Hydro-abrasion at hydraulic structures and steep bedrock rivers

Frontiers in Energy Research

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Outline

- Introduction
  - Reservoirs
  - Reservoir sedimentation
  - Sediment bypass tunnels
  - Hydro-abrasion
- Goals and objectives
- Experimental setup
- Experimental results
- Outlook

Reservoirs

Gries Reservoir, Switzerland (Photo: Dr. Daniel Ehrbar, VAW)

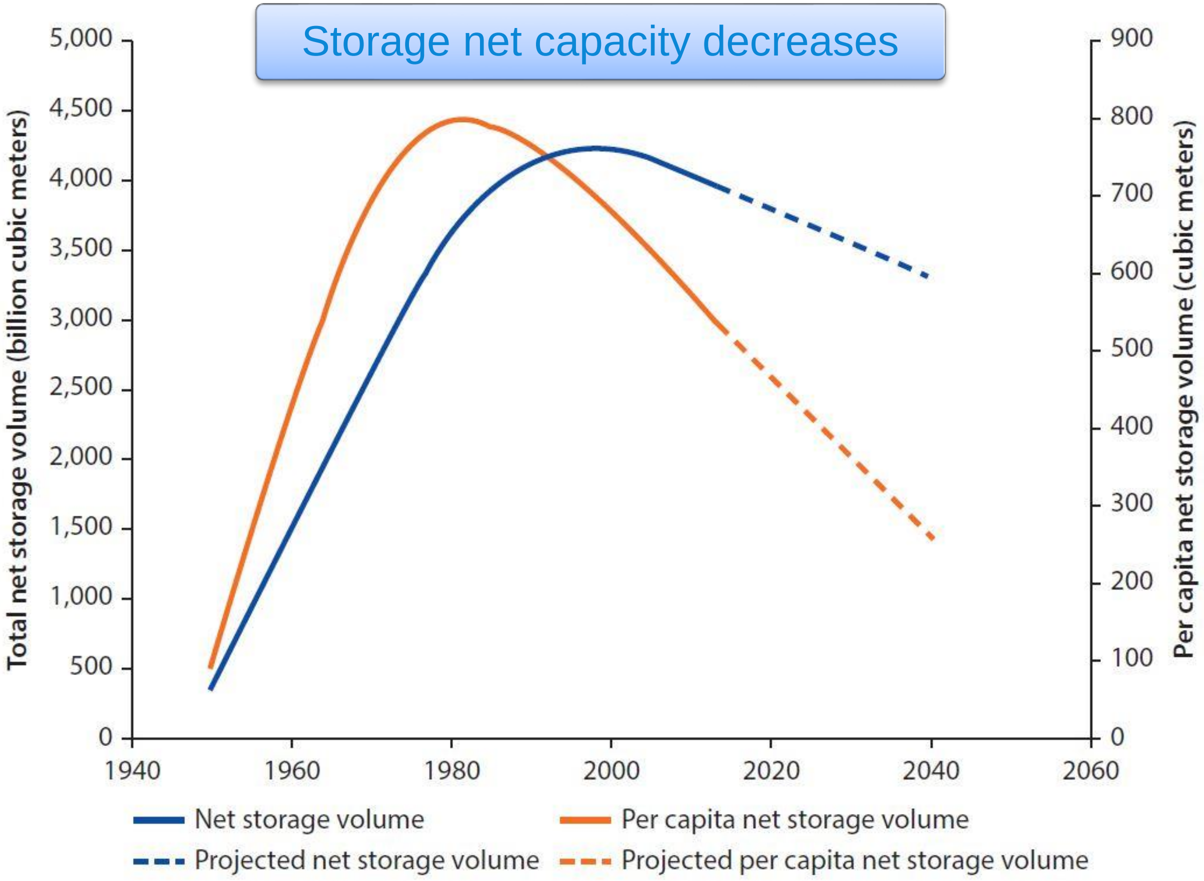
- Hydropower generation
- Water supply
- Irrigation
- Flood and drought control

Reservoir sedimentation

Baihe Reservoir, Taiwan (Photo: Demiral, 2019)

Paonia Reservoir, Hotchkiss, Colorado
(Annandale et al. 2018)

Reservoir sedimentation problems



Net global reservoir storage volume, accounting for storage loss from reservoir sedimentation (Annandale et al. 2016)

- **Decrease of active volume** loss of energy production, water supply, irrigation & retention volume
- **Endangerment of operating safety** due to the blockage of the outlet structures
- **Increased turbine abrasion** due to the high sediment concentration

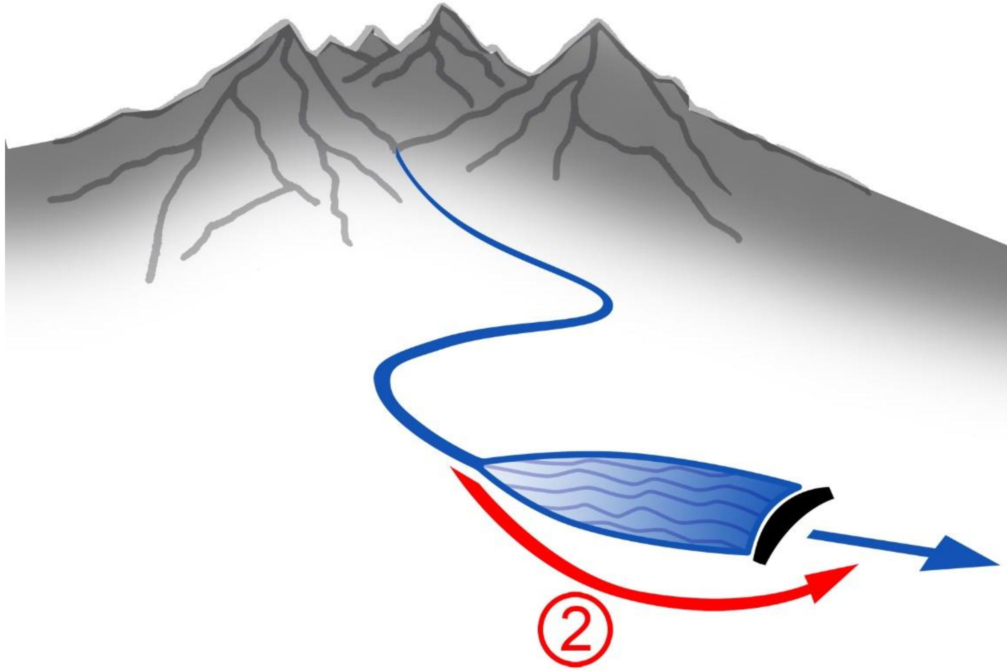
Sedimentation countermeasures

① Sediment yield reduction in the catchment

② Sediment routing

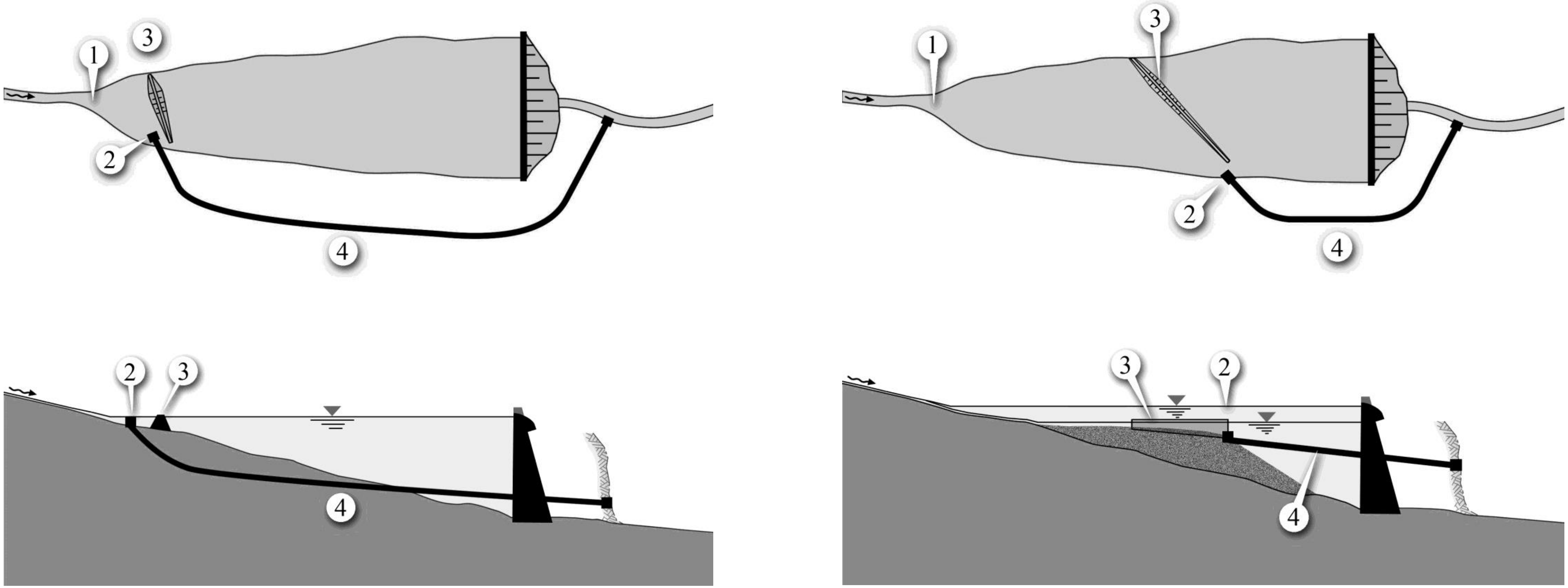
③ Sediment removal

④ Optimized reservoir and dam layout and location



Sediment bypassing

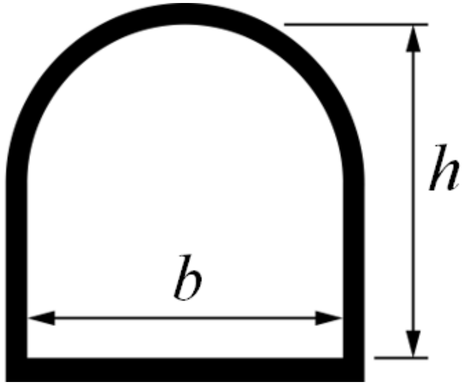
Sediment bypass tunnels (SBT): general design

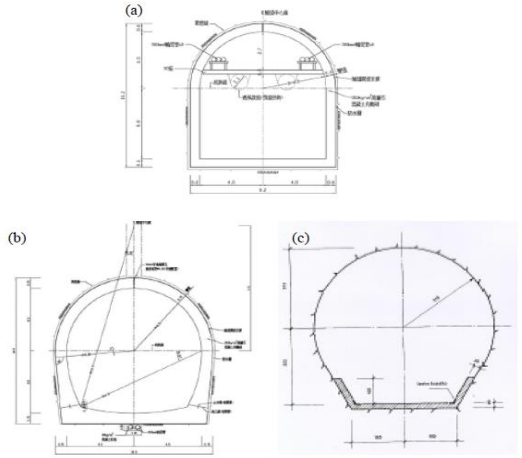


1. Reservoir head, 2. Intake, 3. Guiding structure, 4.Sediment bypass tunnel

Technical details of SBTs

- Cross-sectional shape: archway, horse-shoe, circular
- Aspect ratio (*b/h*): 0.6 – 2
- Bed slope (S_b): 1 – 4%
- Bed lining material: concrete, granite, cast basalt, epoxy, steel





(Photo: VAW, ETHZ)

