



26.11.2018

Interreg
Pohjoinen
Euroopan aluekehitysrahasto



RESEM – Remote sensing supporting surveillance and operation of mines

CFD modelling of thickened tailings

Final project report

Lic.Sc.(Tech.) Reeta Tolonen and Docent Esa Muurinen

University of Oulu

Environmental and Chemical Engineering



Contents

Contents	2
Introduction.....	3
Modelling.....	3
Rheology	3
Computational Fluid Dynamics (CFD).....	3
Simulations	3
Modelling case.....	3
Modelling methods	4
VOF Multiphase model.....	4
Herschel-Bulkley model for the viscosity	5
Boundary conditions.....	5
Modelling results.....	6
Summary and conclusions	11
References.....	12

Introduction

RESEM-project's research area was the remote sensing supporting surveillance and operation of mines, and it was funded by the Interreg Nord 2014-2020. In this project, the tailings dam modelling was carried out by different modelling methods, one of them being Computational Fluid Dynamics (CFD). The common goal in modelling was to increase the knowledge about how the different environmental factors effect on thickened tailings spreading and movement. With CFD modelling the aim of the research was to model thickened tailings behavior and spreading in tailings pond. Volume of Fluid (VOF) multiphase model was used to model the height and location of paste layer, and the non-newtonian behavior of the tailings paste was taken into account with the Herschel-Bulkley model for the viscosity. ANSYS Fluent 17.2 software was used in the simulations. CFD modelling described in this report was done during the time period 1.1.2017-30.6.2018.

Modelling

Rheology

Major components in mine tailings is the mixture of water and solid particles. Mine tailings can be called as slurry, paste or cake depending on the consistency of mixture. When water content reduces in tailings mixture, increases the solid material concentration, and this will cause greater shear strength at all shear rates. (Fitton & Jewell, 2015) Materials can be classified either to newtonian or to non-newtonian fluids. Concentrated mineral tailings often behave as non-newtonian fluids. Non-newtonian fluids have a yield stress and the fluid viscosity varies with shear rate. Empirical models can be used for different types of fluids, and the most common equations for non-newtonian fluids are Ostwald de Waele power law model, Bingham model and Herschel-Bulkley model. Herschel-Bulkley model is used either for yield stress and shear-thinning materials or to yield stress and shear-thickening materials. (Sofra, 2015) The Herschel-Bulkley model is:

$$\tau = \tau_{HB} + K\dot{\gamma}^n \quad (1)$$

where, τ is the shear stress, τ_{HB} the yield stress, K and n are experimentally determined constants and $\dot{\gamma}$ is the shear rate (Sofra, 2015). In this study the Herschel-Bulkley model is used as the modelling equation for paste behavior.

Computational Fluid Dynamics (CFD)

Physical aspects of fluid flow can be described with the basic principles: mass is conserved, Newton's 2nd second law (i.e. momentum is conserved) and energy is conserved. In computational fluid dynamics (CFD) these equations are solved to obtain numeric values for the flow field at discrete points (grid points) in the domain. Therefore, the accuracy of CFD solution is strongly influenced by the number of cells in the calculation mesh. (Anderson, 1995)

Simulations

Modelling case

In this research project CFD simulations were used to model the behavior and spreading of thickened tailings in tailings pond. Special interest in modelling was to study the paste accumulation and spreading right after the paste discharge. In the simulations, the modelling geometry was a cross-sectional surface of a tailings pond at the location of a paste discharge pipe. Modelling was done in a simplified 2-dimensional geometry because of the modelling object's (tailings pond) large size. Figure 1 shows the schematic drawing of the modelling domain.

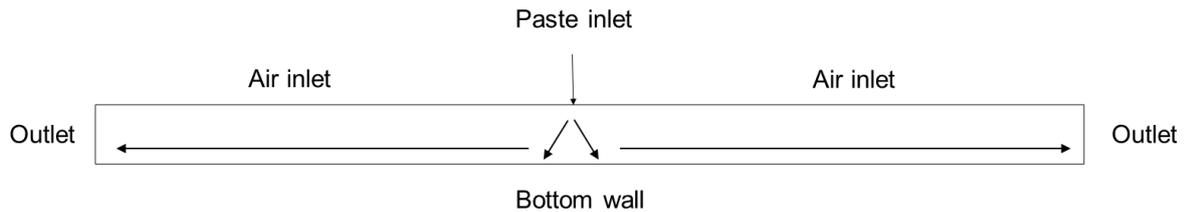


Figure 1. Schematic drawing of the modelling domain (not in scale).

