Bypass tunnels to route sediment around dams

Robert M. Boes, M. Müller-Hagmann, C. Auel, M. Facchini, I. Albayrak, A. Siviglia

*Sediment Management in channel networks: from measurements to best practices*

Bozen-Bolzano, 8 November 2018
Content

Bypass tunnels (SBTs) to route sediment around dams

1. MOTIVATION

2. CHARACTERISTICS AND HYDRAULICS OF SBTs

3. HYDRO-ABRASION OF SBTs

4. DOWNSTREAM MORPHOLOGICAL EFFECTS OF SBTs

5. CONCLUSIONS
1. MOTIVATION

Aggradation pattern in *Gries reservoir*, Switzerland, with lowered reservoir level during refurbishment works at the dam on 2 July 2015

Photo: D. Ehrbar, VAW
Reservoir sedimentation

Increasing demand vs. decreasing capacity
Sediment deficit in the downstream

→ Sustainable use of reservoirs requires efficient sediment management

Based on White (2001), ICOLD (2009) and Annandale (2013)
Sediment management to counter reservoir sedimentation

1. Sediment yield reduction in the catchment
2. Sediment routing
3. Sediment removal
4. Optimized reservoir and dam layout and location
2. CHARACTERISTICS AND HYDRAULICS OF SBTs
Characteristics of Sediment Bypass Tunnels (SBTs)

Effects:
- Reduce reservoir sedimentation
- (partly) restore pre-dam sediment transport
- Recover downstream reach from sediment deficit

Operating conditions:
- High-velocity flow
- High sediment transport rates

→ Hydro-abrasion
Typical application range of SBTs

Sediment bypassing:
CIR < 0.3 … 0.4

Outlet of SBT Sera (CH)

Photo: R. Boes

Source: adapted from Sumi (2005)
Location of intake structure

Typically requires partial reservoir drawdown

Source: Auel & Boes (2011)
Examples of SBTs

SBT Patrind, Pakistan

SBT particularly apt for smaller reservoirs, where

- delta formation by coarse material (bed load) is dominant
- deposition of fines (suspended load) is rather small due to short resident times
- tunnel length is short
- water availability is high

Source: VAW (2015)
Hydraulic characteristics of SBTs

- Free-surface, transition or pressurized flow
- **Supercritical flow**, typically with $F_d < 3.2$ at design flow $Q_d$ (Auel 2015)
- Significant sediment transport
- Typical design flow capacity 5- to 10-year flood

Free-surface flow for small $Q$

Possibly transition flow regime with increasing $Q$
- pulsations / pressure surges
  → requires proper tunnel lining design

Possibly pressurized flow for large $Q$:
  → generally decisive load case for design of SBT diameter
Combination sediment routing / removal

*bypassing / flushing / mechanical dredging*

Example of SBT Pfaffensprung (CH)

Source: adapted from Schweizer Bauzeitung (1925/26)
Combination sediment routing / removal
bypassing / flushing / mechanical dredging

Example of SBT Pfaffensprung (CH)

Source: adapted from Schweizer Bauzeitung (1925/26)
3. HYDRO-ABRASION OF SBTs
How to limit hydro-abrasion?

1) **Minimize loads** by optimized flow conditions → SBT layout

2) **Select suitable invert material** to maximize resistance → use **mechanistic abrasion models** for **life-cycle cost** approach
1) SBT design: tunnel layout in plan view

Effect of SBT alignment in plan view

→ Avoid bends if possible
1) SBT design: tunnel layout in cross section

Effect of SBT cross section – 2D vs. 3D flow

Lab study of invert abrasion

F = 1.8, \( h_0 = 100 \text{ mm} \), \( S_b = 0.01 \), \( Q_S = 0.200 \text{ kg/s} \), \( D_b = 10.6 \text{ mm} \), \( t = 930 \text{ min} \)

\( F \) \hspace{1cm} \text{Froude number} \hspace{1cm} \( S_b \) \hspace{1cm} \text{Bed slope}
\( h_0 \) \hspace{1cm} \text{Approach flow depth} \hspace{1cm} \( D_b \) \hspace{1cm} \text{Particle diameter}
\( Q_S \) \hspace{1cm} \text{Sediment transport rate [kg/s]} \hspace{1cm} \( t \) \hspace{1cm} \text{Test duration}

Source: Auel (2014)
1) SBT design: tunnel layout in cross section

Effect of SBT cross section – 2D vs. 3D flow

Field study at SBT Runcahez – Invert Abrasion (1996 - 2014)

- Incision channels along the tunnel walls
  → 3D-flow structures in narrow open channel flows

1) SBT design: tunnel layout in cross section

*Effect of SBT cross section – 2D vs. 3D flow*

**lab study**

Source: Auel (2014)

- $b/h = 2.8$
- $F = 1.8$

Normalized bed shear stress

$\tau/\bar{\tau}$

**field study**


- $b/h = 1.9$
- $F = 1.7$
2) Mechanistic abrasion modelling

Transport mode and impact

- Sliding
- Rolling
- Saltation

Abrasion models

**Saltation abrasion models**

- (bed load)
  - Sklar & Dietrich (2004)
  - Auel et al. (2017)

**Total abrasion models**

- (bed load and suspended load)
  - Lamb et al. (2008)
2) Mechanistic abrasion modelling - Saltation Abrasion Model

Sklar and Dietrich (2004):