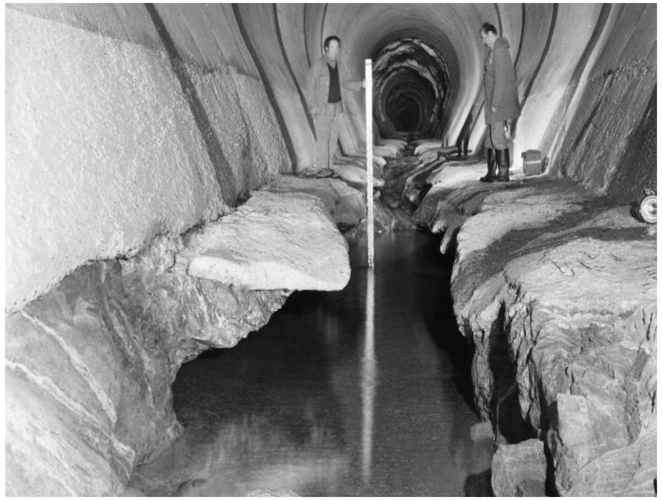
(Müller-Hagmann 2017)

Worldwide application of SBTs

Country	Reservoir	Q_d [m^3/s]	$\bar{U}$ [m/s]	F [-]
CH	Pfaffensprung	220	17.4	2.7
CH	Egschi	50	12.5	2.1
CH	Runcahez	110	**20.2**	1.7
CH	Ual da Mulin	145	14.9	2.5
CH	Palagnedra	220	19.7	2.3
CH	Rempen	100	13.3	2.6
CH	Solis	170	12.7	1.7
Japan	Nunobiki	39	**6.7**	**1.2**
Japan	Asahi	140	13.4	1.9
Japan	Miwa	300	9.8	1.6
Japan	Matsukawa	200	15.2	**3.1**
Japan	Koshibu	370	14.0	2.4
Japan	Yahagi			
Japan	Sakuma			

Hydro-abrasion at SBTs

High flow velocities + high sediment transport rates
= **hydro-abrasion at SBTs**

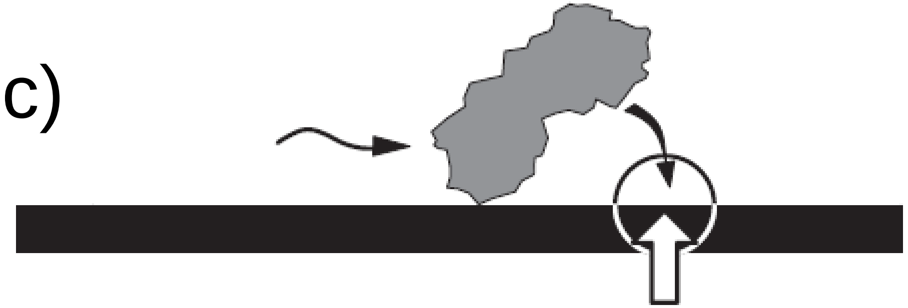


Palagnedra SBT, Switzerland
(Photo: VAW, ETHZ)

Asahi SBT, Japan
(Photo: Dr. Christian Auel)

Hydro-abrasion at SBTs

c)



impacts due to rotating/rolling particles

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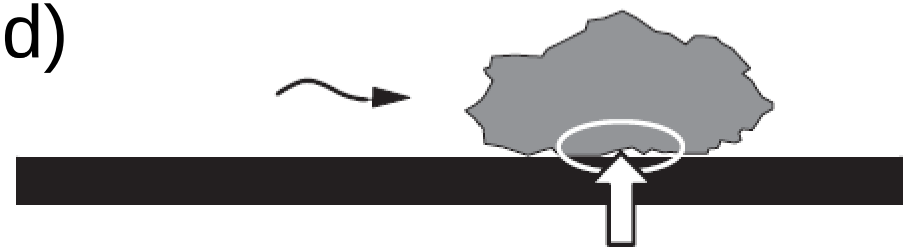
d)



grinding stress due to sliding

(Auel 2014, Ph.D. dissertation)

Bedrock incision

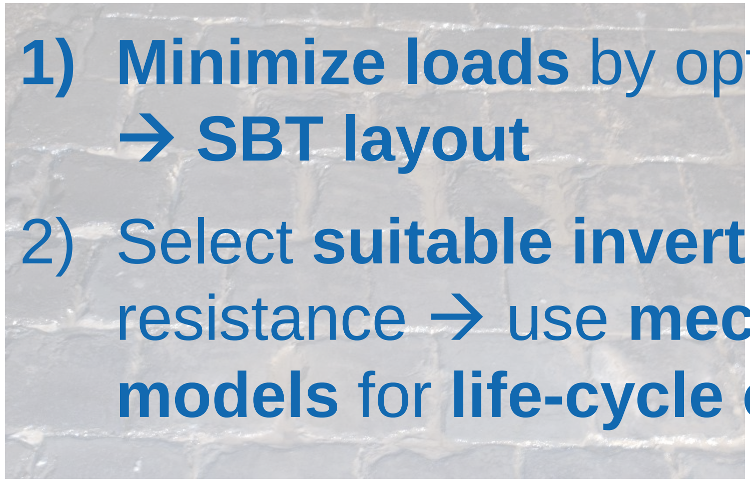
Ukak River, Alaska, US
(https://sites.google.com/site/phairotchat/)

Bialka River, Poland-Slovakia border
(http://czech-rivers.blogspot.com/2016/10/)

Hydro-abrasion at SBTs


Runcahez (CH)
(Müller-Hagmann)

Asahi (JP)
(Kansai Electric)


Pfaffensprung (CH)
(Müller-Hagmann)

Egschi (CH)
(sopr AG)

How to limit hydro-abrasion?

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

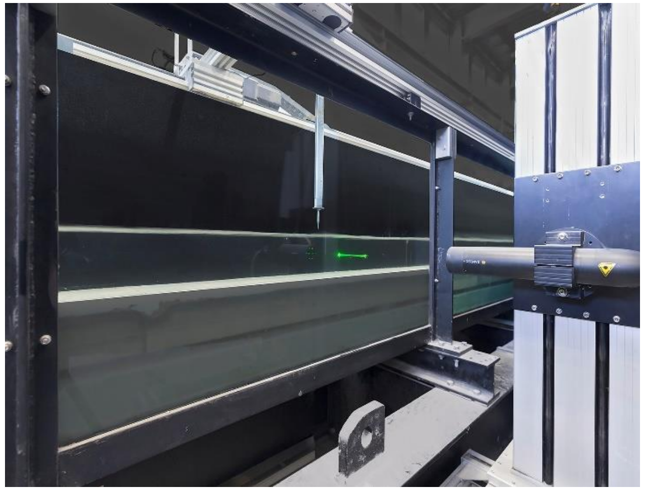
2) Select **suitable invert material** to maximize resistance → use **mechanistic abrasion models** for **life-cycle cost** approach

Goals and objectives

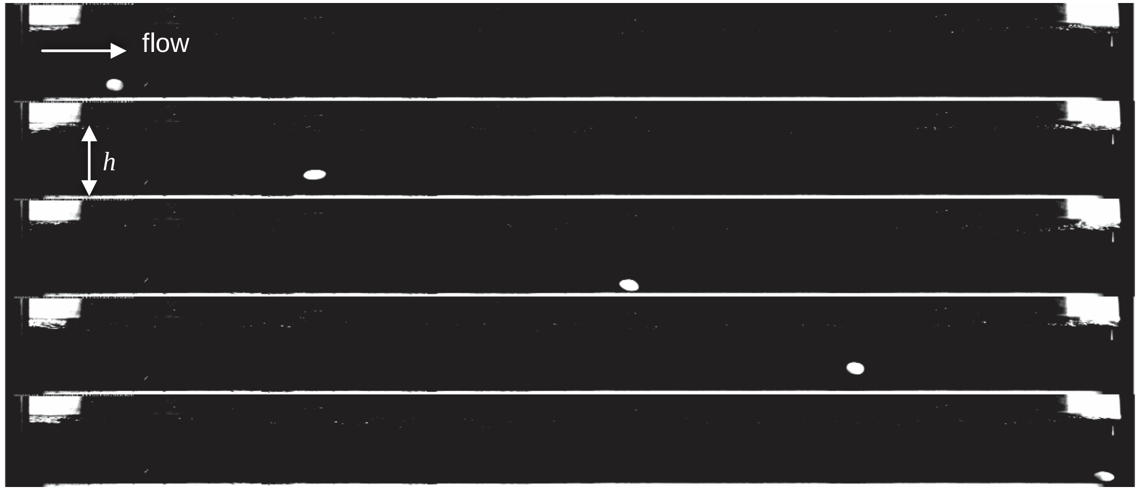
Goals

- Mitigating the hydro-abrasion problem
- Optimizing design and operation of SBTs

