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BASEMENT

Mixed-size bedload transport model for BASEHPC

BASEMENT Users Meeting 2024

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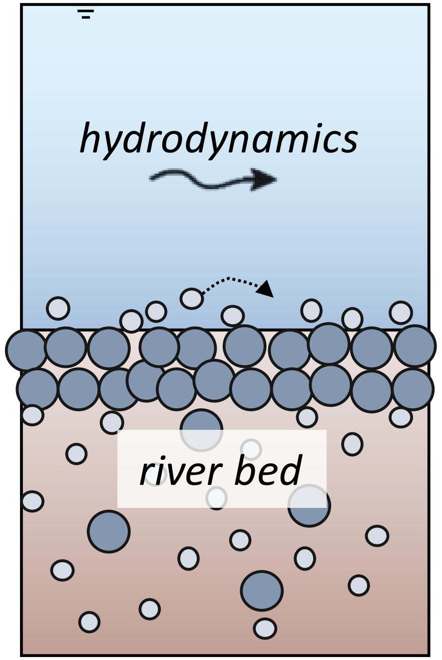
Agenda

- The Hirano-Exner model
- How to setup a mixed-size bedload transport model for BASEHPC
- Comparison of BASEHPC and BASEMD
- Conclusion

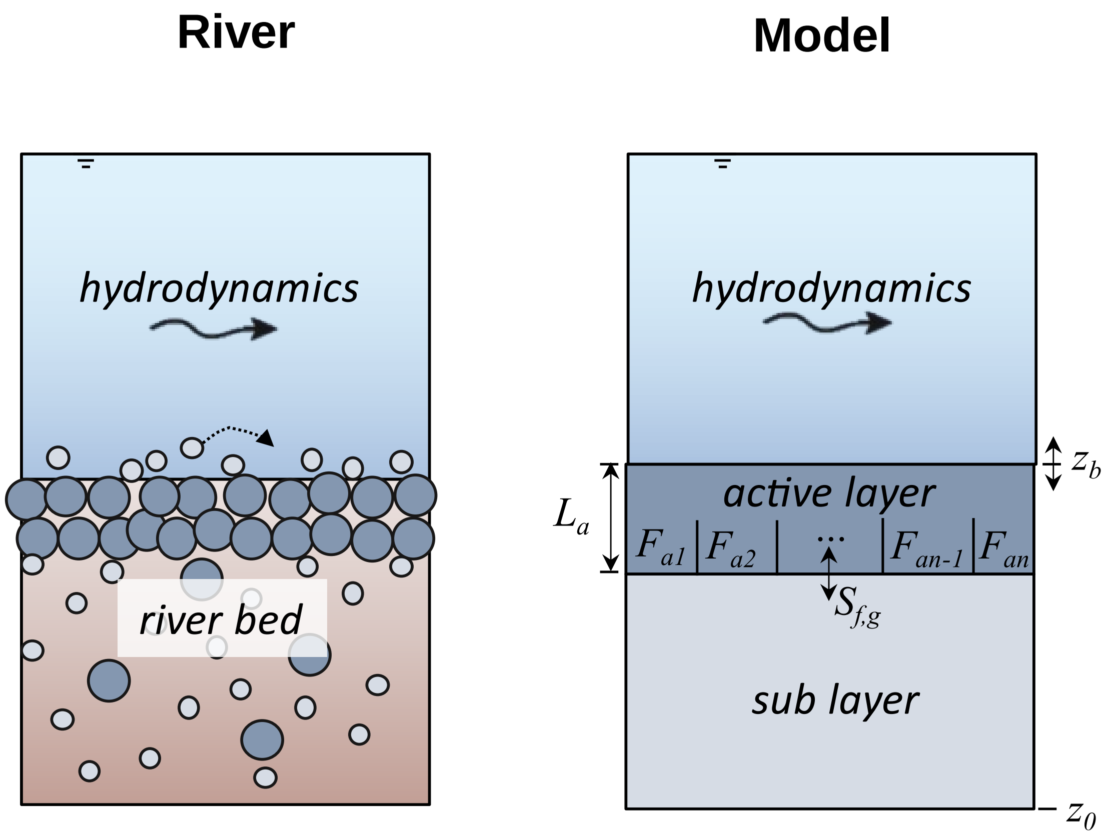
The Hirano-Exner model

The Hirano-Exner model

River



The Hirano-Exner model



St. Venant equations

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = 0$$

$$\frac{\partial q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{q^2}{h}\right) + gh\frac{\partial h}{\partial x} = -gh\left(\frac{\partial z_B}{\partial x} + S_f\right)$$

Exner equation

$$(1-p)\frac{\partial z_B}{\partial t} = -\frac{\partial q_B}{\partial x}$$

n Mass conservation of grain classes

$$(1-p)\left[L_a\frac{\partial F_{ak}}{\partial t} + \left(F_{ak} - f_{Ik}\right)\frac{\partial L_a}{\partial t}\right] = -\frac{\partial q_{Bk}}{\partial x} + f_{Ik}\frac{\partial q_B}{\partial x}$$

How to setup a mixed-size bedload transport model for BASEHPC

Bed material

Grain classes and mixtures

- 10 grain size classes to define sediment mixtures

```
BEDMATERIAL
  GRAIN_CLASS
    diameters
      [0]  ▶ 0.001
      [1]  ▶ 0.003
      [2]  ▶ 0.005
      [3]  ▶ 0.007
      [4]  ▶ 0.009
  MIXTURE
    [0]
      name  ▶ "mixture_fine"
      volume_fraction
        [0]  ▶ 25.0
        [1]  ▶ 40.0
        [2]  ▶ 30.0
        [3]  ▶ 5.0
        [4]  ▶ 0.0
    [1]
      name  ▶ "mixture_coarse"
      volume_fraction
        [0]  ▶ 5.0
        [1]  ▶ 10.0
        [2]  ▶ 20.0
        [3]  ▶ 40.0
        [4]  ▶ 25.0
```

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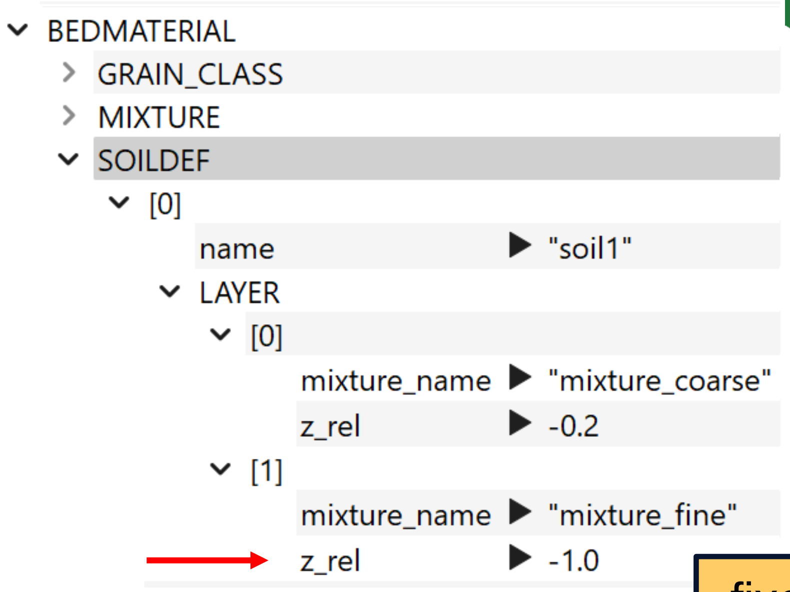
Bed material

Grain classes and mixtures

- Max. 10 grain size classes to define sediment mixtures

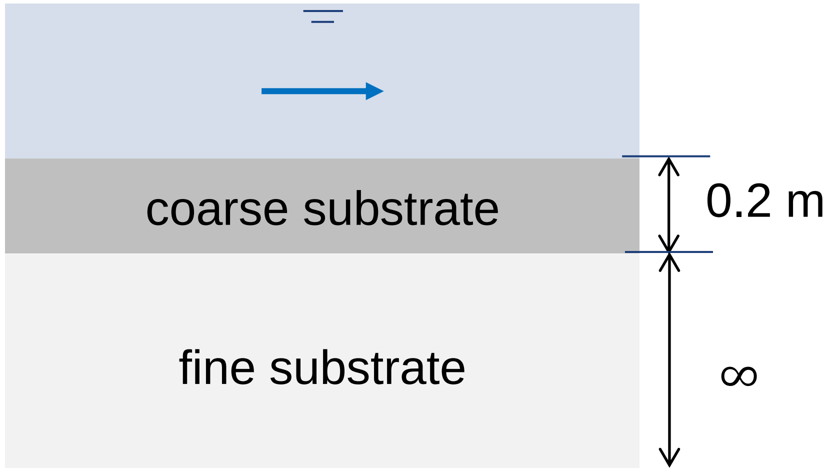
Soil definition

- Max. 2 layers available to characterize soils with mixtures
- Default relative elevation *z_rel*: -999.0 [m]
- *z_rel* > -999.0 in lowest layer results in definition of fixed bed

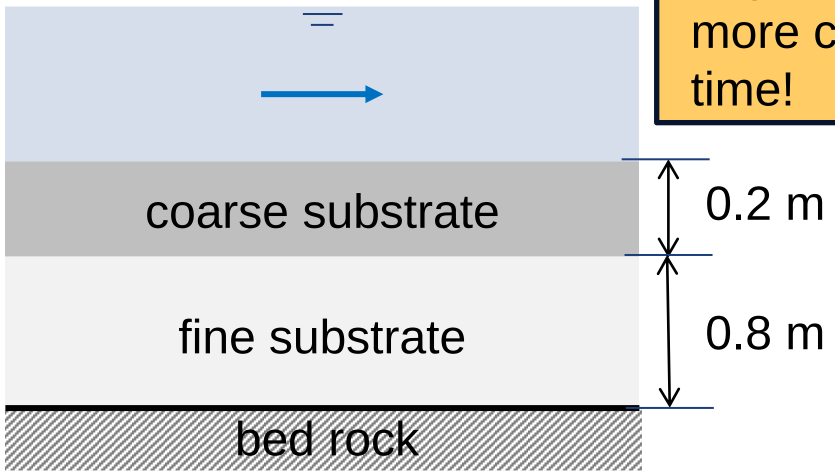


fixed bed requires more comp. time!

default:



fixed bed:



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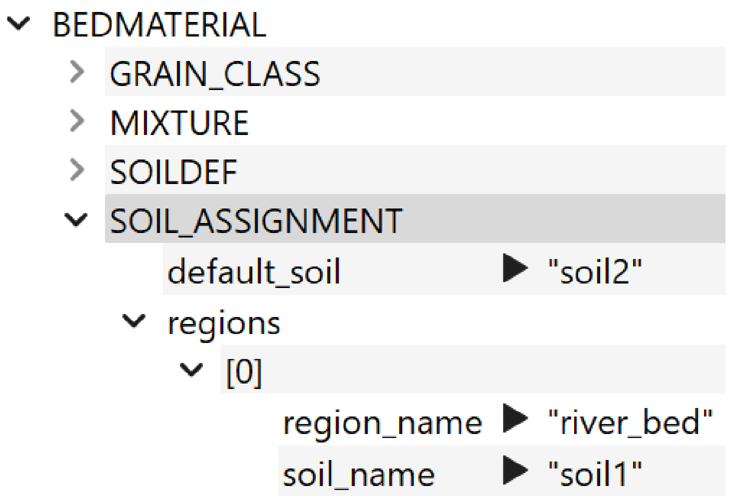
Soil assignment

- Soils can be assigned to different mesh regions



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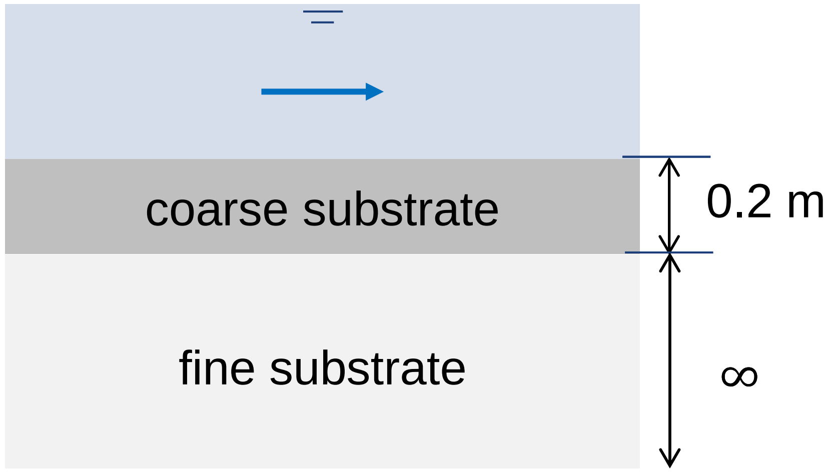
Active layer (control volume)

