IMPLEMENTATION OF NON-NEWTONIAN RHEOLOGY FOR DEBRIS FLOW SIMULATION WITH REEF3D

PETTER FORNES(1), HANS BIHS(2), VIKAS THAKUR(3) & STEINAR NORDAL(4)

(1,2,3,4) Department of Civil and Environmental Engineering, Norwegian University of Science and Technology (NTNU), Trondheim, Norway
petter.fornes@ntnu.no

ABSTRACT

Landslides triggered by hydro-meteorological processes are a serious natural hazard in many areas of the world. The landslides of the debris flow type are often triggered by extreme precipitation events. These landslides are composed of water and poorly graded soil particles, and usually forms a dense flow. To predict the runout distance of such landslides and to design countermeasures to reduce their consequences, a solid understanding and description of the debris flow mechanism is essential. Debris flows are often modeled with depth-averaged models, which are fast to simulate. To better capture the physics of the problem, computational fluid dynamics (CFD) can be used. A non-Newtonian rheology for modelling the behavior of the dense fluid phase, representing fine solids suspended in water, is implemented in the open-source CFD code REEF3D. The three-dimensional numerical model employs the level set method for representing the free surface. This approach can handle the complex air-debris flow interface topology. The Reynolds-Averaged Navier-Stokes (RANS) equations are discretized with the fifth-order accurate Weighted Essentially Non-Oscillatory (WENO) scheme in space and with a third-order Runge-Kutta based fractional step scheme in time. The model behavior is validated through comparisons with laboratory model tests with slurry of water and fine grained soil.

Keywords: CFD, Non-Newtonian Rheology, Free Surface, Debris Flow, REEF3D

1 INTRODUCTION

Rapid debris flows, debris avalanches, earth flows, landslides, rock avalanches and failures of loose fill are among the most dangerous and most damaging of all landslide phenomena. Their runout determines a large portion of the consequences and the risk associated with the landslides. Runout parameters include the maximum distance reached, flow velocities, thickness and distribution of deposits, as well as the behavior at obstacles in the flow path (Crosta et al., 2003; Rickenman, 2005; Hungr, 2005; Lacasse, 2013; Hungr, 2016; Strand et al., 2017).

The landslides of the debris flow type are typically triggered by hydro-meteorological processes during extreme precipitation events. Debris flows are often composed of water and poorly graded soil particles, forming a dense flow (Iverson, 1997). To predict the runout distance of such landslides and to design countermeasures to reduce their consequences, a solid understanding and description of the debris flow mechanism is necessary. Complete understanding of the mechanisms involved in debris flow is a complex and challenging task. However, owing to the crucial nature of assessing the initiation and mobility of debris flow, researchers and practitioners have attempted to address such problems in pragmatic approaches that involve several logical simplifications.

In engineering practice, the propagation of these flows are traditionally simulated with depth-averaged models. The main advantage of integrating over the height of the flow, is to reduce the problem from three dimensions to two, and thereby reducing the simulation time significantly. However, this simplification reduces the accuracy, by applying all the resistance through the base friction and using an average over the height shear rate profile. The traditional depth averaged methods often use a single phase rheology, modelling the debris flow as a continuum, for example using Voellmy rheology. If so, the base shear is applied as a constant frictional resistance term and viscous term non-linear dependent on the average shear rate. The material parameters in these models typically have to be calibrated based on field cases, in order to make any predictions. With the recent increases in computer power, it might be more feasible to consider a full three dimensional solution of the debris flows propagation. Computational fluid dynamics (CFD) can therefore be used to try to capture more of the problem physics.

