



Field calibration of abrasion prediction models for concrete and granite invert linings

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Abstract

Hydroabrasive wear is an omnipresent issue at hydraulic structures exposed to high sediment loads and flow velocities, causing considerable refurbishment costs. Its prediction is mandatory for design life estimations and cost-effectiveness analyses. Despite available abrasion prediction models, their applicability to hydraulic structures is scarcely investigated, leaving a lack of knowledge. Therefore, prototype experiments were conducted at several Swiss sediment bypass tunnels and abrasion models were evaluated. The results indicate that the abrasion models are applicable to predict abrasion depth and rate at hydraulic structures. Furthermore, average and material-specific calibration coefficients were determined. The latter significantly reduce the prediction error.

Keywords: invert abrasion, abrasion prediction models, field calibration, 3D laser scan

1 Introduction

Hydraulic structures exposed to mechanical stress caused by sediment-laden flow suffer continuous material loss, i.e. so-called hydroabrasion. This is an important but still not satisfactorily solved issue negatively affecting the cost-effectiveness of hydraulic structures. Most of the existing research studies mainly focus on bedrock incision of rivers as a landscape shaping process, whereas hydroabrasion of concrete and other invert materials such as granite and basalt plates has been less investigated in the past (Ishibashi 1983, Sklar and Dietrich 2004, 2012, Huang and Yuan 2006, Helbig and Horlacher 2007, Lamb *et al.* 2008, 2015, Chatanantavet and Parker 2009, Helbig *et al.* 2012, Auel 2014, Beer and Turowski 2015, Auel *et al.* 2017a). In particular, prototype experiments are rare and the field application of established abrasion models to highly supercritical flows over fixed planar beds of low relative roughness height is questionable. To fill this research gap, prototype tests of various invert materials at Swiss sediment bypass tunnels (SBTs) were conducted in the scope of a PhD research project (Mueller-Hagmann 2017). The obtained data serve for evaluation and enhancement of existing abrasion prediction models, namely the *saltation abrasion model* (SAM) developed by Sklar and Dietrich (2004) and its enhanced version, the *saltation abrasion model Auel* (SAMA) in particular accounting for supercritical flow conditions introduced by Auel *et al.* (2017a).

2 Methodology

Prototype experiments were conducted at the Pfaffensprung, Runcahez and Solis SBTs. The abrasion depths of the test fields were measured using a high resolution 3D-laser scanner and a digital levelling device. The high resolution 3D laser scans performed at Solis SBT resulted in abrasion depths in the range of the measurement accuracy of the device and hence were not used for further analysis. The test fields of the Runcahez SBT were already implemented and monitored in the 1990s in the scope of a former project (Jacobs *et al.* 2001) and hence provide the first long-term prototype hydroabrasion data set to the authors' knowledge (Jacobs and Haggmann 2015). Furthermore, additional data provided by different SBT operators were also included for the evaluation of abrasion prediction models.

2.1 Test site Pfaffensprung SBT

The Pfaffensprung SBT is located in the Swiss Alps, featuring a catchment area of 390 km². The tunnel is 280 m long, has a design discharge capacity of 220 m³/s in free-surface flow and is in operation around 100 to 200 days per year on average (Mueller and Walker 2015, Mueller-Haggmann 2017). Four different 4.4 m wide and 0.3 m thick test fields were implemented in the SBT during the refurbishment works in the low flow winter seasons 2011/12 and 2012/13. Two 10 m long test fields were located at the outlet of the tunnel (location 1 in Figure 1) and another two 20 m long test fields were located in the bend section of the tunnel (location 2 in Figure 1). At both test locations, granite and concrete test fields were implemented. Their properties, namely compression strength f_c , splitting tensile strength f_t and Young's modulus Y_M are listed in Table 1.

Between 2012 and 2015, the SBT was in operation for 118 days per year on average. The mean discharge, flow velocity and annual bedload mass amounted to $Q = 68$ m³/s, $U = 10.3$ m/s and 350 000 ton, respectively.

