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

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Introduction

Clay is challenging to dredge due to its complex soil behaviour, high **plasticity**, and **strong adhesion**, causing clogging of equipment, clay balls in pipelines, and unpredictable production rates and increased downtime. At the same time, there is a **growing demand** for construction materials making clay a potential **alternative** for civil engineering applications, if challenges in handling clay can be addressed. Predicting cutting forces and power demand remains challenging. This research aims to improve simulation of clay behaviour to achieve a more reliable prediction of the behaviour of the clay during cutting. **Soil bin experiments** (Figure 3) validated flow type cutting models by **Miedema** which are similar to **Herschel–Bulkley**–type behaviour (Figure 1). As the Miedema models are not available in Ansys, the Herschel-Bulkey model enables numerical simulation of clay using **Ansys Fluent**. A limitation for this method, is that no discontinuities in the chip formation are allowed, as this is not covered in the models.

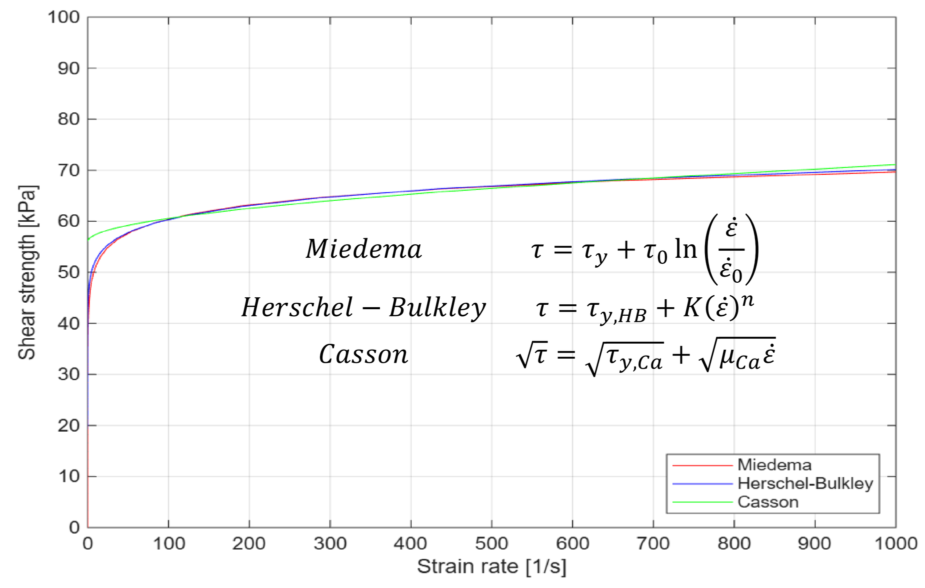

Figure 1. Comparison of Miedema clay model with viscoplastic fluids

Method

Initial measurements in the **soil bin experiment**, resulted in **velocity fields** and **strain rate maps** by analysing video with **PIVlab**. The clay cutting process was simulated using computational fluid dynamics (**CFD**) to assess the ability of a **non-Newtonian** rheological model to reproduce experimentally observed cutting forces and deformation patterns.

- Clay was modelled as an **incompressible viscoplastic fluid** following a Herschel–Bulkley (HB) constitutive law (Eq. 1), accounting for yield stress and shear-thinning behaviour observed in the soil-bin experiments.

$$\eta = \begin{cases} \frac{\tau_0}{\dot{\gamma}_c} + K\left(\frac{\dot{\gamma}}{\dot{\gamma}_c}\right)^{n-1} & ,\dot{\gamma} > \dot{\gamma}_c \\ \frac{\tau_0\left(2 - \frac{\dot{\gamma}}{\dot{\gamma}_c}\right)}{\dot{\gamma}_c} + K\left((2-n) + (n-1)\frac{\dot{\gamma}}{\dot{\gamma}_c}\right) & ,\dot{\gamma} \le \dot{\gamma}_c \end{cases} \quad \text{(Eq. 1)}$$

- **Adhesion** and near wall behaviour was approximated with a power law function (Eq. 2) using plausible values for the parameters from literature.

$$\tau = K\left(\frac{\partial u}{\partial y}\right)^n \quad \text{(Eq. 2)}$$

- To account for the clay and the water in the experiment, a **Volume of Flow** (VoF) multi-phase model was used.
- A **dynamic mesh** was used to accommodate blade movement and large clay deformation.

