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***Abstract*— Sediment layer thickness and grain size distributions influence the bed erosion stability and the flow field due to grain roughness and bed form roughness. Vice versa flow sorts sediments and develops bed forms. Therefore many hydrodynamic numerical simulations cannot be completed successfully without considering flow-sediment interaction. In Sisyphe sediment transport, sediment sorting and development of bed forms are all highly influenced by one parameter, the active layer thickness. The concept of active layer has been developed in 1971 by Hirano and expanded by Ribberink among others. With new high performance computers, it is possible to overcome several limitations of this meanwhile 40 year old concept. The limitation to 9 layers, the a priori chosen layer thicknesses and the continuous remixing of the top layer strongly influences the sediment transport.**

The authors were inspired by continuous vertical sorting models , which were examined in Delft during the last decade by Astrid Blom among others. The new approach still uses an active bed zone, similar to the active layer, but all sedimentation, erosion and change of grain fractions is stored in a high resolution depth profile for each node of the hydraulic mesh, instead of 9 discreet layers. For evolution calculations, at each time step the active layer is updated with averaged data from the vertical sorting profile. With this new concept it is possible to avoid smearing effects in grain fraction calculations. This leads to a better reproduction of the natural sediment profile and thus to a better prediction of the transport processes.

To validate this concept, comparisons were made with the Hirano / Ribberink approach with flume data from Astrid Blom. Ongoing validations with more flume experiments will open the way to further developments. A modular addition of algorithms for compacting or moving of fines within a coarse matrix is possible, as the implementation of this storage concept is kept similar to the classic layer & fraction approach in Sisyphe.

I. State of the Art & Limitations of Sediment Layer Model of Sisyphe V6P0

Considering sediment distribution and a vertical sorting of the sediments is essential for a successful modelling and prediction of river morphology. Sediment parameters and flow interact together and influence each other in a complex way. E.g. grain roughness is dependent on sediment distribution, which is influenced by bed forms. Both change the flow and vice versa the flow changes the sediment distribution and develops bed forms. Therefore many hydrodynamic numerical simulations cannot be completed successfully without considering flow-sediment interaction.

In Sisyphe sediment transport, sediment sorting and development of bed forms are all highly influenced by one parameter: the active layer thickness. The concept of an active layer (HR-VSM) has been developed in 1971 by Hirano [5] and expanded by Ribberink in 1987 [6] among others. The idea was that flow interacts with a fully mixed top-most layer. The active layer describes the common depth of morphological processes in the riverbed per time step. The active layer thickness is usually chosen between $3d_{90}$ and the mean height of bed forms. For numerical reasons it is the maximum depth

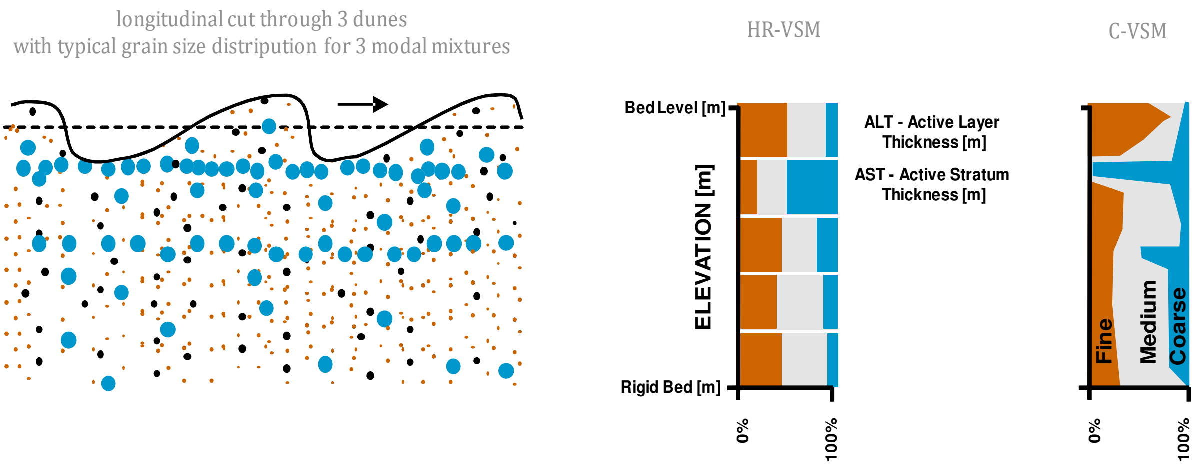

Figure 1. Scheme of the classic Hirano/Ribberink vertical sorting model (HR-VSM) and the later explained continous vertical sorting model (C-VSM).

