Cutting of Clay: Experimental Results and Validation of a Herschel-Bulkley Model

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Thank you for your interest in my topic of the cutting of clay. Our research compares the results of a Herschel-Bulkley model in a CFD application with real measured values in experiments of a blade moving through a block of clay. This is to improve the understanding of the cutting process in the field of dredging.

Dredging: Marine Civil Construction

Dredging is the craft of moving soil under water. This is either for removing the soil from a place you don’t want it or collecting the soil to a place where you do want it. This is a typical dredge vessel used in the dredging industry. On the right you see the cutter head. The soil is sucked up into the vessel with a dredge pump and transported to a destination through a pipeline on the left.

Dredge Cutter Head: the Business End of the Machine

Here are two typical executions of the cutter head. It is a rotating crown with replaceable teeth. The excavated soil moves to the inside of the cutter head. Different cutter teeth can be selected for adjusting the soil type: sand, rock or clay.

Clay and Cutter Heads…

- Cutter Suction Dredges can dredge clay
- Not when the clay is plastic and/or adhesive
- Unpredictable behaviour
- Unreliable production estimation
- High costs
- Risky business

- Sand is scarce, clay could be an alternative
- Clients seek solutions
- Damen initiated research in improving clay dredging

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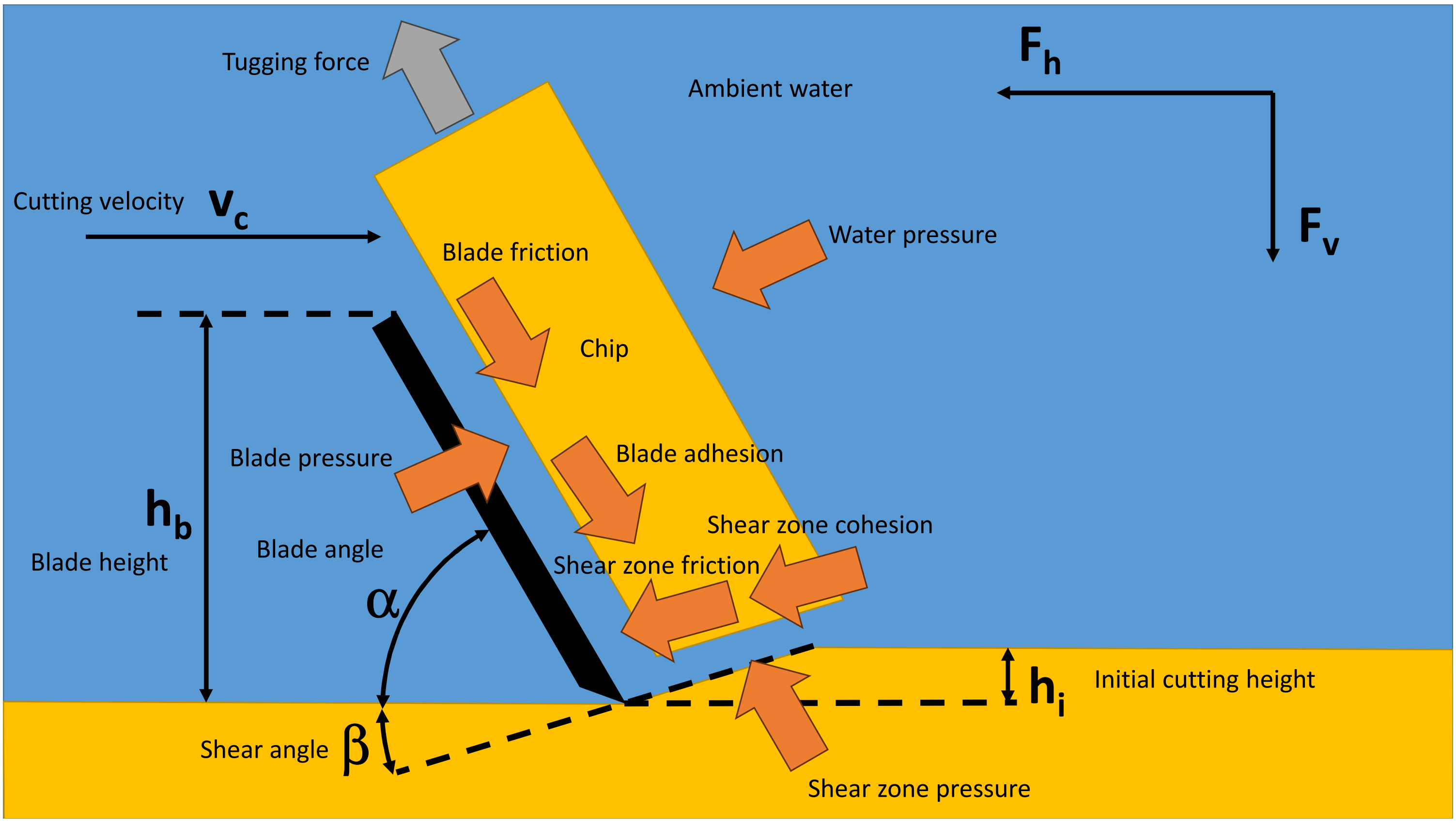
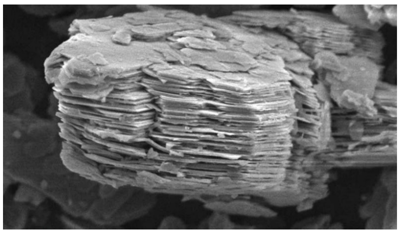
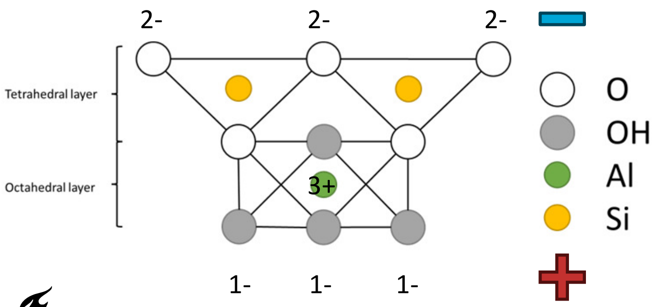
Although clay may sometimes be a problem when it is too plastic and/or to adhesive. Under certain conditions, the cutter head may become covered in the clay, and the dredging operation has to be stopped for cleaning. This leads to costly downtime. Also, the characteristics of clay make it difficult to estimate the production. Often, the contractors miscalculate the costs and either the contractor either misses the project or looses a considerable amount of money on the project.