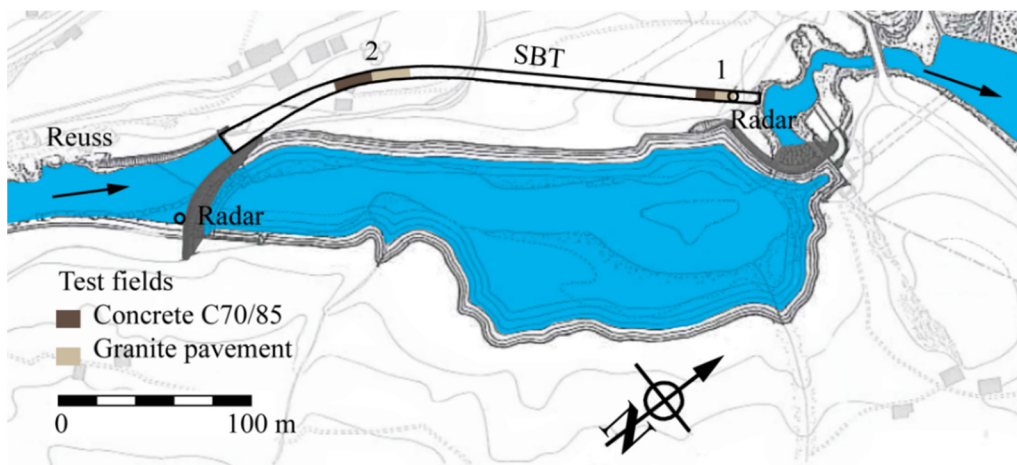


Figure 1: Overview of the Pfaffensprung SBT with the test fields 1 and 2 and the discharge measurement devices (radars)

Table 1: Properties of the implemented material at the Pfaffensprung SBT

Material (Implementation)		f_c [MPa]	f_t [MPa]	Y_M [GPa]
Concrete C1 (2011/12), location 1	C1	108 ± 2 (n=9)	11.3 ± 0.3	38.6
Concrete C2 (2012/13), location 2	C2	78 ± 2 (n=18)	11.2 ± 1.1	34.6
Granite G1 (2011/12), location 1	G1	260 ± 20	10 ± 2	59.0
Granite G2 (2012/13), location 2	G2	260 ± 20	10 ± 2	59.0

2.2 Test site Runcahez SBT

The Runcahez SBT is located in the Eastern Alps of Switzerland, featuring a direct catchment area of 55.6 km^2 . The tunnel is 570 m long, has a design discharge capacity of $110 \text{ m}^3/\text{s}$ in free-surface flow and is in operation during flood events for a few days per year. In 1995, five test fields were implemented along the tunnel section after the acceleration section and bend (Figure 2). They are 10 m long, 3.8 m wide and 30 cm thick and consist of different concrete mixtures. Their material properties are listed in Table 2. Note that the roller compacted concrete (RCC) suffered massive abrasion and required a replacement after Jacobs *et al.*'s (2001) investigation. More details on the Runcahez SBT are given by Jacobs *et al.* (2001), Jacobs and Hagmann (2015) and Mueller-Hagmann (2017).

Since hydraulic conditions were monitored neither in the river nor in the SBT, the discharges were derived from the hydrograph of a nearby gauging station located 3.5 km upstream. Between 1995 and 2014, the annual SBT operation duration of 1.5 days was assumed and accordingly the estimated mean discharge, flow velocity and annual bedload mass amounted to $Q = 60 \text{ m}^3/\text{s}$, $U = 7.6 \text{ m/s}$ and 13'900 ton, respectively.

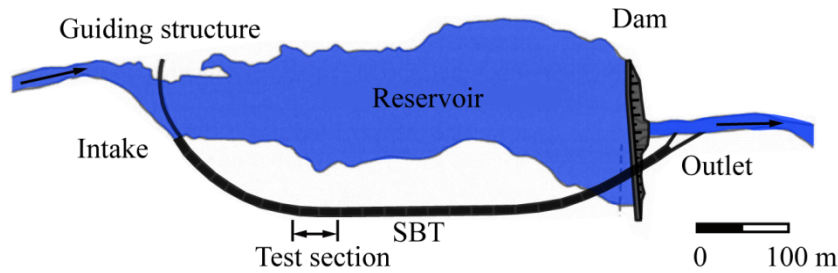


Figure 2: Overview of Runcahez SBT and location of the test section

Table 2: Properties of invert materials implemented at Runcahez SBT (Jacobs *et al.* 2001)

Material	Silica fume concrete (SC)	High performance concrete (HPC)	Steel fiber reinforced concrete (SF)	Roller compacted concrete (RCC)	Polymer concrete (PC)
f_c [MPa]	85.9 ± 3.1	76.7 ± 2.0	95.9 ± 2.3	55.7 ± 4.6	66.8 ± 3.0
f_t [MPa]	8.5 ± 2.1	7.1 ± 3.0	8.3 ± 2.0	6.1 ± 1.0	11.7 ± 1.0
Y_M [GPa]	54.1 ± 2.8	52.7 ± 4.1	52.1 ± 2.7	49.7 ± 1.3	16.3 ± 1.3

