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C-VSM-II: Large Scale and Long Time Simulations with Sisyphe's Continuous Vertical Grain Sorting Model

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Abstract— The stratigraphy of a river bed is of essential influence on the development of the bathymetry and the resulting flow patterns. Sorting of sediment grains results in armouring layers, sand lentils, dunes, antidunes, ripples, scours and deposits. Furthermore the tracking of sediments is a necessary functionality for sustainable sediment management on waterways, especially for dredging and dumping.

Like most hydro-morphodynamic software packages Telemac & Sisyphe calculate sediment transport, sediment sorting and development of bed forms depending on the sediment distribution and the assumption of a fully mixed "active layer" of the river bed. The empirical active layer concept has been developed in 1971 by Hirano and expanded by Ribberink among others to fit the numerical models and demands of their time. Nowadays long time and large scale models reach the limit of this mean value theory. The presented "Continuous Vertical Grain Sorting Model" (CVSM) and its dynamically estimated active layer thickness overcomes several limitations of this meanwhile 40 years old concept.

Results of this new vertical sorting model were compared to the classical Hirano-Ribberink implementations on 3 laboratory flumes during the CVSM-I project, which was finished in 2012. In the second project CVSM-II (finished in 2016) the algorithms robustness was enforced for industrial strength and proofed by the simulation of two large scale and long term projects along a large shippable river. It is now implemented in the new version of Sisyphe V7P3. Additionally, the new CVSM-II is now extended to work with the new dredging module called "Nestor" which can be coupled to Sisyphe. The article gives a short overview about the implemented algorithms. It mainly focuses on a real world example and lists configuration recommendations for Sisyphe users.

I. INTRODUCTION

Vertical grain sorting is one of the leading processes for many hydrodynamic and morphodynamic simulations. Like most hydraulic & morphological software packages Telemac & Sisyphe calculate sediment transport, sediment sorting and development of bed forms depending on the active layer of the bed. The empiric active layer thickness concept has been developed in 1971 by Hirano [1] and expanded by Ribberink [3] among others to fit the numerical models and demands of their time. Todays long run and wide range models reach the limit of this mean value theory. With new high performance computers the here presented continuous vertical grain sorting model and its dynamically estimated active layer thickness overcome several limitations of this meanwhile 40 year old concept.





The complete theoretical description of the CVSM Sisyphe implementation, which might be necessary to understand the following pages, is given in [4]. This document focuses on the algorithm updates, practical experiences and new usage recommendations.

With the C-VSM-II project came the clear project target to make the C-VSM algorithms as robust as possible for practical applications. The BAW provided two wide range and long time scale models from pending projects. Both models are very well known and are in use already since several years with the classic HR-CVSM. Both models include dredging and dumping rules with time and dynamic triggers (handled by the new Nestor module).

II. INTERACTION WITH NESTOR

As the combination of dredging and dumping with C-VSM was run for the first time, a new academic flume case "Flume 4" was necessary to proof the expected functionality and especially the mass conservation at the interfaces between Sisyphe, Dredgesim, Nestor and the C-VSM.

A. Model Properties

•	Points	= 1 111
•	Triangles	= 2 000
•	Time Step	= 0.25s
•	Number of Time Steps	= 240 000
•	Coupling Period	= 10 = 2.5s

• Grain Size Classes = 3

The following figure 2 shows a simulation with 3 grain size classes over ~ 16.6 hours. One dredging area in the upper (green) half and 3 dumping events are time triggered. Additionally, all grain sizes are chosen to move under different conditions, to produce a new stratigraphy which is disturbed by dredging and disposal. The figures are snapshots from a set of videos which show the described effects more precise.

B. Results

Figure 2 shows some results of the Nestor <-> CVSM interaction tests. The four pictures, from top to bottom, show

- the mean grain size before flooding the flume,
- the first dredging (in the upper flume half) and dumping (lower half) procedures. As expected, immediately after starting the flume, the surface sediments start to sort, especially blue (very fine) material leaves the flume in an early stage.
- the deformed sediment heap after 16.6h.
- a cut through the sediment heap, which developed over time. It is over formed by incoming sediments and erosion effects at the same time. It shows the stratigraphy (as mean diameter) in 500 sections.

The tests on Flume 4 resulted in various minor changes in Sisyphe and Dredgesim / Nestor with the result, that the share of volume errors can be reduced to less than 10^{-15} , if all thresholds are chosen to that accuracy. For practical purposes, where CPU time matters, the thresholds are set to 10^{-8} .