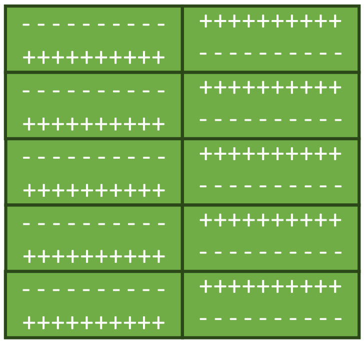


This is a elementary model of the cutting teeth moving through the clay. There is a deformation in the shear zone, and the remoulded clay is transported up the blade to be moved into the cutter head. Several forces due to the remoulding and the interaction with the tool results in the required cutting forces.

Microscopic Structure of Clay Mineral Particles

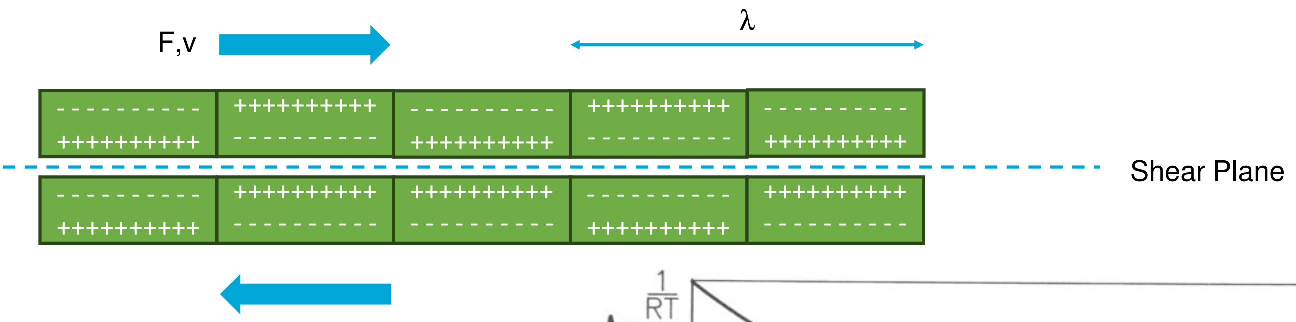


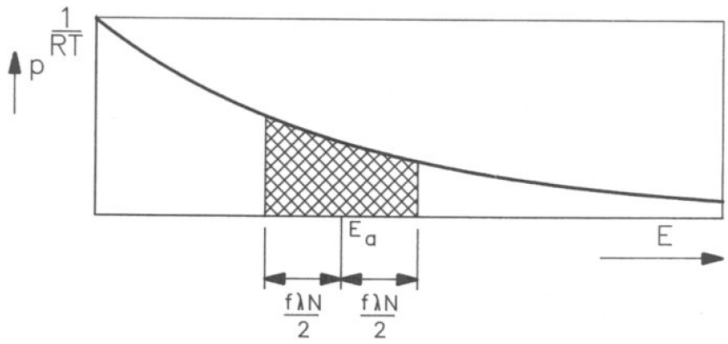




The clay itself is a micro mineral, consisting of stacks of electrostatically charged plates. The charge originates from the asymmetric distribution of the constituting elements. Due to the charge distribution, the plates stack easily and stacks of plates can attach themselves on the alternating charge distribution.

