Draft Bulletin Workshop

ICOLD Technical Committee on Sedimentation of Reservoirs

Sediment Bypassing and Transfer

Robert Boes
Laboratory of Hydraulics and Glaciology,
ETH Zurich, Switzerland

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4.4.1 Mechanistic Hydro-abrasion Models

$$A_r = \begin{cases} \boxed{\dfrac{Y_M}{k_v f_{st}^2}} \boxed{\dfrac{g(s-1)}{112}(T^*)^{-0.07} q_s} \boxed{\exp\left(-\dfrac{q_s}{q_s^*}\right)} \boxed{\left(\dfrac{MH}{MH_B}\right)^{1.3}} \boxed{\left[1-1.05(T^*)^{-0.90}\right]}, & \text{for } q_s < q_s^* \text{ and } 1 \le \dfrac{MH}{MH_B} \le 2.3 \\ \dfrac{Y_M}{k_v f_{st}^2} \dfrac{g(s-1)}{112}(T^*)^{-0.07} q_s \exp\left(-\dfrac{q_s}{q_s^*}\right) \boxed{\left(\dfrac{MH}{MH_B}\right)^{0.3}} \left[1-1.05(T^*)^{-0.90}\right], & \text{for } q_s < q_s^* \text{ and } \dfrac{MH}{MH_B} < 1 \\ 0 & , \text{for } q_s \ge q_s^* \end{cases}$$

- □ Material resistance
- □ Energy flux term
- □ Cover effect term
- □ Particle hardness effect
- □ Saltation probability