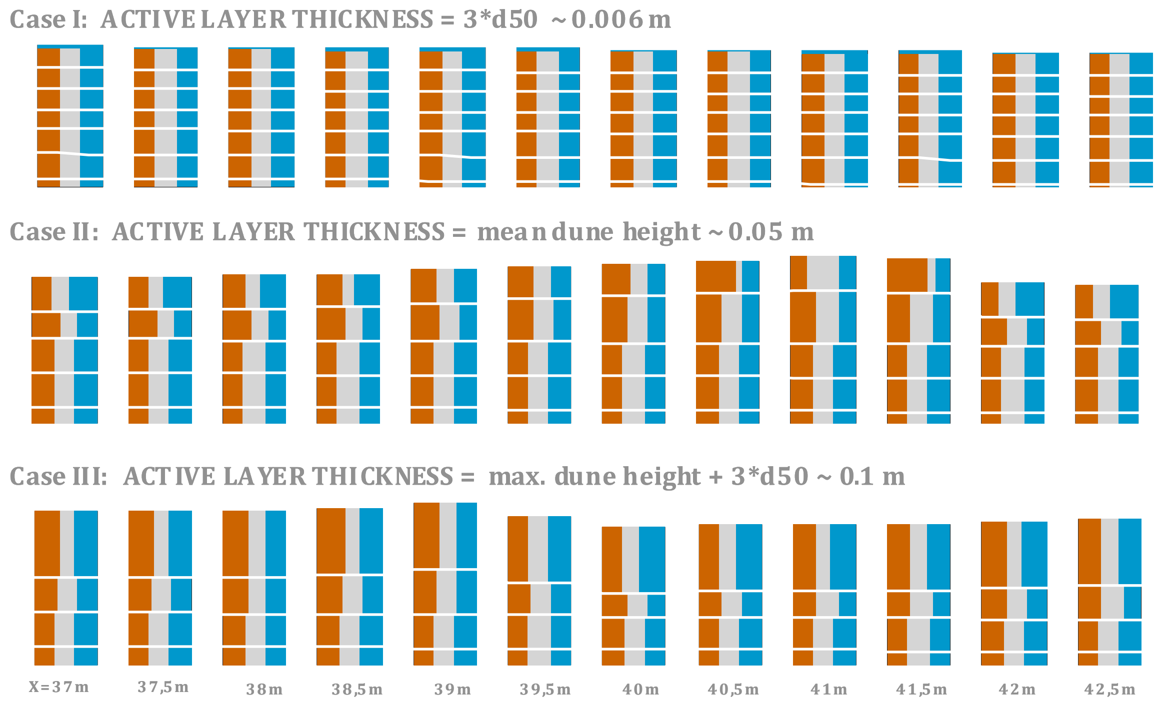

Figure 2. HR-VSM for a flume with artificial trimodal sediment mix, as calcualted with Telemac + Sisyphe v6p0. The *Active Layer Thickness* (ALT) strongly changes the vertical sorting of the grain sizes, and might produce armouring top layers which change the system behavior totally as in case I.

that can be eroded in one time step. Below the active layer follows another theoretical layer, the active stratum. It is used to refill or reduce the active layer to the predefined thickness after evolution calculations changed the active layer thickness. Below these 2 layers up to 7 more storage layers can hold different sediment mixtures until they are activated by erosive processes. Within 1 time step evolution only affects the active layer and the active stratum, see Fig. 1.

This meanwhile 40 year old concept was developed during a time where the average computational performance was 10^{10} times less than in 2011. It incorporates several limitations:

- The number of layers is limited to 9 layers.
- The a priori chosen layer thicknesses depend on dune heights, grain roughness, depth of the rigid bed, mesh density and other parameters.
- The continuous remixing of the top layer strongly influences the sediment transport e.g. development of bed forms.

While the first two limitations could be removed, the last one requires a new concept.