Height of the modelling geometry was 1 meter and the total length of the geometry was 40 meters. Height of the modelling geometry was based on the approximation of the paste discharge pipe altitude. Length of the modelling geometry was evaluated based on the minimum free distance to all directions at the location of paste discharge pipe at real tailings pond. Paste inlet was located in the middle of the upper edge in the modelling geometry, and the diameter of the paste inlet was 0.12 meter. Modelling geometry was meshed with structured, tetrahedral mesh. Example of used the calculation mesh is presented in figure 2.

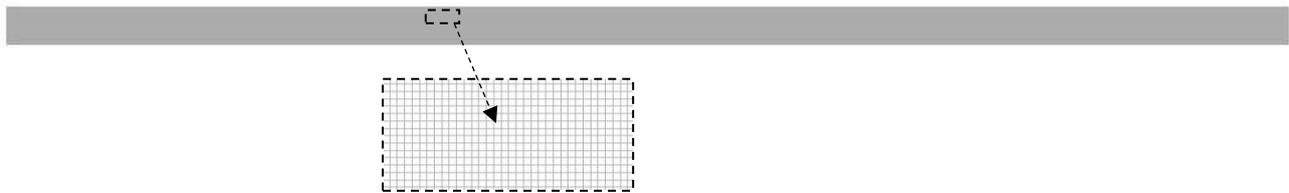


Figure 2. Calculation mesh used in the modelling, which contained tetrahedral cells.

In CFD modelling the commercial ANSYS Workbench and ANSYS Fluent softwares were used. ANSYS Workbench was used for the geometry and mesh generation. Numerical calculation and results plotting was done with ANSYS Fluent, version 17.2.

Modelling methods

VOF Multiphase model

Modelling case contained two different fluids, air and paste, and therefore in CFD modelling the multiphase model was needed. In ANSYS Fluent the VOF (Volume of Fluid) model is designed for cases where the position of the interface between the fluids is the modelling interest (ANSYS Fluent, 2016a). In this modelling case the interface between the paste and air was the particular interest in modelling, and therefore the VOF model was used in the CFD calculations. Modelling domain consisted of two separated fluids, paste and air, having free surface and a clear interphase. The aim of the CFD modelling was to study the filling of a tailings dam. Tailings dam filling is a time-dependent process by nature, therefore the VOF calculations were done as time-dependent cases.

Herschel-Bulkley model for the viscosity

In this modelling case the fluid viscosity was used to define the non-Newtonian behavior of paste. ANSYS Fluent provides different modelling options for the physical properties of non-newtonian fluids. In these simulations, the Herschel-Bulkley model for Bingham plastics was used to describe the viscosity of the paste.

With Bingham plastics when the strain rate is zero, equals the shear stress to non-zero value. In ANSYS Fluent the Herschel-Bulkley equation for viscosity is:

when $\dot{\gamma} > \dot{\gamma}_c$

$$\eta = \frac{\tau_0}{\dot{\gamma}} + k\dot{\gamma}^{n-1} \quad (2)$$

where $\dot{\gamma}$ is shear rate, $\dot{\gamma}_c$ critical shear rate, η viscosity, τ_0 yield stress threshold, k consistency index and n power-law index. (ANSYS Fluent, 2016b)

In the simulations presented in this report, the Herschel-Bulkley model for viscosity was used only as shear rate dependent, and not as shear rate and temperature dependent which was the other modelling option. Properties of the tailings paste used in the simulations, were based on the measurement data provided by the Water Resources and Environmental Engineering research unit, University of Oulu. Measurement data was given in four different temperatures (20°C, 10°C, 0°C and -5°C) and the Herschel-Bulkley model was fitted to these data sets with the help of Excel software. Parameters that Fluent software required for Herschel-Bulkley model of paste viscosity (consistency index, power-law index, yield stress threshold and critical shear rate) were obtained from model fitting and from experimental data. In modelling paste was treated as a dense uniform fluid, having a density of 1800 kg/m³. Material properties for air were obtained from the Fluent database.