A_r [m/s] = spatially averaged vertical hydro-abrasion rate per unit time

k_v [-] = hydro-abrasion resistance coefficient

Y_M [Pa] = Young's modulus of the bed lining material

f_{st} [Pa] = splitting tensile strength of the bed lining material

$s = \rho_s/\rho_w$ = relative paricle density

$T^* = \theta/\theta_c - 1$ [-] = excess transport stage

q_s [kg/(ms)] = unit gravimetric bedload transport rate

q^*_s [kg/(ms)] = unit gravimetric bedload transport capacity

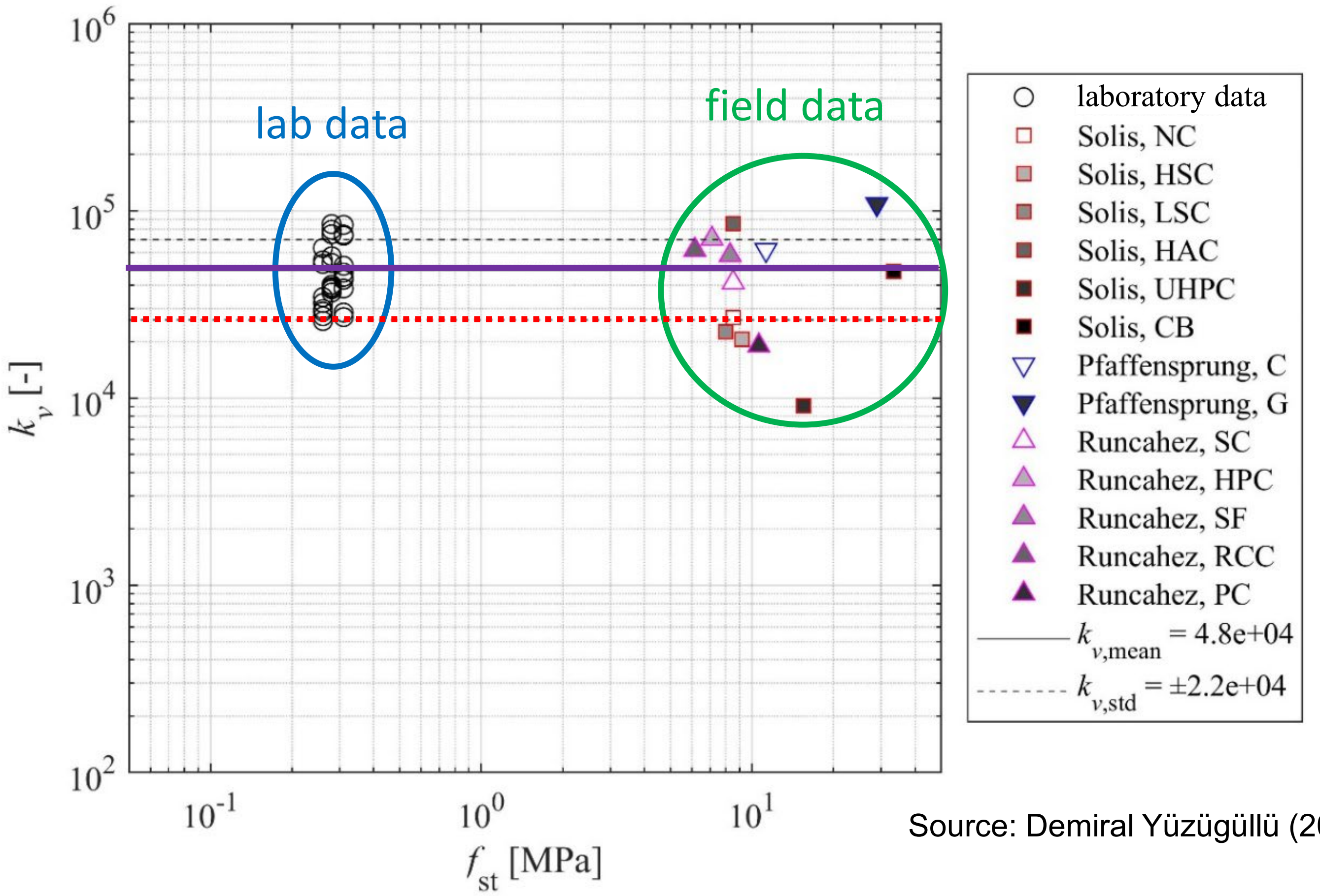
MH [-]= Bulk Mohs hardness of the sediment particles

MH_B [-] = Mohs hardness of the bed lining material

Source: Demiral Yüzügüllü (2021)

4.4.1 Mechanistic Hydro-abrasion Models

- Calibration of the hydro-abrasion coefficient for **concrete and natural stone liners**



Constant k_v value for both laboratory and field data (independent of material strength)

$k_{v,mean} = 4.8e+04$

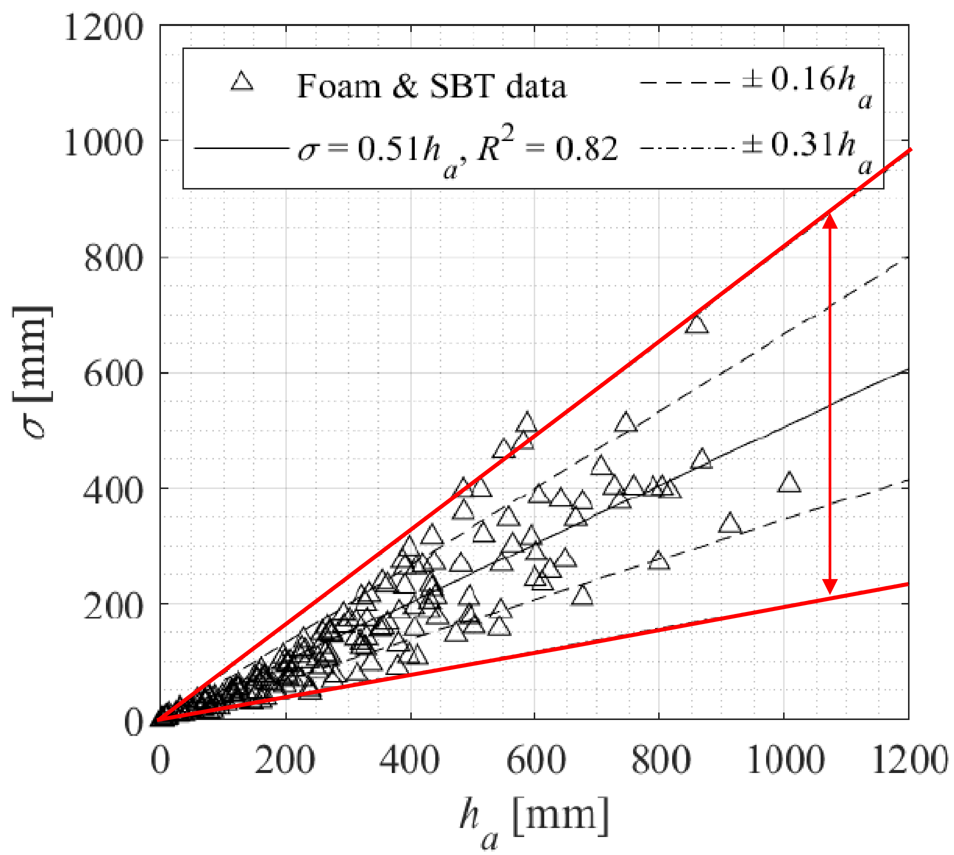
$k_{v,low} = k_{v,mean} - k_{v,std} = 2.6e+04$