The problem of a fully mixed active layer becomes obvious in the flume experiment explained later. Dunes occurred but could only be simulated, if the active layer thickness is set to be equal the mean dune height. Due to this the modeller needs to know a priori the expected dune regime and he can't change it in case of time dependent flow conditions. Otherwise an active layer thickness calculated according to the grain size (e.g. $3d_m$) results in an armoured bed without dune development (see Fig. 2). Another negative effect is the inability to preserve thin but prominent layers, e.g. the armoured bottom of dunes in Fig. 1.

Due to strong averaging and clipping effects of the HR-VSM, good results can be achieved only in a wider spatial context. Reason is the modification of the active layer, which might influence results stronger than any other parameter, including d_{50}. Unfortunately the active layer thickness (ALT) is a deterministic, theoretical mean value, originally meant to describe the thickness of the morphological active top layer of the bed. It is difficult to measure and its natural complement strongly varies with shear stress and many other variables. Choosing the ALT beforehand the calculation, e.g. without knowing dune heights, leads to mixing and smearing effects of the grain fractions within the upper 2 layers. This happens because the ALT is deterministic and all changes in volume have to be passed proportionately through to the active stratum. The active stratum might grow to unlimited size without any internal vertical discretization.

Fig. 2 shows the ALT problematic exemplarily along the middle axis of a flume experiment calculated by the authors with Telemac 2D coupled with Sisyphe v6p0 using different ALTs. Case II "*ALT = mean dune height*" fits the average measured fractions the best. Here mean dune height doesn't represent the mean value of all dune crowns, but the dune amplitude, see Ribberink [6].

II. The Vertical Sorting Experiments of Blom et al.

Astrid Blom [1,2,3,4] conducted flume experiments at Delft Hydraulic Laboratories in 1998 to investigate vertical sorting processes. She used the obtained data to develop her own vertical sorting model. The authors decided to use these experiments as validation cases as well.

The appendent laboratory flume was 50m long, 1m wide and filled with an artificial three modal grain mixture (0.00068, 0.0021 and 0.0057 m, 33% each). For a discharge of 0.267

m^3/s a slope of 0.0018 produced a normal flow depth of 0.386 m for case "*B2*". The sediments were recirculated (see Fig. 4). In both physical and numerical experiments the field of flow requires the first half of the flume to develop constant conditions, thus only the second half is used for comparison.

Blom numerically simulated the morphology of the flume experiments with different vertical sorting models, using a constant backwater curve and not a multidimensional hydrodynamic numerical model like Telemac2D or 3D. Among other methods she experimented with an own continuous vertical sorting model, which is in fact a storage model with a high, but limited number of very fine layers. Evolution is calculated with classic approaches like van Rijn or Meyer-Peter & Müller.

Erosive impact forces lose their power over penetration depth according to a probability density function, which equals the *ALT* concept in case of a constant distribution function. Compared to her own Hirano & Ribberink implementations the