Boundary conditions

At boundaries of modelling geometry, the pressure and the velocity inlets and the pressure outlets were used as boundary conditions. For air flow the pressure inlet and the open channel flow was used. Inflow of the paste was defined by the velocity inlet, and the inflow velocity of paste was set to 1.0 m/s. Pressure outlet boundary condition was used for outflow boundaries. Location of the boundaries can be seen from the figure 1 presented in previous page.

Modelling results

CFD modelling results describe the initial stage of the paste discharge and tailings dam filling process. Simulation results presented in this reports cover only limited 100 seconds time from the very beginning of the filling process. Figure 3 presents the paste volume fractions ($T=10^{\circ}\text{C}$) at times 25 s, 50 s, 75 s and 100 s.

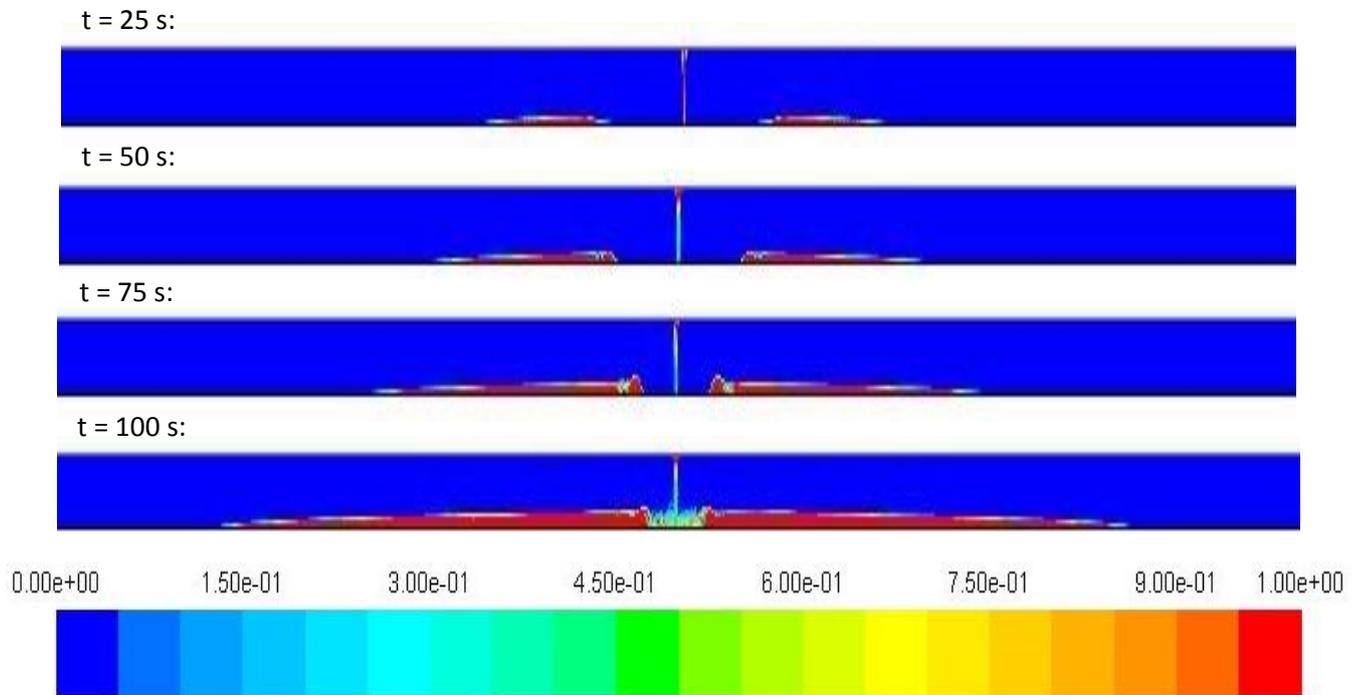


Figure 3. Contours of paste volume fraction at times 25 s, 50 s, 75 s and 100s, when $T = 10^{\circ}\text{C}$.

In figure 3 the areas colored with red are filled with paste and the blue areas contain air. In the middle of upper edge is the paste inflow where the paste was discharged to modelling geometry. At all time steps when the paste hit the bottom wall, the paste flow was divided symmetrically towards to outlets. When comparing these results, it can be seen that the paste flows towards the outflows and paste layer is also thickened towards the center of the geometry. Small paste ridges formed close to inflow, and after a certain time they collapsed. After this the paste layer profile was more uniform and paste moved a bit faster towards to outflows.