→ use for high A_r estimate

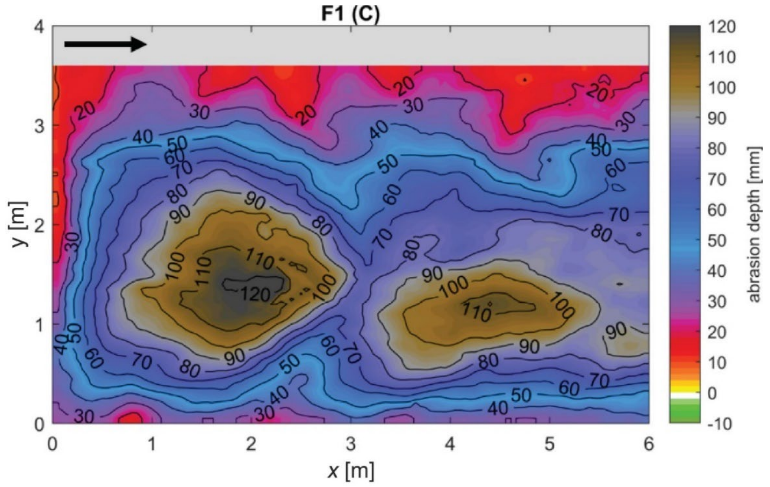
Source: Demiral Yüzügüllü (2021)

4.4.1 Mechanistic Hydro-abrasion Models

- Maximum abrasion depth



$$\int A_r \mathrm{d}t = h_a$$



maximum abrasion depths (95th percentile):

$$h_{a,max} = h_a + 2\sigma = h_a + 2\cdot(0.51+0.31)h_a = 2.64h_a$$
$$h_{a,min} = 0$$

h_a [mm] = spatially averaged abrasion depth

σ [mm] = standard deviation of abrasion distribution in area of interest

Source: Demiral Yüzügüllü (2021)