- Constant: $L_a = \text{const.}$
- d90: $L_a = f \cdot d_{90}$

Example:
→ Layer 1: *z_rel* = -0.2 m
→ Layer 2: *z_rel* = -999.0 m
→ L_a = 0.2 m



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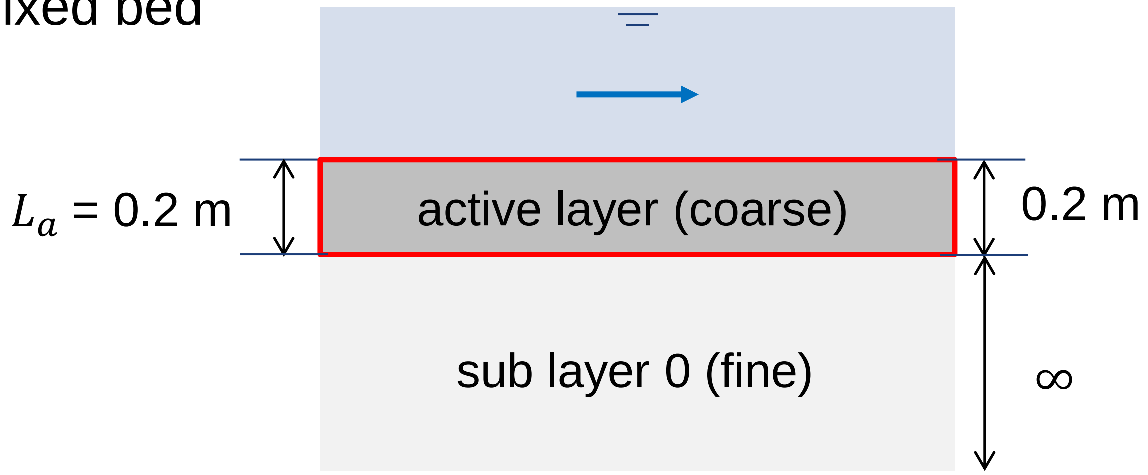

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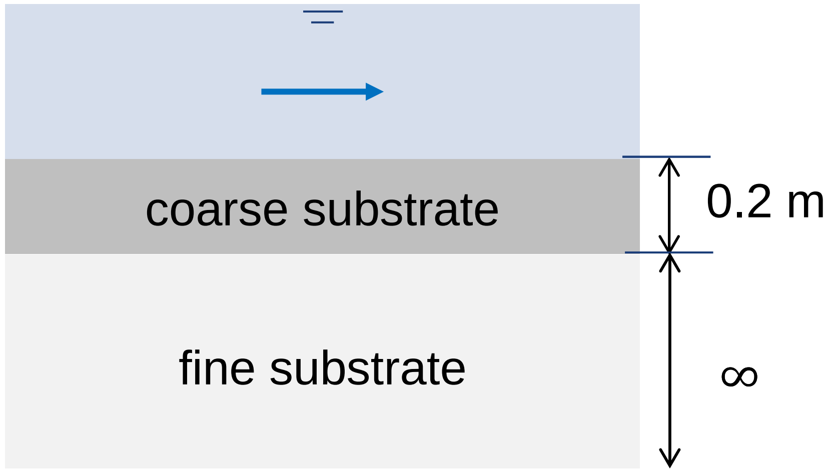
Example:
→ Layer 1: *z_rel* = -0.2 m
→ Layer 2: *z_rel* = -999.0 m
→ L_a = 0.1 m



Bed material

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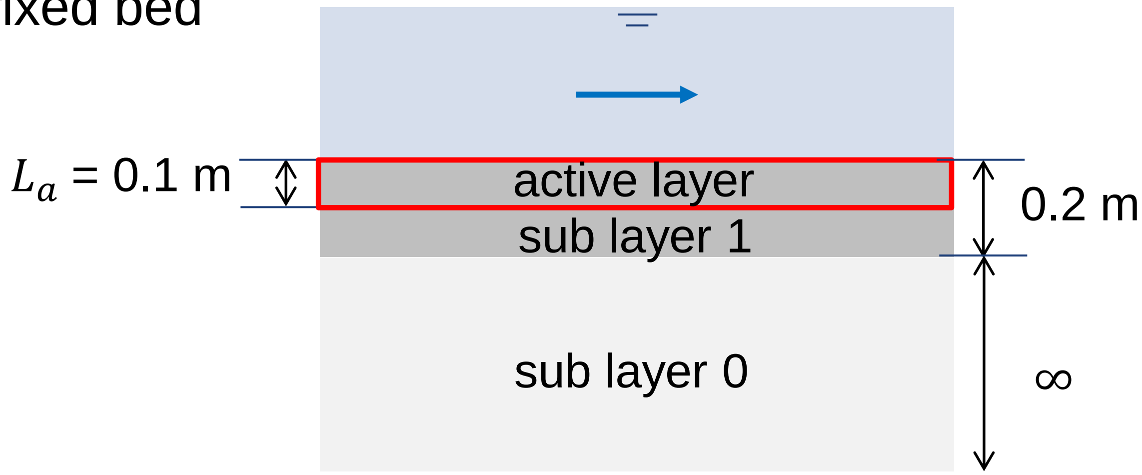


Fixed bed

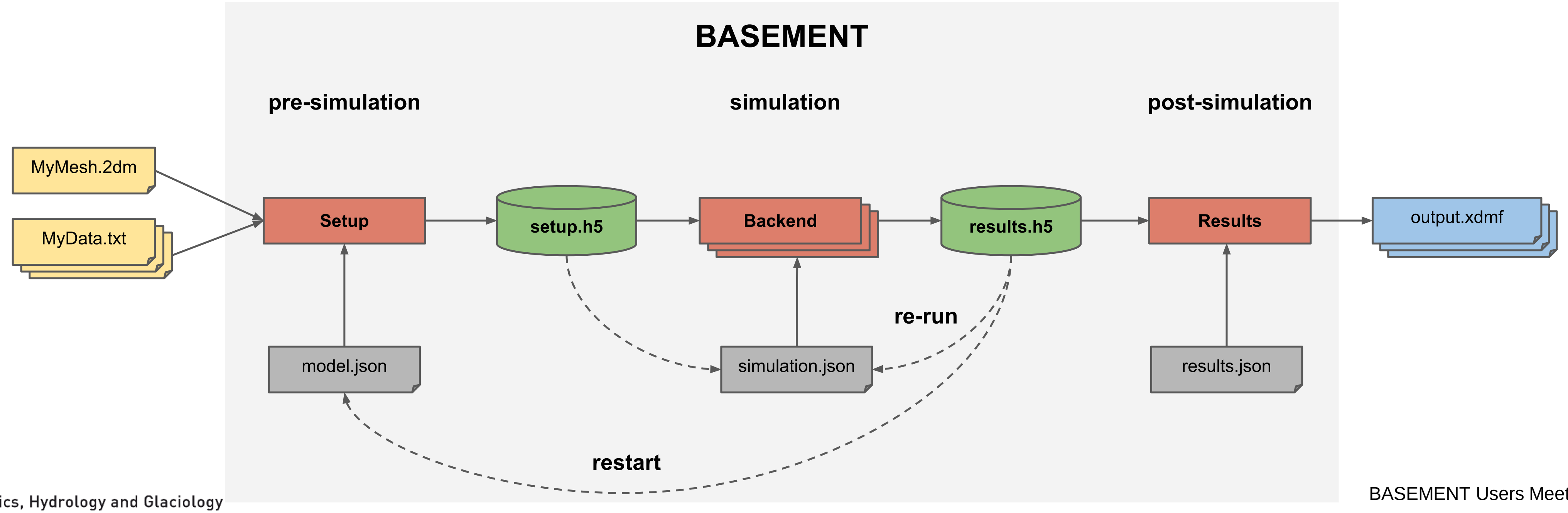
Two ways to define a fixed bed elevations:

1. Definition via *FIXED_BED* block
   - Provide a separate mesh (2dm-format)
   - Assign *z_rel* to regions
2. Definition via *LAYER*s in *SOILDEF*
   - Assign *z_rel* > -999.0 to layers

definitions in *FIXED_BED* block overwrite fixed bed information from *SOILDEF block*

Restart and re-run simulations

- Substrate information of existing simulation can be used as initial conditions (restart)
  - Definition via separate *INITIAL* block in the *BEDMATERIAL* block
  - Either *SOILDEF* and *SOIL_ASSIGNMENT* blocks, or *INITIAL* block must be provided
- Re-run simulations possible by setting start time > 0



Bedload transport capacity

- Extension of Meyer-Peter & Müller (1948) with hiding and exposition effects of Ashida & Michiue (1971)

$$q_{b,i} = \alpha \sqrt{(s-1) g d_i^3} \left(\theta_i - \theta_{cr,i}\right)^m$$

$$\theta_{cr,i} = \theta_{cr,ref} \xi_i$$

$$\xi_i = \begin{cases} \left[\log(19) / \log(19 d_i / d_m)\right]^2 & if \quad d_i/d_m \geq 0.4 \\ 0.843 d_m / d_i & if \quad d_i/d_m < 0.4 \end{cases}$$

- Hunziker (1995)

$$q_{b,i} = 5\beta_i \sqrt{(s-1) g d_{ms}^3} \left[\xi_i \left(\theta'_{dms} - \theta_{c,dms}\right)\right]^{3/2}$$

$$\theta'_{dms} = \frac{\tau'_b}{\rho_w (s-1) d_{ms}}$$

$$\theta_{c,dms} = \theta_{c,e} (d_{mo}/d_{ms})^{0.33}$$

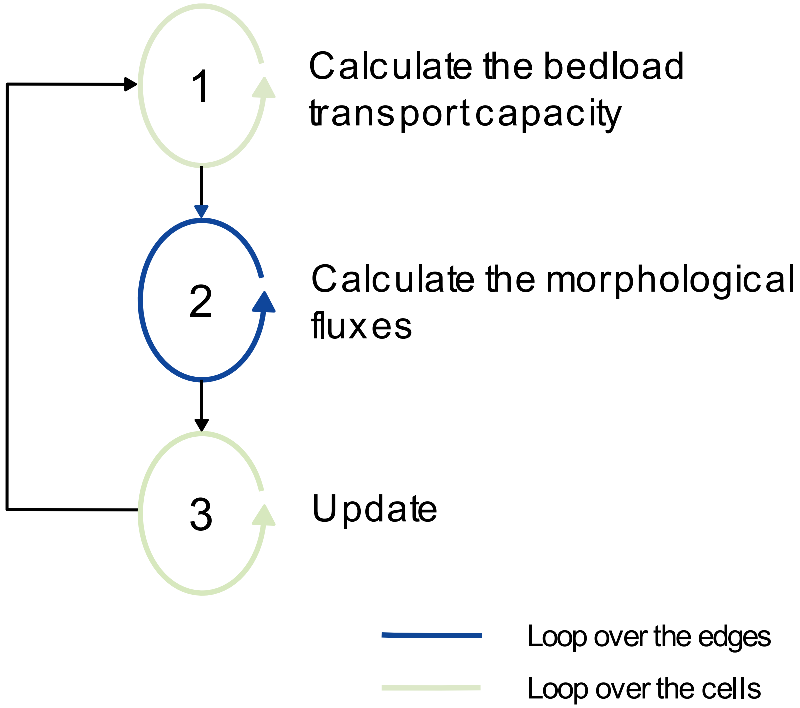
$$d_{mo}/d_{ms} = 0.0163\, \theta'^{-1.45}_{dms} + 0.6$$