Objectives



Task A: Supercritical open channel flow characteristics

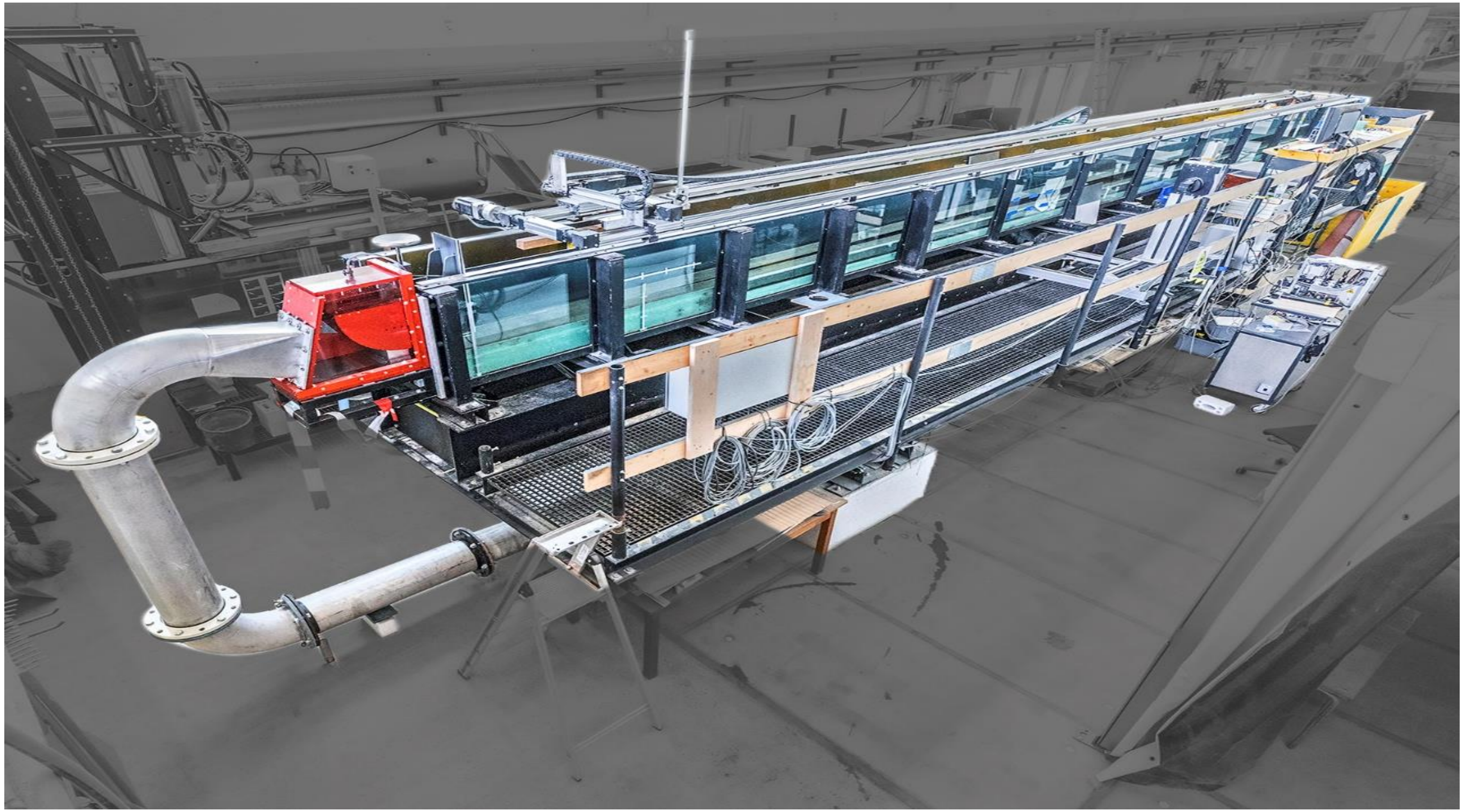


Task B: Sediment transport modes

Task C: Hydro-abrasion

Task D: Development of hydro-abrasion model

Experimental setup

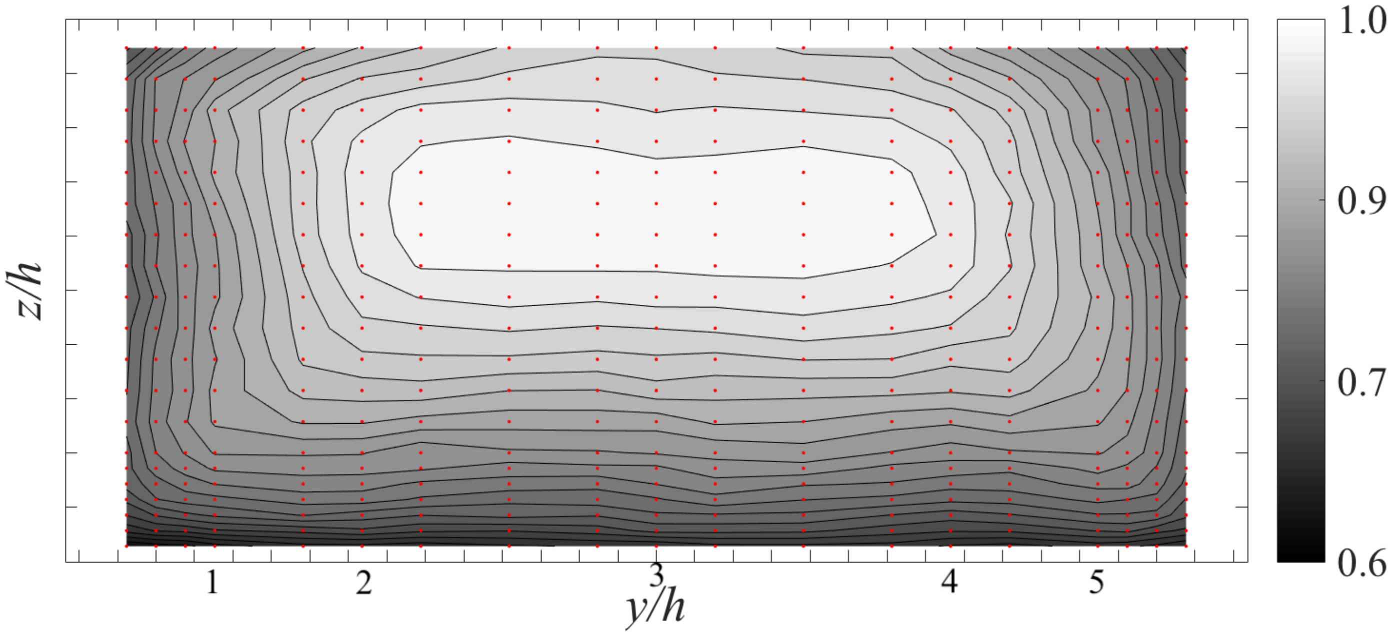


Experimental flume (VAW, ETH Zurich)

- l = 13.50 m
- b = 0.20 m
- h = 0.50 m
- S_b = 1% - 4%
- Concrete + polyurethane foam bed lining

Task A: flow characteristics

- Velocity measurements using Laser Doppler Anemometer (LDA)
  - Cross-sectional distributions of mean flow velocities
  - Turbulence intensities
  - Bed shear stresses

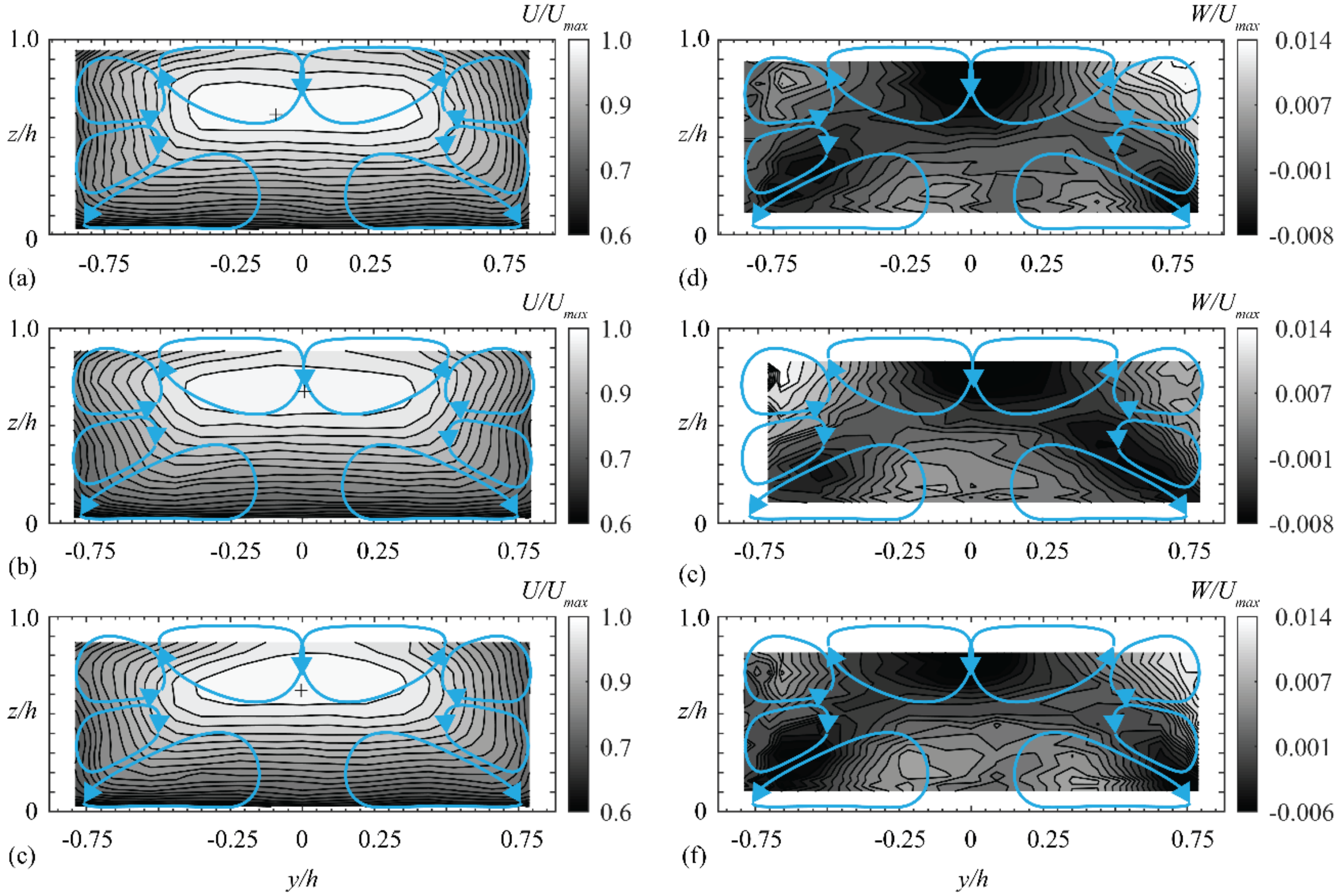


Cross-sectional velocity measurement points for x=5.40 m. Numbered profiles (1-5) show the measurement points for x=5.15 and x=4.90 m

Task A: test matrix

Tests	S_b [-]	F_0 [-]	F [-]	h_0 [cm]	h [cm]	b/h_0 [-]	b/h [-]	U [m/s]
TA1	0.01	2.0	1.93	10	10.45	2	1.91	1.95
TA2	0.01	3.0	2.54	10	11.20	2	1.79	2.66
TA3	0.01	4.0	3.33	10	11.40	2	1.75	3.52
TA4	0.01	2.0	1.85	15	15.95	1.33	1.25	2.31
TA5	0.01	3.0	2.60	15	16.56	1.33	1.21	3.31
TA6	0.01	4.0	3.32	15	17.04	1.33	1.17	4.30
TA7	0.01	3.0	2.56	20	22.29	1	0.90	3.79
TA8	0.01	3.5	2.96	20	22.39	1	0.89	4.39