Figure 4 shows the velocity flow field at the corresponding times (25 s, 50 s, 75 s and 100 s) when the paste temperature was 10°C .

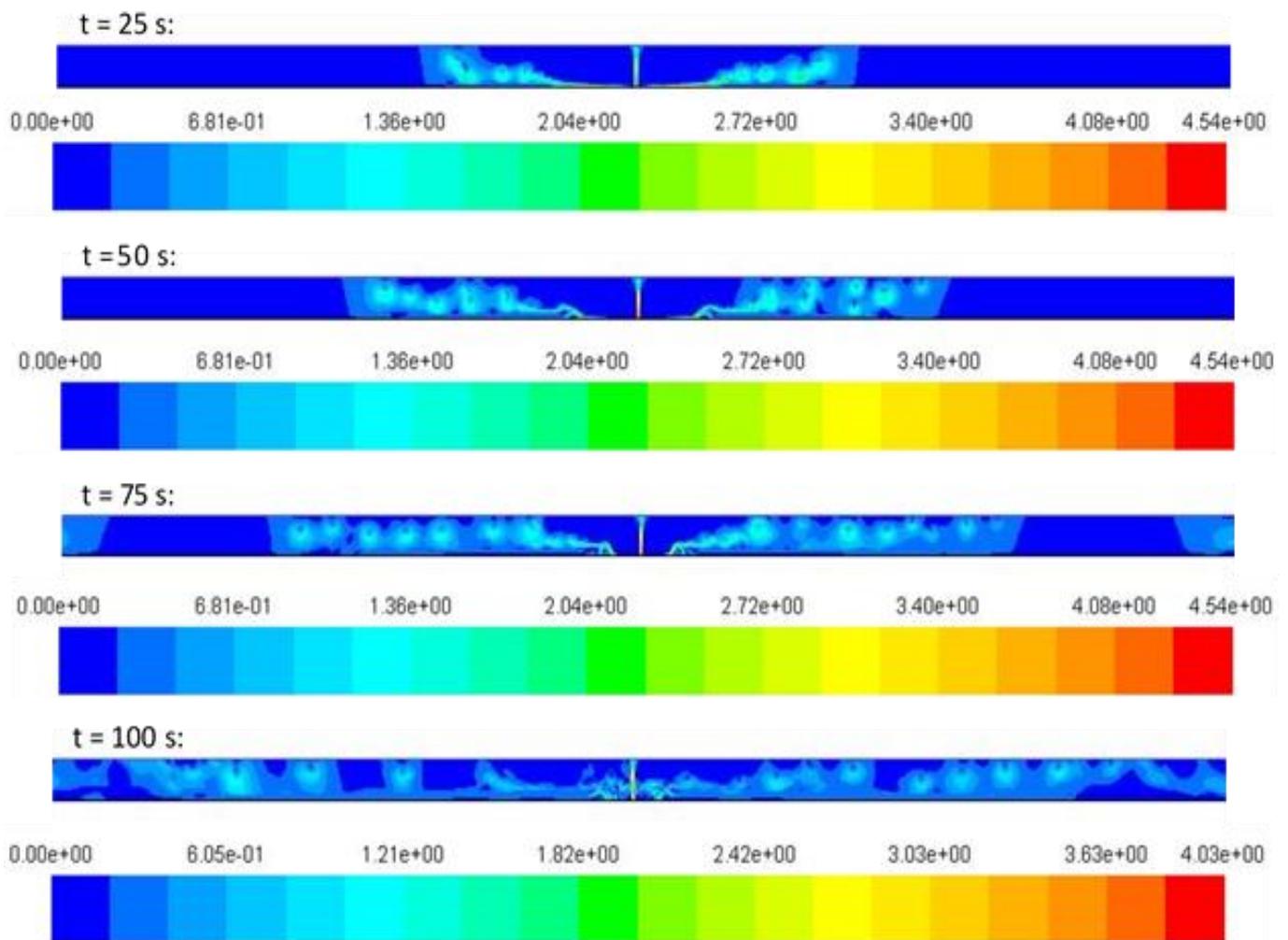


Figure 4. Contours of velocity magnitude (m/s) at the times 25 s, 50 s, 75 s and 100 s, when $T = 10^\circ\text{C}$.