Boltzmann Activation Energy

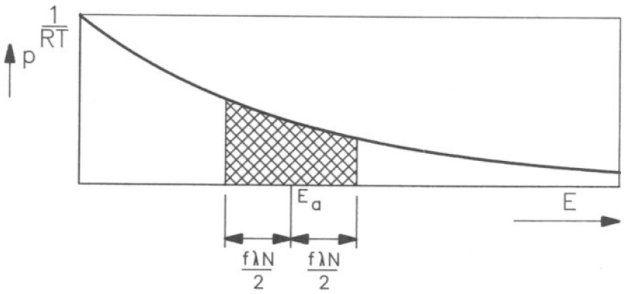




The probability of net activation in direction of force

When stacks of coalesced clay particles are gliding over a shear plane, they alternatively move over repelling and attracting electrostatic fields. It requires a certain threshold energy, or activation energy to pass the repelling fields. This is similar to the Boltzmann model for the required activation energy to pass a barrier. This model can be applied to all kind of particle physics where energy is needed to reach the next state.

Rate Process Theory



$$\dot{\varepsilon} = 2 \cdot X \cdot \frac{k \cdot T}{h} e^{\frac{-E_a}{R \cdot T}} \sinh \frac{\tau \cdot \lambda \cdot N}{2 \cdot S \cdot R \cdot T}$$

$$\frac{\tau \cdot \lambda \cdot N}{2 \cdot S \cdot R \cdot T} < 1, \quad \sinh \frac{\tau \cdot \lambda \cdot N}{2 \cdot S \cdot R \cdot T} \approx \frac{\tau \cdot \lambda \cdot N}{2 \cdot S \cdot R \cdot T}: \qquad Newtonian\ Fluid$$

$$\frac{\tau \cdot \lambda \cdot N}{2 \cdot S \cdot R \cdot T} > 1, \quad \sinh \frac{\tau \cdot \lambda \cdot N}{2 \cdot S \cdot R \cdot T} \approx \frac{1}{2} e^{\frac{\tau \cdot \lambda \cdot N}{2 \cdot S \cdot R \cdot T}}: \qquad Mohr - Coulomb\ Failure$$

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Conversely, when the energy available is driving the process, the strain rate can be calculated. One simplification can be made when the fraction in the hyperbolic sine is transiting one. When it is much smaller than one, the medium can be considered a Newtonian fluid. When it is much larger than one, it will behave as a solid with a Mohr-Coulomb Failure mechanism. This aligns with the state of clay that can be either a fluid mud or a soft rock.

Deformation to Stress

$$\dot{\varepsilon} = 2 \cdot X \cdot \frac{k \cdot T}{h} e^{\frac{-E_a}{R \cdot T}} \sinh \frac{\tau \cdot \lambda \cdot N}{2 \cdot S \cdot R \cdot T}$$

$$\tau = (E_a - E_l) \cdot \frac{2 \cdot S}{\lambda \cdot N} + R \cdot T \cdot \frac{2 \cdot S}{\lambda \cdot N} \cdot \ln\left(1 + \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)$$

$$\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \gg 1, \quad \tau = \tau_y + \tau_0 \ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)$$

Miedema, 1992, New Developments Of Cutting Theories With Respect To Dredging The Cutting Of Clay