III. LARGE SCALE AND LONG TERM SIMULATIONS

The following case is the largest case calculated so far with the C-VSM. The model itself was developed at the *"Bundesanstalt für Wasserbau"* in Karlsruhe over several years for multiple sediment surveys on a shippable river in Germany. The river bed is up to 2 kilometres wide and 30 km long. The original version includes a 3-layer Hirano-Ribberink stratigraphy model and 9 grain size fractions. The old implementation of Dredgesim was converted to the new Nestor module. Dredging occurs demand driven.









Figure 2. Development of a new stratigraphy which is disturbed by dredging and dumping events. (Color: Mean Diameter D50 [m])

A special focus is laid on a sediment trap, islands, groynes, bridge piers and confluences which affect the development of the morphology. (Overview: Fig.3)

Even though this river stretch is well known to the BAW from many surveys, a large uncertainty remains for the initial grain distribution, and therefore for the development of the bed.

Special to this model is the usage of the "Morphological Factor (MOFAC)". This means, that evolution in every time step is magnified through the MOFAC, which was chosen to be 10 here. The hydraulic simulation time, and therefore the CPU hours are cut to 1/10th. The price is an excessive sediment movement. The MOFAC should be handled with great care, especially for unsteady simulations. This project was not meant to observe the MOFAC advantages and disadvantages, but on many smaller issues the impression shall not be suppressed, that already the Hirano-Ripperink original model can only be seen as a generalized sediment movement theory. One shall not take every nodes value as certain. It is the coarse spatial context, which shows the sediments main moving path.

From this point of view it is questionable and needs to be observed if a strong 2D and 3D smoothing MOFAC and a very high 3D resolution makes sense, if used together.

From the technical point of view, which had robustness of the algorithm as another main goal, the MOFAC does not disturb the C-VSM. Without the MOFAC, the results are even more plausible.

A. Model Properties

•	Points	= 314 963
•	Triangles	= 625 097
•	Time Step	= 4 s
•	Number of Time Steps	= 5 523 120

•	Coupling Period	$= 30 = 2 \min$

- Morphological Factor = 10
- Layers for Hirano = 3
- Grain Size Classes = 9

The C-VSM is technically hard to visualize, due to its excessive memory consumption. One time step of the model consumes: 314963 points * 500 depth sections * 10 fractions * 16 byte ~ 24GByte RAM

The values are normally overwritten by the next time step. The recommended usual output is automatic reconversion to the HR-VSM layers. It is written as common Sisyphe Selafin file, which needs only 3/500th memory of the C-VSM. Today's computers can handle this amount of data for calculations, especially clusters. But it is difficult to render the 3D stratigraphy as volume, like Figure 2 of the before mentioned "*Flume 4*". The following Figure 4 renders only 1 of 200 domain parts to illustrate the general development of the stratigraphy.

- B. Interpretation
 - Figure 4 (top): This cut is 10 times vertically exaggerated to make the armouring layer visible. The C-VSM model starts from the previous HR-C-VSM computation. Therefore the 3 layer stratigraphy can still be seen after the first 30 days (x10 MOFAC). Especially the former boundary between L2 and L3 is still visible, as they are untouched by the C-VSM algorithms until the displayed time. This L2 / L3 layer boundary was originally 1m below the bed level. The armouring layer is 3 to 10 cm strong and covered in an average of 4 cm (but up to 40 cm) of moving fine sediments. The given values of this illustration example are only valid for this setup and not calibrated to natural data.



Figure 3. Left: Perspective view of the river and slice of the initial sediment stratigraphy. Flow direction top to bottom. Right: A 2D hydraulic model drives the sediments in 3 depth layers (HR-VSM).

- More interesting is the dark layer below the bright surface layer. This is a clear proof that the moving fines are separated from the coarse grains. In some places, e.g. the front corner, the initial L2 was eroded and the new armouring layer covers the former L3.
- Figure 4 (bottom) shows a cross section through the same river section.
- C. Dynamic Active Layer Thickness

The original Hirano idea assumes the active layer bottom as the limit of the moving part of the bed. It is clear that a fix active layer thickness can not account for changing hydraulics, morphology and grain sorting.

This empirical mean value is hard to measure and

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

Replacing these influence factors with mean values increases the morphological uncertainties. A collection of formulas for dynamic ALT approximations during a

simulation is available in Malcherek [2] and implemented in Sisyphe. Some formulas use the bottom shear stress τ_B , the critical shear stress τ_C , the characteristic diameters

 d_{50}, d_{90}, d_{MAX} or the transport stage parameter D^* .

Their implementation in Sisyphe v7p3 divers from the old implementation. The formula can be chosen by the following keyword:

"C-VSM DYNAMIC ALT MODEL"

• Option 0: Constant Active Layer Thickness (uses additional keyword "Active Layer Thickness")

ALT = const.