Such complex problems have also been approached by focusing on certain selected aspects of the problem at a time, one of which is to understand the flow behavior of remolded debris. This paper addresses and validates this aspect, numerically, in light of laboratory measurements. The objective of this work is then to model only the behavior of the dense fluid phase of debris flow landslides, using CFD. Here, the flow is in this three dimensional method modeled as a single-phase continuum, even though a single-phase viscoplastic rheology is not sufficient to capture all the complex mechanisms of debris flows (Iverson, 2003). Full debris flow behavior, including the friction between the larger sized grains, the buildup of excess pore pressure, and temporal and spatial rheological changes, cannot realistically be captured when modeled as a single phase continuum fluid. To account for this, while still considering the debris flow as a continuum, a multiphase approach seems necessary (von Boetticher et al., 2015). However, that is outside the scope of this paper. Regardless, a viscoplastic non-Newtonian rheology may be sufficient for the interstitial fluid phase of a debris flow, consisting of water with fine particles in suspension (Laigle and Coussot, 1997). It may also be appropriate for other fluidized fine-grained soils, such as mudflows and flow slides in sensitive clays (Jeong et al., 2012). For this purpose, a non-Newtonian viscoplastic rheology has been implemented in the open-source CFD code REEF3D (Bihs et al., 2016).

2 NUMERICAL MODEL

The open-source CFD code REEF3D is documented by Bihs et al. (2016). The three-dimensional finite difference numerical model solves the Navier-Stokes equations, which govern the behavior of viscous and incompressible fluids. For mass and momentum conservation of the fluid domain, the continuity and Reynolds Averaged Navier-Stokes (RANS) equations are considered:

$$\frac{\partial u_i}{\partial x_i} = 0 \qquad [1]$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\left(\nu + \nu_t\right)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] + g_i \qquad [2]$$

where u is the velocity, ρ is the fluid density, p is the pressure, ν is the kinematic viscosity, ν_t is the eddy viscosity, g is the gravitational acceleration. On the left hand side of the RANS equations are the transient and convective velocity terms. On the right hand side are the surface and volume forces, the viscous and pressure terms, and the gravity, respectively. The Reynold stress term capturing the turbulence is modeled separately.

The RANS equations are discretized with the fifth-order accurate Weighted Essentially Non-Oscillatory (WENO) scheme in space (Jiang and Shu, 1996) and with a third-order Runge-Kutta based fractional step scheme in time (Shu and Osher, 1988).

The pressure gradient is modeled with Chorin's projection method (Chorin, 1968) for incompressible flow. A staggered grid is used to avoid decoupling of velocity and pressure. The momentum equation with the pressure gradient removed is solved for an intermediate velocity field u_i^*. The pressure for the new time step p^{n+1} is determined and used to correct the velocity field. In order to create divergence free flow field, the pressure needs to fulfil the following equation:

$$\frac{\partial}{\partial x_i}\left(\frac{1}{\rho(\phi^n)}\frac{\partial p^{n+1}}{\partial x_i}\right) = \frac{1}{\Delta t}\frac{\partial u_i^*}{\partial x_i} \qquad [3]$$

The level set method proposed by Osher and Sethian (1988) is employed for locating the free surface. This approach can handle the complex air-debris flow interface topology. To define the interface between the two fluids, the following continuous signed distance function is used:

$$\phi(\vec{x},t)\begin{cases} >0 & \text{if } \vec{x} \text{ is in phase 1} \\ =0 & \text{if } \vec{x} \text{ is at the interface} \\ <0 & \text{if } \vec{x} \text{ is in phase 2} \end{cases} \qquad [4]$$

The level set function $\phi(\vec{x},t)$ is coupled to the velocity field u_j with a convection equation, and the spatial discretization is determined with the Hamilton-Jacobi WENO scheme version (Jiang and Peng, 2000):

$$\frac{\partial \phi}{\partial t} + u_j \frac{\partial \phi}{\partial x_j} = 0 \qquad [5]$$

3 NON-NEWTONIAN RHEOLOGY

For modelling the interstitial fluid of debris flows, consisting of water with fine particles in suspension, the viscoplastic Herschel-Bulkley rheology may be appropriate. Kaitna and Rickenmann (2007) and Kaitna et al. (2007) found that Herschel-Bulkley can be fitted to experiments on debris flow material with small particle diameters and high clay content. Coussot et al. (1998) determined Herschel-Bulkley parameters for debris flow deposit samples (without the largest particles).