4.5 Abrasion Resistant Invert Materials

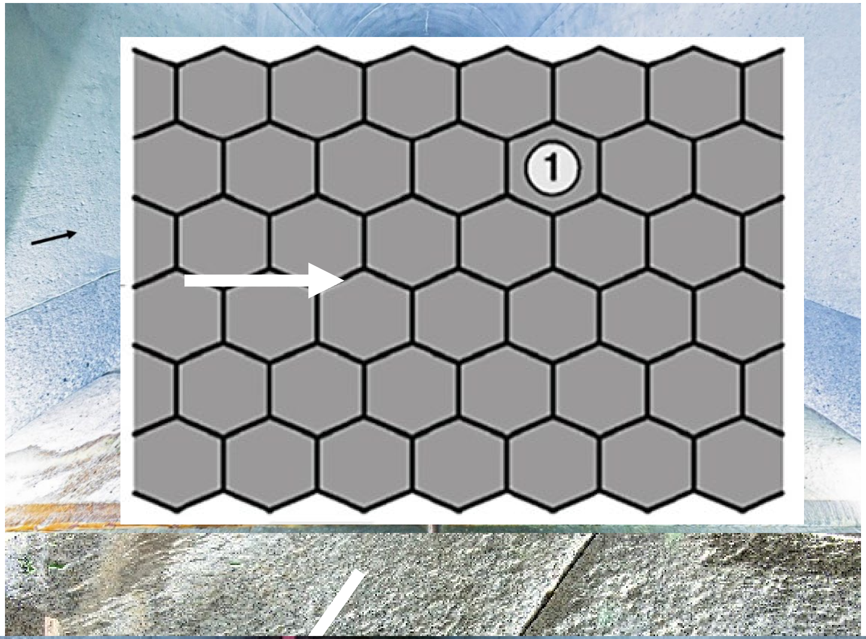
- Typically made of:

Country	Dam	Material	Compressive strength [MPa]	median sediment Ø [mm]	Mean abrasion [mm/a]
CH	Pfaffensprung	Granite	250	250	8
CH	Egschi	Granite	184	60	5
CH	Ual da Mulin	Cast basalt	450	40	< 2
CH	Runcahez	High-strength concrete	77	230	8
CH	Palagnedra	High-strength concrete	80	74	1.5
CH	Solis	High-strength concrete	105	60	29
JPN	Asahi	High-strength concrete	70	50	23

- (Surface) irregularities trigger and intensify abrasion

4.5.1 Lining Material

- Medium- and **high-strength concrete (HPC)**
  - wavy pattern of abrasion
  - preferable for very large saltating sediment particles (> 30 cm)
- **Natural stone** (cast basalt, granite)
  - damages typically occur along plate joints
  - **jointless** tight plate installation preferable
  - or place in staggered way
- Sometimes **steel armoring** in reaches with high wear
  → e.g. acceleration section at SBT inlet