2.3 Abrasion prediction models

Sklar and Dietrich (2004) investigated bedrock abrasion caused by bedload particles in saltation motion by using an in-house designed abrasion mill device. They developed the following physically-based model for the estimation of the bedrock incision rate, the so-called *saltation abrasion model* (SAM):

$$A_r = \frac{Y_M}{k_v f_t^2} \cdot \frac{W_{im}^2}{L_p} \cdot q_s \cdot \left(1 - \frac{q_s}{q_s^*}\right) \quad [1]$$

where A_r = abrasion rate [m/s], k_v = dimensionless abrasion coefficient, W_{im} = vertical particle impact velocity, L_p = particle hop length, q_s = specific gravimetric bedload transport rate per unit width [kg/(s·m)] and q_s^* = specific bedload transport capacity per unit width [kg/(s·m)]. Explanations of each term in the equation are given by and Sklar and Dietrich (2004) and Auel *et al.* (2017b).

Sklar and Dietrich (2004) re-arranged Eq. [1] by applying particle saltation trajectory equations resulting in:

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

where g = gravitation acceleration, $s = \rho_s/\rho =$ ratio of solid (index s) to water density, $\theta =$ non-dimensional shear stress $= R_h S / [(s-1)D]$, $R_h =$ hydraulic radius, $S =$ energy slope, $D =$ characteristic particle diameter, $\theta_c =$ critical shear stress for incipient motion and $V_s =$ particle settling velocity. Within this study, $\theta_c = 0.005$ was chosen for particle motion over plane fixed beds according to Auel *et al.* (2017c). The specific gravimetric bed load transport capacity per unit width was determined according to Smart and Jäggi (1983) using:

$$q_s^* = 7.35 \cdot q \frac{\rho_s}{(s-1)} \left(\frac{d_{90}}{d_{30}}\right)^{0.2} S^{1.6} \left(\frac{1.5\theta - \theta_c}{1.5\theta}\right) \quad [3]$$

Note that the term $(d_{90}/d_{30})^{0.2}$ is typically taken as 1.05 (Smart and Jäggi 1983). Since the bedload transport capacity q_s^* of SBTs is typically significantly larger than the effective bedload transport rate q_s of the inflowing river, the term $(1 - q_s/q_s^*)$ in Eqs. [1] and [2], expressing the so-called cover effect, tends to unity and therefore is sometimes neglected. The cover effect describes the complete cover of a fixed bed by sediment, resulting in an effective transport of particles over a movable bed. Depending on the boundary conditions, temporary bed cover may occur, particularly in pressurized inflow conditions (Boes *et al.* 2017), so that the cover effect in the abrasion models term should not generally be skipped.

Sklar and Dietrich (2004) assumed a constant Young's modulus of $Y_M = 50$ GPa and determined k_v for a range of invert materials. They proposed $k_v = 10^6$ while the effective

values ranged from 1.3×10^6 to 9.1×10^6 (Sklar and Dietrich 2004, 2012). This parameter is a function of material properties and therefore requires additional investigations for an appropriate determination (Whipple and Tucker 1999, Momber 2014, Beer and Turowski 2015, Lamb *et al.* 2015, Oertli and Auel 2015, Small *et al.* 2015).

Auel *et al.* (2017a) revised Eq. [1] based on data obtained from their experimental investigation on bedload particle motion and supercritical flow characteristics over a fixed planar bed simulating the flow conditions in SBTs. They proposed:

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

This model is herein called *saltation abrasion model Auel* (SAMA) and the effective Young's moduli are accounted for in contrast to Sklar and Dietrich (2004).

3 Results

The k_v values were determined from the present prototype results and additional SBT data applying (I) SAM, i.e. constant Young's modulus, (II) SAM using the corresponding Young's moduli of the materials, denoted as SAM* and (III) SAMA. Figure 3 shows the k_v values as a function of the corresponding splitting tensile strength. For all three approaches a considerable scatter of more than an order of magnitude is observed. The scatter of k_v values from SAM is higher than that from SAM*, while the k_v values from SAMA scatter the least in particular by neglecting the outliers. This result indicates that SAMA is more suitable than SAM and SAM* for the abrasion prediction in high-speed flows.

The k_v values marked with red circles in Figure 3 are from the other SBTs, where no systematic and precise measurements were conducted and many input parameters were based on estimations or assumptions. As a result, the k_v values determined for those SBTs have high uncertainties and highly scatter. Apart from that, the k_v values for concrete from the Pfaffensprung and Runcahez SBTs are in good agreement. Only the value for the polymer concrete is relatively low due to the effect of polymer causing higher ductility and hence different abrasion behavior. Therefore, this data point is not considered in the data evaluation (marked by a green circle in Figure 3a, b and c).