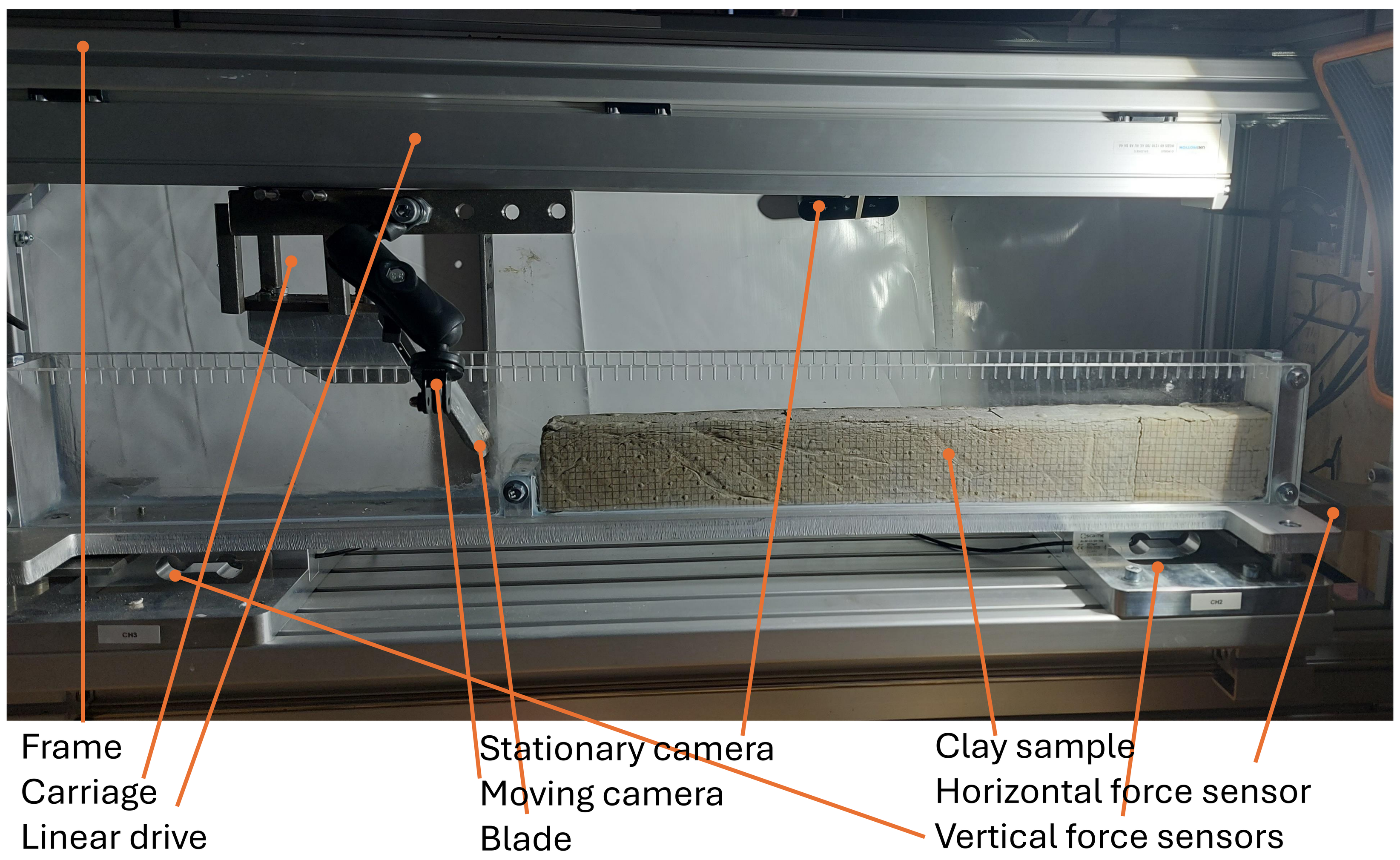

Figure 2. General arrangement of the experimental setup

Results

- The fluid flow direction is **consistent** between the CFD and experiments, with the clay moving upwards and away from the blade.
- The CFD results show velocity magnitudes in the range of 0–0.3 m/s, exhibiting **similar trends** in the velocity vector fields.
- Vector plots from PIVlab and Fluent indicate zones of **reduced velocity** near the tip of the cutter blade (Figure 3).
- This zone corresponds to the **negative strain rate effects** (compressive effects), and the vector plots reflect the expected effects (Figure 4) and could lead to rupture and discontinuities.
- The magnitude of the simulated shear stress and the total forces was a **magnitude higher** than the measurements.