Task A: mean velocity distributions

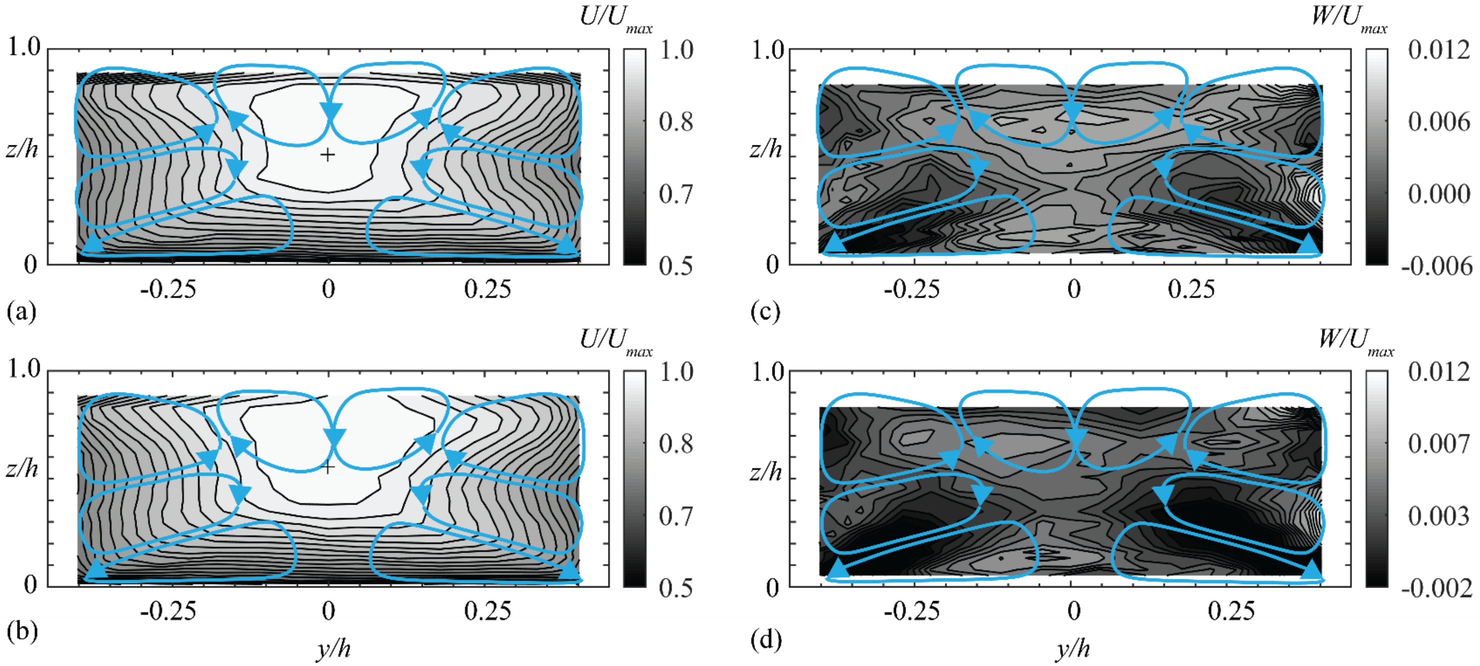


$h_o = 10$ cm, $\mathrm{F_o} = 2$, $b/h_o = 2$

$h_o = 10$ cm, $\mathrm{F_o} = 3$, $b/h_o = 2$

$h_o = 10$ cm, $\mathrm{F_o} = 4$, $b/h_o = 2$

Task A: mean velocity distributions

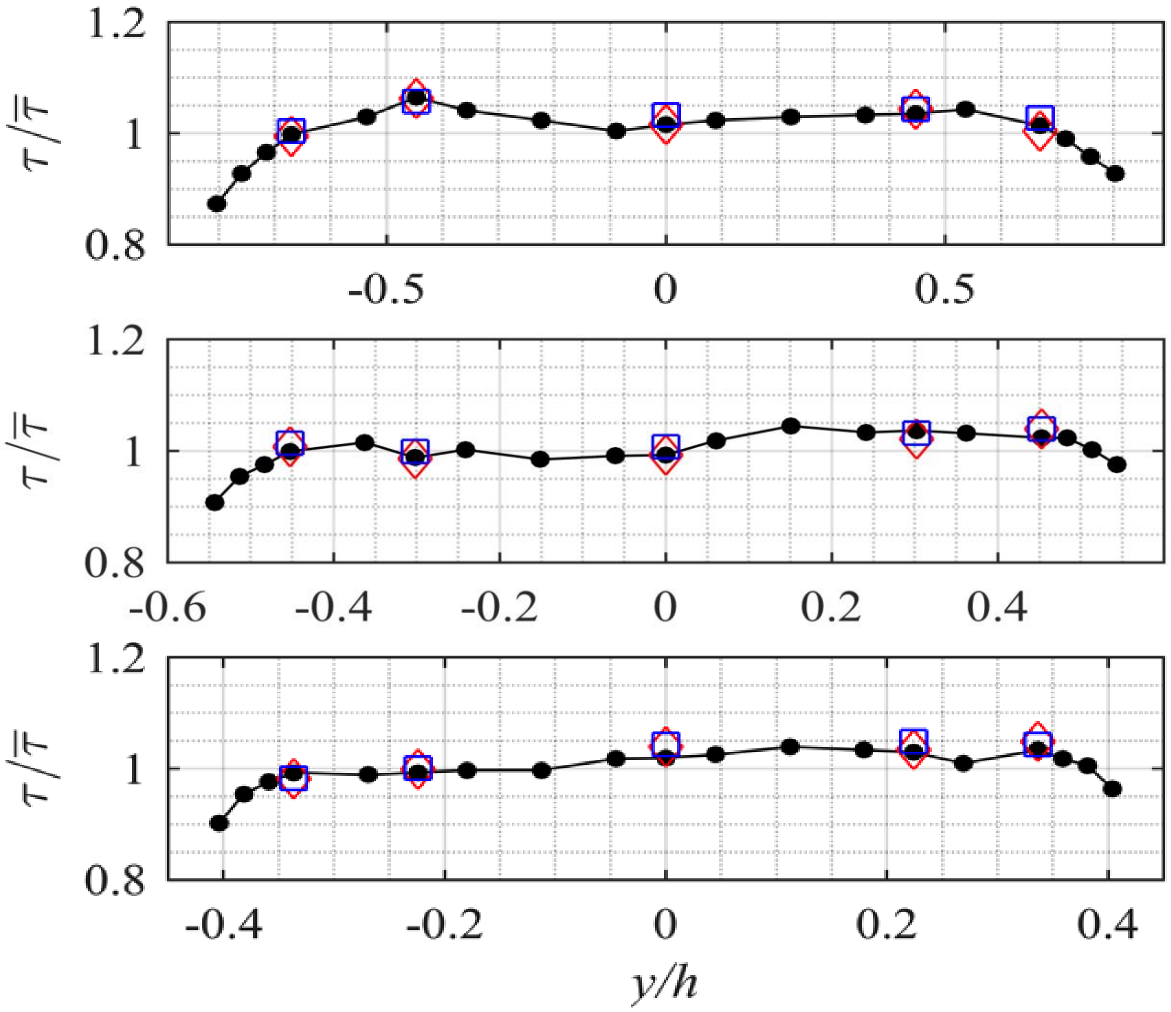


$h_o = 20$ cm, $F_o = 3$, $b/h_o = 1$

$h_o = 20$ cm, $F_o = 3.5$, $b/h_o = 1$

- 3D flow pattern due to the strong secondary currents
- Velocity dip phenomenon
- Velocity pattern changes with changing aspect ratio
- Velocity distribution is independent from F

Task A: bed shear stress distributions



h_o = 10 cm, F_o = 3, b/h_o = 2

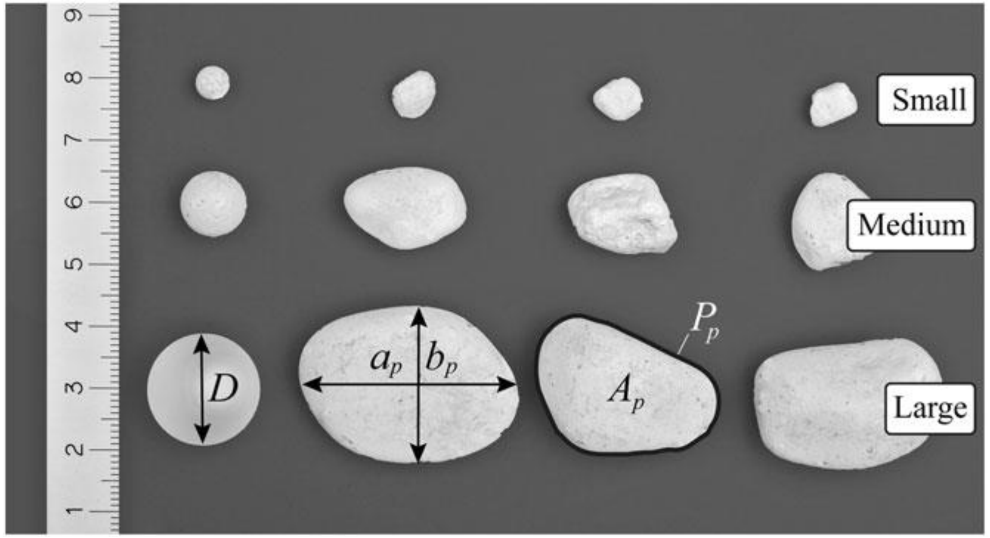
h_o = 15 cm, F_o = 3, b/h_o = 1.33

h_o = 20 cm, F_o = 3, b/h_o = 1

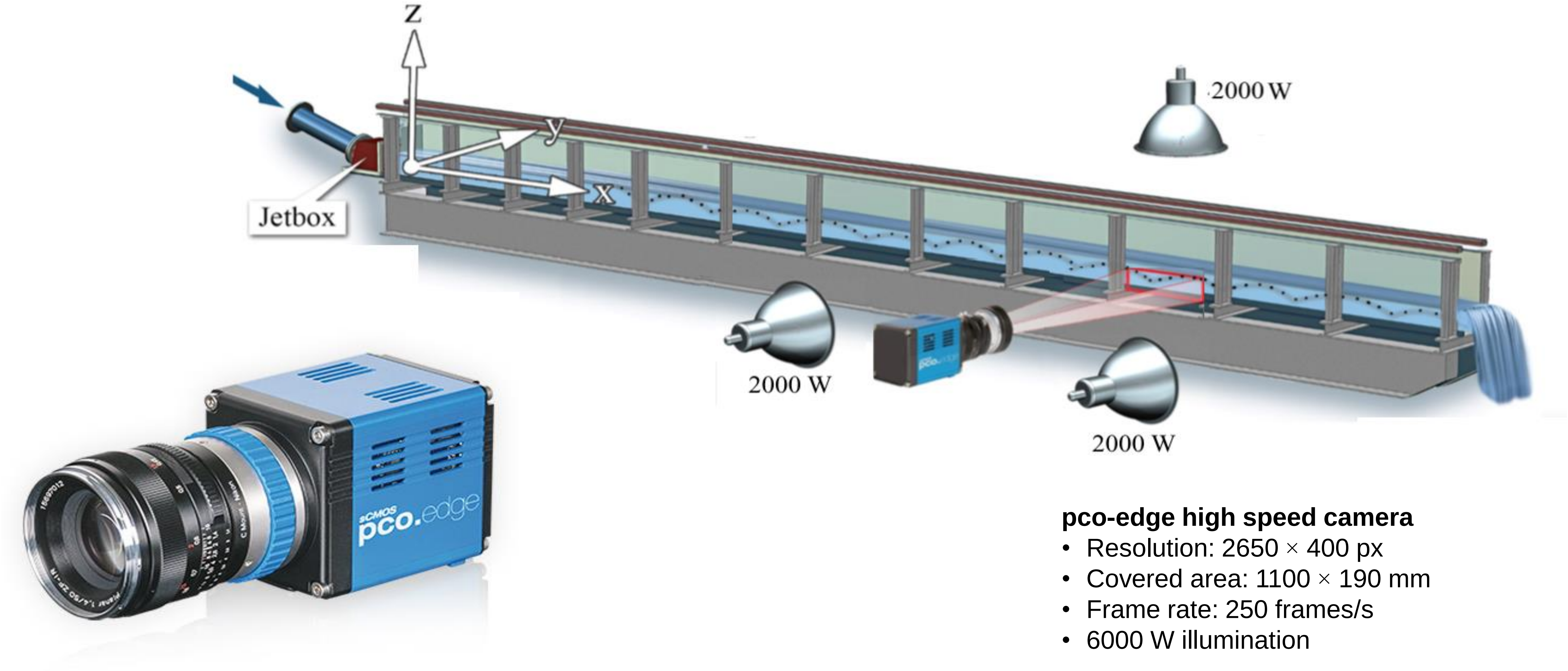
●: x = 5.40 m; ◊: x = 5.15 m; □: x = 4.90 m

Task B: particle motions

- Particle transport modes (high-speed camera)
  - Saltation trajectory parameters
  - Particle impact and rebound angles
  - Particle properties such as area, perimeter



Task B: experimental setup



pco-edge high speed camera
- Resolution: 2650 × 400 px
- Covered area: 1100 × 190 mm
- Frame rate: 250 frames/s
- 6000 W illumination