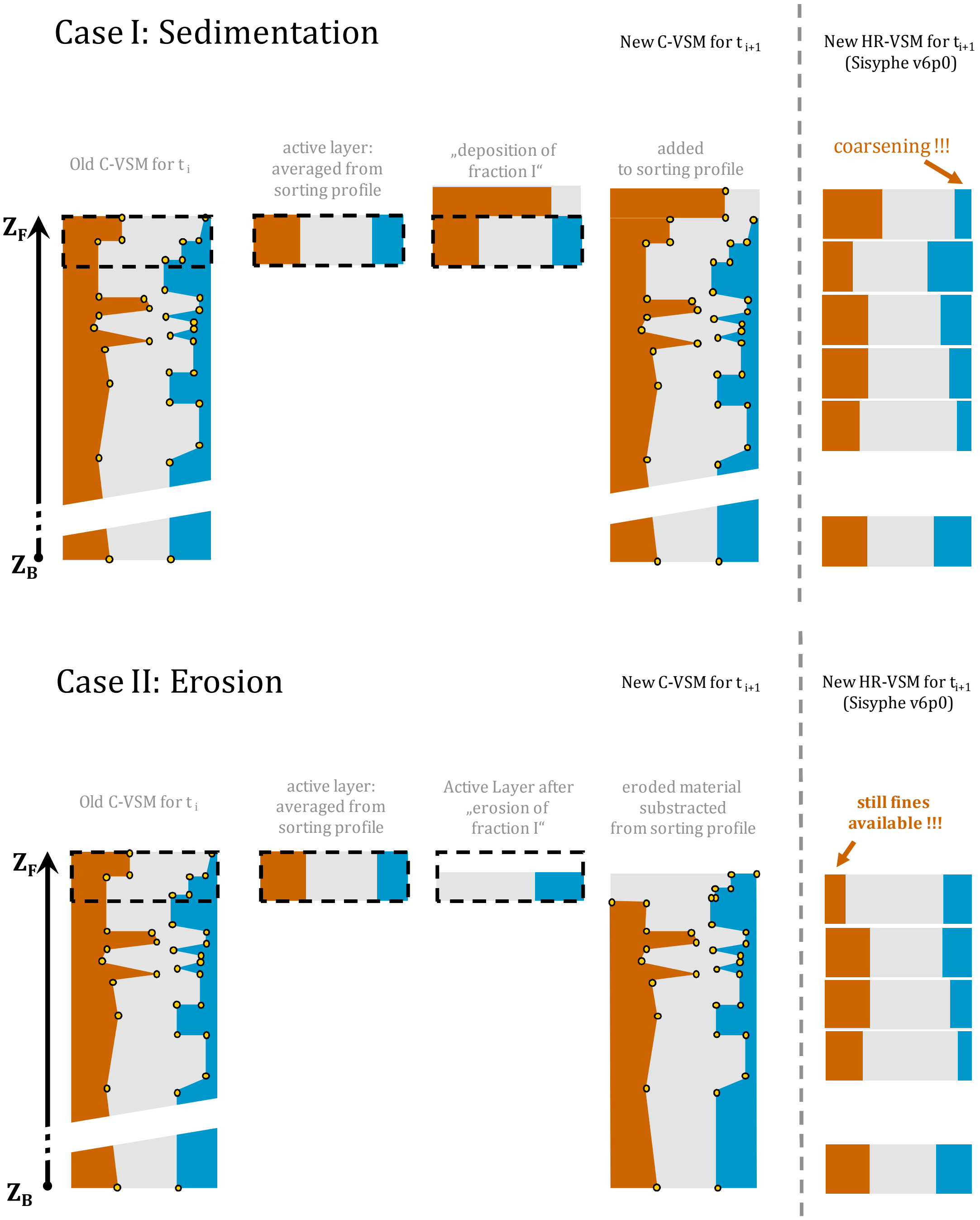

Figure 3. The changed and finer book keeping of Continuous Vertical Sorting Profiles (*C-VSM*) avoids smearing problems due to averaging in the classic Hirano/Ribberink layer method (*HR-VSM*). This sketch shows the behavior of both book keeping algorithm for one time step.

C-VSM succeeds when using averaged vertical sorting profiles. This academic numerical model didn't adapt the hydrodynamic and the surface after every time step, it was custom made for this single project.

Figure 4. Pictures by Astrid Blom [1] of flume experiment before (left).

III. Implementation of a Continuous Vertical Sorting Model (C-VSM)

Similar to the vertical sorting model of Astrid Blom [3] we decided to add a depth dependent storage model with unlimited resolution for the grain sizes. The transport model remains unchanged. Both are kept in separate modules to enable an independent development. The addition of a consolidation model as well as an implementation of statistical methods for the erosive impact depth are possible for future developments without mayor changes.

The new storage model can be described as book keeping model as shown in Fig. 4. It is a data set of virtual layers, theoretically unlimited in their numbers, thicknesses and grain size fractions. A drilling profile is the physical equivalent. For better visualization the grain size fractions of each layer are sorted from fine (left) to coarse (right) (legend: see Fig. 1). In contrast to the classic Hirano-Ribberink layer model there are no theoretical limitations to the discretization of thicknesses, but the capabilities of the hardware.

Transport model calculations of Sisyphe are not touched by the implementation of the *C-VSM*. The Hirano / Ribberink concept (*HR-VSM*) is still used to calculate evolution based on the active layer, but the content of the active layer changes. The grain size fractions are now taken from the *C-VSP* and averaged over the *ALT* for each time step. Therefore it is called "Projected Layer HR-VSM" (*PL-VSM*). The main benefit is the conservation of any layering that is finer than the ALT without changing the classic transport models.

Fig. 3 shows the difference between the storage models in *HR-VSM* and the *C-VSM* in case of sedimentation and erosion.

