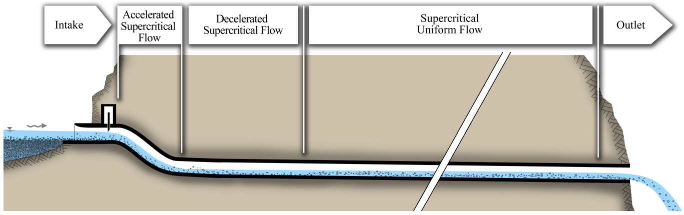

Fig. 2 SBT flow conditions sketch (adopted from Auel 2014).

Pros & Cons

The first advantage of a SBT is the high efficiency keeping the reservoir free of sediments. Research on the Japanese SBTs Asahi and Nunobiki showed that in average 77% and 94% of the incoming sediments are diverted to the downstream river reach, and the estimated reservoir life enlarged to 450 and 1200 years, respectively (Auel et al. 2016a). The second advantage is its ecological function by connecting the up- and downstream reaches. Only sediments that are transported towards the reservoir are bypassed whereas already deposited sediment is not mobilized. The natural morphological river characteristics are thereby reestablished and microhabitat and invertebrate richness in the downstream reaches is leveled to the upstream values (Kobayashi et al. 2016).

The main disadvantage is the high construction cost, hence SBT are best applicable for small and medium-sized reservoirs (<10^7 m^3) as tunnel length plays a crucial role in terms of cost per meter length. Secondly, the flood is directly diverted into the downstream and no retention occurs. Therefore, SBT are favorable in regions with high water availability whereas in arid regions the priority is to retain the flood by all means.

The flow velocity in free surface open channel flow depends on the width and slope. As the tunnel cross section should be compact in order to confine construction costs, the slope is the governing parameter. Two contrary requirements have to be fulfilled. The tunnel has to be steep enough to transport all sediment, but the slope should be as mild as possible to limit the flow velocity. Due to both high flow velocities up to 15 m/s and bedload sediment transport with grain sizes in the decimeter range, many SBT face severe invert abrasion (Jacobs et al. 2001, Auel and Boes 2011, Boes et al. 2014). Figure 3 shows abrasion damages up to several meters at Palagnedra SBT in Switzerland and several decimeter at Asahi SBT, Japan. The up to 4 m deep damage in Palagnedra was mainly caused by an extreme flood event shortly after inauguration in 1978. In 2012 and 2013, about 20% of the invert were refurbished. The invert of Asahi SBT was abraded by 1.3 m since 1998 leading to periodical repair works.

These tunnels, however, operate effectively despite the large abrasion. These abrasion problems cause high periodical maintenance costs additionally inhibiting the successful implementation on site.

Fig. 3 Abrasion patterns at a) Palagnedra SBT, Switzerland and b) Asahi, Japan (courtesy of C. Auel).

ABRASION

Abrasion is a wear phenomenon involving progressive material loss due to hard particles forced against and moving along a solid surface controlled by kinetic energy due the vertical component of a saltating particle impact (deformation wear), and friction due to grinding stress (cutting wear) caused by the horizontal component (Bitter 1963a, b). In general, abrasive damage can always be expected when particle bed-load transport takes place. The governing process causing abrasion on brittle materials such as bedrock and concrete is saltation, whereas sliding and rolling do not cause significant wear (Whipple et al., 2000; Sklar and Dietrich, 2004; Turowski, 2012; Beer and Turowski, 2015).

The extent of damages along the wetted perimeter, i.e. mainly on the invert and the lower parts of the tunnel walls, typically increases with increasing sediment load, particle size and distribution and flow velocities i.e. shear stress as well as quartz content in the mineralogical composition of the sediments (Boes et al. 2014).

Abrasion prediction models

A number of mechanistic models exist to predict the abrasion rate. While the models for prediction of bedrock incision (e.g., Sklar and Dietrich 2004, Lamb et al. 2008, Chatanantavet and Parker 2009) focus on typical flow conditions in river systems in the sub- and low supercritical flow regime, the others for prediction of abrasion on concrete surfaces (Ishibashi 1983, Helbig and Horlacher 2007, Auel et al. 2016b, c) have to account for highly supercritical flows. All models take the physical process of particle impact into account and are derived from experimental research on particle motion characteristics, i.e. the analysis of particle impacts, velocities and saltation trajectories.