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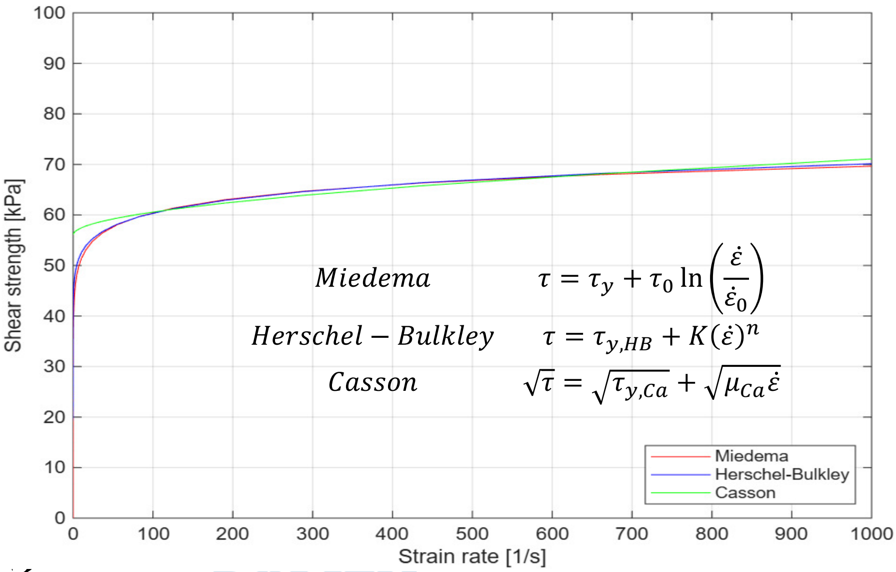
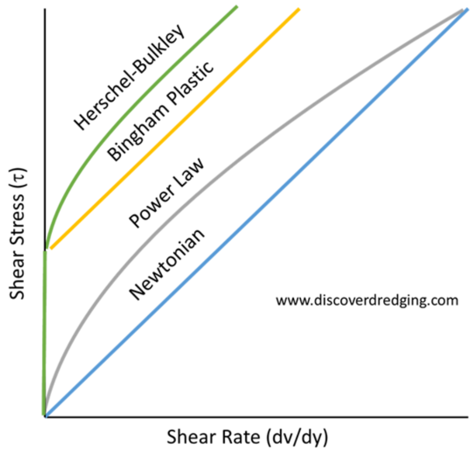
As the rate process theory seems to describe the complete range of conditions for clay, Miedema proposed to use this to relate the strain rate to the shear stress in clay. Furthermore, he simplified the equation even further by stating that when the clay deforms, the movement is so much higher than the initial movement, that the logarithm can be assumed a fraction. Combining the detailed components of the original shear stress equation, into a reduced form. Here, the shear stress is a result of a yield stress and a shear stiffening factor related to the strain rate.

Miedema Deformation and Herschel-Bulkley





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Consequently, we can use this reduced form to plot the shear strength to the strain rate. The equation proposed by Miedema is similar in form as the description for a Herschel-Bulkley fluid. Even better than e.g. the approximation proposed by Casson. The equation from Miedema also illustrates that the clay is more than a Bingham Plastic fluid that is often used as a simplification.

Research Questions

As the Miedema derived Rate Process model for deformation is not available in Ansys Fluent, can the behaviour of clay accurately be described with a Herschel-Bulkley model which demonstrates a similar strain-stress relation?

- What pre-process settings are necessary?
- Does the simulation result relate to the actual measurements?
- What are the limitations?