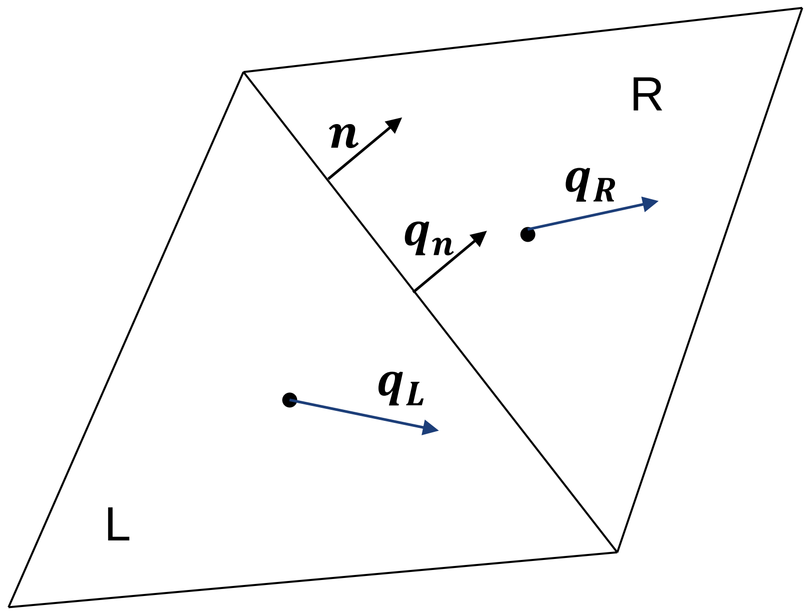
$$\xi_i = (d_i / d_{ms})^{-\gamma} \qquad \gamma = 0.011\, \theta'^{-1.5}_{dms} - 0.3$$

$q_{b,i}$ transport capacity of grain class i [m³/s]
s relative sediment density ($= \rho_s/\rho$) [-]
g gravtiational acceleration [m/s²]
d_i mean diameter of grain class i [m]
d_m mean diameter [m]
θ_i dimensionless shear stress [-]
$\theta_{cr,i}$ critical dimensionless shear stress [-]
α bedload factor [-]
m bedload exponent [-]
d_{ms} mean grain size of surface mat. [m]
d_{mo} mean grain size of subsurface mat. [-]

Numerical solver

Numerical procedure for bedload transport





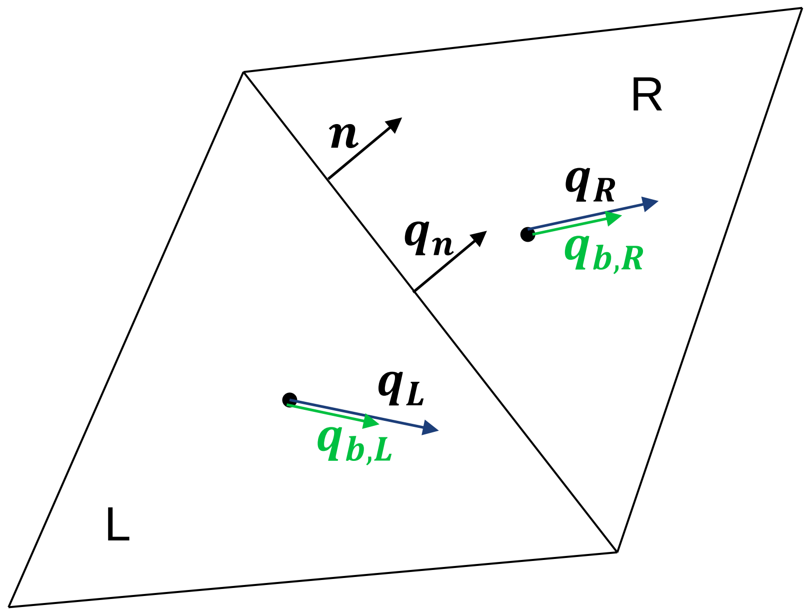
Numerical solver

Numerical procedure for bedload transport

1. Calculate the bedload transport capacity
2. Calculate the morphological fluxes
3. Update

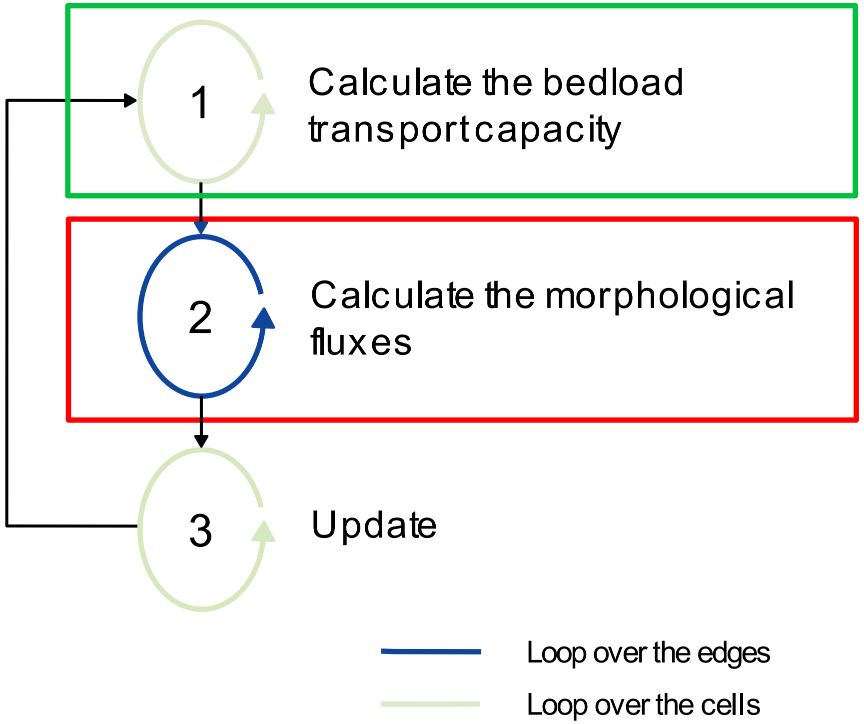
Loop over the edges

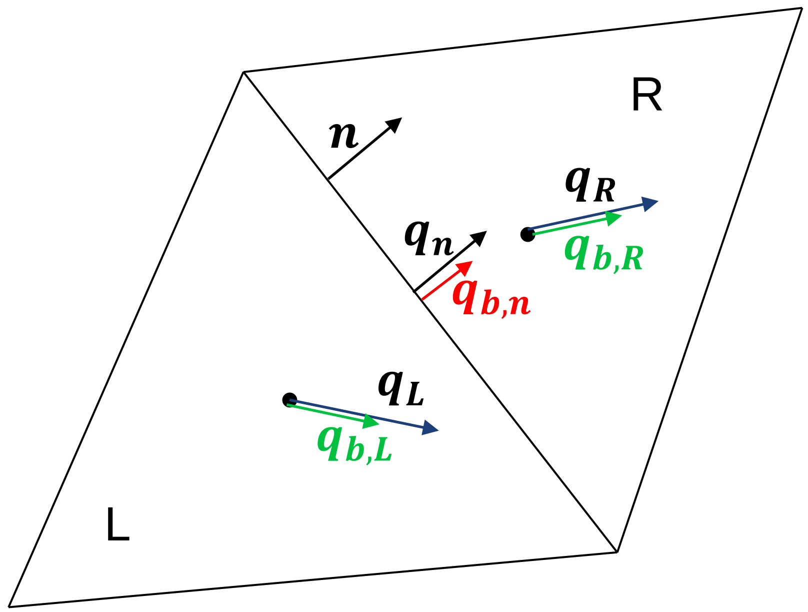
Loop over the cells



Numerical solver

Numerical procedure for bedload transport

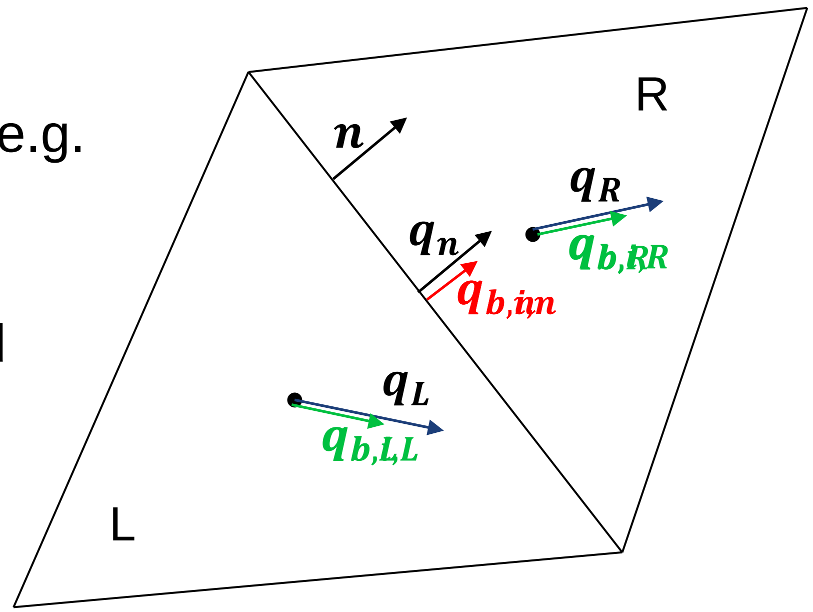




Numerical solver

Numerical procedure for bedload transport

- For uniform sediment, mathematically sound approaches available in literature to calculate morphological fluxes $\boldsymbol{q_{b,n}}$, e.g. HLLC solver in BASEHPC (Soares-Frazão and Zech, 2011)
- For mixed-size sediment, calculation of $\boldsymbol{q_{b,i,n}}$ is complex and approaches in literature did not provide satisfactory results
- Implemented solver: weighting by upwind factor f_u