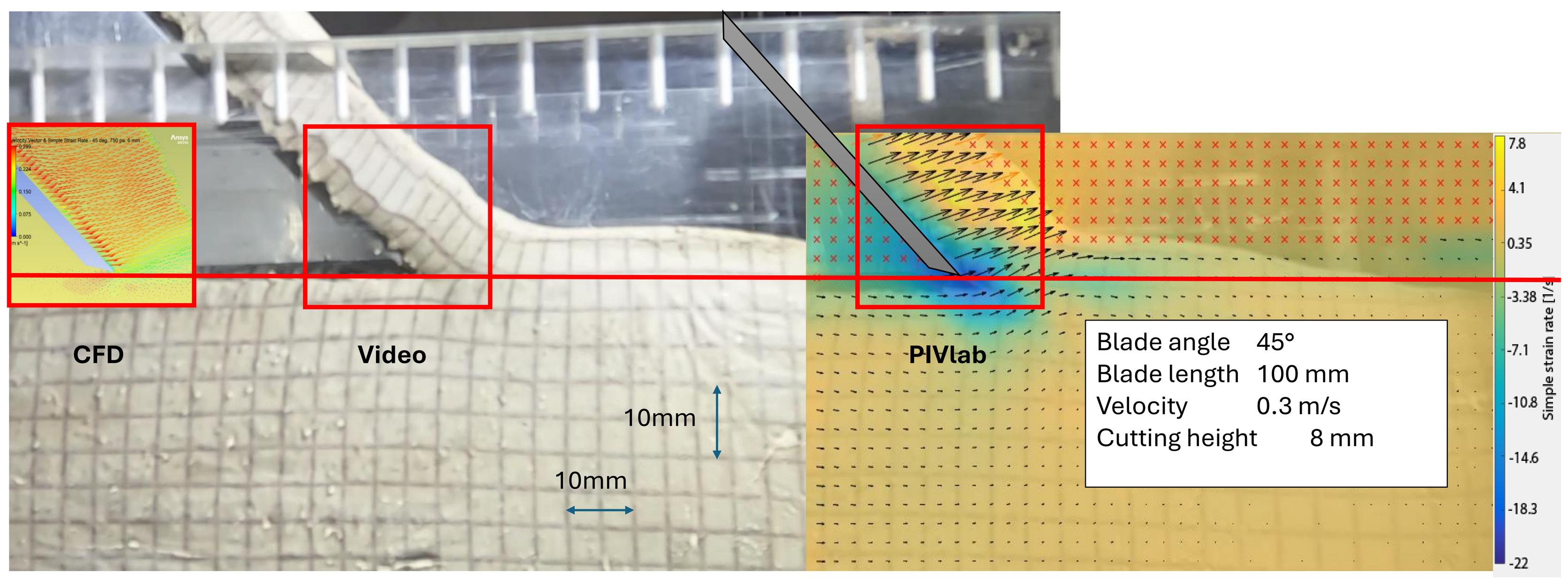

Figure 3. Comparing CFD (l), Video (m) and PIVlab (r) analysis

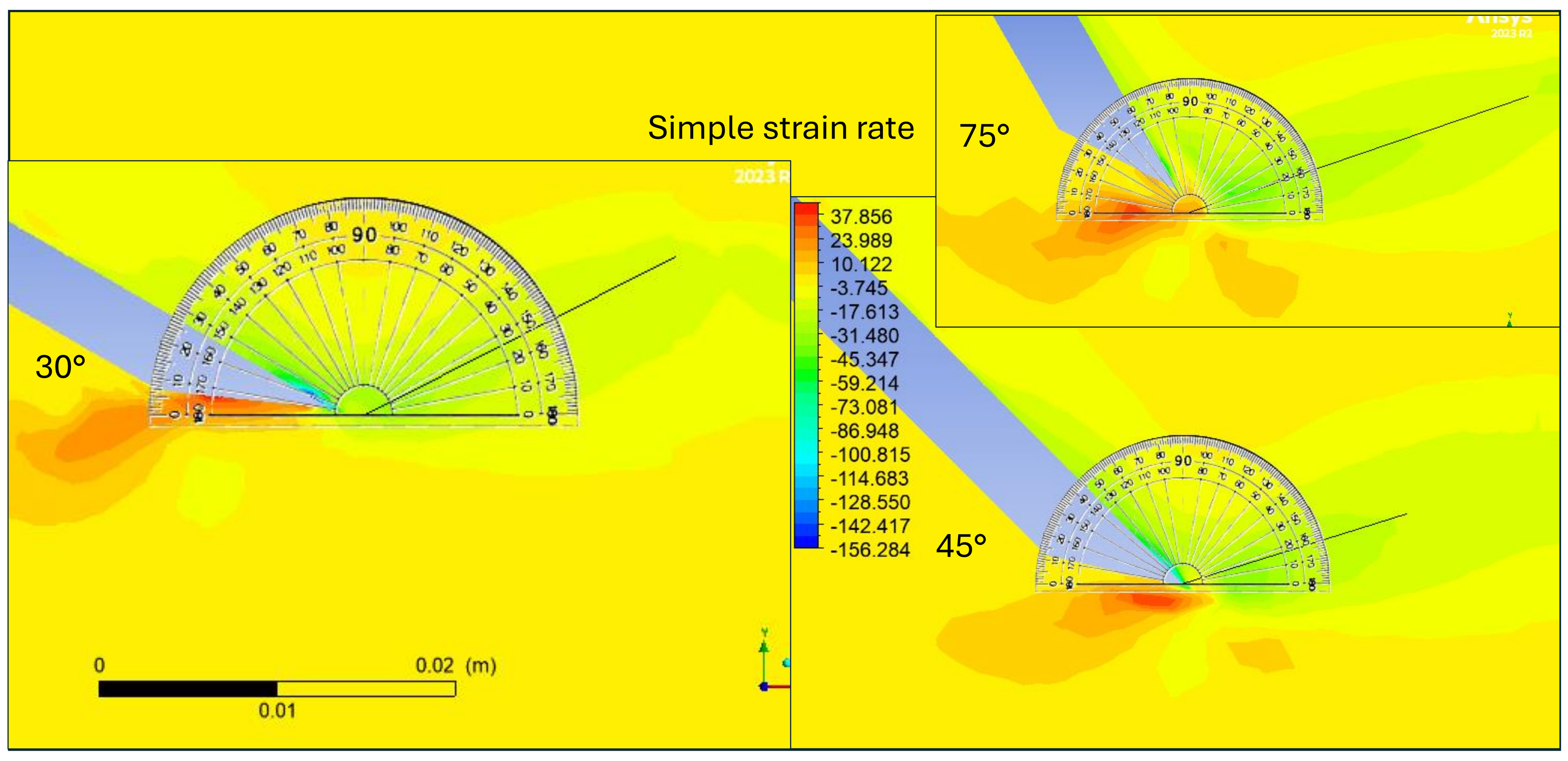

Figure 4. Simple strain rate from CFD simulations for various blade angles

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.

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