京都大学防災研究所年報 第 58 号 B 平成 27 年 6 月
Annuals of Disas. Prev. Res. Inst., Kyoto Univ., No. 58 B, 2015

Abrasion Damage Estimation of Sediment Bypass Tunnels: Validation and Comparison of two Prediction Models

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Synopsis

Two abrasion prediction models developed for hydraulic structures prone to supercritical flows are compared herein: The models by Ishibashi (1983) and Auel *et al.* (2015). Both models are compared and validated using prototype data from the Asahi sediment bypass tunnel in Japan. The prediction model by Ishibashi (1983) contains some inconsistences in its grinding stress term being much higher than its particle impact term which contradicts statements by other researchers. However, it is shown herein that the model leads to good results if only the particle impact term is considered. The prediction model by Auel *et al.* (2015) shows excellent performance if the abrasion coefficient k_v is adjusted to prototype measurements. The analysis presented herein leads to the conclusion that k_v for concrete is lower than 10^6 being a widely accepted value for bedrock abrasion. Independent of the prediction model, utmost interest has to be laid on the estimation of the sediment transport. The theoretical transport capacity may be much higher than the real transport and should be calibrated using prototype field data such as reservoir bed topography surveys.

Keywords: Reservoir sedimentation, Sediment bypass tunnel, Abrasion prediction model, Hydro-abrasive wear

1 Introduction

The use of sediment bypass tunnels (SBTs) is an effective strategy to counteract reservoir sedimentation. During flood events sediment-laden flows are bypassed around the dam into the tailwater inhibiting sedimentation in the reservoir. Due to high flow velocities in combination with bedload sediment transport, many SBTs worldwide are prone to hydro-abrasive wear as shown in Fig. 1 (Jacobs *et al.* 2001, Sumi *et al.* 2004, Auel and Boes 2011, Boes *et al.* 2014, Nakajima *et al.* 2015, Baumer and Radogna 2015, Müller and Walker 2015).

Abrasion is a wear phenomenon involving progressive material loss due to hard particles forced against and moving along a solid surface. In bedrock rivers, abrasion is the driving process for bed incision (Sklar and Dietrich 2004, 2006, Lamb *et al*. 2008, Turowski 2009) while at hydraulic structures such as spillways, weirs, flushing channels and SBTs abrasion causes severe damage of the invert surface. In general, abrasive damage can always be expected when particle bedload transport takes place. Particles are transported in sliding, rolling or saltation motion depending on the flow conditions causing grinding, rolling or saltating impact stress on the bed. The vertical component of a saltating particle causes the so called *deformation wear*, which is related to the particle impact, whereas the horizontal component causes *cutting wear*, which is related to grinding stress (Bitter 1963a, 1963b). Engel (1978) stated that erosion depends on the sine of the impact angle because the magnitude of the peak tensile stress varies with the normal component of the impact velocity, i.e. the vertical velocity component is the driving factor. Cutting wear caused by the horizontal velocity component is important in ductile materials and in case of highly angular impacting particles, but is not significant when brittle materials are impacted by rounded grains as present in river systems (Head and Harr 1970, Sklar and Dietrich 2004).

A number of models exist to predict abrasion. While the models for the prediction of bedrock incision rate (Sklar and Dietrich 2004, Lamb *et al.* 2008) focus on typical flow conditions in river systems in the sub- and low supercritical flow regime, the others for prediction of abrasion on hydraulic structure surfaces (Ishibashi 1983, Helbig and Horlacher 2007, Auel *et al.* 2015) have to account for highly supercritical flows. In this paper, the abrasion prediction model of Ishibashi (1983) is explained in detail and compared to a model recently developed by Auel *et al.* (2015).

Fig. 1 Concrete invert abrasion at Asahi SBT, Japan (photo: C. Auel).