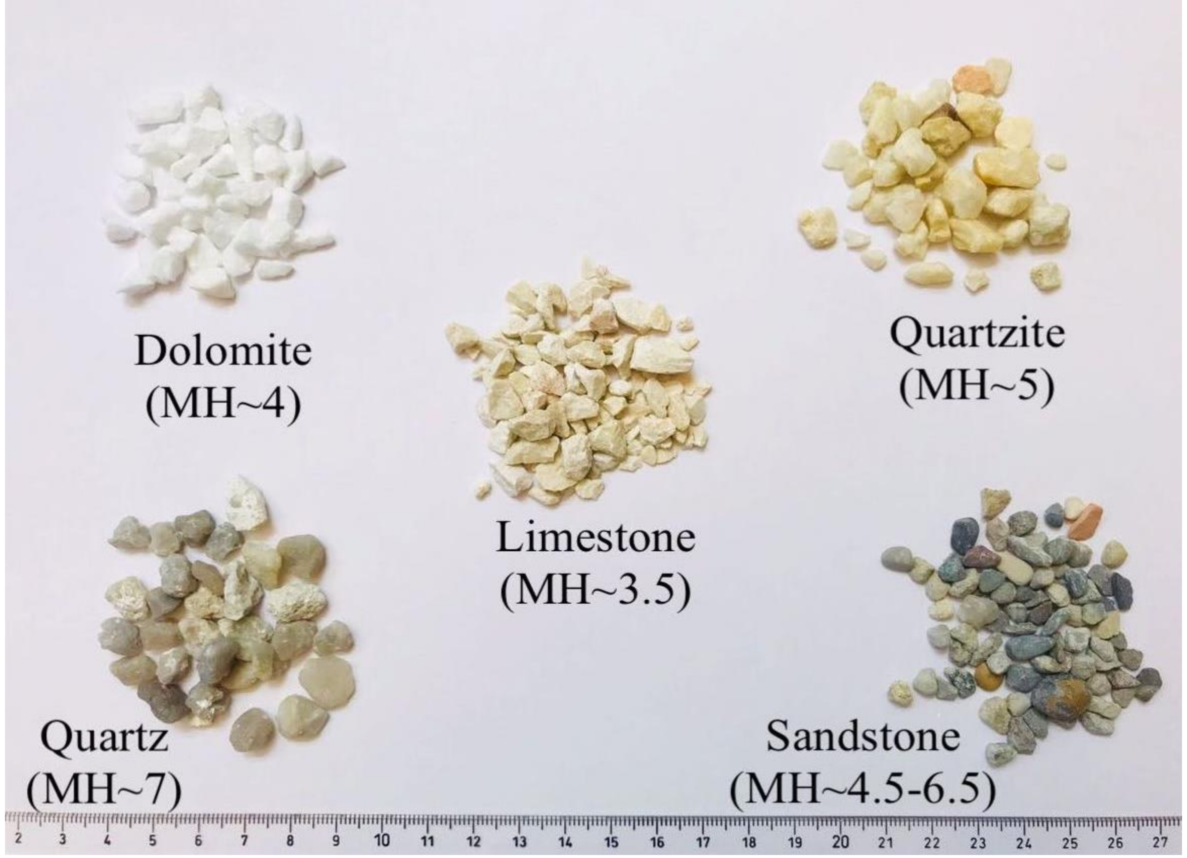
Experimental setup for Task B

Task B: test conditions

- F_o = 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0
- b/h_o = 1, 1.33, 2, 4
- D_{50} [mm] ≈ 7, 13, 21
- S_b = 1%, 4%
- limestone, sandstone, quartz

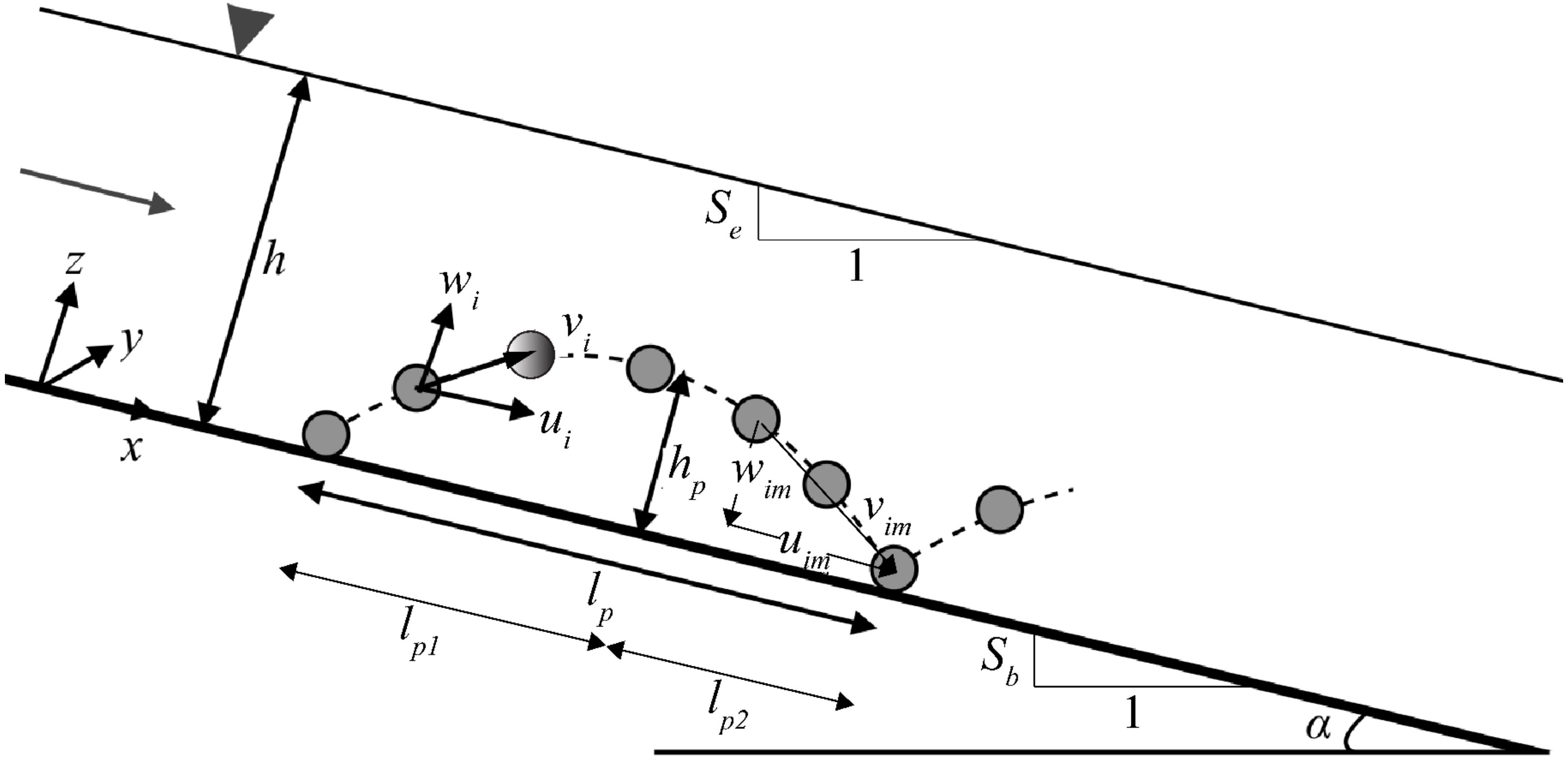
Σ 120 particles

Σ 51 tests



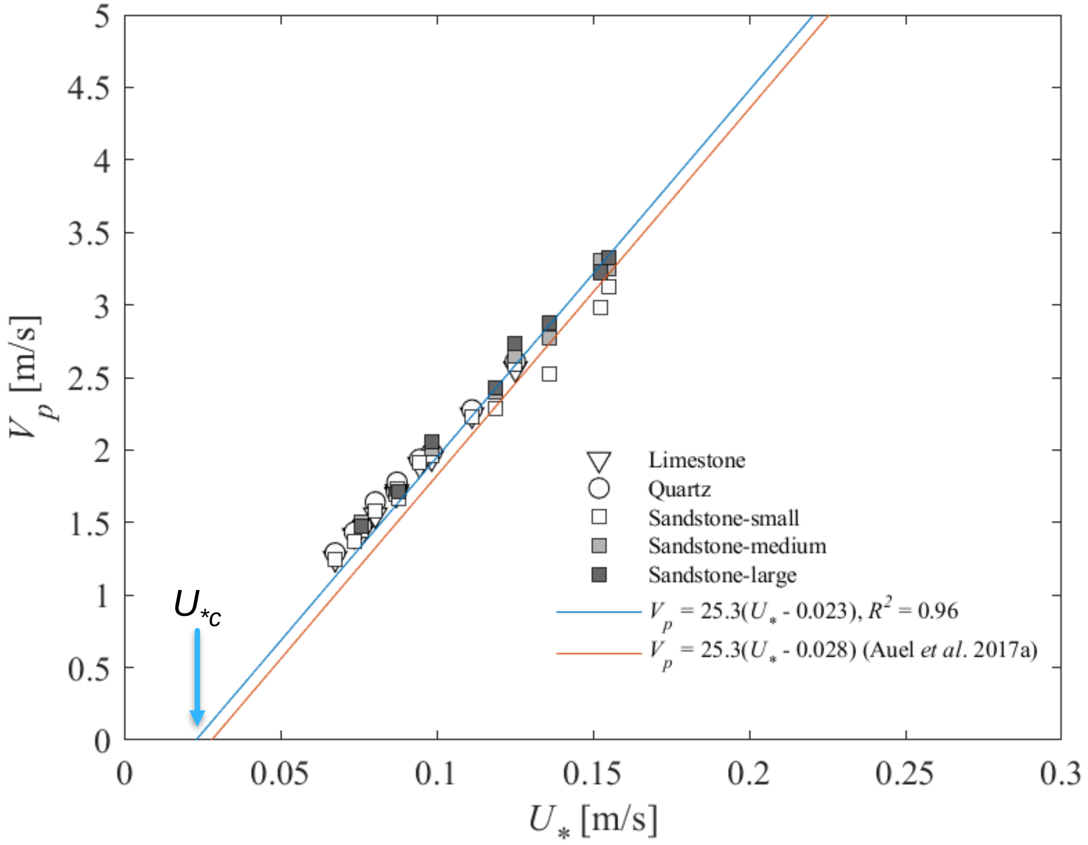
Particle types types and their Mohs Hardness (MH)

Task B: data analysis



Particle saltation trajectory

Task B: particle velocities and incipient motion

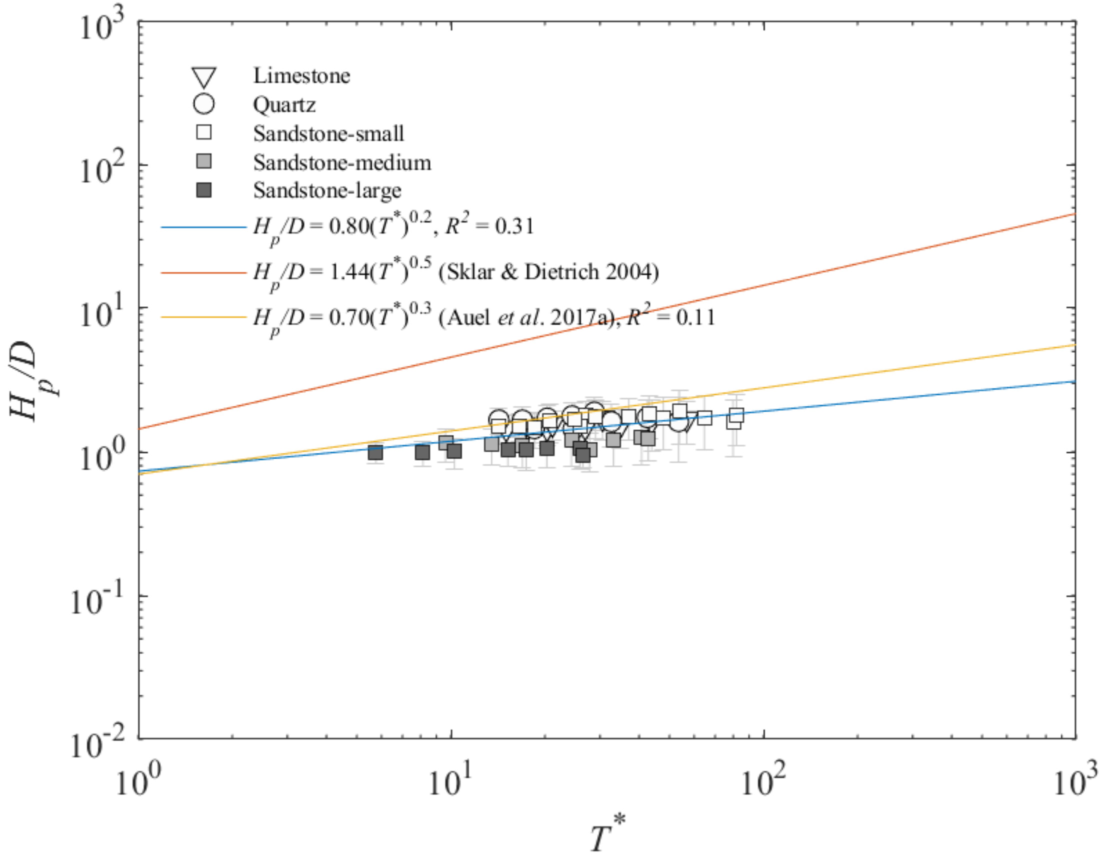


Particle velocity (V_p) versus friction velocity (U_*)