Extraction of fines and burying of coarses can be found in the BLOM flume model case B2 as well as in many rivers, contrary to the armouring example in Fig. 2. The *HR-VSM* might not be able to reproduce this. A theoretical example would be a channel with erosion and deposition, dependent on turbulence and multidimensional effects. We use an *ALT* of 0.2 m, which is chosen to 50% of the expected average dune height. Fig. 5 shows a typical vertical sorting profile developing in 2 time steps.

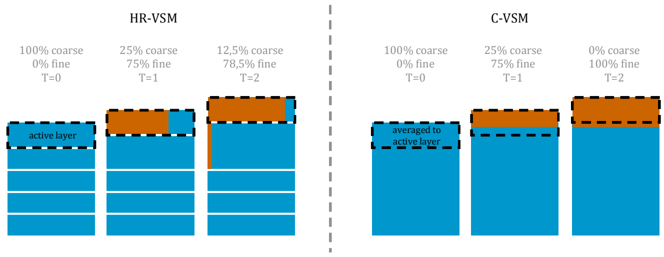

Figure 5. Theoretical behavior of HR-VSM (left) and C-VSM (right) in case of sedimentation over 2 dimensionless time steps.

The *HR-VSM* will develop as follows:

- A first deposition phase of 15 cm of fine material on coarse material will be saved in an active layer mixture of 75% fine + 25% coarse material. $T = 1$.
- A second deposition phase will mix 10 cm fine with 10 cm of (75% fine + 25% coarse) resulting in 12.5% coarse saved in the active layer. $T = 2$.
- If flow conditions change to erosion, coarse material is not moving.
- Depositing additional fine material (less than the *ALT* in 1 time step) will always result in numerical lifting of coarse to the top layer due to the averaging.

The *C-VSM* model places the newly deposited material on top and does not mix it with the underlying material. It will develop as follows:

- A first deposition phase of 15 cm of fine material on fine material will be saved on top of the VSP without mixing. An active layer mixture of 75% fine + 25% coarse material is averaged from the VSP. No changes to *HR-VSP* so far. $T = 1$.
- A second deposition phase will save 10 cm fine material on top of the underlying material in the VSP. Averaging the top 20 cm for the new active layer mixture results in 100% fine material, which might result in a full erodible layer when it comes to erosion. $T = 2$.
- Additionally the bed roughness changes, as a function of the mean diameter d_{50}.

The practical implementation in Sisyphe is a set of bief objects, defined in DECLARATIONS_SISYPHE.F. They describe fractions over the depth for each mesh point. In the LAYER.F module the active layer mixture is averaged each time on demand from the C-VSP by calling MAKE_ActiveLayer. If new material is deposited according to BEDLOAD.F it is set on top of the VSP by calling ADD_VSP_Layer & ADD_Fraction.

If a certain volume is eroded from the active layer, it will be removed in the vertical sorting profile starting form top by calling RM_Fraction. (Other options are possible, e.g. erode equally over the *ALT*.)

IV. First Results of the new C-VSM for Sisyphe

Figs. 6 and Fig. 7 show first results of simulations of case "Blom B2" calculated with Sisyphe v6p0 and Sisyphe v6p0 + *C-VSM*. A 2D mesh with 2193 nodes and an average edge length of 0.1 to 0.25 had sufficient density for this case. Fig. 6 shows initial and developed drilling profiles every 5 meters along the middle axis of the flume for both sorting models. Fig. 7 shows the mean grain size d_{50} of the surface after 4h for the classic HR-VSM, the C-VSM and the PL-VSM (which is the averaged from the top 3 cm of the C-VSM).

The *C-VSM* case shows exactly the burying effects observed in the flume experiments and described in the last chapter with example values.

- Only the fine and parts of the medium grain fraction are moving.
- Fine grains are soaked out from sub surface. Remaining coarse grains fill the gap and create a coarse layer with lower elevation.
- Deposition of fine grains is on top of the existing sediments, eventually burying the coarse material.
- Continuing erosion / deposition cycles pull out fine and bury the coarse grains, which are resistant to erosion.

In the experiment the fraction of the fine material reached around 70% after 4h. In the numerical model more than 42% were reached. This correct tendency can be improved by calibration.

V. Conclusion & Outlook

The continuous vertical sorting model (*C-VSM*) already shows promising results that overcome many limitations of the layer concept (*HR-VSM*) in Sisyphe v6p0. This is despite the fact that it is still implemented with a strong focus on code compatibility for validation purposes, which restricts some possibilities, like dynamic active layer thicknesses.

