Abrasion Damage Estimation of Sediment Bypass Tunnels: Comparison between Swiss and Japanese Formulas

〇Christian AUEL, Tetsuya SUMI

1. Introduction

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; Lamb et al., 2008), while in hydraulic structures such as spillways, weirs, flushing channels and sediment bypass tunnels abrasion causes severe damage of the concrete invert surface as shown in Fig. 1 (Jacobs et al., 2001; Sumi et al., 2004; Auel and Boes, 2011; Auel 2014; Boes et al., 2014). 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. According to Sklar and Dietrich (2001; 2004) the governing process causing abrasion is saltation, whereas sliding and rolling do not cause significant wear. A number of models exist to predict the abrasion rate. While the models for 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 rate on concrete surfaces (Ishibashi, 1983; Auel et al., 2015b) have to account for highly supercritical flows.

Fig. 1 Invert abrasion of Palagnedra bypass tunnel, Ticino, Switzerland (Auel 2014)

2. Abrasion prediction models

Based on open-channel flow experiments in a laboratory flume conducted by Auel (2014) a saltation abrasion model applicable for hydraulic structures prone to supercritical flows was proposed by Auel et al. (2015b) as:

$$A_r = \frac{1}{k_v}\frac{Y_M}{f_t^2} W_{im}^2 \cdot I \cdot q_s \qquad \text{[m/s]} \qquad [1]$$

where W_{im} = mean vertical particle impact velocity, Y_M = Young's Modulus of elasticity, k_v = abrasion resistance coefficient, and q_s = specific gravimetric bedload rate. The number of impacts per unit length I is defined as the reciprocal value of the particle saltation length L_p as:

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

where U_* = friction velocity, V_s = particle settling velocity, and 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 and hop length L_p for supercritical flows are given in Auel et al. (2015a). Auel et al. (2015b) found a correlation of W_{im} to the friction velocity U_* and proposed $W_{im} = U_*$. Furthermore, the value $k_v = 10^6$ given by Sklar and Dietrich (2004) for bedrock abrasion may be applied as well for concrete structures (Auel et al., 2015b).

A widely applied formula in Japan to predict abrasion is given by Ishibashi (1983). He conducted open-channel flow experiments in a 9 m long, 0.2 m wide and 0.2 m high laboratory flume and proposed correlations for the particle saltation length L_p, particle impact angle γ_{im} and impact force F_i. Based on his findings the abraded invert volume V_a is calculated as:

$$V_a = C_1 E_k + C_2 E_f \qquad \text{[m}^3\text{]} \qquad [3]$$

where E_k = total particle kinetic energy by saltating particles, E_f = total friction energy by grinding particles, and C_1 and C_2 = material property constants [m^2/(kgf)]. The total kinetic energy E_k is given by:

$$E_k = 1.5 V_{ts} \sum E_i N_i n_i \qquad \text{[kgf m]} \qquad [4]$$

The total friction energy E_f is given by:

$$E_f = 5.513 \mu_s V_{ts} \sum \gamma_{im} E_i N_i n_i \qquad \text{[kgf m]} \qquad [5]$$

where V_{ts} = amount of transported sediment [m^3], μ_s = dynamic friction coefficient, E_i = kinetic energy of single particle, $N_i = L_p/L$ = impact frequency with L = total invert length, and n_i = amount of particles per volume:

$$n_i = \frac{(1-\lambda_p)\rho_s}{M_p} \qquad [1/\text{m}^3] \qquad [6]$$

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

$$E_i = \beta F_i^{5/3} \qquad \text{[kgf m]} \qquad [7]$$

where β = auxiliary parameter given as:

$$\beta = \left[2.5 n_1^{2/3} \left(D/2\right)^{1/3}\right]^{-1} \qquad [\text{m/(kgf)}^{2/3}] \qquad [8]$$

where n_1 = auxiliary parameter given as:

$$n_1 = \frac{4}{3\left(k_1 + k_2\right)} \qquad [\text{kgf/m}^2] \qquad [9]$$

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.

3. Conclusions

Herein, the saltation-abrasion model for supercritical flows developed by Auel et al. (2015b) is compared to the abrasion model of Ishibashi (1983) applying prototype data from a Japanese sediment bypass tunnel.

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References

Auel, C. and Boes, R.M. (2011): Sediment bypass tunnel design – review and outlook. Proc. ICOLD Symposium "Dams under changing challenges" (A.J. Schleiss & R.M. Boes, eds.), 79th Annual Meeting, Lucerne. Taylor & Francis, London, UK, pp. 403-412.

Auel, C. (2014): Flow characteristics, particle motion and invert abrasion in sediment bypass tunnels. PhD thesis 22008, also published as VAW-Mitteilung 229 (R. Boes, ed.), ETH Zurich, Switzerland.

Auel, C., Albayrak, I., and Boes, R.M. (2015a): Particle motion in supercritical open channel flows. Journal of Geophysical Research: Earth Surface (in preparation).

Auel, C., Albayrak, I., Sumi, T., and Boes, R.M. (2015b): Saltation abrasion model for hydraulic structures. Proc. 1st Int. Sediment Bypass Tunnel Workshop, ETH Zurich, Switzerland (submitted).

Boes, R.M., Auel, C., Hagmann, M., and Albayrak, I. (2014): Sediment bypass tunnels to mitigate reservoir sedimentation and restore sediment continuity. Reservoir Sedimentation (Schleiss, A.J., De Cesare, G., Franca, M.J., Pfister, M., eds.), Taylor & Francis, London, UK, pp. 221-228.

Ishibashi, T. (1983): Hydraulic study on protection for erosion of sediment flush equipments of dams. Civil Society Proc. Vol. 334, No. 6, pp. 103-112 (in Japanese).

Jacobs, F., Winkler, K., Hunkeler, F., and Volkart, P. (2001): Betonabrasion im Wasserbau (Concrete abrasion in hydraulic structures). VAW-Mitteilung 168 (H.-E. Minor, ed.), ETH Zurich, Switzerland (in German).

Lamb, M.P., Dietrich, W.E., and Sklar, L.S. (2008): A model for fluvial bedrock incision by impacting suspended and bed load sediment. Journal of Geophysical Research Vol. 113, No. F03025, 18p.

Sklar, L.S., and Dietrich, W.E. (2001): Sediment and rock strength controls on river incision into bedrock. Geology Vol. 29, No. 12, pp. 1087-1090.

Sklar, L.S., and Dietrich, W.E. (2004): A mechanistic model for river incision into bedrock by saltating bed load. Water Resources Research Vol, 40, No. W06301, 21p.

Sumi, T., Okano, M., and Takata, Y. (2004): Reservoir sedimentation management with bypass tunnels in Japan. Proc. 9th International Symposium on River Sedimentation, Yichang, China, pp. 1036-1043.