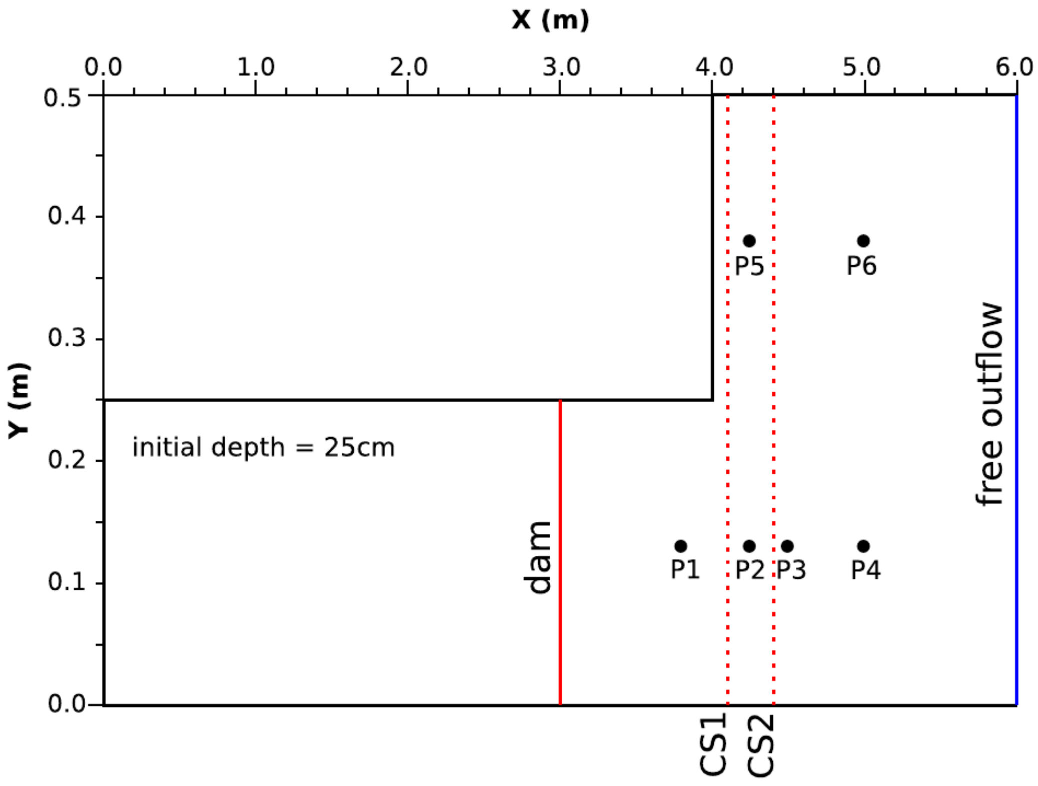


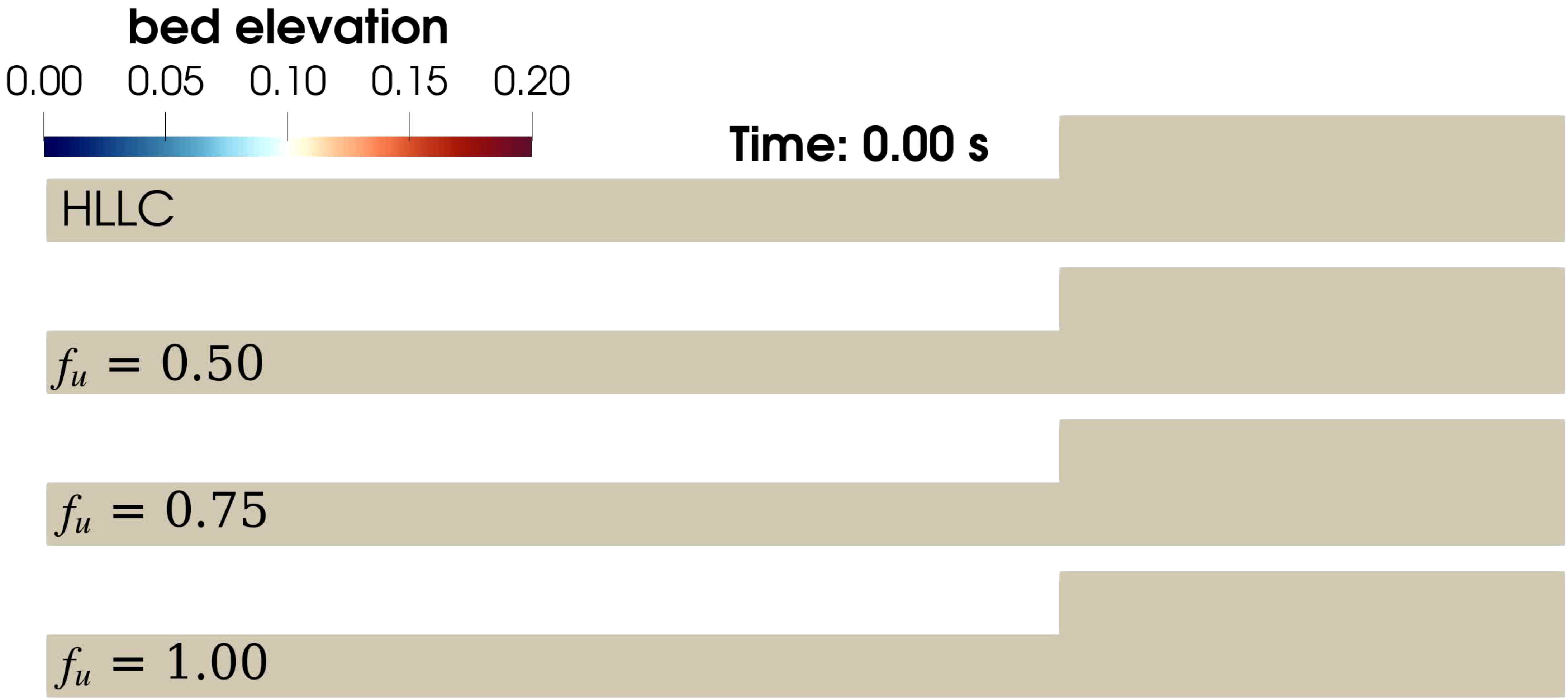
$$q_{b,i,n} = \begin{cases} f_u \cdot q_{b,i,L} + (1 - f_u) q_{b,i,R} & q_n \geq 0 \\ f_u \cdot q_{b,i,R} + (1 - f_u) q_{b,i,L} & q_n < 0 \end{cases}$$

Numerical solver

Effect of upwind factor f_u

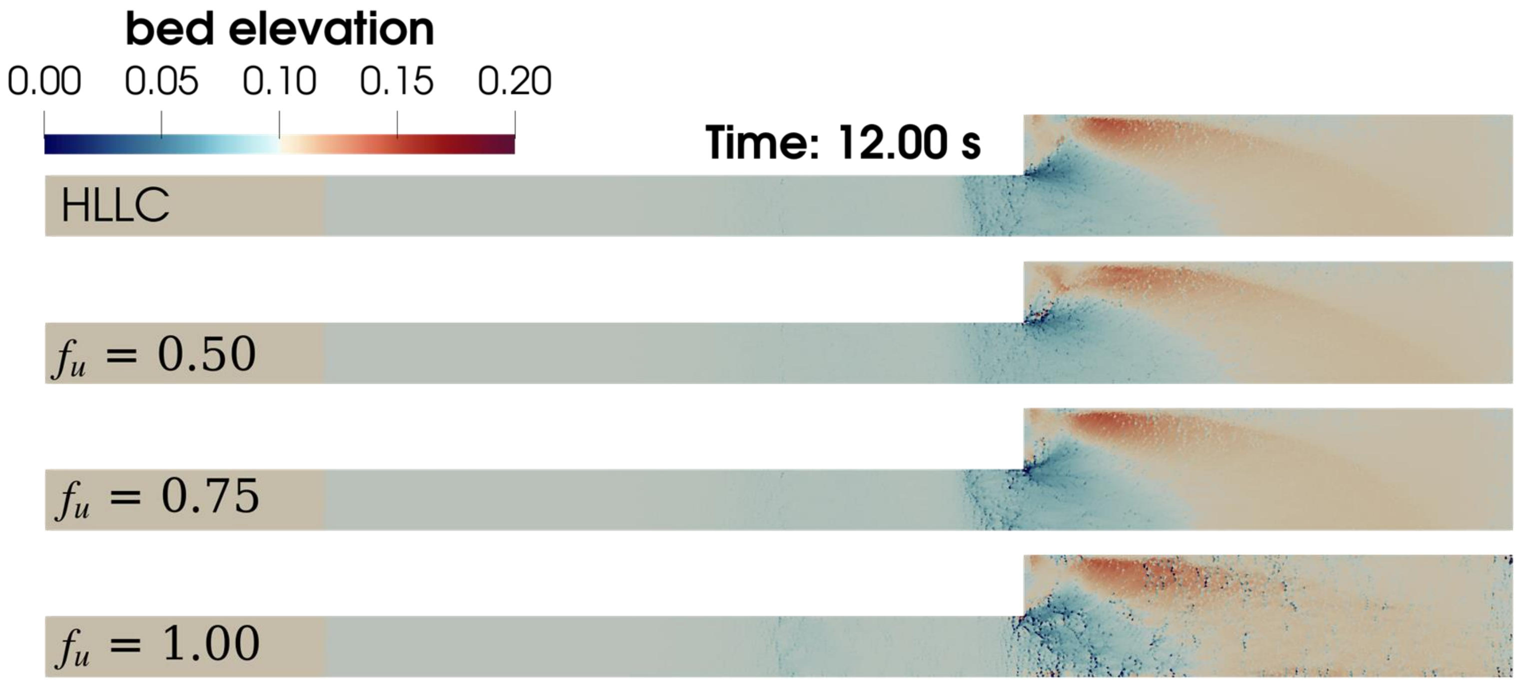
- Dam-break over a mobile bed with a sudden enlargement
- Left side initialized with 0.25 m water depth
- Instantaneous removal of dam at t = 0 s
- Uniform sediment with d_m = 1.82 mm
- Test to assess robustness in simulating sediment transport at wet-dry interface, and the accuracy in reproducing scour/deposition patterns




bed elevation
0.00 0.05 0.10 0.15 0.20
Time: 0.00 s
HLLC
f_u = 0.50
f_u = 0.75
f_u = 1.00

Numerical solver

- Upwind factor f_u has impact on stability and results of simulation
- f_u = 0.5 more stable, more diffusive
- f_u = 1.0 less stable, less diffusive
- Recommended: $0.7 \leq f_u \leq 0.8$
- HLLC remains recommended solver for uniform sediment

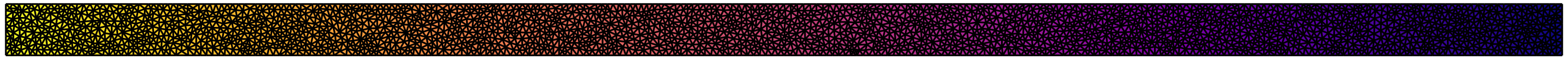


Comparison of BASEHPC and BASEMD

Ribberink (1987) test case

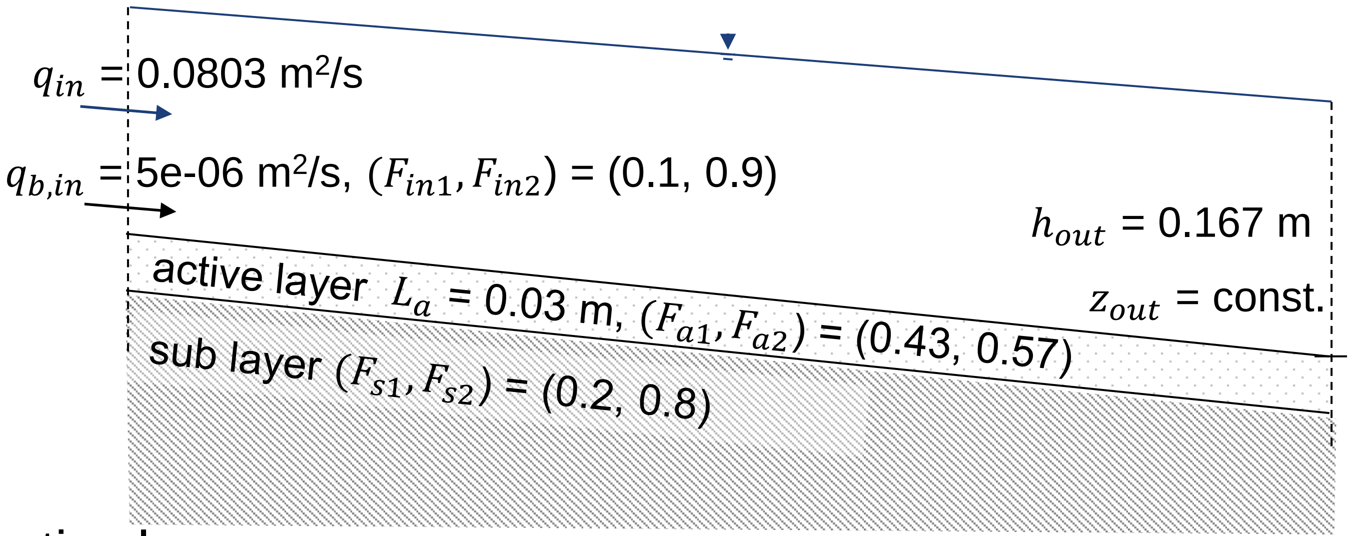
→ Test capability of depicting streamwise sorting processes

Numerical model setup



- Straight channel (30 m x 1 m) with slope J = 0.165%, 4'873 mesh elements
- Two grain size classes:

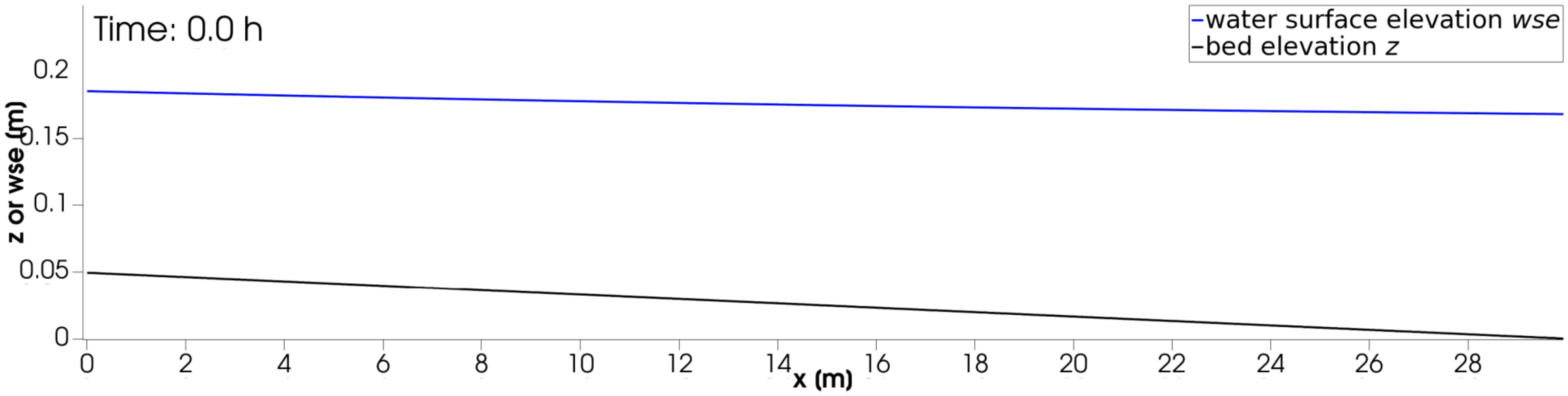
  d_1 = 0.78 mm and d_2 = 1.29 mm
- Heterogenous initial active layer
- Sediment feed with mostly coarse material
- Sediment feed > transport capacity