The smearing effects and the lack of vertical discretization of the bottom are improved and now only limited by computational power. With the new model it is possible to keep minor but prominent grain mixture zones even after a high number of time steps.

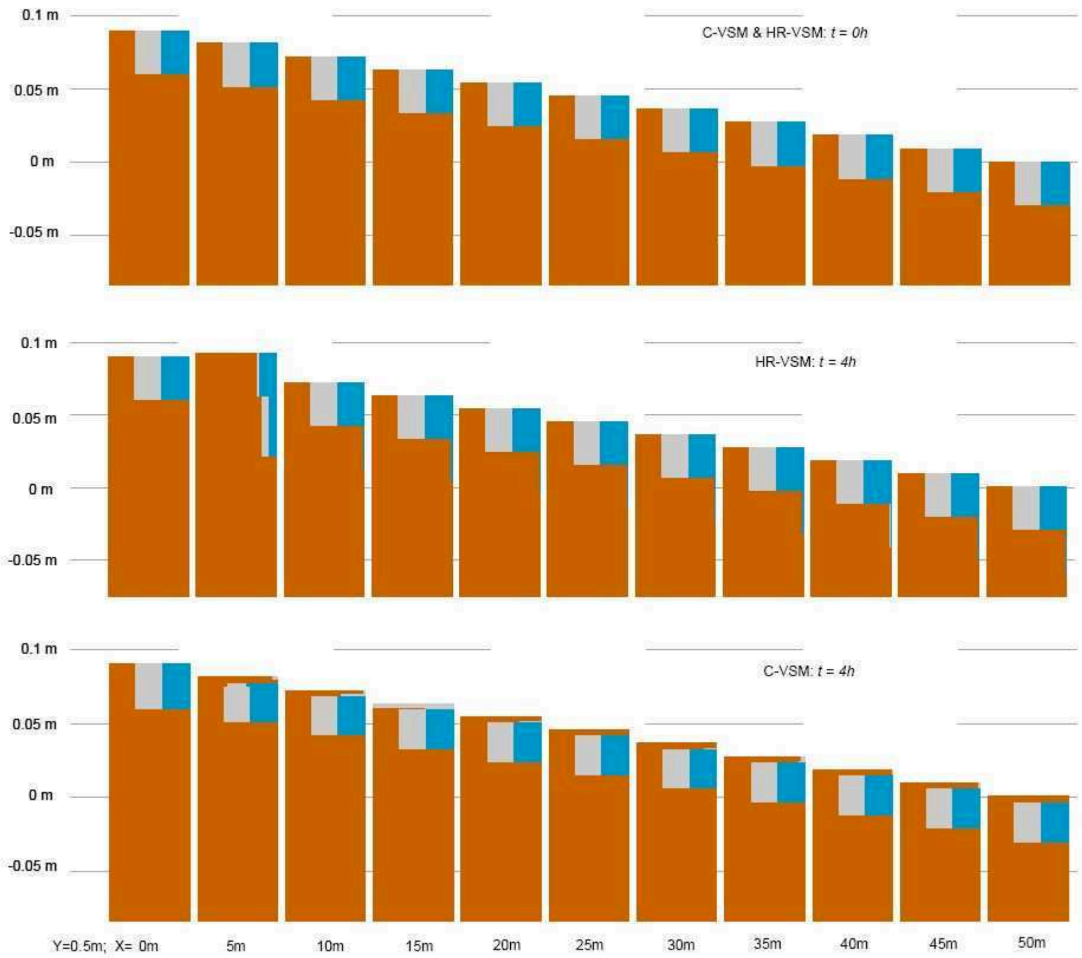

Figure 6. Drilling profiles along flume middle axis at initial time 0 h (top) and after 4 h shown as HR-VSP (middle) and C-VSP (bottom) (orange: fine material, grey: median, blue: coarse). Simulation with recirculating sediment, old layer concept with 9 layers.