2 Abrasion prediction models

2.1 Ishibashi model

A widely applied formula in Japan to predict abrasion is given by Ishibashi (1983). He considered both *deformation* and *cutting* wear due to the fact that ductile materials such as steel were also investigated besides the brittle material concrete. As the original work is written in Japanese, a short description of the developed equations is given hereafter. Ishibashi (1983) calculated the abraded invert volume V_a as:

$$V_a = C_1 E_k + C_2 W_f \quad [\mathrm{m}^3] \quad [1]$$

where E_k = total particle kinetic energy by saltating particles, W_f = total friction work by grinding particles, and C_1 and C_2 = material property constants [m²/(kgf)] given in Table 1. Note that the unit kilogram force corresponds to Newton as 1 kgf = 9.806 N. The total kinetic energy E_k is given by:

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

and the total friction work W_f by:

$$W_f = 5.513 \mu_s V_{ts} \sum \gamma_{im} E_i N_i n_i \quad [\mathrm{kgf\,m}] \quad [3]$$

where V_{ts} = amount of transported sediment [m³], μ_s = 0.3 = dynamic friction coefficient, E_i = kinetic energy of a single particle, γ_{im} = particle impact angle, $N_i = L/L_p$ = impact frequency, with L_p = particle saltation length and L = total invert length, and n_i = amount of particles per volume. The value n_i is calculated as:

$$n_i = \frac{(1-\lambda_p)\rho_s}{M_p} \quad [1/\mathrm{m}^3] \quad [4]$$

where λ_p = 0.4 = air porosity, ρ_s = particle density and $M_p = 1/6\pi\rho_s D^3$ = particle mass, with D = mean particle diameter. The single impact energy E_i is calculated as:

$$E_i = \beta F_i^{5/3} \quad [\mathrm{kgf\,m}] \quad [5]$$

where F_i = impact force, and β = auxiliary parameter given as:

$$\beta = \left[2.5 n_1^{2/3} (D/2)^{1/3}\right]^{-1} \quad [\mathrm{m/(kgf)^{2/3}}] \quad [6]$$

where n_1 = auxiliary parameter given as:

$$n_1 = \frac{4}{3(k_1 + k_2)} \quad [\mathrm{kgf/m^2}] \quad [7]$$

where k_1 and k_2 = auxiliary parameter accounting for the Young's modulus and Poisson's ratio of both the particle and invert materials, respectively. Ishibashi (1983) proposed a constant value of $n_1 = 2.41\times10^9$ kgf/m² for sediment gravel transported over concrete.

The abrasion prediction model is based on laboratory data published in Ishibashi and Isobe (1968). Open-channel flow experiments were conducted in a 9 m long, 0.2 m wide and 0.2 m high laboratory flume to investigate the impact forces and saltation trajectories of bedload particles at supercritical flow conditions. Correlations for the particle saltation length L_p, impact force F_i, and impact angle γ_{im} were proposed by Ishibashi (1983) based on Ishibashi and Isobe (1968). L_p follows:

$$\frac{L_p}{D} = 100\left(\theta - \theta_c\right)^{1.21} \qquad [8]$$

with $\theta = U_*^2/[(s-1)gD]$ = Shields parameter, U_* = friction velocity, $s = \rho_s/\rho$ with ρ = fluid density, and θ_c = critical Shields parameter. θ_c for fixed beds with low relative roughness heights is given by Ishibashi (1983) based on Novak and Nalluri (1975) as:

$$\theta_c = 0.0907 D_*^{-2/5} \qquad [9]$$

where $D_* = [(s-1)gD^3]^{0.5}/\nu$ = dimensionless grain size with ν = kinematic viscosity. The impact force F_i is given as follows:

$$F_i = 1.95\times10^3 M_p^*\left(\theta - \theta_c\right) \quad \text{[kgf]} \qquad [10]$$

where $M_p^* = 1/6\pi(\rho_s-1000)D^3$ = submerged particle weight in [kg]. The impact angle is approximated as:

$$\gamma_{im} \approx \frac{U_p}{V_s} = 19.2\left(\theta - \theta_c\right)^{-0.13} \quad \text{[-]} \qquad [11]$$

where V_s = vertical particle settling velocity in still water, and U_p = horizontal particle velocity.