The non-newtonian viscoplastic Herschel-Bulkley rheology features a yield stress τ_0 and a non-linear stress relationship with the shear rate $\dot{\gamma}$. In order to have shear deformation the shear stress acting on the fluid must supersede the yield stress. For shear stress lower than the yield stress, the shear rate is zero. The Herschel-Bulkley rheology is defined by the shear stress and shear rate relation:

$$\tau = \tau_o + K\dot{\gamma}^n \qquad [6]$$

$$\dot{\gamma} = \begin{cases} 0 & \text{if } \tau < \tau_0 \\ \left(\frac{1}{K}(\tau - \tau_0)\right)^{\frac{1}{n}} & \text{if } \tau \geq \tau_0 \end{cases} \qquad [7]$$

where τ is the shear stress, $\dot{\gamma}$ is the shear rate, τ_0 is the yield stress, K is the consistency parameter, n is the Herschel-Bulkley exponent. If $n > 1$ shear-thickening behavior is defined, and $n < 1$ defines shear-thinning behavior. If $n = 1$ the equations provide the Bingham rheology, and if additionally $\tau_0 = 0$, they provide the Newtonian rheology. The Herschel-Bulkley rheology can be considered as a generalized Newtonian fluid by determining the apparent shear rate dependent dynamic viscosity μ, as the shear stress divided by the shear rate. As the shear rate decreases towards zero, the apparent viscosity increases towards infinity:

$$\mu = \frac{\tau}{\dot{\gamma}} = \frac{\tau_o}{\dot{\gamma}} + K\dot{\gamma}^{n-1} \qquad [8]$$

The Herschel-Bulkley rheology has been implemented in the REEF3D CFD code. The kinematic viscosity $\nu = \mu / \rho$ in the Navier-Stokes equations Eq. [2] is determined locally for each cell every time step since it varies spatially and temporally. It is determined by normalizing the apparent dynamic viscosity by the fluid density, and a maximum value ν_0 is specified to avoid numerical problems:

$$\nu = \min\left[\nu_0, \left(\frac{\tau_o}{\dot{\gamma}} + K\dot{\gamma}^{n-1}\right) \Big/ \rho\right] \qquad [9]$$

where τ_0 is the yield stress, K is the consistency parameter, n is the Herschel-Bulkley exponent, ρ is the density and ν_0 is a maximum kinematic viscosity value used for small shear rates when the apparent viscosity approaches infinity. The viscosity is considered isotropic, and the scalar shear rate magnitude $\dot{\gamma}$ is determined from the shear rate tensor:

$$\dot{\gamma} = \sqrt{\frac{1}{2}\sum_{i=1}^{3}\sum_{j=1}^{3}\dot{\gamma}_{ij}\dot{\gamma}_{ij}} \qquad [10]$$

The implementation in Eq. [9] results in a material with a very high viscosity for low shear rates instead of a yield stress preventing deformation. This means that the flowing material will never come fully to rest with a sloped angle, which can be expected for a landslide deposited at a flat area. However, when the magnitude of velocity is several orders of magnitude lower than while propagating it will be considered to have stopped. The implementation is bi-viscous, making the rheology discontinuous. Instead a regularization parameter could be employed (Saramito and Wachs, 2016), which may improve the accuracy. It would also help to obtain rigid body motion for the unyielded material, but it has not been considered necessary to obtain the precise location of solid material.

4 EXPERIMENTS

To validate the implementation of the Herschel-Bulkley rheology in REEF3D, laboratory experiments with fine-grained soil materials are considered. Sensitive clays are fine grained soil materials that exhibit viscoplastic flow behavior when remolded (Locat and Demers, 1988). When these clays are deformed, their intact structure disintegrates and they can transform from a solid material to essentially a fluid with potentially less than 1 kPa shear strength ('quick'). This brittle behavior has caused many landslides to develop retrogressively and the consequences can become large (Thakur et al., 2013).