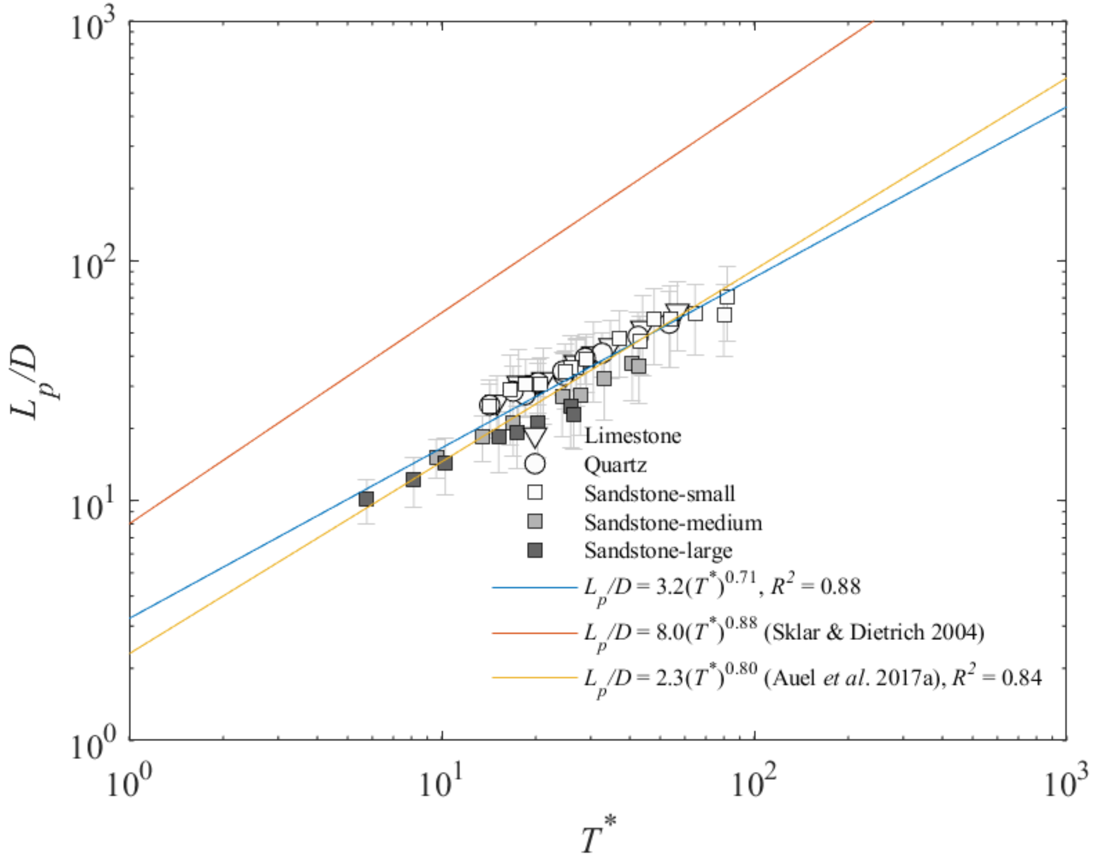
	All data	Small particles	Medium particles	Large particles
D_{50} [mm]	-	7.2	13.5	21.3
U_{*c}	0.023	0.017	0.023	0.029
θ_c	0.0025	0.0025	0.0025	0.0026
R^2	0.96	0.98	0.98	0.96

$T^* = (\theta/\theta_c) - 1$ (excessive transport stage)

Task B: hop heights & hop lengths

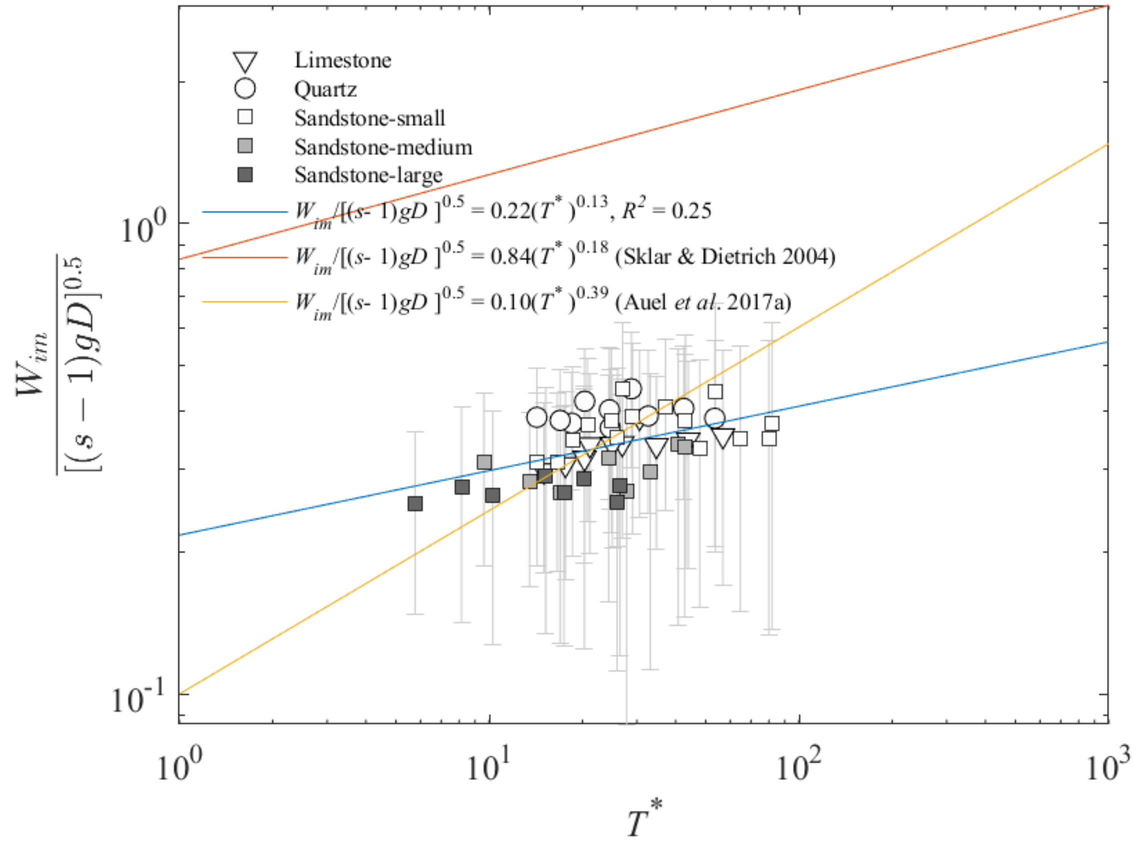


Normalized hop height (H_p/D) versus excess transport stage (T^*)



Normalized hop length (L_p/D) versus excess transport stage (T^*)

Task B: particle impact velocities



Normalized vertical impact velocity versus excess transport stage (T^*)