• Option 1: Hunziker & Günther

$$ALT = 5 * d_{MAX}$$

• Option 2: Fredsoe & Deigaard

$$ALT = \frac{2 \cdot \tau_B}{(1-n) \cdot g \cdot (\rho_s - \rho) \tan \phi}$$



Figure 5. The implemented Active Layer Thickness (ALT) estimation formulas produce very different results. Not every formula seems to be transferable from laboratory scale to every river.

• Option 3: van RIJN

$$ALT = 0.3 \cdot D_*^{0.7} \cdot (\frac{\tau_B - \tau_C}{\tau_B})^{0.5} \cdot d_{50}$$

• Option 4: Wong

$$ALT = 5 \cdot \left(\frac{\tau_B}{(\rho_S - \rho) \cdot g \cdot d} - 0,0549\right)^{0.56} \cdot d_{50}$$

Option 5: Malcherek

$$ALT = \frac{d_{90}}{1-n} \max(1, \frac{\tau_B}{\tau_C})$$

- Option 6: 3*d₅₀
 - $ALT = 3 * d_{50}$

Other used parameters: ρ_s ... density solid; ρ ... density water; n ... porosity; $\tan \phi$... friction angle.

The implementation of these formulas would be possible for HR-VSP with very long morphological time steps. But it is limited, due to the smearing problem shown in Figure 2. Especially in pulsating eddy zones the ALT changes by several 100% within few time steps instead of the above shown 0.0001%. This increases the smearing problem.

With the new C-VSM this problem is obsolete and the formulas for a dynamic ALT can be used over longer simulation periods in coupled morphodynamic and hydrodynamic models. No further recommendation is given on these formulas, as their usability is strongly dependent to the project.

Figure 7 (top) shows as an example for the last time step the relation shear stress to critical shear stress. Figure 7 (others) shows, that the implemented dynamic Active Layer Thickness estimation formulas have strongly varying values.

• Option 1, Hunziker & Günther, is just 5 * d_{MAX} , and therefore does not reflect the shear stress. In places, where only a single grain of the biggest grain fraction is found in the last time steps active layer, the new ALT will be automatically the maximum possible size, here 40cm. Therefore, the original formula was changed to use 5* d_{99} instead of 5* d_{MAX} . Then thinner active layers are possible in parts with moving fines on the surface.



Figure 4. CVSM with 500 vertical sections and an Active Layer Thickness of 5 x d_{Max}. Color: Mean grain size d₅₀. An armouring layer covers sand lentiles and fine sediments are moving above the armouring layer.



Figure 7. Model inflow (flow from right to left), sediment trap in the picture middle. No dredging.

- The Fredsoe option 2 does not bring any useful results and is not displayed.
- The van Rijn option 3 leads to generally very thin ALTs which can not be trusted. It seams that the formula, which worked better for the flume cases is out of range for this setup.
- The same applies to the Wong option 4.
- Malcherek's option 5 reflects the shear stress / critical shear stress ratio and the grain size. In general the relative ALT characteristics are good, but with a tendency to underestimate the ALT. This behaviour of Malcherek's formula was observed for any tested model so far. It can be recommended to investigate more in this direction, as it seams to be the most promising of all formulas.
 - Tweaking porosity, critical shear stress and shear stress approximations can easily multiply the ALT.
 - An easy, less physical way, is to implement a magnification factor.
- Option 6 again is just a grain size based formula like formula 1. Both are very robust in comparison to shear stress and critical shear stress based formulas, which are difficult to calibrate as the quotient τ_B / τ_C can easily make a change by some 100%. It is confusing that these formulas deliver the strongest ALT on the flood plains. Explanation:
 - The sediment volume on the flood plains is 0. In those cases, for consistency reasons each

fraction is set to 1 / "Number of Fractions". A d_{50} is assigned to zero volume.

• This is not a problem, as erosion will not take place if there is no free material.

D. Discussion of results

1) Full model

An analysis over the full model (fig. 6) shows clearly less strong evolution effects of the C-VSM. The following detail figures 7,8 & 9 give an impression of the general behaviour.



Figure 6. Comparison of evolution values between HR-VSM and C-VSM (250 sections, both constant ALT=40 cm)

2) Inflow and sediment trap

Right after the inflow, when flow patterns are still biased by the imposed velocity direction vectors, heavy erosion and deposition effects with amplitudes of up to 5 meters



Figure 9. Moving sediment bodies and scours do not appear in the C-VSM. This leads to a generally narrower histogram of the evolution (valid only for the above printed stretch)

characterize the HR-VSM (fig. 7). A funnel develops through erosion in the middle and deposition on the right bank. This funnel presses accelerated flow in the next hundred meters, where deeper scours develop.