Tab. 1 Material property constants (Ishibashi 1983)

Material	C_1 [m²/(kgf)]	C_2 [m²/(kgf)]
Concrete	1.189×10^{-7}	1.135×10^{-8}
Steel (SM 41)	3.73×10^{-11}	6.59×10^{-11}
Steel (HT 80)	2.53×10^{-11}	4.78×10^{-11}
Steel (SUS 304)	2.04×10^{-11}	3.25×10^{-11}
Steel (SCMnH 11)	1.18×10^{-11}	1.33×10^{-11}

2.2 Auel model

Based on open-channel flow experiments in a laboratory flume conducted by Auel (2014), an abrasion prediction model applicable for hydraulic structures prone to supercritical flows was proposed by Auel *et al.* (2015). The model is based on the state-of-the-art saltation abrasion model by Sklar and Dietrich (2004) developed to estimate abrasion in bedrock river systems. The abrasion rate A_r is calculated as:

$$A_r = \frac{Y_M}{k_v f_t^2} W_{im}^2 \cdot I \cdot q_s \quad \text{[m/s]} \qquad [12]$$

where k_v = abrasion resistance coefficient, Y_M = Young's Modulus of elasticity of the invert material [Pa], f_t = invert material splitting tensile strength [Pa], W_{im} = mean vertical particle impact velocity [m/s], I = impact rate [1/m], and q_s = specific gravimetric bedload rate [kg/(sm)]. The number of impacts per unit length I is defined as the reciprocal value of the particle saltation length L_p as:

$$I = \frac{\left(1-\left(U_*/V_s\right)^2\right)^{0.5}}{L_p}\left(1 - P_R\right) \quad \text{[1/m]} \qquad [13]$$

where P_R = rolling probability. The numerator of the first term on the right hand side is proposed by Sklar and Dietrich (2004) and accounts for the mode shift from saltation to suspension. The rolling probability P_R follows (Auel 2014):

$$P_R = 8.5\times10^{-4}\left(\theta\left(\frac{k}{D}\right)^2\right)^{-0.55} \qquad [14]$$

with k = geometric roughness height and D = mean particle diameter. The hop length L_p for supercritical flows is given with (Auel 2014, Auel *et al.* 2015):

$$\frac{L_p}{D} = 251\theta \qquad [15]$$

Auel *et al.* (2015) found a simple linear correlation of W_{im} to the friction velocity U_* as

$$W_{im} = U_* \quad \text{[m/s]} \qquad [16]$$

Additionally, Auel *et al.* (2015) analyzed bedrock abrasion laboratory experiments and compared them to concrete abrasion tests. It was suggested to use the abrasion coefficient value $k_v = 10^6$ given by Sklar and Dietrich (2004) for bedrock abrasion as well as for concrete structures. Based on field data of Asahi SBT, it is shown in the following that k_v varies from the above mentioned value and should be adjusted for concrete inverts accordingly.

3 Procedure of model comparison

Comparison of the two prediction models is done by analyzing prototype data of the Asahi River, reservoir and SBT in Kii Peninsula, Japan. The reservoir is operated by *Kansai Electric Power Co. Inc.* and is part of the Okuyoshino pump storage hydropower scheme together with the upper Seto dam. The reservoir has been facing severe sedimentation since its inauguration in 1978 due to large flood events caused by heavy rainfall and typhoons (Harada *et al.* 1997, Nakajima *et al.* 2015). To counter the ongoing sedimentation, a SBT was constructed in 1998 with a design discharge of Q_d = 140 m^3/s. The total tunnel length of 2,383.5 m includes an 18.5 m long steel-lined inlet section, a 2,350 m long concrete-lined tunnel and a 15 m long concrete-lined outlet. The tunnel is b = 3.80 m wide with a slope of S_b = 0.029. Since its inauguration the tunnel faces severe abrasion up to several decimeters. *Kansai Electric* conducts regular invert abrasion measurements on an annual basis (Fig. 2).

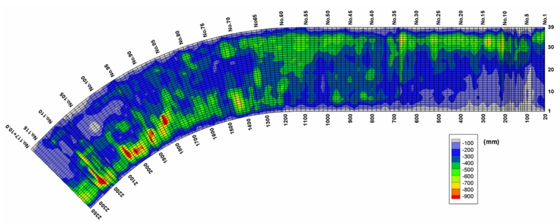

Fig. 2 Cumulative abrasion pattern of Asahi SBT from 1998 to 2011. Flow from right to left (adapted from Nakajima *et al.* 2015).