$$k_R = \frac{P_p^2}{4pA_p}$$

κ_R = shape factor

P_p = particle perimeter

A_p = particle area

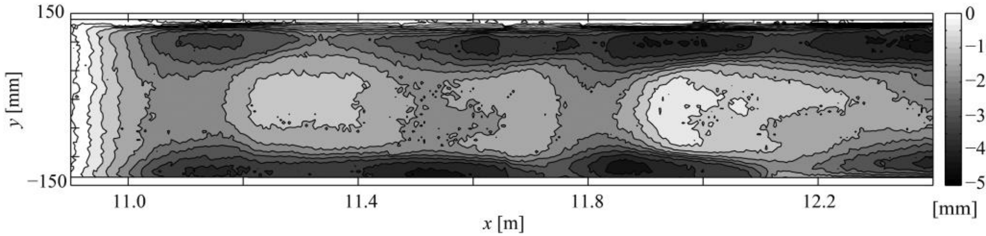
$\kappa_R = 1.27 \pm 0.10$ limestone

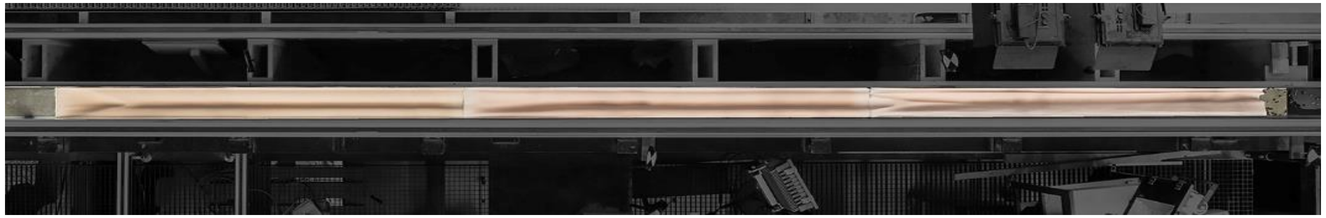
$\kappa_R = 1.20 \pm 0.05$ quartz

$\kappa_R = 1.27 \pm 0.10$ sandstone

Task C: hydro-abrasion

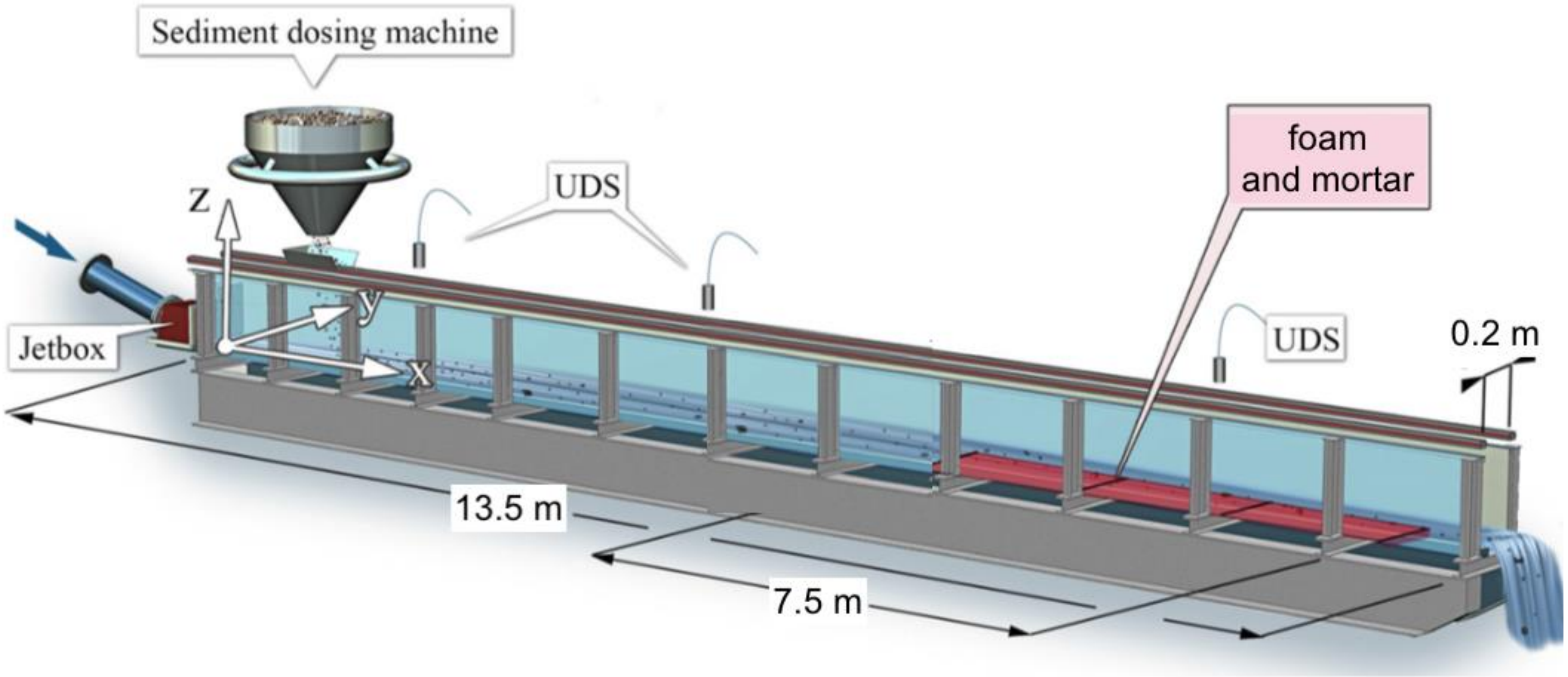
- Hydro-abrasion experiments
  - Hydro-abrasion depths and patterns: bottom scans using 3D laser scanner
  - Time development of hydro-abrasion: intermediate scans to obtain the development





Auel *et al.* (2014)

Task C: experimental setup

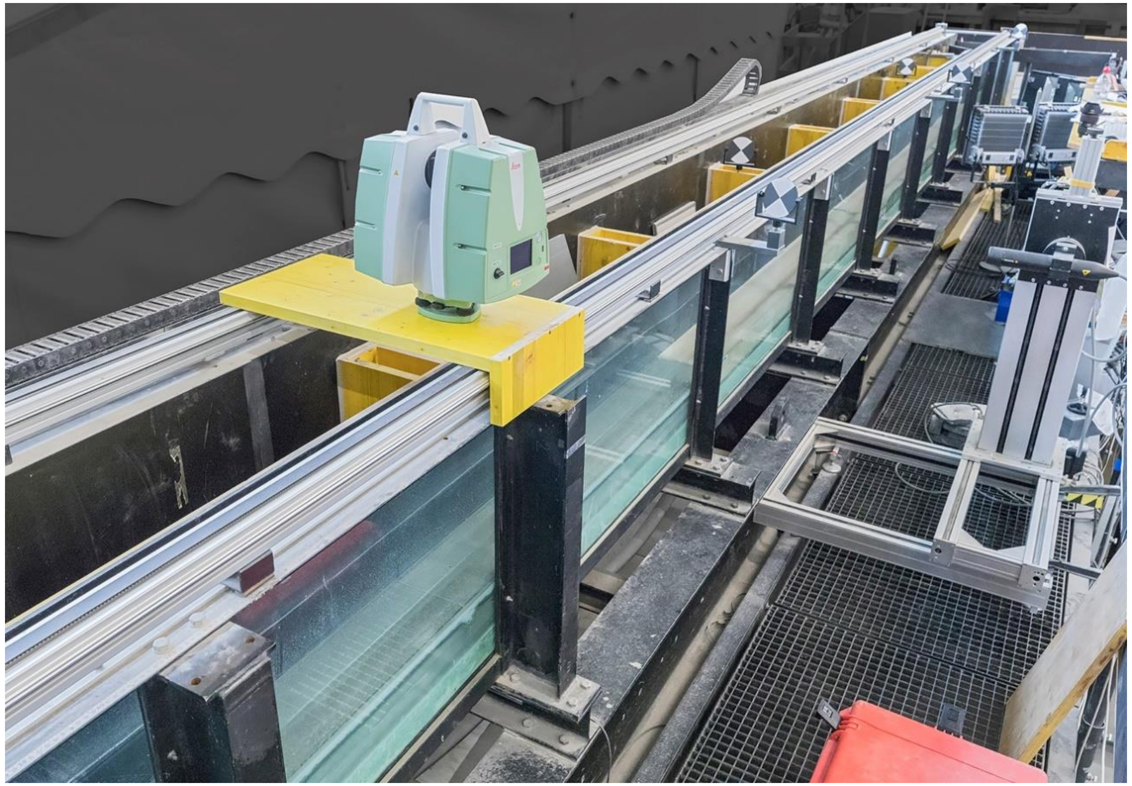


Experimental setup for Task C

Task C: test conditions

- F_o = 2, 3, 4 b/h_o = 1, 1.33, 2
- Particles: limestone, dolomite, quartzite, sandstone, quartz
- Q_s [g/s] = 100, 200, 400, 800
- Bed lining: foam and mortar
- S_b = 1%, 4%

Σ 12+ tests

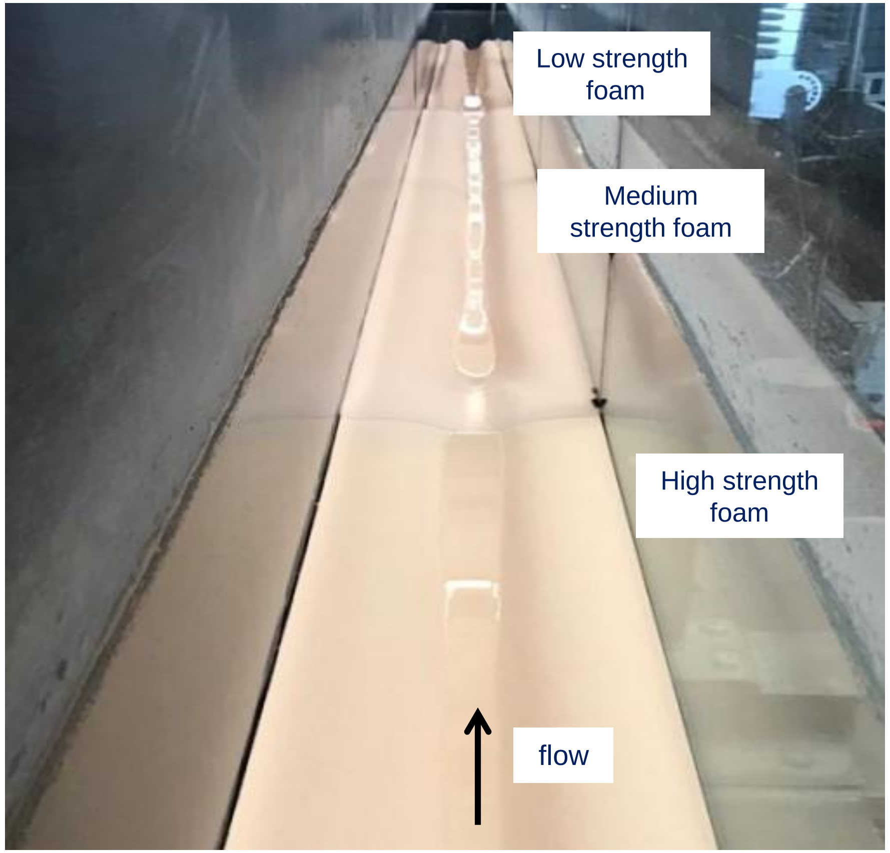


Hydro-abrasion experiments

Task C: first experiment

- $F_o = 3$, $h_0 = 10$ cm, sandstone, Σ 15 h run time

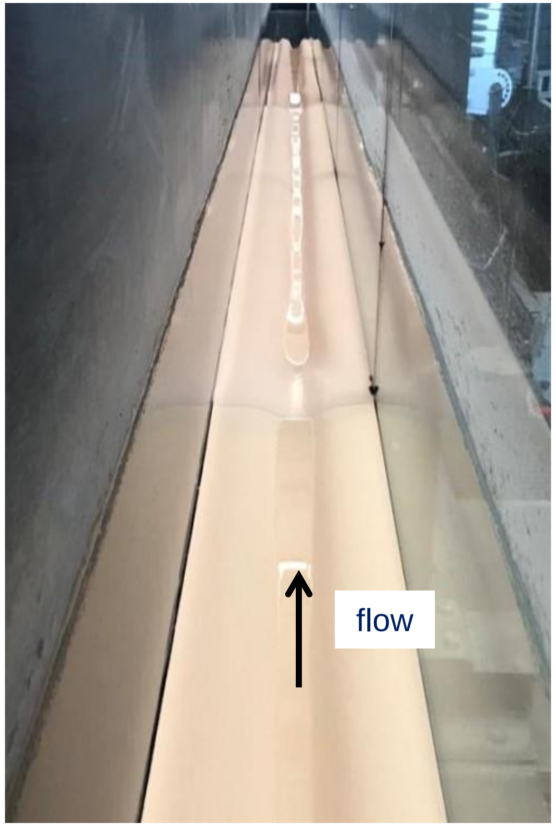
Experiment	Q_s [g/s]	M_s [kg]	t (h)
TC1_1	0	0	0
TC1_2	97.7	1896	5.28
TC1_3	100.2	1896	5.27
TC1_4	208.2	948	1.28
TC1_5	202.9	948	1.32
TC1_6	395.6	948	0.67
TC1_7	416.4	948	0.65
TC1_8	719.3	948	0.35
TC1_9	719.3	948	0.37