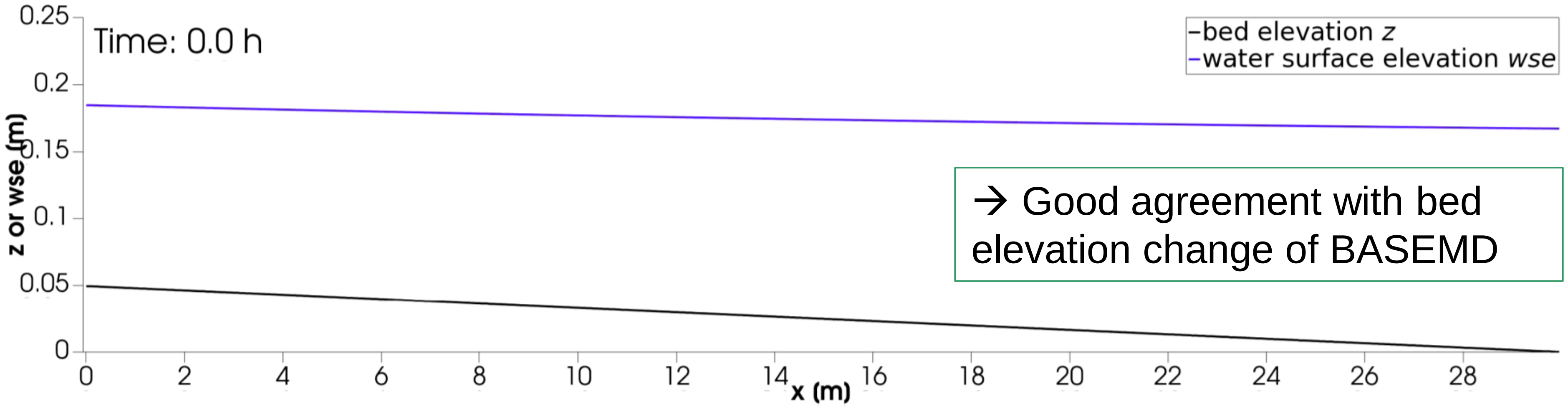
<u>Expected result:</u> deposition and coarsening of active layer

Ribberink test case – bed elevation change

BASEMD

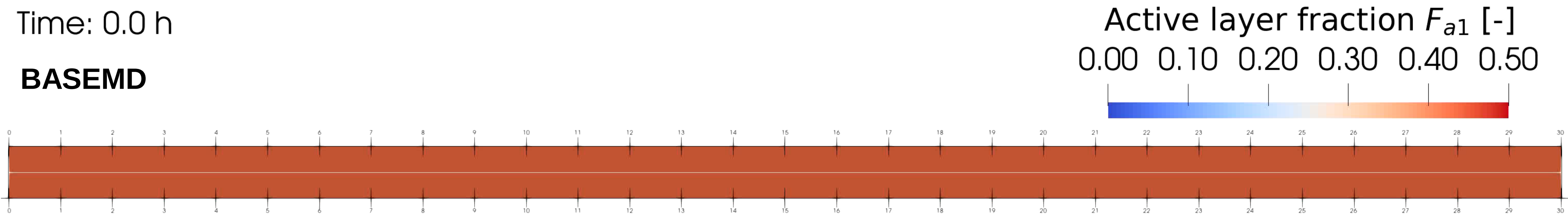


BASEHPC

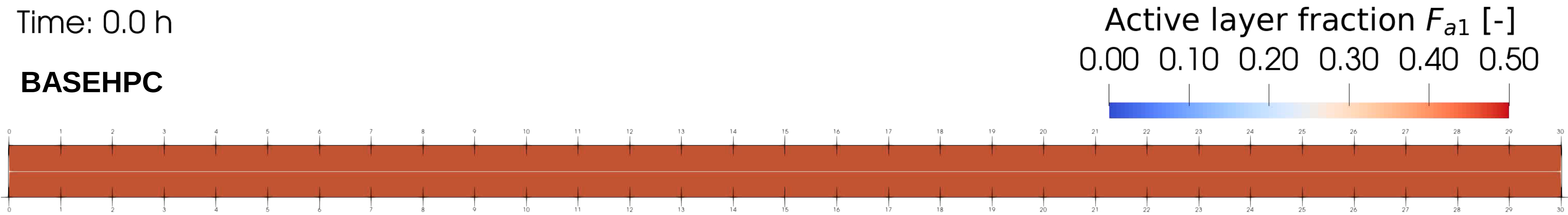


→ Good agreement with bed elevation change of BASEMD

Ribberink test case – grain sorting process



BASEMD



BASEHPC

- Initially, 43% fine fraction in active layer
- After 36h, approx. 7% fine fraction in active layer
- Coarsening of active layer occurs as expected

Ribberink test case – grain sorting process

→ Streamwise sorting process accurately captured by BASEHPC

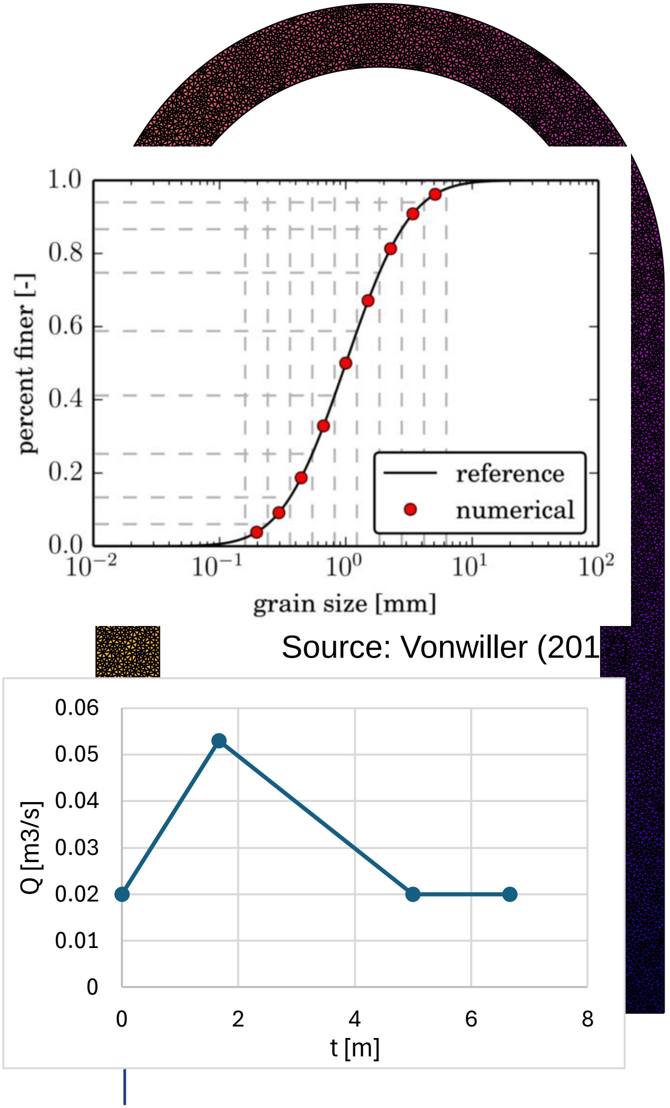
→ Sorting process occurs slightly slower, e.g. due to different sediment mesh in BASEMD

180° river bend test case

→ Test capability to depict streamwise and lateral sorting

Numerical model setup

- Channel with 180° bend (37 m x 1 m) with slope J = 0.2%, 12’122 mesh elements
- Grain size distribution (GSD) with nine size classes, d_{50} = 1 mm
- Same GSD for initial bed material and sediment feed
- Inflow boundary: Hydrograph and equilibrium transport



Inflow

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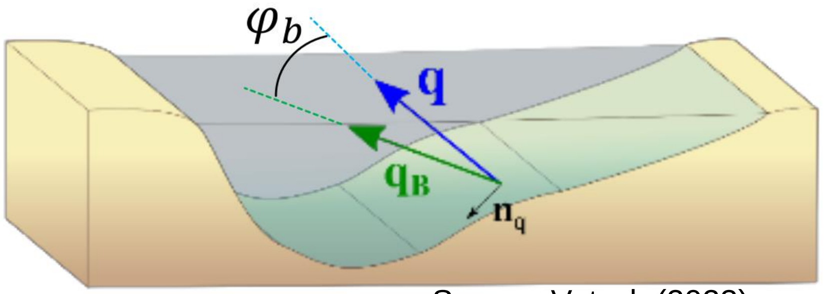
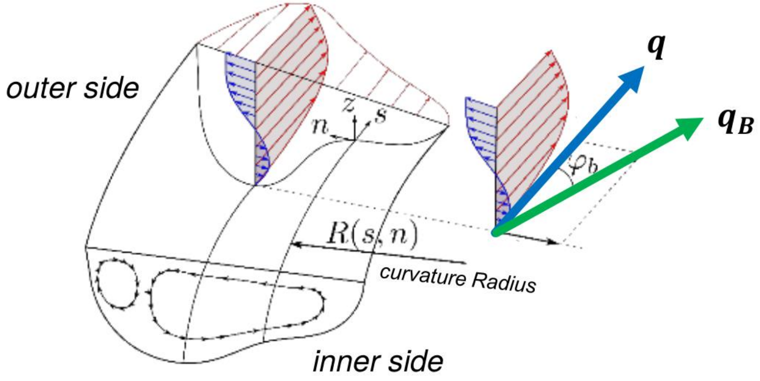
- Consideration of lateral bed slope and flow curvature effects

Lateral bed slope effect



Source: Vetsch (2023)

Flow curvature effect

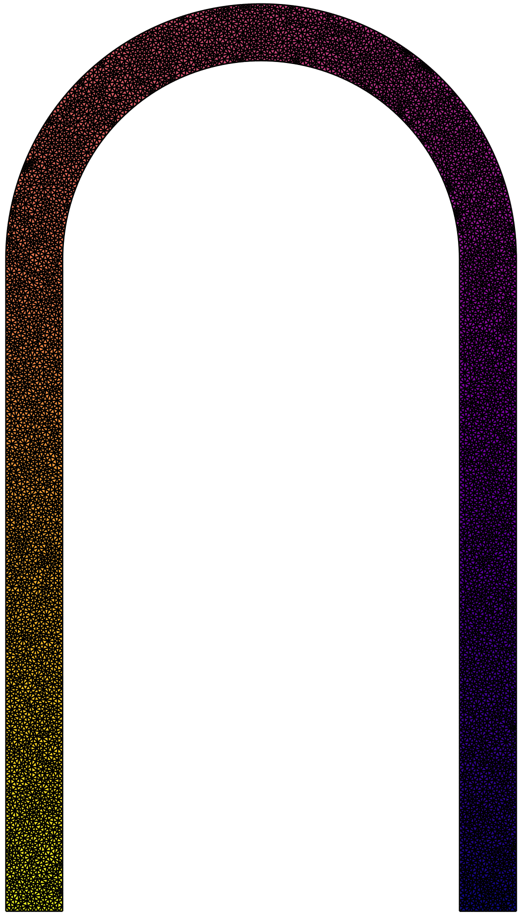


Source: Vetsch (2023)

Expected result: erosion and coarsening of active layer along outer side of 180° bend