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

- \( A_r \) = Abrasion rate [m/s]
- \( k_v \) = Abrasion coefficient [-]
- \( Y_M \) = Young’s modulus
- \( f_t \) = Splitting tensile strength
- \( W_{im} \) = Vertical impact velocity
- \( L_p \) = Particle hop length
- \( q_s \) = Specific bedload transport rate
- \( q_s^* \) = Specific bedload transport capacity

- Abrasion coefficient
- Material resistance
- Energy flux term
- Cover effect term

Auel et al. (2017)

\[ A_r \approx \frac{Y_M}{k_v f_t^2} \frac{0.1(T^*)^{0.39} [(s-1)gD^{0.5}]^2}{2.3(T^*)^{0.8} D} \frac{q_s}{q_s^*} \left( 1 - \frac{q_s}{q_s^*} \right) \]

\[ \approx \frac{Y_M}{k_v f_t^2} \frac{(s-1)g}{230} \frac{q_s}{q_s^*} \left( 1 - \frac{q_s}{q_s^*} \right) \]
2) Mechanistic abrasion modelling - Saltation Abrasion Model

Abras ion Coefficient

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

- Abrasion coefficient
- Material resistance
- Energy flux term
- Cover effect term

Sklar and Dietrich (2004):
- Laboratory experiments
- Mortars and rocks
- \(k_v = (1.30 - 9.09) \times 10^6\)

Auel et al. (2017):
- Japanese SBT Asahi
- Concrete \(f_c = 36/70\) MPa
- \(k_v = (1.9 \pm 0.7) \times 10^5\)

→ Prototype data from 3 Swiss SBTs to validate and calibrate \(k_v\)
2) Mechanistic abrasion modelling

**Abrasion Coefficient - Calibration**

- $k_v$ increases with $f_t$
- Material-specific $k_v$
- $k_v$: granite > concrete
- Scatter due to:
  - measurement errors
  - model uncertainties
  - abrasiveness of sediment not yet considered
2) Select suitable invert material

Cost-Effectiveness Analysis - SBT Pfaffensprung field study

Net present value (NPV):

\[
NPV = \sum_{t=0}^{T} \frac{C_t}{(1+r)^t}
\]

\(T\) = accounting period (here 80 yr)

\(C_t\) = net cash flow at time point \(t\)

\(r\) = interest rate (here 3%)

Input parameters / assumptions:

- Actual investment cost
- Maintenance costs: 25 CHF/(m²yr)
- Replacement at abrasion depths ≥ 20 cm → mechanistic abrasion modelling

Cost-effectiveness:

\(T < 75\) yr: Concrete > granite

\(T ≥ 75\) yr: Concrete < granite
4. DOWNSTREAM MORPHOLOGICAL EFFECTS OF SBTs
Test case Solis
Overview

- Solis reservoir on Albula River (CH)

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full supply level</td>
<td>823.75 m asl</td>
</tr>
<tr>
<td>Reservoir volume</td>
<td>4.1 Mio. m³</td>
</tr>
<tr>
<td>Catchment area</td>
<td>900 km²</td>
</tr>
<tr>
<td>Length</td>
<td>3.3 km</td>
</tr>
<tr>
<td>Sedimentation rate</td>
<td>2% / yr</td>
</tr>
</tbody>
</table>
Test case Solis

**SBT features**

- Commissioned in 2012
- 973 m long, bed slope 1.9 %
- Max. discharge capacity 170 m³/s
- ca. 10 SBT operations during floods until now (autumn 2018)
- Largest events: 13-08-2014 and 16-06-2016
  
  mean SBT discharge: 153 / 129 m³/s, duration: 14 / 24 hours
  
  total bypassed sediment volume: ~22'000 / 23’000 m³
Test case Solis

*Morphological effects in Albula*

- **deposition and erosion volumes** between 10/2014 and 10/2016 after 37 h of SBT operation with ~40'000 m³ of bypassed sediment

Source: Facchini (2017)
Sediment budget from DEM$^2$ of Difference

Example of erosion-deposition patterns

$^2$DEM stands for Digital Elevation Model
Sediment budget from DEM of Difference

Volumes involved

- ~12,500 m³
- ~8,000 m³
- ~4,500 m³
Morphological effects of SBTs

- sediment load to downstream is largely affected by
  - location of intake structure
  - shape of reservoir and operation of reservoir level
  - extent of delta

- with increasing operation duration (decades to centuries) the downstream morphology (1D effect, i.e. river bed level) slowly approaches the pre-dam conditions (mobile-bed equilibrium)

- reworking of bed material (away from static armour towards mobile-bed composition) occurs much faster than adaptation of longitudinal slope

- monitoring and continuous adaptation of operation needed to avoid negative effects and promote sediment relocation with positive ecological effects
4. CONCLUSIONS
Conclusions

*Bypass tunnels to route sediment around dams*

- **SBTs** are a means to route sediment around dams for **CIR < 0.3…0.4**
- **Optimal hydraulic and structural design** needed to minimize adverse effects
- **Avoid bends** in plan view if possible
- **Local invert strengthening is an option** to avoid abrasion concentration induced by 3D flow structures
- **Optimum invert material** in terms of life-cycle cost can be selected based on abrasion predictions using **mechanistic models with adequate $k_v$ values**
- **SBTs help improve morphology downstream of reservoirs** by
  - Reworking of bed material within short time (few operations)
  - Adaptation of longitudinal slope (morphological 1D effect) over long periods (> decades)
THANK YOU FOR YOUR ATTENTION