Abrasion is measured manually every 2 m in the streamwise and every 10 cm in the lateral direction. In case of deep scour holes in between the 2 m sections, the streamwise distance is adapted accordingly. The tunnel invert was originally lined with a concrete of compression strength f_c = 30 MPa. During annual maintenance works the invert was successively lined with 70 MPa concrete. The annual ratio of old to new concrete is given in Fig. 3 (Nakajima *et al.* 2015).
The discharge in the upstream Asahi River reach is given on an hourly basis. The catchment is rather steep with a river bed slope varying from S_b = 0.03 to 0.10 and river widths varying from about 20 to 40 m. The transported sediment has been calculated by *Newjec Inc.* by means of a 1D numerical model using the bedload formula of Ashida and Michiue (1972) and calibrated with data of annual reservoir bed topography surveys (Harada *et al.* 1997, Kataoka 2000, 2003). As a result *Newjec* provided a correlation of the river discharge to the amount of transported sediment which is used in the presented calculations.

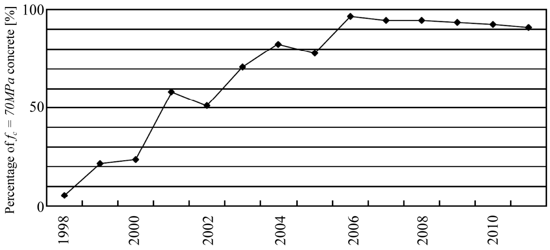

Fig. 3 Percentage of high performance concrete (f_c = 70 MPa) on tunnel invert (adopted from Nakajima *et al.* 2015).

Fig. 4 shows the annual sediment amount bypassed through the tunnel compared to the measured invert abrasion. Note that the bypassed sediment volume given in Fig. 4 is calculated from the given raw-data and slightly differs from a similar figure given in Nakajima *et al.* (2015) due to the following reasons: Firstly, Q_s is calculated with a sediment diameter D_{50} = 7.5 cm based on a recent survey (Awazu 2015) whereas the latter is based on field survey data where D_{50} = 5 cm was found. Secondly, herein only the mean diameter is taken into account, whereas in Nakajima *et al.* (2015) a fraction-wise sediment transport is applied accounting for the entire size distribution.

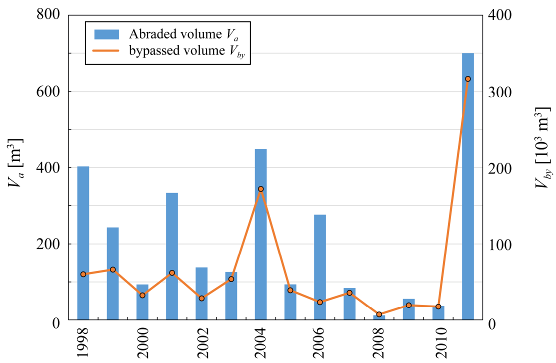

Fig. 4 Abraded invert volume and bypassed sediment volume of Asahi SBT from 1998 to 2011.

4 Results and discussion

Calculations for both models are made using a mean grain size diameter of D = 7.5 cm to estimate both the sediment transport and the abrasion volume. A fraction-wise calculation considering the grain size distribution was not carried out.

4.1 Ishibashi model

The results of the abrasion prediction model given in

Eq. (1) by Ishibashi (1983) are shown in Fig. 5. The kinetic impact and grinding stress terms C_1E_k and C_2W_f, respectively, are separated to better understand their effects. The total abraded volume V_a is the sum of the two terms. To compare the results the relative change δ is calculated as

$$\delta = \frac{V_{a,estimate} - V_{a,real}}{V_{a,real}} \cdot 100 \quad [\%] \qquad [17]$$

The results show that the abrasion volume is largely overestimated by $\delta = 190 \pm 118\%$ considering both terms. The grinding stress term is in average 2.6 times higher than the kinetic impact term. Considering the fact that W_f has a negligible effect in case of brittle materials (Head and Harr 1970) and is neglected by other researchers (Sklar and Dietrich 2001, 2004, Auel *et al.* 2015), the value should be at least smaller than C_1E_k. Additionally, Auel (2014) showed for an exemplary calculation that the energy induced by rolling and sliding motion of a particle on a concrete surface is about 10% and 0.1%, respectively, compared to the kinetic energy by saltating particles. Hence, the conclusion may be drawn that the grinding stress term in Eq. (1) is only appropriate in case of ductile materials and should not be considered in case of brittle inverts such as concrete. It is proposed to omit the grinding stress term and rewrite Eq. (1) as:

$$V_a = C_1 \cdot 1.5 V_{ts} \sum E_i N_i n_i \quad [\mathrm{m}^3] \qquad [18]$$

Fig. 5 reveals a good agreement of the measured to the estimated data applying only the kinetic energy as given in Eq. (18). The average deviation over 14 years is only $\delta = 35 \pm 23\%$.