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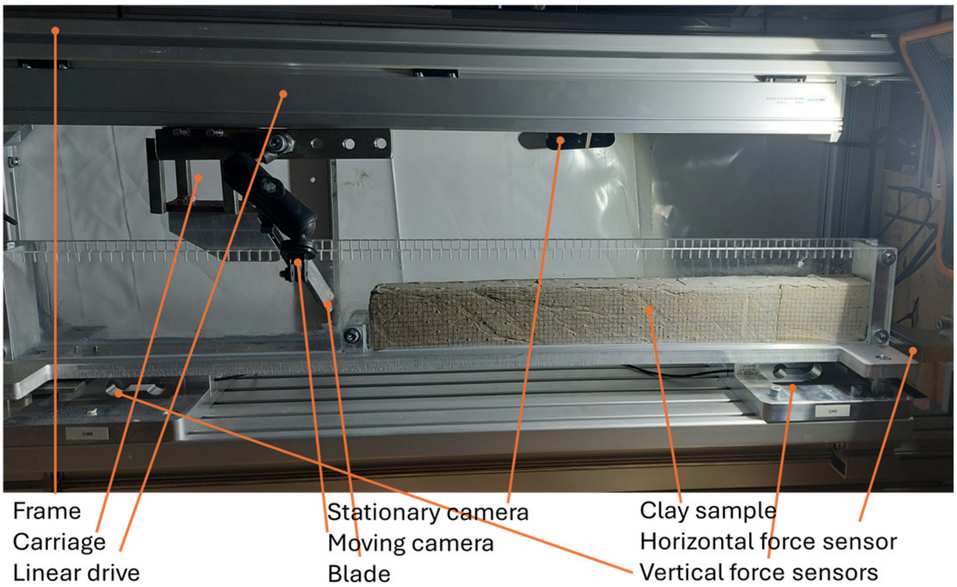
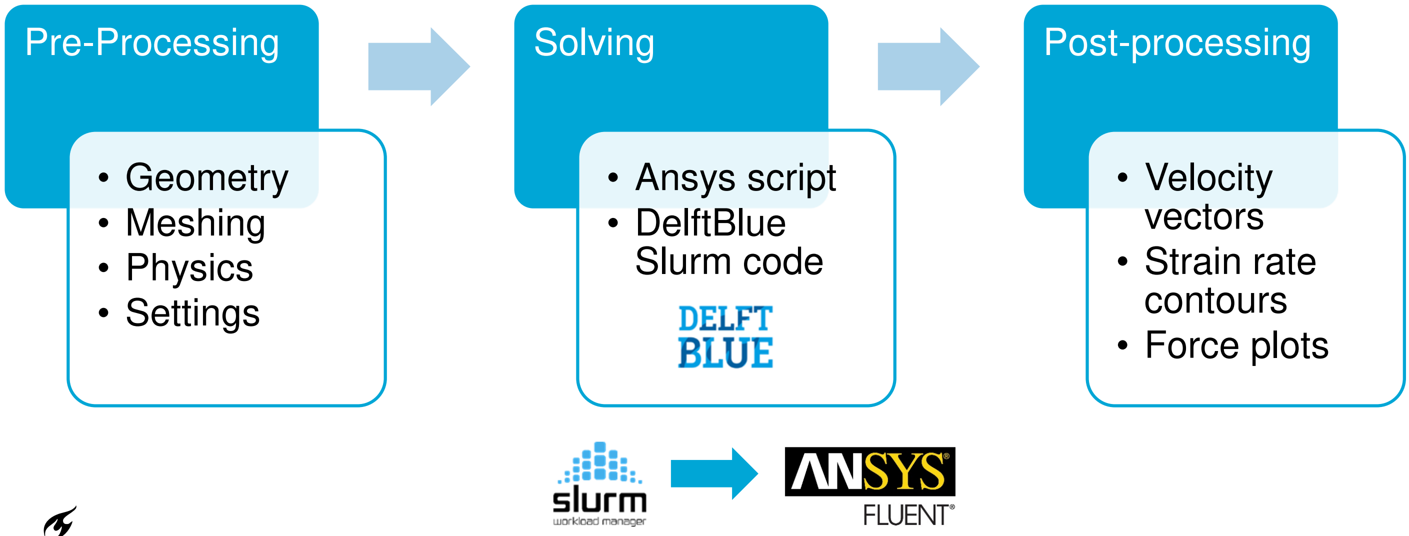
We have been doing experimental tests in a soil bin to understand the behaviour of clay during cutting. We wanted to explore this further by simulating the process with Ansys Fluent, however, Fluent does not have a description for the viscosity according to the rate process theory and the proposed equations of Miedema. But as we've seen that the resulting deformation behaviour is similar to the Herschel-Bulkley model, we would like to explore whether we could simulate the cutting of clay with the Herschel-Bulkley description.

Experimental Setup



This is our original soil bin experiment. There is a blade driven by a linear drive through the block of clay. The resulting forces are recorded. The process is captured by two video cameras for further analysis of the deformation of the clay around the blade. From the 25 experiments, only those with a flow type cutting behaviour were selected for comparison. Some experiments showed discontinuous behaviour which cannot be modelled in Fluent.