180° river bend test case

→ Test capability to depict streamwise and lateral sorting



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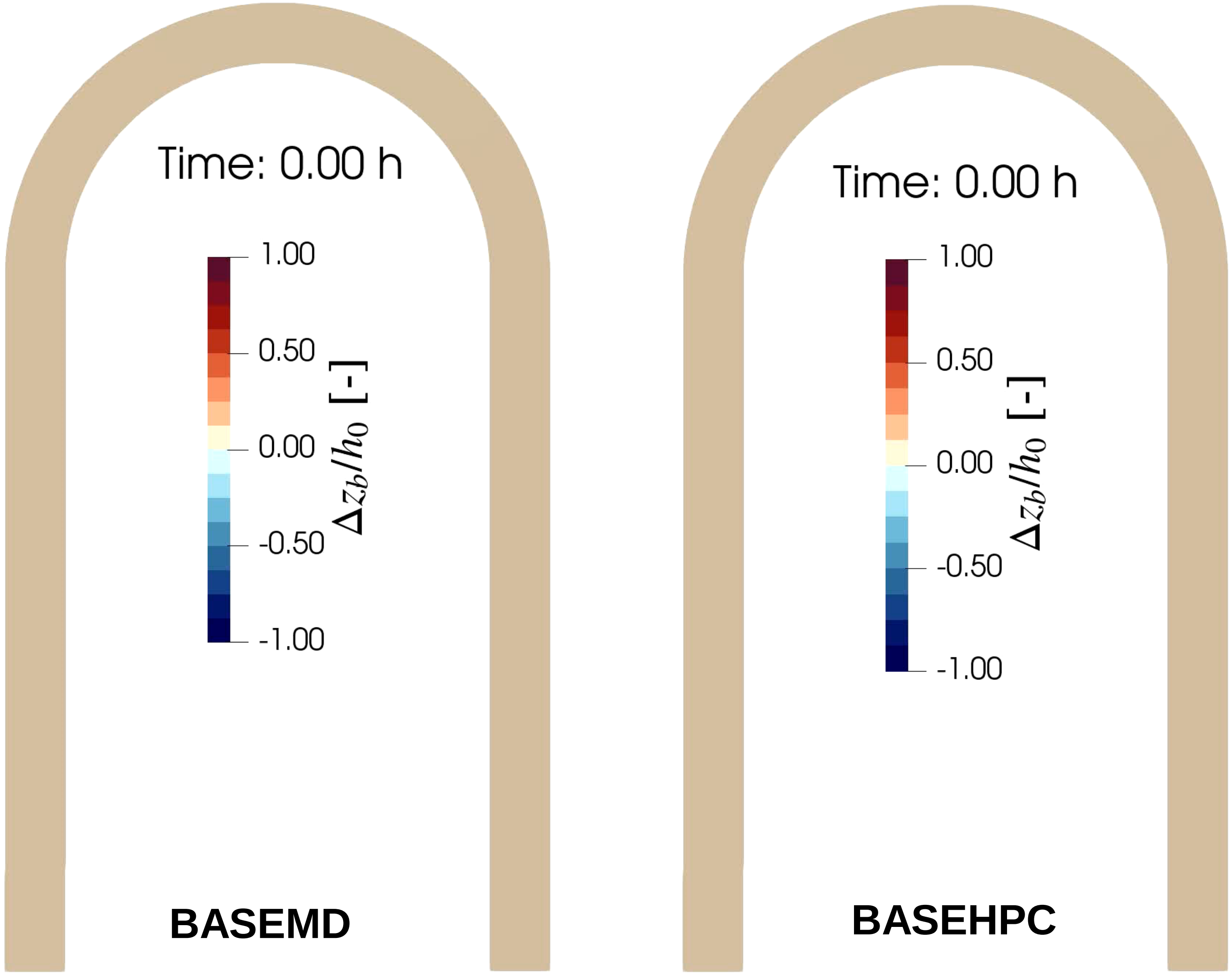
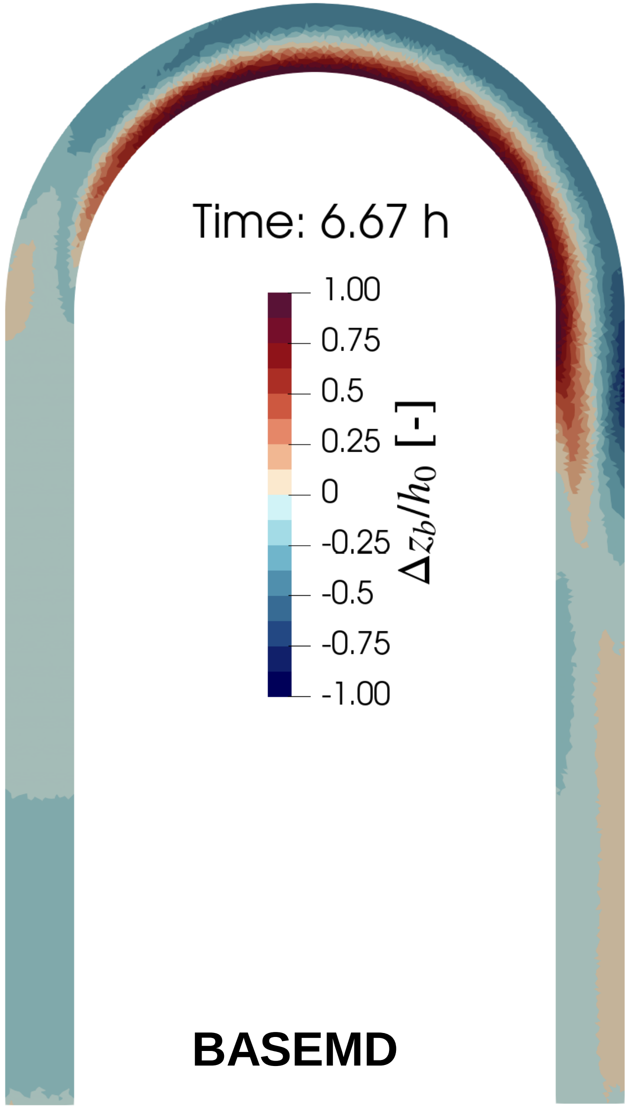
180° river bend test case – bed elevation change

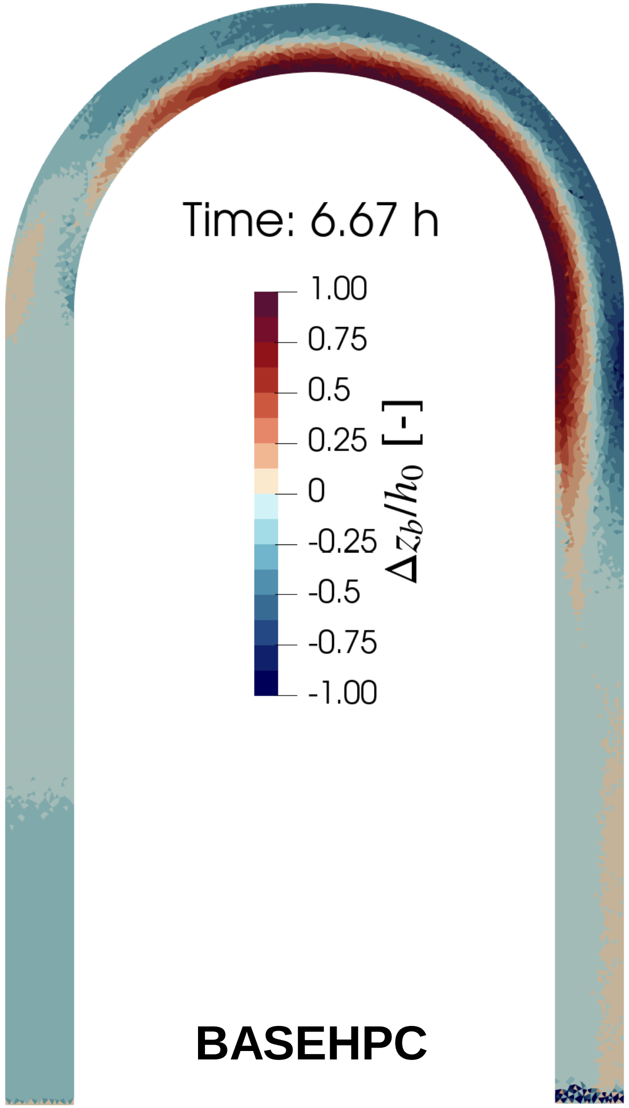


→ Comparable bed elevation changes

→ Erosion and deposition processes due to flow curvature and lateral bed slope effects are accurately captured with BASEHPC

180° river bend test case – bed elevation change





→ Comparable bed elevation changes

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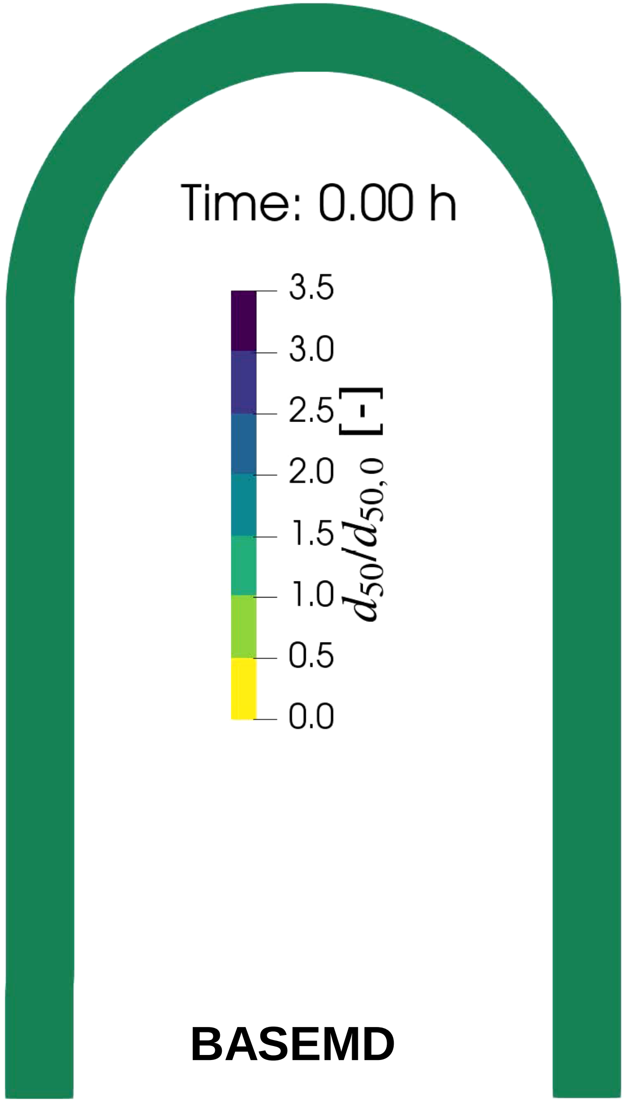
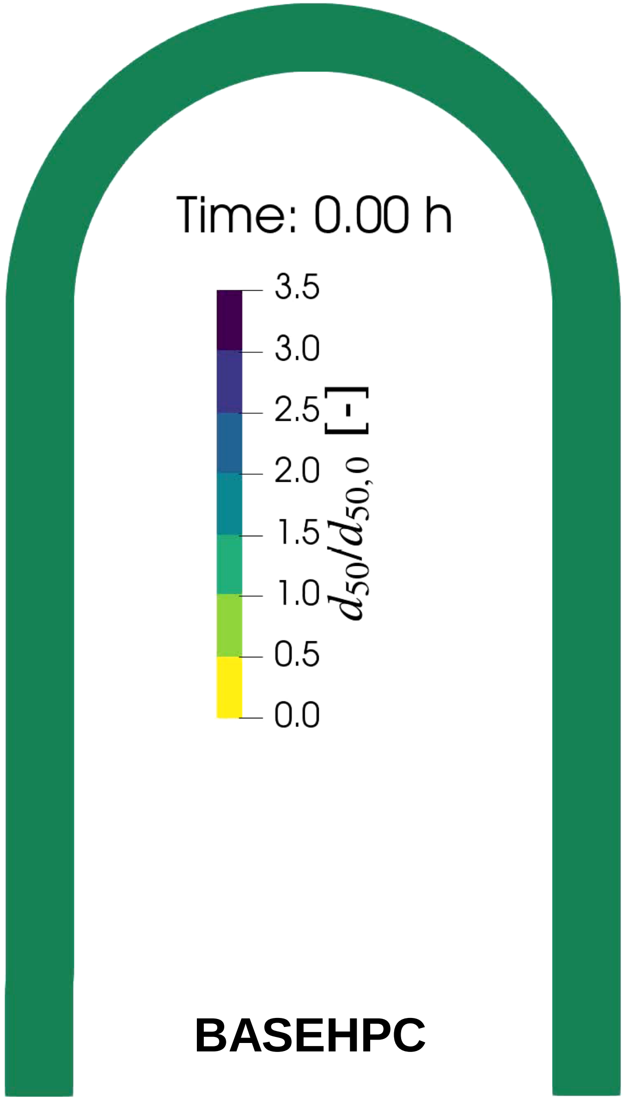
180° river bend test case – grain sorting process