A disadvantage of the Ishibashi model is the fact that the material properties are only considered in the coefficients C_1 and C_2 (Table 1). These coefficients are constant for concrete, however, the material strength which largely affects the abrasion depth is not accounted for in the estimation of the abrasion volume.

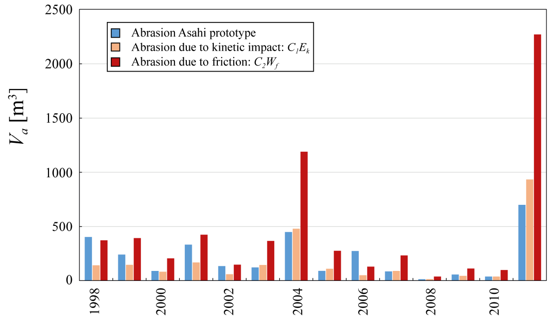

Fig. 5 Measured abraded invert volume of Asahi SBT from 1998 to 2011 and comparison with abrasion volume prediction by Ishibashi (1983).

4.2 Sensitivity of abrasion resistance coefficient k_v

Auel *et al.* (2015) discussed the sensitivity of k_v stating that the coefficient is probably not a constant but dependent on the material properties based on statements from Chatanantavet and Parker (2009) and Turowski *et al.* (2013). Furthermore, Sklar and Dietrich (2004, 2012) showed that k_v ranges from 1 to 9×10^6 for different materials. Fig. 8 shows k_v as a function of f_t for a number of research studies including rock and concrete samples. The splitting tensile strength for concrete is calculated using a correlation to the cubed compression strength f_c after Arioglu *et al.* (2006) and EN 1992-1-1 as:

$$f_t = 0.387\left(0.8 f_c\right)^{0.63} = 0.336 f_c^{0.63} \quad [\mathrm{MPa}] \qquad [19]$$

Six rock and three concrete samples from Sklar and Dietrich (2004) are plotted as well as two theoretical bedrock values by Chatanantavet and Parker (2009). By means of a scaling analysis, the latter proposed $k_v = 10^4$ for weak and $k_v = 10^6$ for hard rock, respectively. Herein, f_t = 1 MPa and 15.5 MPa is assumed for weak and hard rock, respectively, based on values given in Sklar and Dietrich (2001). The values from Auel (2014) are obtained from laboratory experiments using weak mortar as a substitute to allow for invert abrasion in short time. Values range from $k_v = 8(\pm 5) \times 10^2$ to $6(\pm 6) \times 10^3$. Data of Helbig *et al.* (2012) were obtained from rotating drum experiments. 30×30 cm concrete sample plates were mounted in a drum filled with both 10 kg of steel spheres and 10 kg of water. The drum rotates around a horizontal axis with a radius of 43 cm where the concrete samples immerge into the water-sphere mixture at every rotation. Abrasion is measured after different time steps by both laser scanning and weighing. All hydraulic parameters required to estimate k_v from Eq. (12) can be calculated using the rotational velocity and the time the sample is submerged. However, one parameter, the saltation length L_p, turns out to be difficult to estimate. When the sample immerges into the water, the spheres start to impact the sample surface. Depending on the sphere size (D = 4.4 to 8 mm) about 4,782 to 28,744 spheres are present in the water corresponding to 0.3 to 2.1 spheres/cm^3. Additionally, due to the rotation, some spheres are transported towards a higher location inside the drum and drop back into the water. Both the large amount and the falling spheres lead to a very high impact rate. Hence it is assumed that L_p is in the range of a millimeter. In Fig. 8, three data groups of Helbig *et al.* (2012) are plotted corresponding to L_p = 0.1, 1 and 5 mm, resulting in corresponding k_v values of 3.1(±0.8)×10^6, 3.1(±0.8)×10^5 and 6.2(±1.7) ×10^4, respectively. A precise estimate of L_p is difficult, but due to the large amount of particles in the drum, the values of 0.1 and 1 mm seem to be most adequate. Finally, the prototype data from Asahi SBT are calculated and additionally presented in Fig. 7. The data fit into the range of Helbig's data with L_p = 1 mm.