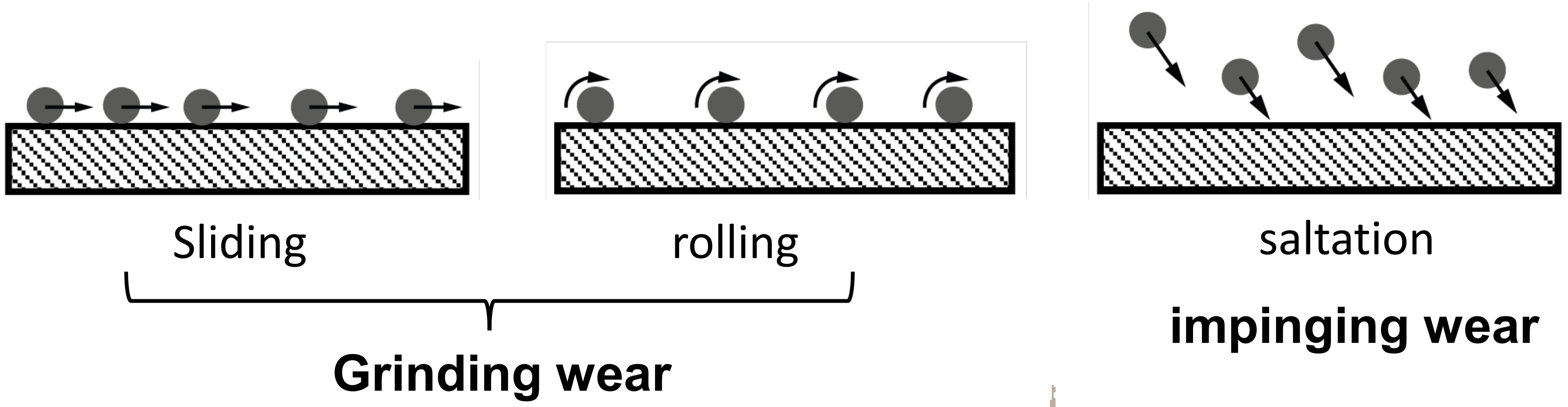
4.5.2 Tunnel Lining Design

- For particles mainly transported in **rolling or sliding mode** (with minor saltation), abrasion processes are mainly grinding, only weakly impinging

  → both **natural stone pavers and HPC liners** are viable options

- For pronounced **particle saltation** (particularly by large grain sizes) there is mainly impinging wear

  → very brittle material should be avoided, i.e. use of **HPC preferable** over (thin) natural stone pavers



4.5.2 Tunnel Lining Design

- recommended: use a **wearing surface top layer** (natural stone or HPC) with conventional concrete underneath

		Concrete aggregate		Cement		Water	
	Layer thickness [m]	Grain size distribution	Mass [kg/m^3]	type	Mass [kg/m^3]	w/c ratio [-]	Mass [kg/m^3]
Normal invert (High strength concrete with steel fiber)	0.3	0/4: 40% 4/8: 24% 8/16: 36%	1900	CEM II/A-D 52.5R	536	0.33	177
Concrete with steel fibers	0.3	0/4: 41% 4/8: 22% 8/16: 37%	1740	CEM II/A-D 52.5R	450	0.41	185
Concrete with shrinkage reduction	0.3	0/4: 40% 4/8: 24% 8/16: 36%	1900	CEM II/A-D 52.5R	390	0.44	172
High alumina cement	0.15	0/4: 50% 4/10: 50%	2060	High alumina cement concrete	515	0.40	206
Ultrahigh performance concrete	0.08	Quartz sand	870	CEM II/B-M	1100	0.17	187

4.6 Invert Maintenance and Refurbishment

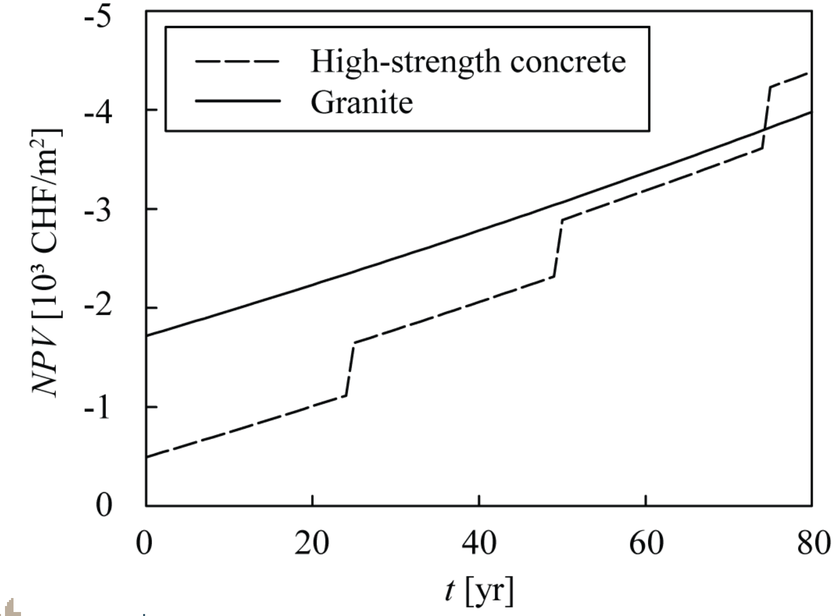
- Erosion of the invert of bypass tunnels not only due to movement of solids but also possibly due to **cavitation**
- SBTs have to be **inspected** to assess damage to the invert and walls at the end of the flood season **every year.**

➢ If damaged: **repairs** should be undertaken **during the next low flow season**