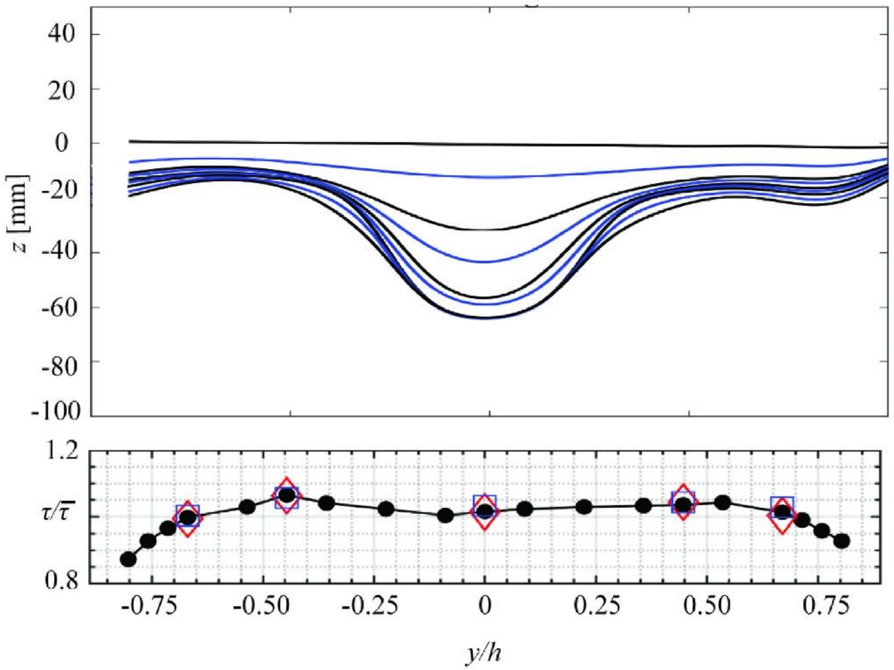


TC1_9 Hydro-abrasion development

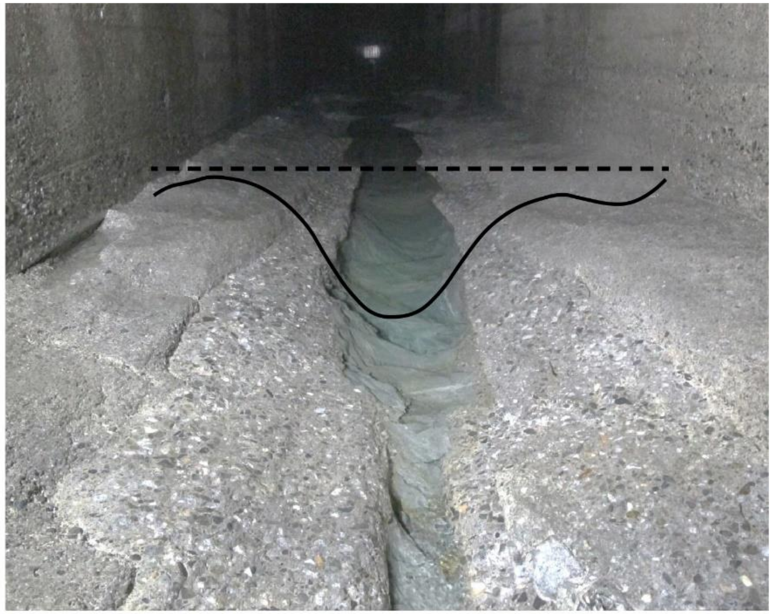
Task C: abrasion time development

Bed shear stress distribution → Sediment motion → hydro-abrasion pattern



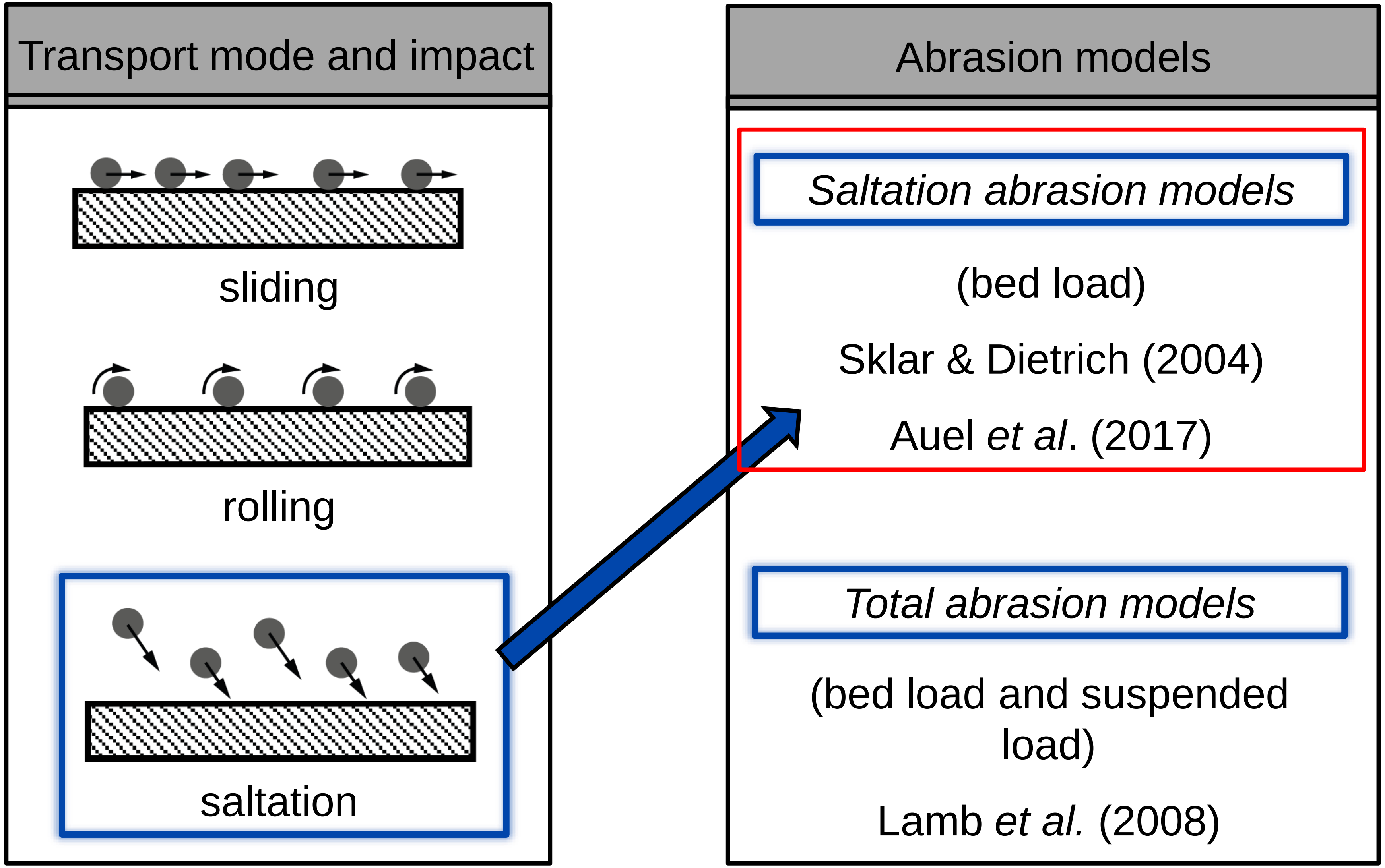


$b/h_o = 2$, $F_o = 3$, $h_o = 10$ cm



$b/h_o = 1.9$, $F = 1.7$
Runcahez SBT, Switzerland

Task D: hydro abrasion model development



Transport mode and impact

sliding

rolling

saltation

Abrasion models

Saltation abrasion models

(bed load)

Sklar & Dietrich (2004)

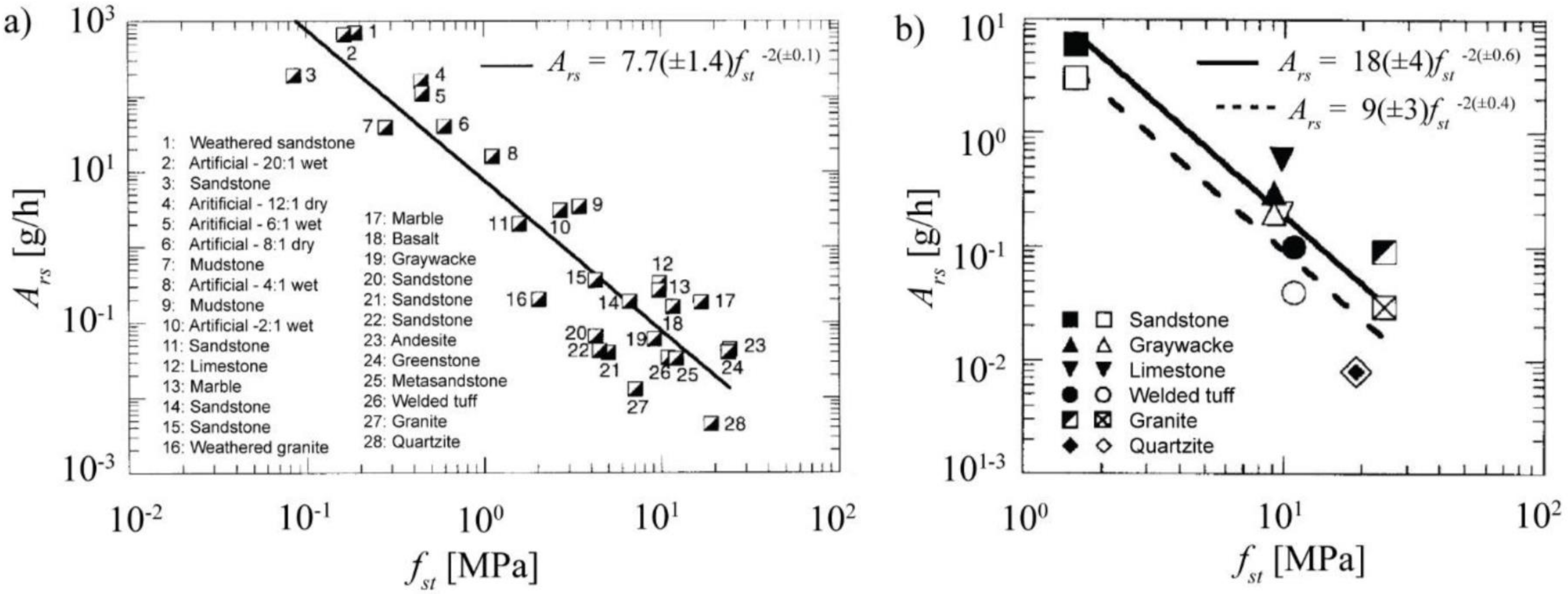
Auel *et al*. (2017)

Total abrasion models

(bed load and suspended load)

Lamb *et al.* (2008)

Abrasion mill tests [Sklar and Dietrich 2001]



Existing hydro-abrasion models

Sklar and Dietrich (2004):

$$A_r = \frac{1}{\boxed{k_v}} \boxed{\frac{Y_M}{f_{st}^{2}}} \boxed{\frac{W_{im}^{2}}{L_p} q_s} \boxed{\left(1-\frac{q_s}{q_s^{*}}\right)}$$

A_r = **Abrasion rate [m/s]**

k_v = **Abrasion coefficient [-]**

Y_M = Young’s modulus

f_{st} = **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)

$$A_r = \frac{Y_M}{k_v f_{st}^{2}} \cdot \boxed{\frac{\left(0.1(T^{*})^{0.39}\left[(s-1)gD\right]^{0.5}\right)^{2}}{2.3(T^{*})^{0.8} D} q_s} \left(1-\frac{q_s}{q_s^{*}}\right)$$

$$\approx \frac{Y_M}{k_v f_{st}^{2}} \cdot \boxed{\frac{(s-1)g}{230} q_s} \left(1-\frac{q_s}{q_s^{*}}\right)$$

Task D: hydro abrasion model development

Sklar and Dietrich (2001)	Christian Auel (2014)	Current study (2017-)
Abrasion mill	Flume experiments	Flume experiments
	$b/h > 2$	b/h = 1 to 2
Abrasive particles: Natural and artificial stones	Sandstone particles	5 types of natural stones
Bed type: Fixed	Fixed planar	Fixed planar and rough
Lining: Mortar, natural rock, foams	Mortar	Polyurethane foam and mortar

Outlook

- Hydraulics, sediment transport and hydro-abrasion
- Hydro abrasion prediction for material selection
- Optimal hydraulic design and operation of hydraulic structures
- Modelling of river bed and landscape evolution

Thank you!

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