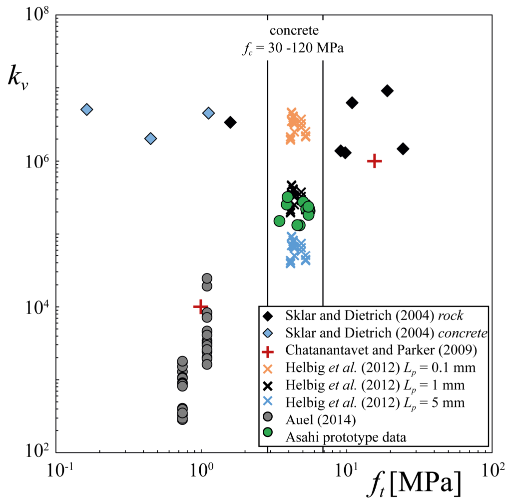

Fig. 7 Abrasion coefficient k_v as a function of splitting tensile strength f_t.

The data do not follow a clear trend. The sets of Auel (2014), Chatanantavet and Parker (2009), the rock set of Sklar and Dietrich (2004), and the prototype data of Asahi indicate an increase of k_v with increasing tensile strength. However, the concrete data of Sklar and Dietrich (2004) show high k_v values even for low f_t, and the data set of Helbig *et al.* (2012) largely depends on the estimation of L_p and does not allow for precise analysis. Further investigation is needed to adequately define the correlation of k_v to the invert material properties.

4.3 Auel model

Applying the prediction model given in Eq. (12) leads to the results given in Fig. 8. As the tunnel invert concrete strength varied over time (Fig. 3), Eq. (12) was applied for both material strengths, i.e. f_c = 30 MPa and 70 MPa, and averaged using the ratio given in Fig. 3. Auel *et al.* (2015) proposed an abrasion coefficient k_v = 10^6 if no additional abrasion measurement data are available. Applying this value leads to an underestimation of the real abrasion volume of about δ = 80±7% in average over 14 years (Fig. 8).

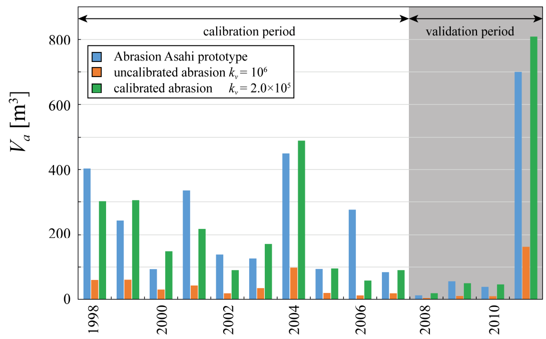

Fig. 8 Measured abraded invert volume of Asahi SBT from 1998 to 2011 and comparison with abrasion volume predictions by Auel *et al.* (2015) based on k_v values calibrated from the 1998 to 2006 data.

However, a calibration is possible, as the real abrasion at Asahi SBT is known. The total measurement period from 1998 to 2011 has been divided into a calibration period (1998 to 2006) and a validation period (2007 to 2011). The abrasion coefficient has been calculated for the calibration period, leading to a value of k_v = 2.0×10^5. Applying this value to the validation period leads to the results given in Fig. 8. The abrasion volumes in 2008 and 2010 are of minor extent leading to an overestimation of 54% and 26%, respectively. However, neglecting these two values, thus taking into account only the three years with considerable abrasion in 2007, 2009, and 2011 leads to a deviation of only δ = 12±4%.

5 Conclusion

Herein, the two abrasion prediction models by Ishibashi (1983) and Auel *et al.* (2015) developed for hydraulic structures prone to supercritical flows are compared. Both models are validated using prototype data from the Asahi sediment bypass tunnel (SBT) in Japan showing good agreement if adjusted and calibrated.

The prediction model by Ishibashi (1983) reveals certain inconsistencies in its grinding stress term accounting for the *cutting wear*. It is proposed to omit this term in case of brittle materials such as concrete. The model leads to good results if the grinding stress is not considered.