- **Time-consuming, difficult, costly refurbishment works → consider total LC cost** (incl. maintenance and repair)

$$\boxed{NPV = \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} = \sum_{t=0}^{T} \frac{E_t - I_t}{(1+r)^t}}$$

T = accounting period
C_t = net cash flow at time t
E_t = earnings at time t
I_t = expenses at time t
r = interest rate



4.6 Invert Maintenance and Refurbishment

- **Minor** damage: epoxy-resin mortar
- **Heavy** damage (h_a in cm to dm range): replace damaged invert with HPC showing high abrasion resistance

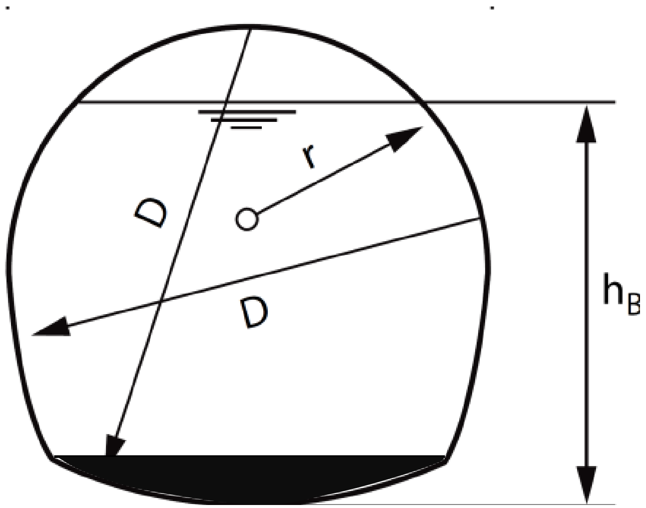
➢ Ensuring **bond** between the old and the new concrete

- high degree of **quality control** necessary while placing micro-resin concrete or HPC

4.7 Design recommendations

Overarching philosophy:

1) **Minimize loads** by optimized flow conditions → SBT layout
2) Choose **appropriate resistance** of invert lining **(relative to sediment hardness)**
3) Select **suitable invert material**



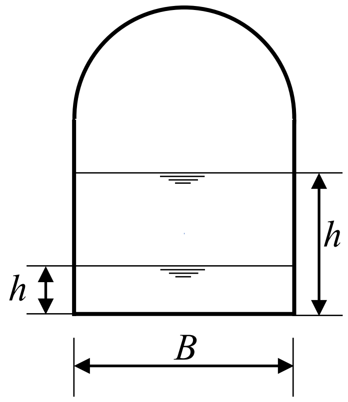
Ad 1)

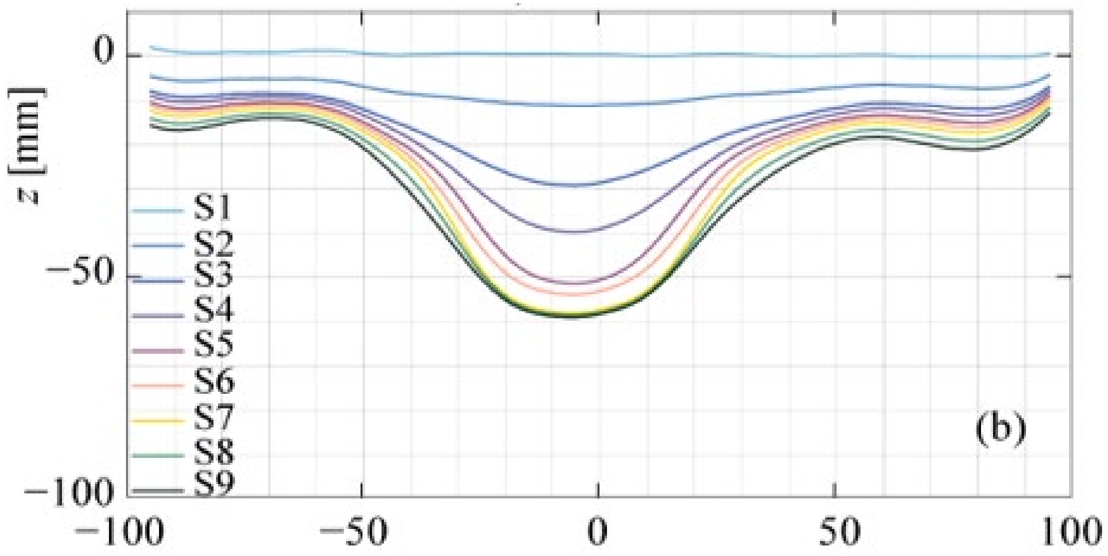
- Use **constant bed slope** as mild as possible but assuring supercritical flow
- **Avoid bends** if possible → high local shear stresses due to secondary currents
- Choose cross section with **level invert** geometry