Velocity magnitude (m/s) of mixture is presented above at different times. Colour scale changing from blue to red indicates the magnitude of velocity. Figure 4 shows clearly the vortices that the flowing paste induced to airflow. When comparing figure 4 to figure 3, a certain analogy can be seen between the distance of the paste flow and the vorticity of the airflow.

Modelling of paste behavior was done in different temperatures and figure 5 shows the volume fraction of paste at times 25 s, 50 s, 75 s and 100 s, when the paste temperature was 20°C .

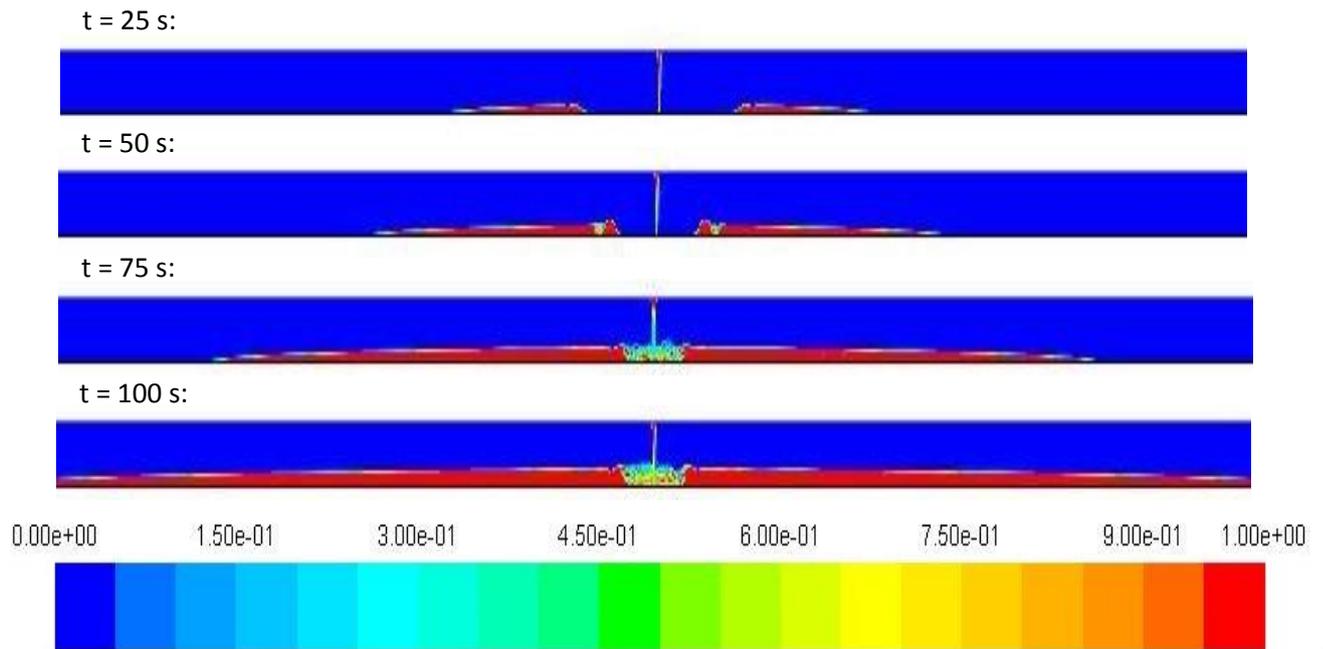


Figure 5. Contours of paste volume fraction at times 25 s, 50 s, 75 s and 100 s, when $T = 20^{\circ}\text{C}$.

Figure 5 shows the volume fraction of paste ($T = 20^{\circ}\text{C}$) by changing color scale from red to blue. Similar figure to paste at 10°C temperature was presented in figure 3, and the paste behaved a lot in the same way in both cases. However, the effect of the temperature to the modelling parameters can be seen in the modelled paste behavior. Biggest differences between figures 3 and 5 were at times 50 s and 75 s. Based on the modelling results the distance of the highest paste ridge to inflow at time 50 seconds was bigger at the lower temperature (10°C). It was also noticeable that according to modelling results the formed paste ridges collapsed earlier at the higher temperature (20°C).

More detailed comparison of the paste behavior can be seen in figures 6, 7 and 8, where the volume fraction of paste is presented in x-y-plots at temperatures of 10°C and 20°C . At the x-y-plots the x-axis is the volume fraction of paste and the y-axis is the position (height) at the modelling domain. Vertical planes for results plotting was drawn at different distances from the paste inlet, and the colored lines in figures 6-8 describe these.