The prediction model by Auel *et al.* (2015) shows excellent performance if adjusted to the prototype measurements. However, if prototype abrasion measurements are not available, a k_v value has to be assumed. The analysis presented herein leads to the conclusion that k_v is lower for concrete than the widely applied value of $k_v = 10^6$ valid for bedrock abrasion. A value around 2.0×10^5 seems to be more adequate in case of Asahi SBT. However, more research on prototype hydraulic facilities as well as laboratory experiments should be conducted to amplify the knowledge of the variation of k_v. Hagmann *et al.* (2015) conduct research at three Swiss SBTs where abrasion volumes as well as sediment transport are measured. These results are expected to complement and enhance the present results.

Independent of the prediction model, utmost focus has to be put on the estimation of the sediment bedload transport as both models are directly correlated to it. The theoretical transport capacity is not always adequate, as the real transport may be much lower. The transport has to be calibrated using prototype data such as periodical sedimentation survey data of the reservoir or direct measurements such as geophones or plate microphones (Hagmann *et al.* 2015, Koshiba 2015). Furthermore the upstream riverbed slope, the river cross-sections as well as the particle size distribution should be analyzed as precisely as possible. In the case of the Asahi River, the theoretical capacity applying local values of bed slope and river width surveyed directly upstream of the SBT intake (Awazu 2015) lead to about 9 times higher theoretical sediment transport capacity as the data evaluated by *Newjec Inc.* using the real reservoir survey data as calibration. This large difference underlines the need for precise estimation of the real sediment transport impacting the hydraulic structure.

Acknowledgments

The support of Sohei Kobayashi and Takahiro Koshiba regarding the translation of Ishibashi's work is gratefully acknowledged. Furthermore, the first author acknowledges the financial support of the Japanese Society for the Promotion of Science (JSPS).

Notation

A_r	vertical abrasion rate	[m/s]
B	tunnel width	[m]
C_1,C_2	material property constants	[m^2/(kgf)]
D	particle diameter	[m]
D_*	dimensionless grain size	[-]
E_i	kinetic energy of a single particle	[kgf]
E_k	kinetic energy by saltating particle	[kgf m]
F_i	impact force	[kgf]
f_c	cubed compression strength	[Pa]
f_t	splitting tensile strength	[Pa]
g	gravitational acceleration	[m/s^2]
h	flow depth	[m]
H_p	particle saltation height	[m]
I	number of particle impacts	[1/m]
k	bed roughness height	[m]
k_1, k_2	auxiliary parameter	[m^2/kgf]
k_v	rock resistance coefficient	[-]
L	total invert length	[m]
L_p	particle saltation length	[m]
M_p	particle mass	[kg]
M_p^*	submerged particle weight	[kg]
N_i	L/L_p = impact frequency	[-]
n_i	amount of particles per volume	[1/m^3]
n_1	auxiliary parameter	[kgf/m^2]
P_R	rolling probability	[-]
Q_d	design discharge	[m^3/s]

Q_s	gravimetric bedload rate	[kg/s]
q_s	specific gravimetric bedload rate	[kg/(sm)]
s	density ratio $s = \rho_s/\rho$	[-]
S_b	bed slope	[-]
U	uniform flow velocity	[m/s]
U_p	horizontal particle velocity	[m/s]
U_*	friction velocity $U_* = (gR_hS)^{0.5}$	[m/s]
V_a	abraded volume	[m^3]
V_{ts}	amount of transported sediment	[m^3]
V_s	particle settling velocity	[m/s]
W_{im}	vertical particle impact velocity	[m/s]
W_f	friction work due to grinding stress	[kgf m]
Y_M	Young's Modulus of elasticity	[Pa]
β	auxiliary parameter	[m/(kgf)$^{2/3}$]
γ_{im}	particle impact angle	[-]
δ	relative change	[%]
θ	Shields parameter $\theta = U_*^2/[(s-1)gD]$	[-]
θ_c	critical Shields parameter	[-]
λ_p	air porosity	[-]
μ_s	dynamic friction coefficient	[-]
v	kinematic viscosity	[m^2/s]
ρ	fluid density	[kg/m^3]
ρ_s	particle density	[kg/m^3]

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(Received June 11, 2015)