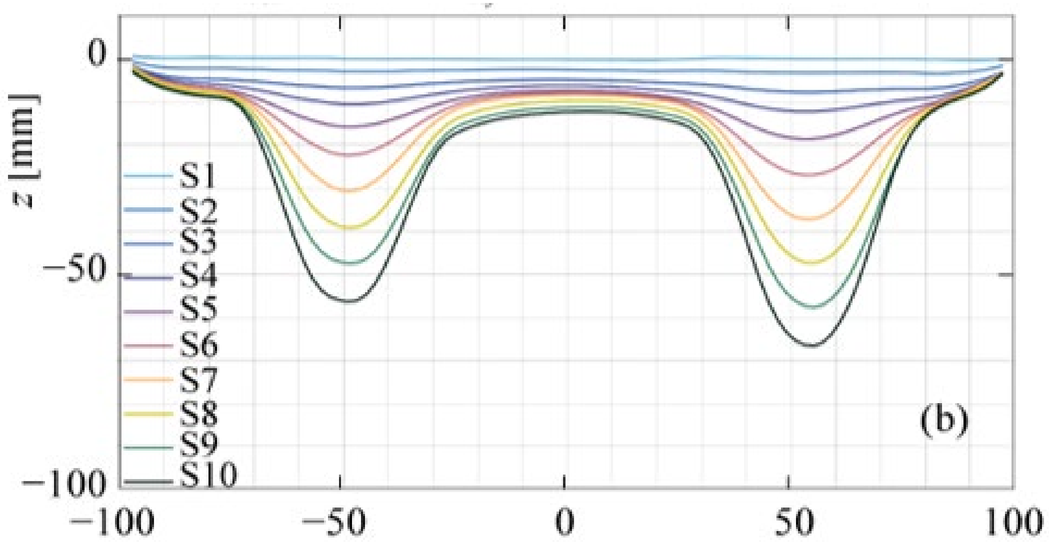
4.7 Design recommendations

Hydraulic considerations

- **Aspect ratio in most SBTs** $B/h < 4$ to 5
  → **3D-flow** (secondary currents → higher abrasion)
  - $B/h < 2.3$: max. abrasion in the **center** of the tunnel
  - $2.3 \leq B/h < 6$: max. abrasion near the tunnel **side walls**







4.7 Design recommendations

Overarching philosophy:

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

2) Choose **appropriate relative resistance** of invert lining

3) Select **suitable invert material**

Ad 1)
- Use constant bed slope as mild as possible but assuring supercritical flow
- Avoid bends that cause high local shear stresses
- Choose cross section with level invert geometry

Ad 2)
- Carry out a mineralogical analysis of the sediment
- **Minimize joint widths and gaps**
- Ensure **proper bonding**/connection of the different layers

Ad 3)
- Consider **transport mechanism** (sliding, saltation) and material characteristics (brittle vs. elastic)
- Do **predictive modelling** using mechanistic models for different materials

→ see above

Thank you for your attention

Merci pour votre attention

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