Simulation Workflow



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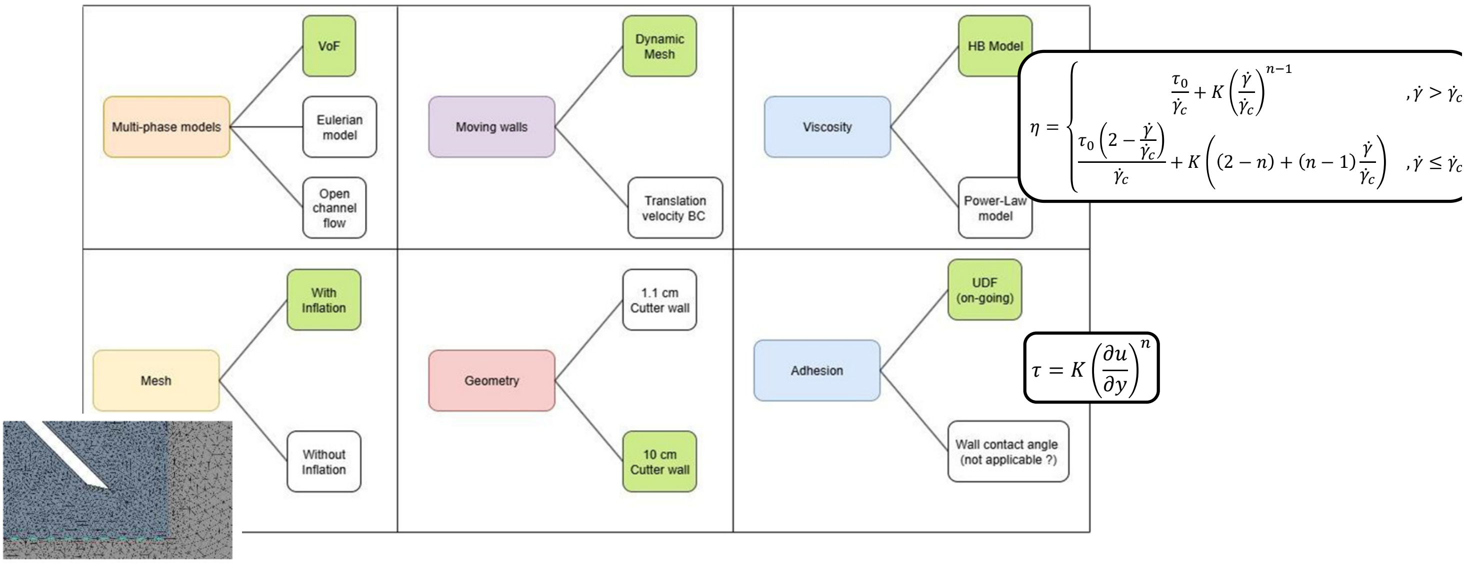
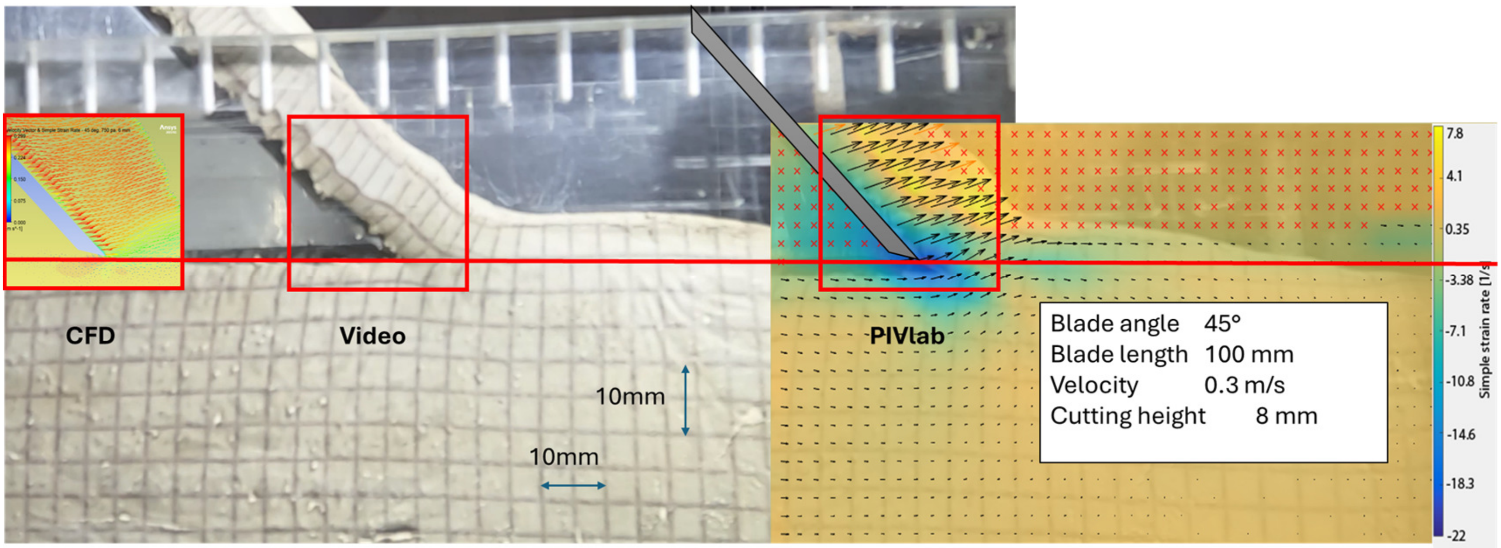
For the simulation in Ansys Fluent, we used the DelftBlue computing cluster of the Delft University of Technology. This required a predefined set of pre-processing settings that could be handled by a SLURM instructions. The pre-processing setting where about the geometry, meshing, physics and numerical settings. The resulting files where post-processed and analysed on the velocity vectors, the strain rates and the integrated reaction forces.