The first mechanistic model to determine concrete abrasion was proposed by Ishibashi (1983). The abraded invert volume V_a is calculated as:

$$V_a = C_1 E_k + C_2 W_f \qquad (1)$$

where E_k = total particle kinetic energy by 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:

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

and the total friction work W_f by:

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

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 = amount of particles per sediment volume. Further details regarding calculation and verification of Eq. (1) are given in Auel et al. (2016d).

A widely applied model for bedrock incision was proposed by Sklar and Dietrich (2004) and follows in its general form:

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

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 = specific gravimetric bed load rate [kg/(sm)], and q_s^* = specific gravimetric bed load transport capacity [kg/(sm)]. The last term on the right of Eq. (4) is related to the cover effect accounting for bed load partly covering the bed, resulting in decreasing impact energy (e.g., Sklar and Dietrich, 1998; Turowski, 2009). Sklar and Dietrich (2004) applied correlations encompassing analysis of particle motion characteristics (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:

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

where $U_* = (g R_h S)^{0.5}$ = 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, and the transport stage T^* follows as (e.g. Sklar and Dietrich, 2004):

$$T^* = \left(\frac{U_*}{U_{*c}} \right)^2 - 1 = \frac{\theta}{\theta_c} - 1 \qquad (6)$$

where θ = Shields parameter calculated as $\theta = U_*^2/[(s-1)gD]$, $s = \rho_s/\rho$ with ρ_s = particle density and ρ = fluid density, g = gravitational acceleration, D = particle diameter, θ_c = critical Shields parameter and U_{*c} = critical friction velocity at the onset of motion. 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 et al. (2016b, c) found new parameter correlations (e.g. particle impact velocity, saltation trajectories) and proposed a revised version of Eq. (4):

$$A_r = \frac{Y_M}{k_v f_t^2} \cdot \frac{(s-1)g}{230} q_s \left(1 - \frac{q_s}{q_s^*} \right) \qquad \text{[m/s]} \qquad (7)$$

with $k_v = 10^5$ due to the new parameter correlations. Eq. (7) reveals that the abrasion rate A_r is linearly dependent on the sediment rate q_s supported by findings of Chatanantavet and Parker (2009), Johnson and Whipple (2010), and Inoue et al. (2014). In contrast, in Eq. (5), A_r is additionally dependent on $(T^*)^{-0.5}$.

For abrasion of concrete, Auel et al. (2016c) used correlations for the compression strength f_c and Young's modulus by Arioglu et al. (2006) and Noguchi et al. (2009) and proposed:

$$A_r \approx c_a \frac{(s-1) g}{k_v f_c^{0.93}} q_s \left(1 - \frac{q_s}{q_s^*} \right) \qquad (8)$$

with f_c in [Pa], c_a = 94.4 = abrasion coefficient in [Pa$^{-0.07}$], and as in Eq. (7), $k_v = 10^5$.

Recommendations

The model of Ishibashi (1983) is an outstanding pioneering work based on laboratory experiments in the 1960ies (Ishibashi and Isobe 1968). Ishibashi introduced two terms, the particle impact and grinding stress, to determine the abrasion. Later works (e.g. Whipple et al., 2000; Sklar and Dietrich, 2004; Turowski, 2012; Beer and Turowski, 2015) suggest that the latter term plays a minor role which is supported by recent results of field data in Asahi SBT (Auel et al. 2016d). The model by Sklar and Dietrich (2004) is widely applied in river engineering and geomorphology and regarded as state-of-the-art. Auel et al. (2016b,c) revised this model and proposed a new version covering various bed configurations, i.e. planar and alluvial beds in a wide range of flow conditions (sub- to highly supercritical). Additionally, a version for concrete abrasion was proposed.

We suggest to estimate the abrasion rate for concrete using all three models to obtain a sound data base. However, it should be kept in mind that in Eq. (1) only the first term (particle impact) should be used, Eq. (5) was developed for moderate flow conditions, whereas Eqs. (7) and (8) are based on the largest data sets covering all flow and bed conditions.

Abrasion may be minimized by (1) optimizing the hydraulic design and (2) the choice of an appropriate invert material as high performance concrete, cast basalt, granite blocks or steel linings. Recommendations for the former are given in Boes et al. (2014), and for the latter in e.g. Jacobs et al. (2001) and Hagmann et al. (2015).

CONCLUSIONS

In this paper, we discuss sediment bypass tunnels as an effective and ecologically sustainable strategy against reservoir sedimentation. Pros and cons are listed and the main disadvantage, invert abrasion, is described in detail. Furthermore, three different models to determine abrasion are described emphasizing their specific advantages and shortcomings.

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