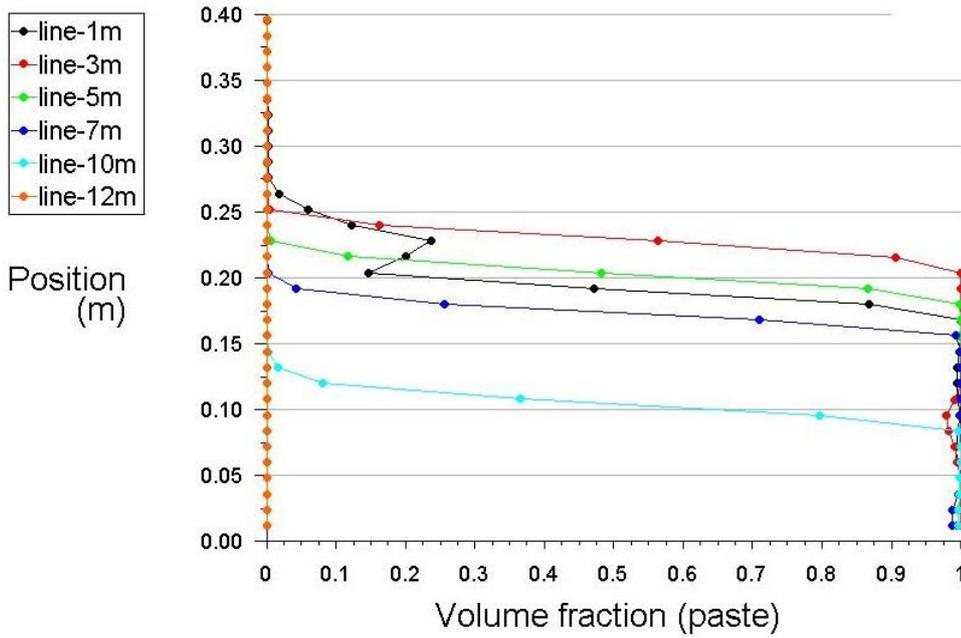


Figure 6. Volume fraction of paste at different distances from the inlet. Paste temperature is 10°C and simulated time 100 seconds.

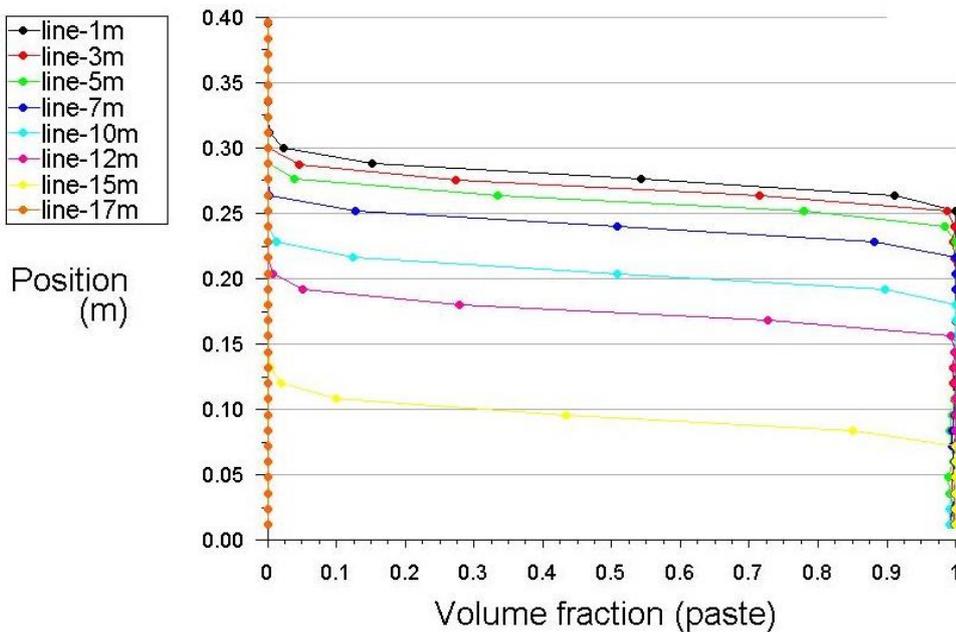


Figure 7. Volume fraction of paste at different distances from the inlet. Paste temperature is 20°C and simulated time 100 seconds.