When remolded and thus fluidized, sensitive clays can be considered to be viscoplastic single phase continuum material (Jeong et al., 2012). Thus, laboratory experiments on remolded sensitive clay are considered for validation of the Herschel-Bulkley implementation. Grue et al. (2017) reports viscometer test results on Norwegian remolded sensitive clays. They established correlations between the Herschel-Bulkley model parameters τ_0, K and n, and the soil characterization parameter Liquidity Index (I_L).

For validation of the Herschel-Bulkley rheology implementation, simulation has been done of a new laboratory test called a 'quickness test', proposed by Thakur and Degago (2012) for determining the run out potential of sensitive clay landslides. This test is performed by first filling a standardized cylinder (height x diameter = 120 mm x 100 mm) resting on a flat smooth surface with remolded clay material, see Figure 1. Afterwards, the cylinder is slowly lifted vertically, and the gravity causes the material to radially flow out to the sides from underneath the cylinder, see Figure 3. The collapse height and deposition diameter are noted. The results of this laboratory test can be used for making correlations with landslide runout distances, and evaluating the susceptibility of long runout distances.

The tests done by Thakur and Degago (2012) were with material from Heimdal, Norway. The material is characterized in Table 1. Samples of the clay with different remolded shear strengths c_{ur} were tested, having correspondingly different degrees of fluidization.

Figure 1. Cylinder (internal height 120 mm, diameter 100 mm) filled with remolded sensitive clay, standing on glass plate. (Photo: Thakur, V.)

Table 1. Heimdal clay properties, Thakur and Degago (2012).

Sampling depth [m]	6-10
Clay fractions (< 2 μm) [%]	30
Water content (w) [%]	22-34
Plasticity index (I_P) [%]	5-7
Liquidity index (I_L) [-]	0.7-2.0
Undisturbed undrained shear strength (c_{ui}) [kPa]	12-58
Remolded undrained shear strength (c_{ur}) [kPa]	0-2
Sensitivity (S_t) [-]	16-29
Over consolidation ratio (OCR) [-]	1.8-2.0

The quickness test was simulated with REEF3D as cylindrical dam break test. The domain considered was 400 mm x 400 mm x 180 mm, with cell length 2 mm, resulting in a mesh with 3.6 million cells. A cylinder of Herschel-Bulkley fluid with initial dimension height 120 mm and diameter 100 mm was immediately released and allowed to flow out due to gravity. The rest of the domain was filled with a fluid phase given Newtonian rheology with the properties of air. Turbulence was not considered in the simulation.

The rheological parameters used in the numerical simulation for the remolded clay are based on the data produced by Grue et al. (2017), due to no viscometer test done for the quickness test material. The sensitive clays used by Thakur and Degago (2012) and Grue et al. (2017) were collected from two different sensitive clay deposits located in Trondheim, Norway. However, the grain size distribution, salt contents, and the mineralogical characteristics of these sensitive clays deposits are rather similar (Thakur et al., 2017). Therefore, the data reported by Grue et al. (2017) have been used as a reference to establish best estimate values of Herschel-Bulkley model parameters for the Heimdal clay with remolded shear strength c_{ur} = 0.2 kPa, see Table 2. Figure 2 shows the corresponding rheology curve according to Eq. [6].