Pre-Processing and Settings



These are a selection of the settings used for the simulation. Next to the clay, we also modeled the air as secondary phase. From the reference soil bin experiments, we selected the 100mm blade length. Modelling the 11mm blade length gave too much problems in the meshing. For meshing we used dynamic meshing reflecting moving walls. The mesh is divided in three sections with the section closest to the blade acting as an inflation layer. The viscosity definition uses the normal Herschel-Bulkley equations. Adhesion is assumed to be a power law as the closest approximation. Preferably this could be improved with a User Defined Funtion.

Results from Experiments, Analysis and Simulation



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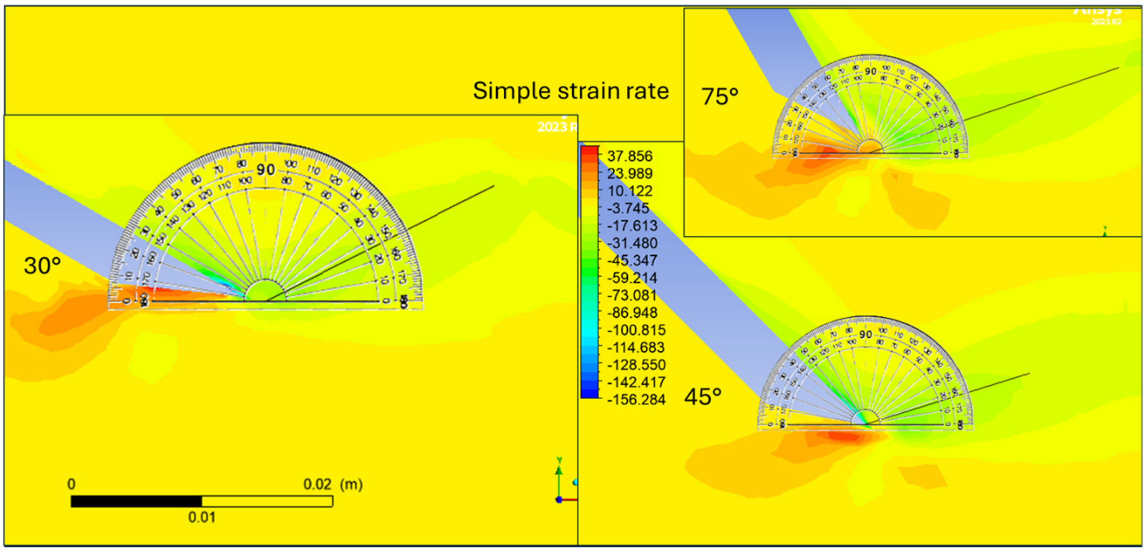
Here are the results from the three approaches. The direct video capture from a test. The deformation has been analysed by tracking the grid in PIVlab. This resulted in vector plots for further evaluation. The simulation gave a vector plot as one of the results. All pictures have been scaled to the same dimensions for comparison.

Resulting Shear Planes from Simulation



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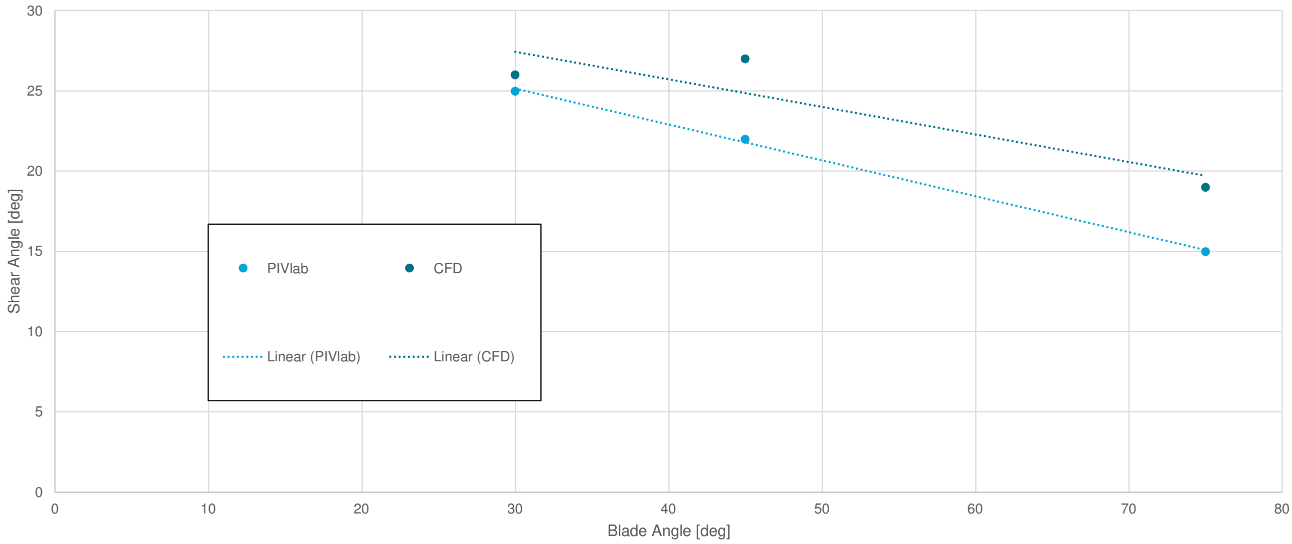
One of the Fluent results was a plot of the simple strain rate, which could be used to find the shear angle. In this case the shear angle is still measured manually.