In the simulations, the influence of temperature was taken into account in the Herschel-Bulkley model parameters for the paste viscosity. The effect of the model parameters to the simulation results can be seen from the figures 6-8. Figure 6 is presenting the volume fraction of paste at the distances of 1 m, 3 m, 5 m, 7 m, 10 m and 12 m from the paste inlet, when the temperature was 10°C and the simulated time 100 s. According to figure 6, during the 100 seconds simulation paste has reached the distance of 10 meters from the inlet, and at that distance there is a bit less than 0.1 m layer of paste.

When compared to results presented in figure 7, there were some differences in the simulation results. Figure 7 shows the volume fraction of paste at the distances of 1 m, 3 m, 5 m, 7 m, 10 m, 12 m, 15 m and 17 m from the paste inlet, when the temperature was 20°C and the simulated time 100 s. Figure 7 shows that the paste has proceeded further than in figure 6. In figure 7, the paste has already reached the distance of 15 meters during the simulated 100 s time, where the paste layer thickness is a little less than 0.1 m. According to results presented in figure 7, the thickness of paste layer at the distance of 10 m is almost twice as much as at temperature 20°C as it was at the temperature 10°C simulations (fig. 6). However, the distances that paste had proceeded during the 100 s simulations seems surprisingly long.

Figure 8 shows the paste volume fraction as a function of vertical position at the distances of 2 m, 5 m and 10 m from the paste inlet. Left-hand graph is for paste at 10°C and right-hand graph for paste at 20°C. Calculated time in both cases was 100 seconds.

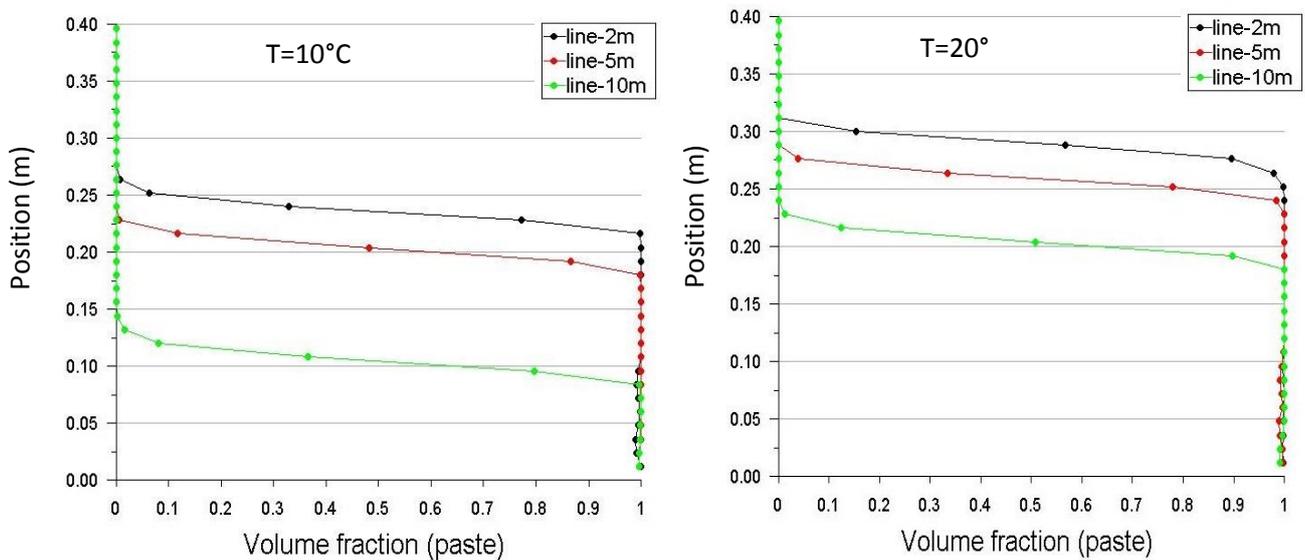


Figure 8. Volume fraction and height of the paste layer at different distances (2 m, 5 m and 10 m) from paste inlet. Left graph is for paste at 10°C and right graph for paste at 20°C (at time 100 seconds).