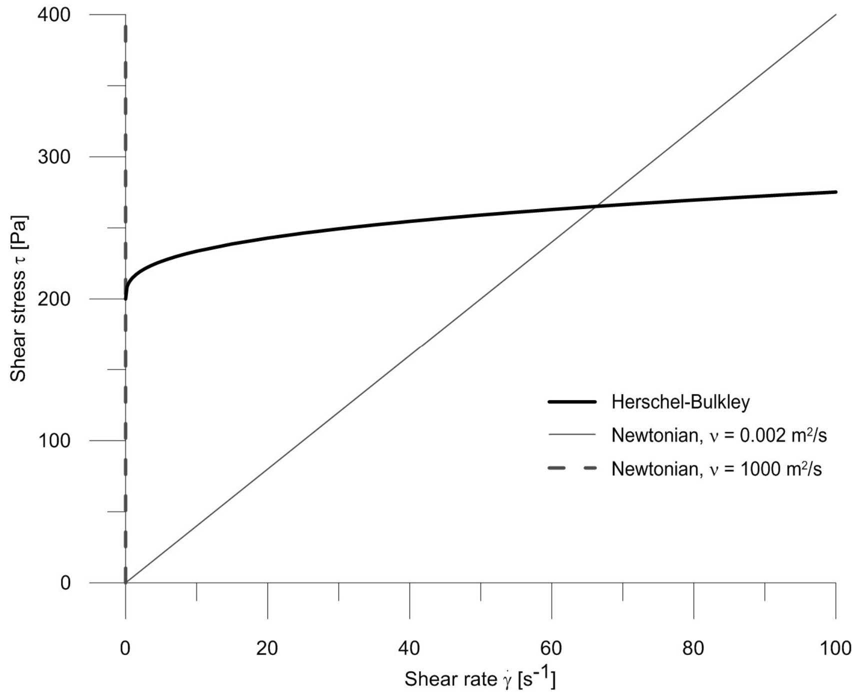

Figure 2. Shear stress and shear rate relation for best estimate Herschel-Bulkley parameters, compared to Newtonian rheology with dynamic viscosity μ = 4.0 and $2{\cdot}10^6$ Pa·s (corresponding to kinematic viscosity ν = 0.002 and 1000 m^2/s, for density ρ = 2000 kg/m^3).

Table 2. Herschel-Bulkley model parameters, REEF3D simulation.

Density (ρ) [kg/m^3]	2000
Maximum kinematic viscosity (ν_0) [m^2/s]	1000
Yield stress (τ_0) [Pa]	200
Herschel-Bulkley exponent (n) [-]	0.35
Consistency parameter (K) [Pa·s^n]	15

5 RESULTS

In the laboratory tests by Thakur and Degago (2012) it was observed a significant change in the material flow behavior for remolded shear strength c_{ur} from 0.2 to 0.5 kPa. For lower shear strength the material is highly liquid, and for higher strength its shape remains more intact. In the in-between range it behaves like a dense fluid with yield stress. Figure 3 shows the final deposition shape of the sample with remolded shear strength c_{ur} = 0.2 kPa. The final deposition height was 40 mm and the diameter 237 mm. The deformed shape is irregular due to variable speed of lifting the cylinder.

Figure 4 shows the simulation results using the Herschel-Bulkley rheology with the parameters in Table 2. The overall deposition of the simulation matches relatively well with the experiments, see Figure 5. The height at rest (low velocity), is lower than in the laboratory experiment. It can be due to the laboratory execution, which resulted in an irregular shape or due to the friction between the material and the surface on which the material was flowing. Without these, the maximum height would probably be slightly lower.

In the simulation, the material was released from the cylinder immediately. The magnitude of deformation velocity reduces significantly after time T = 0.3 s, and the fluid is considered as being at rest. Conversely, the laboratory experiment was performed by lifting the cylinder slowly and unevenly, and thus took longer time to obtain the final deposition.

The material in the simulation is perfectly homogenous, and the starting conditions are symmetric. One would therefore expect a symmetrical deposition pattern. This is not the case, due to the high viscosity considered for this fluid. Numerically, the treatment of the diffusion term in the momentum equation is handled with a staggered grid, and the interpolation algorithms used may introduce an asymmetrical solution. This is not expressed when considering viscosities closer to the value for water.

In this simulation, best estimate rheological parameters were used, established based on correlations with I_L from similar clays. The match could be improved with further calibration of the rheological parameters, or by performing viscometer tests on the actual sample material.