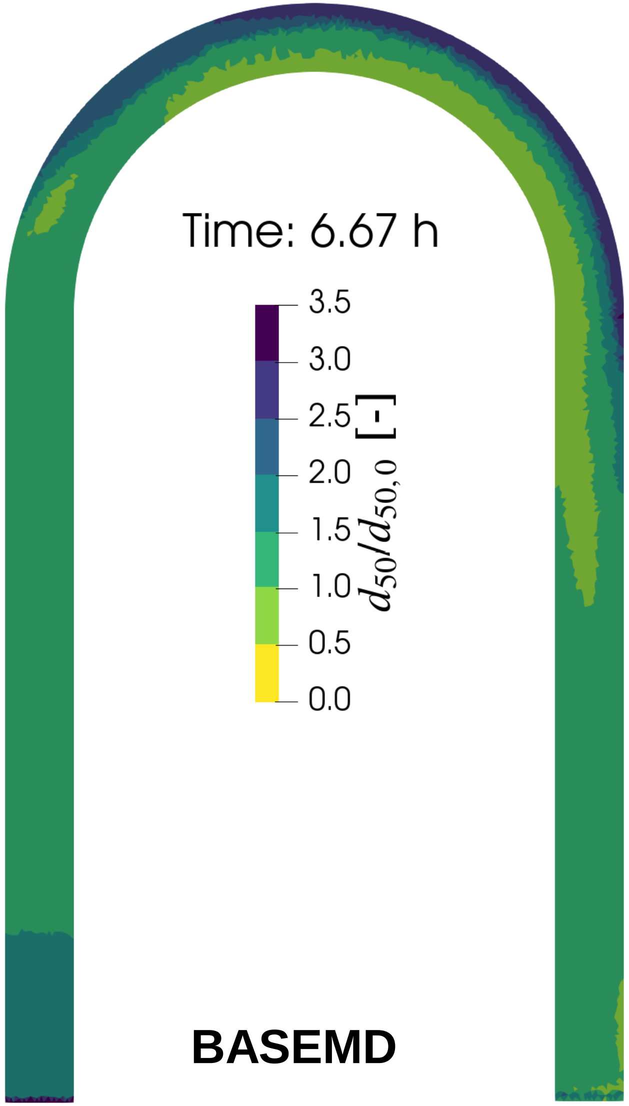


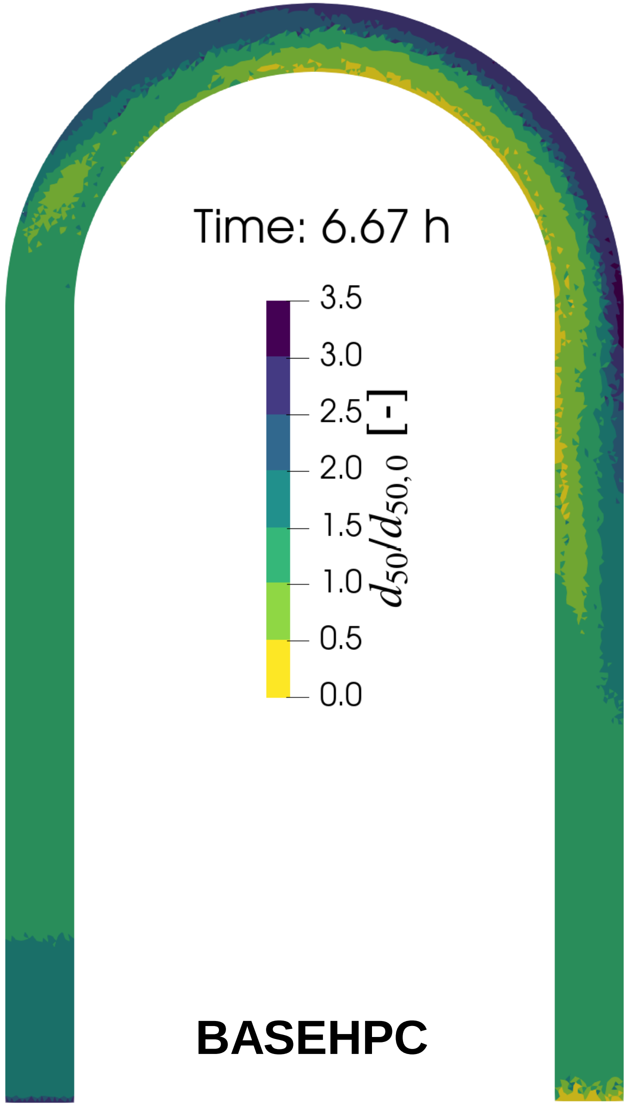


→ Comparable changes median grain size in active layer

→ Lateral grain sorting processes accurately captured with BASEHPC

180° river bend test case – grain sorting process





→ Comparable changes median grain size in active layer

→ Lateral grain sorting processes accurately captured with BASEHPC

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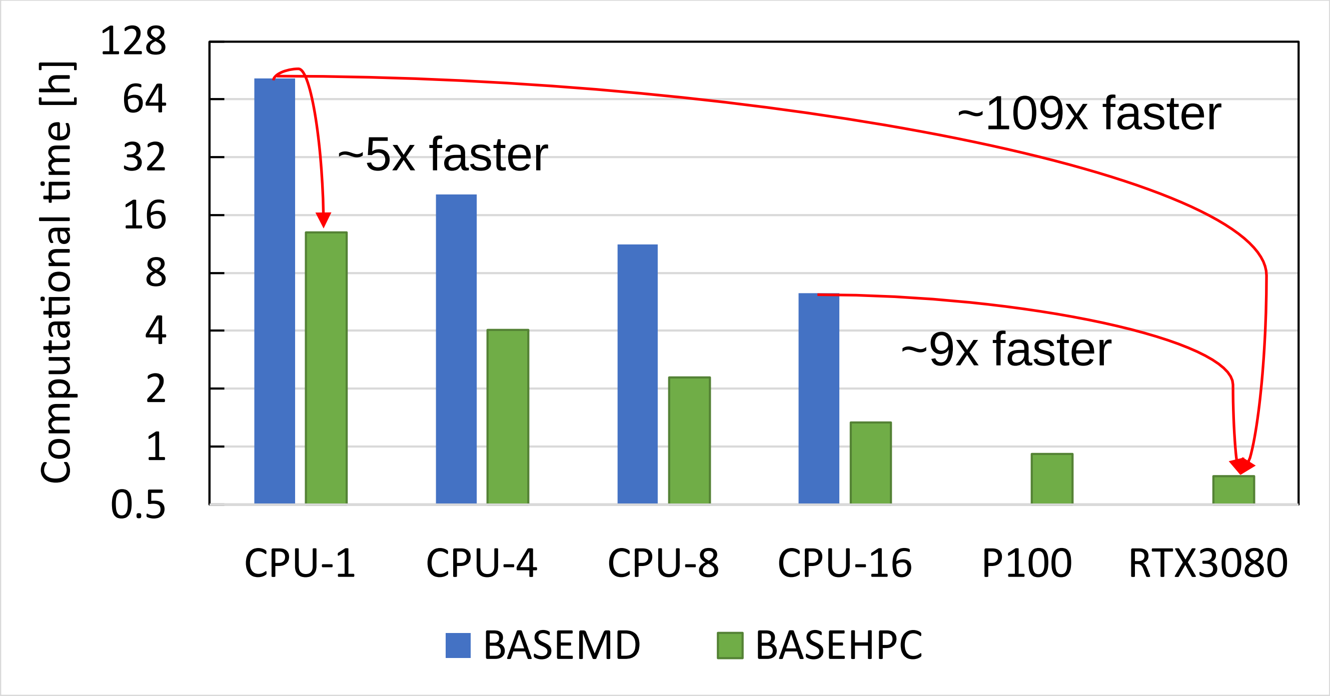
180° river bend test case – computational performance

Specifications

- 12’122 mesh elements
- 9 grain size classes
- Simulation duration 6.67h
- Intel Xeon Gold 5218, 2.30GHz
- GPUs:
  - Tesla P100-PCIE-12GB
  - NVIDIA GeForce RTX 3080



→ BASEHPC ~5x times faster on CPUs than BASEMD

→ BASEHPC on fastest GPU ~9x faster than BASEMD on 16 cores or ~109x than on a single core

Conclusion

- Mixed-size bedload transport model for BASEHPC with focus on performance
- Less comprehensive functionality than BASEMD, e.g. no coupling with suspended load transport
- Model allows accurate prediction streamwise and lateral grain sorting processes
- On CPUs, ~5x faster than BASEMD, on GPU up to ~109x faster than BASEMD on one core
- Release of model planned with next official release (Q1 2024)

Thank you for your attention!

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Additional slides

Bed material

Grain classes and mixtures

- Max. 10 grain size classes to define sediment mixtures

Soil definition

- Max. 2 layers available to characterize soils with mixtures
- Default relative elevation *z_rel*: -999.0 [m]
- *z_rel* > -999.0 in lowest layer results in definition of fixed bed

Soil assignment

- Soils can be assigned to different mesh regions

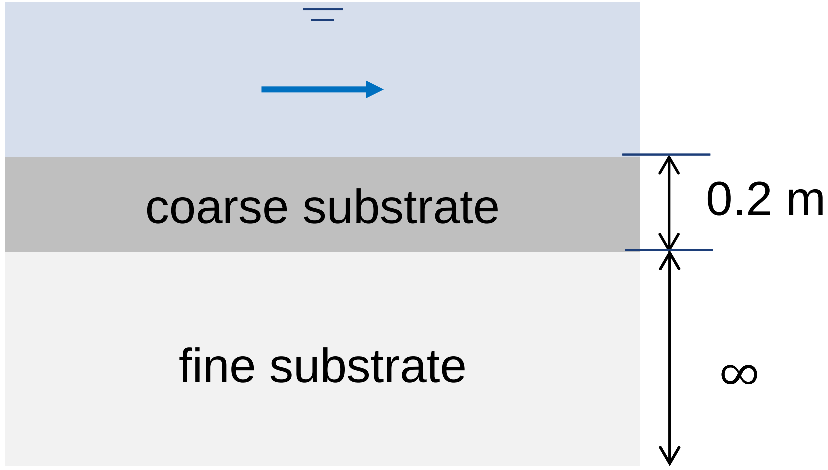
Active layer (control volume)

- Constant: $L_a = \text{const.}$
- d90: $L_a = f \cdot d_{90}$

Recommendation
- 1 layer to define active layer
- 1 layer to define sub layer

→1 sub layer free for deposition

Example:
L_a = 0.2 m
→ Layer 1: *z_rel* = -0.2 m
→ Layer 2: *z_rel* = -999.0 m



Bed material

Grain classes and mixtures

- Max. 10 grain size classes to define sediment mixtures

Soil definition

- Max. 2 layers available to characterize soils with mixtures
- Default relative elevation *z_rel*: -999.0 [m]
- *z_rel* > -999.0 in lowest layer results in definition of fixed bed

Soil assignment

- Soils can be assigned to different mesh regions

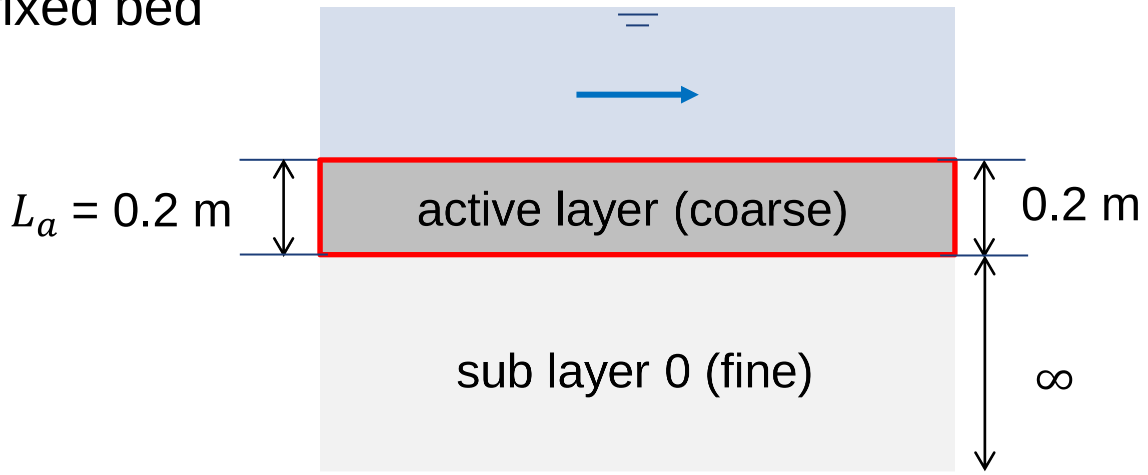
Active layer (control volume)