Figure 8 shows clearly the difference in modelling results at different temperatures, which was already discussed at the figures 6-7. Based on figure 8 certainly the thickest paste layer in both cases was at the distance of 2 m from the paste inlet. At the 2 m distance, the modelling results differed roughly 5 cm from each other. Simulations gave noticeable bigger difference at the distance of 10 m results, where the difference in paste layer thickness was approximately 10 cm. Simulation time was reasonably short (100 s) in the results presented here. Therefore, it would be beneficial to extend the simulation time to see the effect on the simulation results.

Also the velocity magnitude contours of mixture were compared at the temperatures of 10°C and 20°C. There were no remarkably differences in velocity fields when the results of different temperatures were compared at same times (25 s, 50 s, 75 s and 100 s). Properties of the airflow were not modelled as temperature dependent, so the airflow behaved rather similarly in both cases. Slight differences in velocity magnitude contours were probably due to differences that paste had proceeded in the geometry during the simulations.

Simulations for paste flow was also done at the temperatures of 0°C and -5°C, but these cases require still some further research and evaluation.

Summary and conclusions

In this research project the aim of the Computational Fluid Dynamics (CFD) modelling was to predict the paste behavior in tailings pond. Special interest in modelling was to study the paste accumulation and spreading right after the paste discharge. CFD modelling was done in a simplified 2D geometry describing the cross-sectional surface of a tailings pond at the location of a paste discharge pipe.

Volume of Fluid (VOF) multiphase model was used to model the height and location of paste layer, and the non-newtonian behavior of the paste was taken into account with the Herschel-Bulkley model. Determination of the Herschel-Bulkley model parameters was based on the experimental data of the paste properties at different temperatures. CFD modelling was carried out with the ANSYS Fluent 17.2 software.

CFD modelling results described the initial stage of the paste discharge and tailings dam filling processes. Simulation results covered only the time of 100 seconds from the very beginning of these processes. Simulation results were compared at the temperatures 10°C and 20°C. Simulations were also done at the temperatures of 0°C and -5°C, but these cases require still some further research and these results are not included in this report.

The effect of the temperature to modelling parameters was perceptible and it can be seen from the modelling results. CFD modelling results were analyzed mainly with the contour plots and the x-y –graphs. Modelling results showed differences in paste behavior as well as in paste accumulation at the temperatures of 10°C and 20°C. Comparison of the paste behavior was mainly done by the x-y –plots at the different distances of the paste inlet. These plots clearly pointed out the difference in modelling results at different temperatures. Simulated time in these studies was reasonable short (100 s), and it would be beneficial to extend the simulation time to see the longer time scale effect on the results.

CFD modelling is a useful method to study the behavior of paste and tailings dam dynamics. Simulations presented in this report were done by reasonable general CFD model, where not all the dependencies and fluid properties were taken into account, and still the simulations produced very interesting results. Therefore, the further model and parameter development and testing, as well as small-scale validation tests would give additional value and valuable data to CFD modelling. Combination of CFD modelling results with the results of other modelling methods used in this project could increase and deepen the knowledge of paste behavior, especially in longer time scale. Combination of CFD results with the results of e.g. remote sensing would be interesting, but this would require longer simulation runs to obtain longer term information about the paste behavior simulated by CFD. CFD modelling could also benefit from remote sensing in the form of validation data. CFD modelling proved to be a very useful tool also in tailings dam studies, although the large-scale CFD models can be computationally very expensive. This consideration needs to be taken into account in the design of CFD modelling regarding this type of modelling applications.

References

Fitton, T. & Jewell, R. (2015) The tailings continuum: Defining the Boundaries. In Jewell R.J. & Fourie A.B. (eds) Paste and Thickened Tailings – A Guide (pp. 10-17), 3rd edition. Australian Centre for Geomechanics, Australia.

Sofra F. (2015) Rheological Concepts. In Jewell R.J. & Fourie A.B. (eds) Paste and Thickened Tailings – A Guide (pp. 20-43), 3rd edition. Australian Centre for Geomechanics, Australia.

Anderson, J. D. Jr. (1995) Computational Fluid Dynamics: the Basics with Applications (547 p.). McGraw-Hill, New York.

ANSYS Fluent (2016a). ANSYS Fluent Theory Guide, Release 17.2 (812 p.). Ansys Inc., USA.

ANSYS Fluent (2016b). ANSYS Fluent User's Guide, Release 17.2 (2818 p.). Ansys Inc., USA.