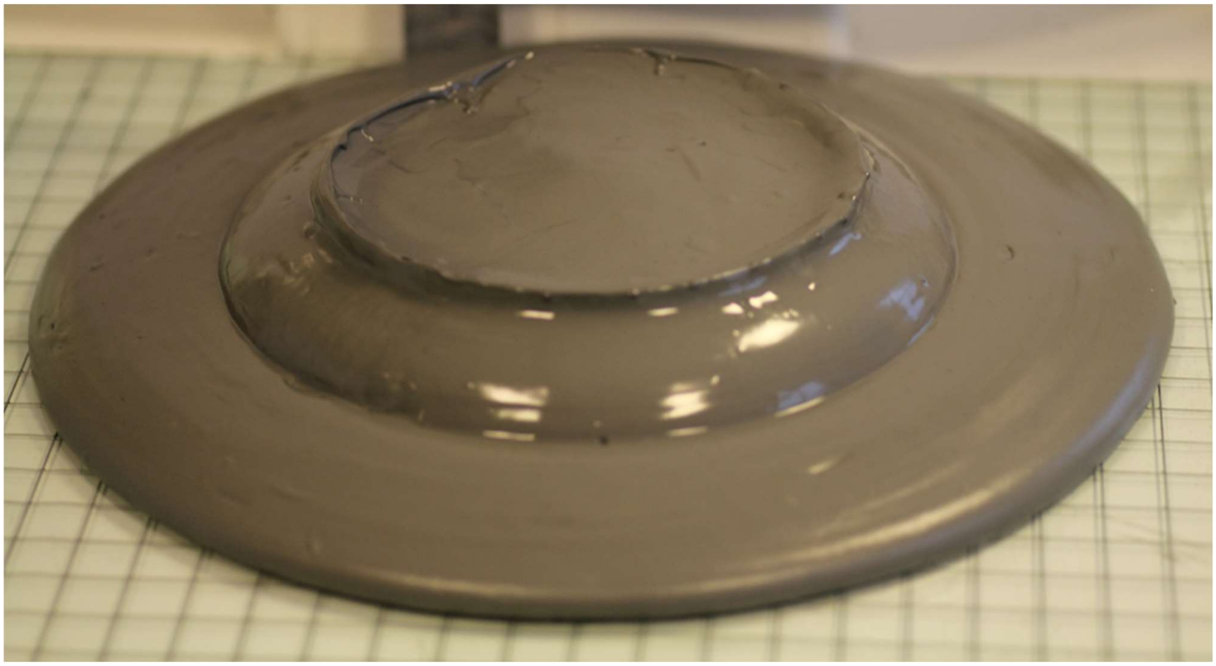

Figure 3. Final shape laboratory quickness test (height 40 mm, diameter 237 mm), Heimdal clay, remolded shear strength c_{ur} = 0.2 kPa (Photo: Thakur, V.)