For the remaining concrete test fields, the mean abrasion coefficients of $k_v = 1.35 \cdot 10^6 \pm 5\%$, $1.2 \cdot 10^6 \pm 30\%$, and $2.0 \cdot 10^5 \pm 5\%$ are determined for SAM, SAM* and SAMA, respectively. These values are in good agreement with both Sklar and Dietrich (2001), who proposed $k_v = 10^6$ for the SAM, and with Auel *et al.* (2017a), who found $k_v = 1.9 \times 10^5$ with SAMA for the concrete invert at the Asahi SBT (Figure 3a, b and c).

Cross comparison of k_v values of different materials revealed significant differences. The k_v values for the granite at the Pfaffensprung SBT is about one order of magnitude higher

than the proposed mean k_v values. This result is against theory on which all three models are based. Despite this fact, the present k_v value for granite is still in a good agreement with Sklar and Dietrich's (2001, 2004) laboratory results where k_v^* for hard rock such as limestone, quartzite and granite was $k_v^* \approx 10^7$. Regarding the steel lining at Mud Mountain SBT, the k_v values are about one order of magnitude below the proposed values. Since these models were developed for brittle materials, deviations for ductile materials such as steel are expected. While brittle materials exhibit a linear elastic stress-strain behavior, the stress-strain curve of ductile materials is linear elasto-plastic. Hence, its fracture energy representing the abrasion resistance is considerable underestimated, which results in lower k_v values.

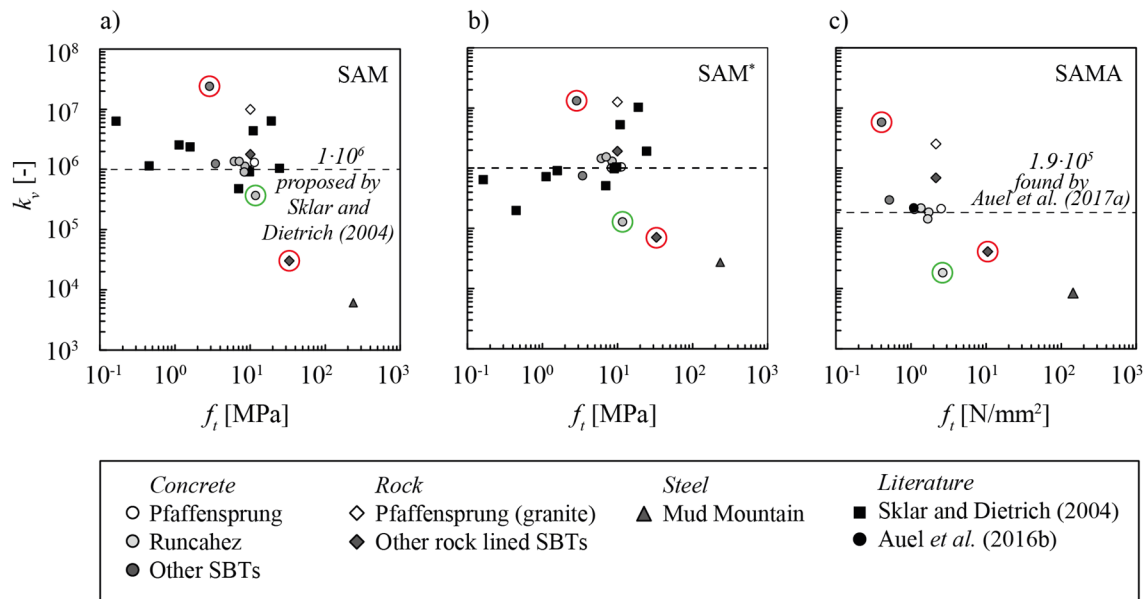


Figure 3: k_v for a) SAM, b) SAM* and c) SAMA as a function of tensile strength; green circle denotes polymer concrete data not further accounted for; red circle denotes data based on uncertain input parameters

4 Conclusions and Outlook

Invert abrasion rates can be predicted by applying various available abrasion models. Amongst others, both saltation abrasion models SAM introduced by Sklar and Dietrich (2004) and SAMA developed by Auel *et al.* (2017a) are applicable for the hydroabrasion prediction in SBTs. The present results indicate that the former should be applied for subcritical flow conditions, while the latter is suitable in particular for the supercritical flow conditions and sediment transport characteristics existing in SBTs.

The prediction accuracy of both models depends on the choice of the abrasion coefficient k_v . In contrast to theory, k_v was found to depend on invert material properties such as strength and hence should be selected accordingly.

Both SAM and SAMA do not account for the effect of sediment shape and hardness, which have a strong influence on the abrasion rate (Sklar and Dietrich 2004). By including these parameters, the prediction accuracy of the models may be additionally enhanced. Therefore, further investigations including the mineral composition and the grain shape of the sediment are recommended.

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