The C-VSM on the other hand shows a much smoother behaviour, for this setup, with a 40 cm constant strength active layer. 40 cm equals 5 times the theoretical d_{MAX} , which should not be mixed up with the real local d_{MAX} at a certain point in time. All active layer formulas approximated less strength and produced varying evolution patterns.

The sediment trap is filled, after a certain time and not dredged in this example. Even though the compatibility to Nestor is given, the right configuration of Nestor is possible after a calibration of the sediment transport model. Without comparison to measured values, a final conclusion cannot be given. Too short is the work period and the number of models run with C-VSM to judge from experience. However, for the here presented section, the slope and variability of the newly developed bed is much too steep in the HR-VSM, compared to the exiting river bed.

3) Patterns of transported sediments

Figure 8 shows a confluence area with excessive evolution patterns in the HR-VSM. Especially in the main branch some areas show strong red blue pattern, which have to be interpreted with up to 8 m elevation difference between two single model nodes. C-VSM misses these patterns, but shows depositions and erosion in right the areas where the engineers experience would expect them. The maximum

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/ New keywords for the Continuous VERTICAL SORTING MODEL by Uwe Merkel
                   VERTICAL GRAIN SORTING MODEL = 1
         0 = Layer = HR-VSM (HIRANO + RIBBERINK = SISYPHE Standard)
          1 = C - VSM
C-VSM MAXIMUM SECTIONS
                              = 250
          Should be at least 4 + 4x Number of fractions,
          better > 100, tested up to 10000
C-VSM FULL PRINTOUT PERIOD
                            = 0
         Anything greater 0 => Sets an own printout period for the C-VSM useful to save disk space!!!
C-VSM PRINTOUT SELECTION = 0|251|3514|1118|1750|2104|3316
            Add any 2D Mesh Point numbers to produce .CSV-Ascii output
            of the C-VSM
            Add 0 for a full C-VSM output as Selafin3D files
            (called VSPRES + VSPHYD)
            expects: "C-VSM FULL PRINTOUT PERIOD" > 0
            All files are saved to your working folder and
            in /VSP & /LAY folders below
C-VSM DYNAMIC ALT MODEL
                             = 5
         'MODEL FOR DYNMIC ACTIVE LAYER THICKNESS APROXIMATION'
          0 = CONSTANT (Requires Keyword: ACTIVE LAYER THICKNESS)
1 = Hunziker & Guenther 5*d99
          2 = Fredsoe & Deigaard (1992)
          3 = van RIJN (1993)
          4 = Wong (2006)
          5 = Malcherek (2003)
          6 = 3*d50 within last time steps ALT
```

Figure 10. Keywords and recommended standard values, starting from Sisyphe v7p3

secondary bed slope change (left to right bank) is approx. 3.5 m. As for the other figures and examples, a final conclusion cannot be given without calibration to measured values. Figure 9 shows the same effects in a straight river section.

E. Computational cost of the C-VSM

Based on the parameter sets of figures 6-9, a performance test has been run over 10000 time steps to show the general cost of the C-VSM. These results are only roughly transferable to other projects, as they depend strongly on the size of the model, the number of MPI processes and the hardware (e.g. RAM size, bandwidth and frequency, CPU) a.o. From the software side, thresholds and the number of fractions affect the performance.

Table 1 gives an impression of necessary extra CPU times for the shown model.

Table 1: Runtime comparison

Туре	HR- VSM	C- VSM	C- VSM	C- VSM	C- VSM	C- VSM	C- VSM	Only T2D
ALT Formula	0	0	0	0	0	0	5	
Coupling Period	30	30	30	30	30	10	30	
Sections / Layers	3 Lay.	100	250	500	1000	250	250	
Runtime [s]	125	163	352	695	3619	1230	363	66
Extra Time over HR-VSM [multiples]	1	1.3	2.8	5.5	28.9	9.8	2.9	0.53

IV. HOW TO USE C-VSM II IN SISYPHE

Add the lines of Figure 10 to a Sisyphes.CAS file. The full C-VSM output can be found in the Selafin files VSPRES & VSPHYD in the tmp-folders, they are erased after the calculation if the option –t is not used. As the higher resolution of the C-VSM needs resources, one can reduce the print output period, or suppress the output at all. The common Sisyphe result files only show the Hirano output. Even more disk space can be saved, if only few points are printed out as .VSP.CSV files in the subfolder /VSP/. It is recommended to use between 200 and 500 vertical sections. More will not improve the accuracy much, and less will lead to increased data management, as the profile compression algorithms are called more often.

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