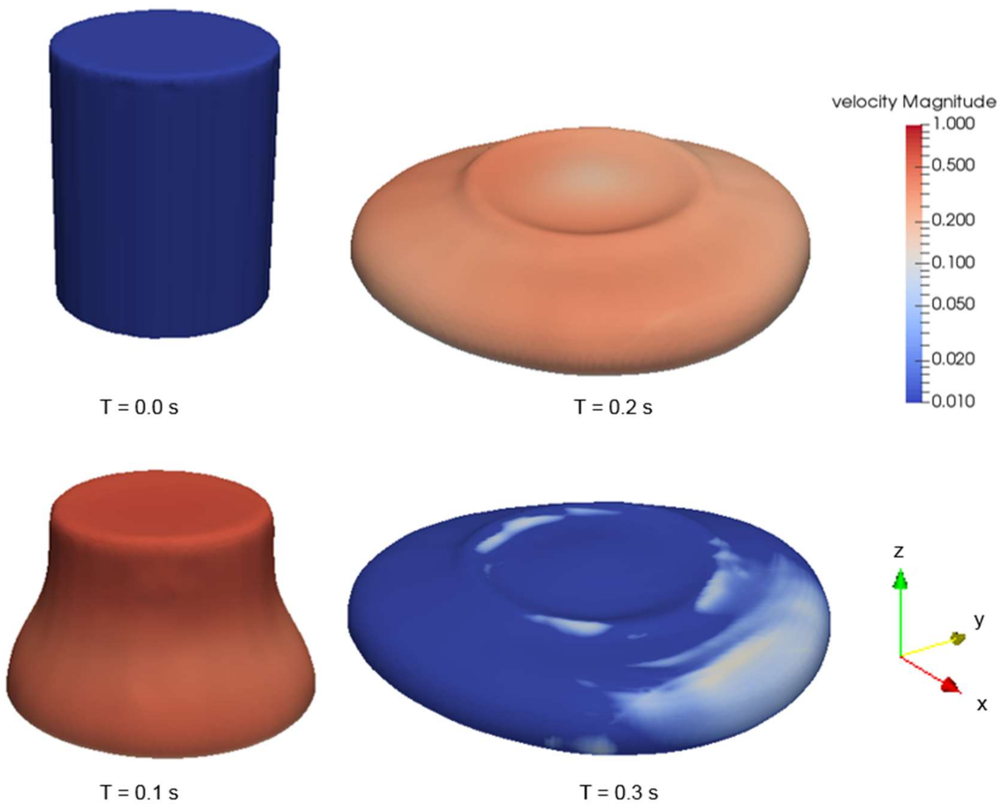

Figure 4. Simulation of quickness test, velocity contours during deformation from time T = 0.0-0.3 s.

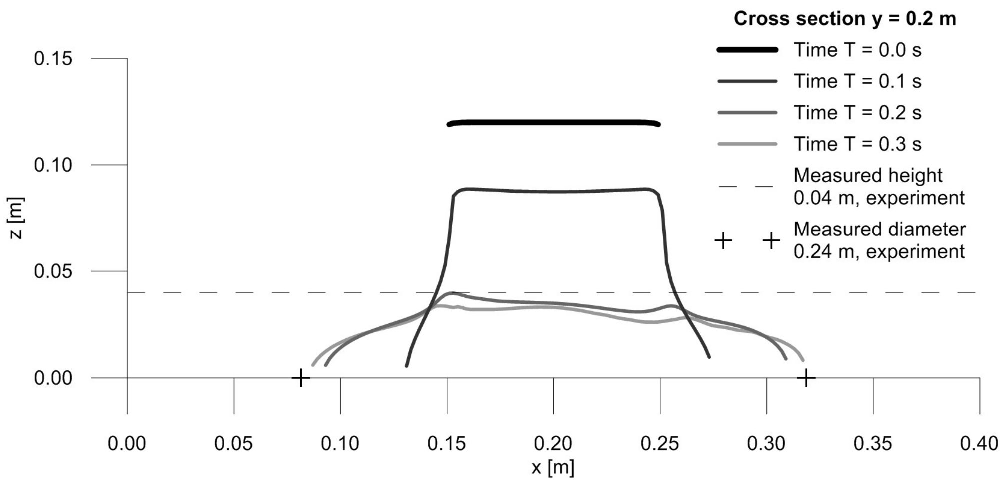

Figure 5. Simulated free surface elevation for the Herschel-Bulkley fluid at cross section y = 0.2 m (middle).

6 CONCLUSIONS

The implementation of the non-Newtonian Herchel-Bulkey rheology in the REEF3D open-source CFD code has been validated for laboratory experiments on remolded sensitive clay. This material can be described as a single-phase viscoplastic fluid for low remolded shear strengths. Despite some simplifications and assumptions, the flow behaviors observed in the laboratory was captured quite well in the numerical simulation.

With the current implementation, the yield stress is modeled as a very high viscosity for low shear rates. The deformation of a fluid modeled this way will finally slow down significantly, but never stop completely without resting with a level surface. To obtain a steady state solution where the material can stop with a sloped surface, the yield stress should be accounted for more realistically.

Although the Herschel-Bulkley rheology can be appropriate for the interstitial fluid of debris flows, a more advanced multiphase model is necessary for capturing full debris flow behavior using a continuum approach in CFD.

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