- Constant: $L_a = \text{const.}$
- d90: $L_a = f \cdot d_{90}$

Recommendation
- 1 layer to define active layer
- 1 layer to define sub layer

→1 sub layer free for deposition

Example:
L_a = 0.2 m
→ Layer 1: *z_rel* = -0.2 m
→ Layer 2: *z_rel* = -999.0 m



Bed material

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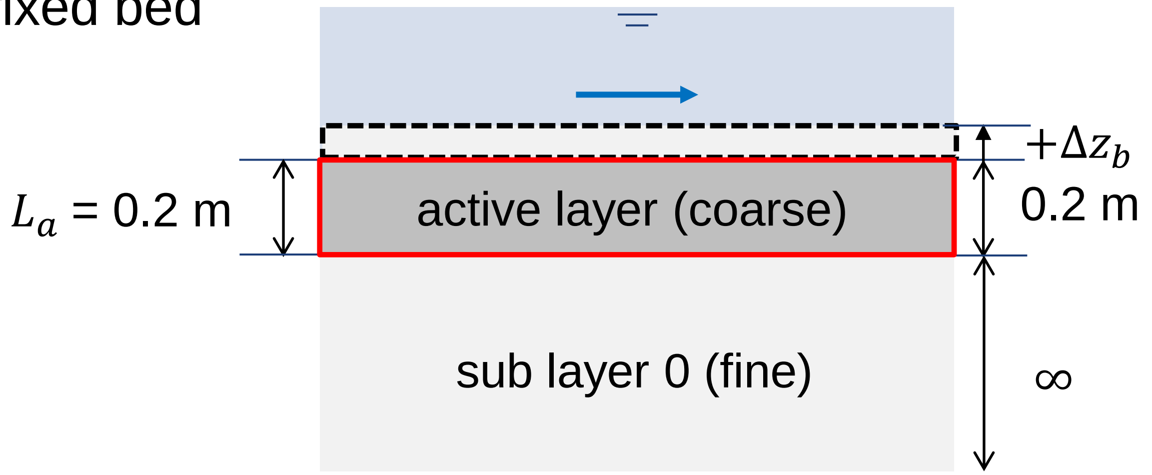
- 1 layer to define sub layer

→1 sub layer free for deposition

Example:
L_a = 0.2 m
→ Layer 1: *z_rel* = -0.2 m
→ Layer 2: *z_rel* = -999.0 m



Bed material

Grain classes and mixtures

- Max. 10 grain size classes to define sediment mixtures

Soil definition

- Max. 2 layers available to characterize soils with mixtures
- Default relative elevation *z_rel*: -999.0 [m]
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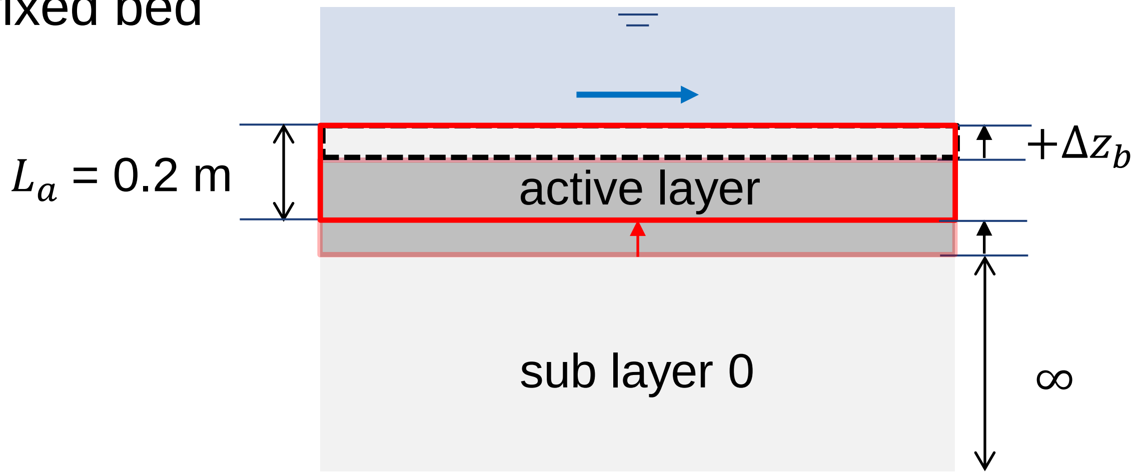
- d90: $L_a = f \cdot d_{90}$

Recommendation
- 1 layer to define active layer
- 1 layer to define sub layer

→1 sub layer free for deposition

Example:
L_a = 0.2 m
→ Layer 1: *z_rel* = -0.2 m
→ Layer 2: *z_rel* = -999.0 m



Bed material

Grain classes and mixtures

- Max. 10 grain size classes to define sediment mixtures

Soil definition

- Max. 2 layers available to characterize soils with mixtures
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Recommendation
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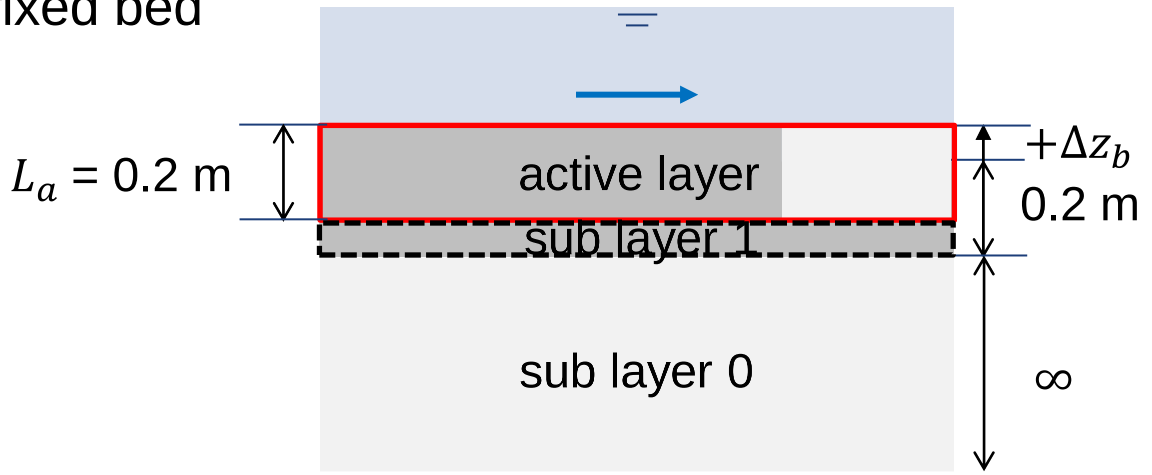
- 1 layer to define sub layer

→1 sub layer free for deposition

Example:
L_a = 0.2 m
→ Layer 1: *z_rel* = -0.2 m
→ Layer 2: *z_rel* = -999.0 m



Bed material

Grain classes and mixtures

- Max. 10 grain size classes to define sediment mixtures

Soil definition

- Max. 2 layers available to characterize soils with mixtures
- Default relative elevation *z_rel*: -999.0 [m]
- *z_rel* > -999.0 in lowest layer results in definition of fixed bed

Soil assignment

- Soils can be assigned to different mesh regions

Active layer (control volume)

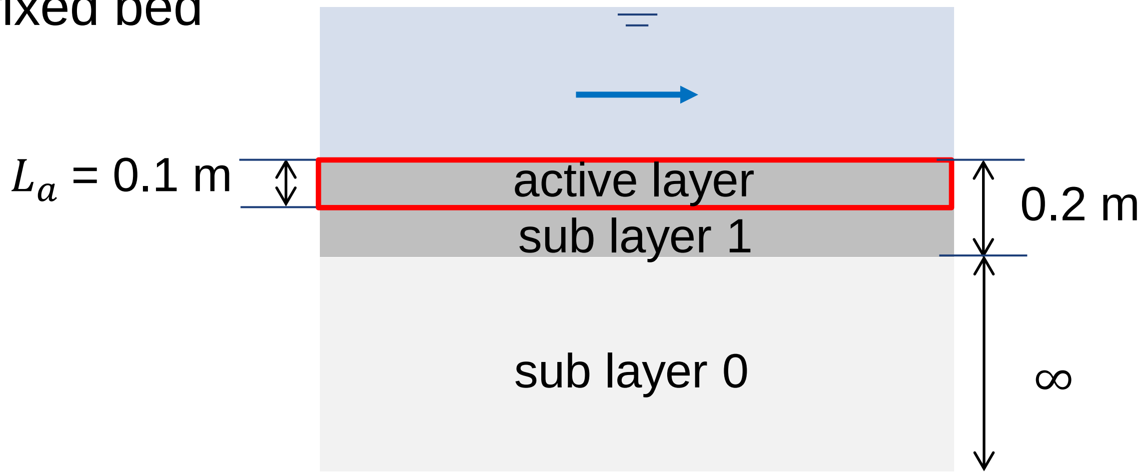
- Constant: $L_a = \text{const.}$
- d90: $L_a = f \cdot d_{90}$

Recommendation

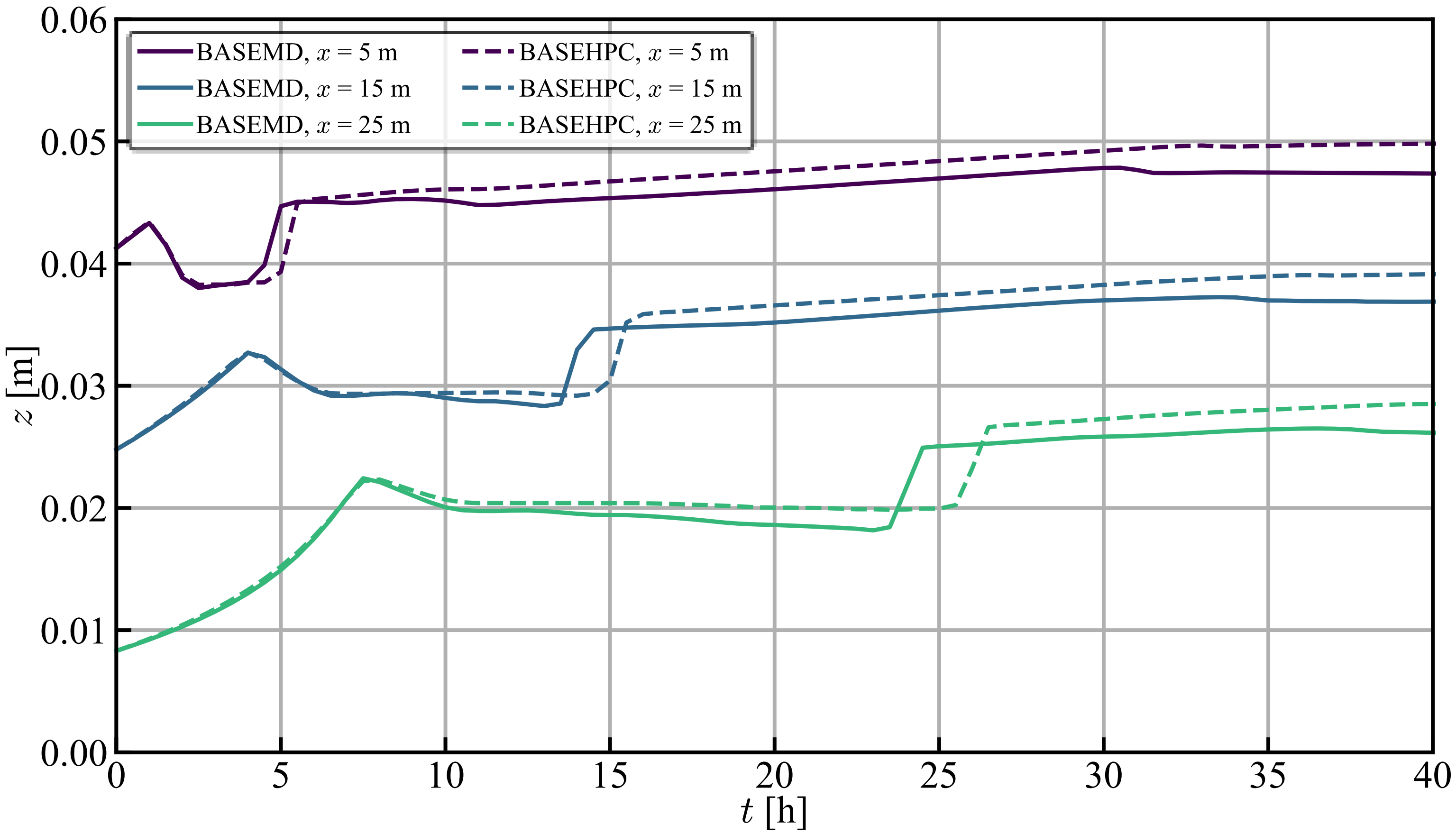
- 1 layer to define active layer
- 1 layer to define sub layer

→1 sub layer free for deposition

Example:
L_a = 0.1 m
→ Layer 1: *z_rel* = -0.2 m
→ Layer 2: *z_rel* = -999.0 m



Ribberink test case – bed elevation change



Ribberink test case – grain sorting process