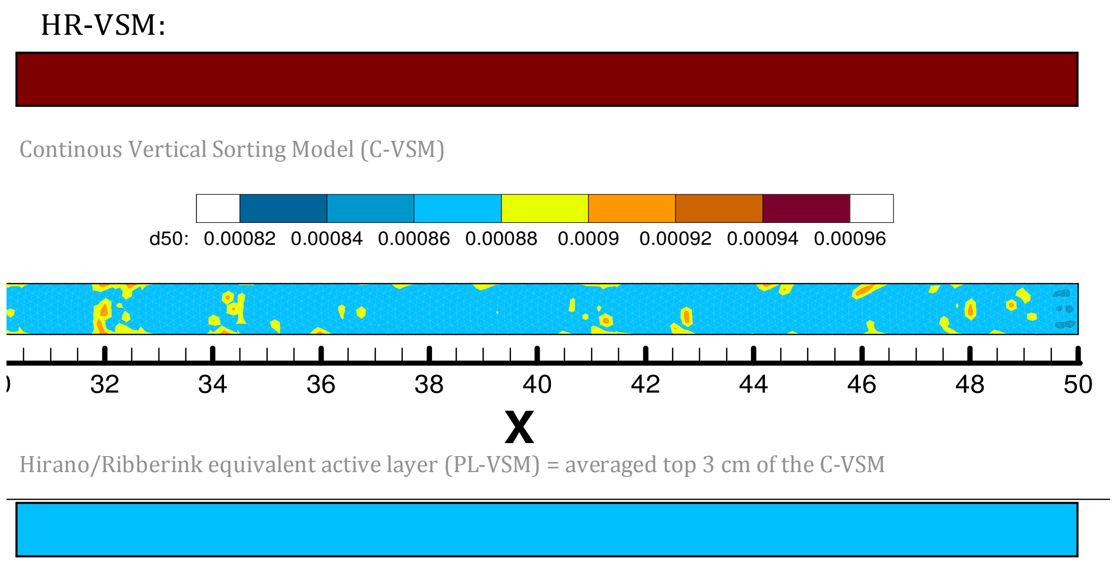

Figure7. Top view on the active layers mean grain size distribution (flume section 30.5 m to 50 m (outflow)), with a stable flow field, *ALT* = 0.03 m, t = 4h. For the Sisyphe v6p0 classic *HR-VSM* (top) all grain classes still have almost the 33% fraction initial value and d_{50} reamains 0.00095 m. Significant changes shows the *C-VSM* (bottom), where d_{50} decreases and moving patterns can be observed. The derived *PL-VSM* (bottom) is used for further morpholgical calculations with Sisyphe.

Further validation cases will be calculated to prove the superiority of C-VSM. The new storage model has the following advantages:

- A dynamic active layer thickness that now is more independent of smearing effects of grain size fractions due to less averaging processes.
- Depth functions (probability density functions) for the impact of the shear stress instead of a fixed average active layer thickness. For an overview over these functions see e.g. Malcherek [8]
- Consolidation models for time-dependent porosity changes of sedimentation zones.

The sub models provide an interface for important future developments. They are inspired by Hiranos original idea, where the active layer thickness is the depth at which morphological activity normally stops. Until now, this depth is an empirical mean value, hard to measure and

- has growing uncertainties the coarser the spatial steps gets (mesh width),
- is sensitive to the length of the observed morphological activity (time step),
- and dependent on the shear stress magnitude.

Acknowledgement

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References

[1] Blom, A. A vertical sorting model for rivers with non-uniform sediment and dunes. Ph.D. thesis. University of Twente (NL). 2003

[2] Blom, A. and Ribberink, J.S. and de Vriend, H.J. Vertical sorting in bed forms: Flume experiments with a natural and a trimodal sediment mixture. Water Resources Research. Vol.39. 2003

[3] Blom, A. Different approaches to handling vertical and streamwise sorting in modeling river morphodynamics. Water Resources Research. Vol.44. 2008

[4] Blom, A. and Ribberink, J.S. and Parker, G. Vertical sorting and the morphodynamics of bed form-dominated rivers: A sorting evolution model. J. Geophys. Res. Vol.113. 2008

[5] Hirano, M. River bed degradation with armouring. Proceedings Japan Society of Civil. Engineers 195. 1971

[6] Ribberink, JS. Mathematical modelling of one-dimensional morphological changes in rivers with non-uniform sediment. Delft University of Technology. 1987

[7] Villaret C. Sisyphe user manual, EDF R&D Report N° H-P73-2010-01219, www.systemtelemac.com. 2010

[8] Malcherek, A. Sedimenttransport und Morphodynamik, Scriptum Institut für Wasserwesen, Universität München, 2007