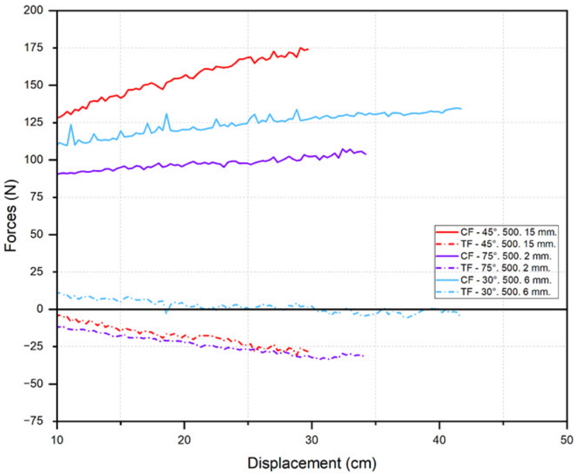
Validation for Deformation



Comparing the shear angles from the soil bin experiments with the shear angles from the CFD simulation shows a similar trend and magnitude. Further analysis of the data from both approaches could also provide a statistical basis for confirming the validation.

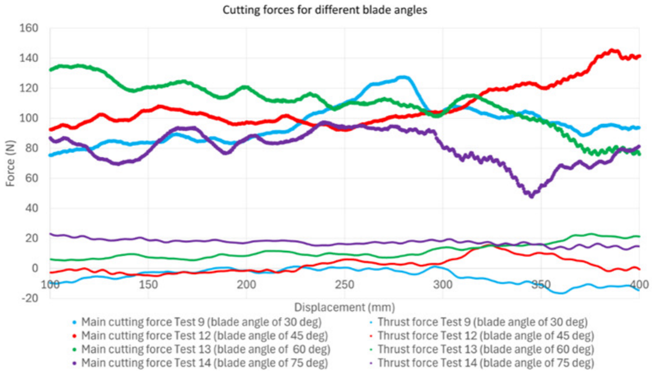
Cutting Forces Comparison

Ansys Fluent



Cohesion: 750 Pa

Measurements



Cohesion: 60 kPa

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Also, the forces have been compared. The stresses from the CFD are integrated on the blade and the resulting forces compared to the soil bin experiments. The simulation overestimates the actual forces by two magnitudes. Comparable results were found by reducing the cohesion in the simulation to 750 Pa against the actual cohesion in the experiments of 60 kPa.

Conclusion

The results show that clay **deformation** in a flow-type cutting regime can be **accurately** captured by modelling clay viscosity using a **Herschel–Bulkley** model. Further conclusions are:

- **Cutting kinematics** and deformation patterns are **accurately** reproduced, but **force** magnitudes remain **over-predicted**.
- Internal and external **friction** strongly govern cutting forces, beyond viscous effects alone.
- Current **adhesion** and **wall-shear** representations are insufficient for quantitative force prediction but could be improved with User Defined Functions.
- Improved friction and adhesion modelling can enable **better cutter design**, **reduce clogging**, and support **cost-effective clay dredging**.

Concluding: the deformation in flow type clay cutting can be accurately modeled by Fluent using the Herschel-Bulkley viscosity model. The kinematics are accurate, but the forces are overpredicted. In the details there are indications that internal and external friction do have an influence that the eventual behaviour is more than viscous. The workflow can be improved when there is a better User Defined Function for the adhesion and wall-shear. Overall, using Ansys Fluent with a Herschel-Bulkley model will enable us to make more accurate prediction in the flow of clay over the blade, improving cutter design and reduce clogging, resulting in a more cost-effective dredging operation for the owner.

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In case you want to discuss our work, you can contact me at this email address or visit my website through the QR code.

Thank you for your attention

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