XLI CILAMCE
XLI Ibero-Latin American Congress on Computational Methods in Engineering
16-19 November, 2020 FOZ DO IGUAÇU PARANÁ - BRAZIL

Numerical evaluation of clayey soil under jetting procedure using Lattice Boltzmann Method

Eduardo M. A. Pacheco, João P. L. Santos

Laboratory of Scientific Computing and Visualization, Federal University of Alagoas
Campus A. C. Simões, Tabuleiro dos Martins, 57072-900, Maceió, Alagoas, Brazil
eduardo.pacheco@lccv.ufal.br, jpls@lccv.ufal.br

Abstract. Offshore operations in deep and ultra-deepwater increasingly demand usage of different well construction methods. Regarding a well casing system, the conductor installation by jetting is one of the adopted techniques in top hole operations in these scenarios. In a deepwater environment, marine soil is cohesive, presenting mud characteristics and low shear strength. Consequently, from a mechanical perspective, those soils behave as a combination of an elastic solid and viscous fluid. Thus, the use of fluid rheology by Herschel Bulkley's constitutive equations to analyze it is a valid approach. Numerical modeling stands out as an interesting choice for analysis of jetting problems due to its accuracy and affordable cost of development in the design phase. The Present work investigates soil response under high shear rates from a vertical jet. The numerical simulations are performed based on the Lattice Boltzmann Method (LBM). We perform parametric analysis of rheological parameters of the soil as yielding viscosity and yield stress. Results show that soil behaves in an increasingly structured way by increasing the values for the yield stress and the yielding viscosity, demanding higher jet speeds or longer jetting time in order to drill larger depths.

Keywords: Conductor jetting, Clayey Soil, Lattice Boltzmann, Computational Fluid Dynamics, Oil and Gas.

1 Introduction

With offshore exploration in deepwater regions, the need for different methods of well drilling has increased. Among the stages of drilling is the well top-hole phase, in which the conductor is settled. This casing is the foundation for the other casings and the wellhead equipment. One of the most common methods of installing the conductor casing is jetting. This technique is carried out on soils with low structural resistance [1].

In ultra-deepwater, the soil is predominantly clayey, like a fine mud and has little resistance to shearing. Although initially static, the soil begins to drain when the applied load exceeds its yield stress. At this moment, it starts to behave like a highly viscous fluid [2] and this behavior is understood as viscoplastic flow. This was verified by Vyalov [3], who carried out experimental tests in the relations between the shear stress and the strain rate of various clay soils.

This work investigated the reactions of the marine soil suffering jet deformation, using the Lattice-Boltzmann Method to develop the flow calculations. To validate the model, information available in the literature was used.

1.1 State of art

The most suitable way to analyze the soil of a region is describing it in similar conditions to those seen empirically [4]. Some works in literature adopt the fluid approach of clay soil for landslides or for excavations in marine environments. The velocity of the jetted fluid is a determining factor in the depths and widths reached by the borehole, as described by Zhou et al. [5]. In the study, the authors calculated a minimum velocity to be reached for the most effective jet.

Wang and Li [2] used ANSYS Fluent Computational Fluid Dynamic (CFD) software and discussed how the range of certain characteristics affects the soil response. The authors evaluated the velocity of the jet beyond its relative height by treating the soil as a Herschel-Bulkley fluid and by studying the influence of its rheological parameters on the jetting.

Melo [4] analyzed the behavior of clayey soils in different situations approaching them as viscoplastic fluids. The author performed experimental analyses of clay samples from landslides in the mountainous region of Rio de Janeiro, used rheological models to approximate the results obtained and concluded that the soil is well represented by the Herschel-Bulkley model.

2 Methodology

The model and numerical simulations were performed in the CFD software XFlow© 2020 (Dassault Système), which uses the Lattice-Boltzmann method to develop the calculations. The methodology of this work is summarized in Figure 1, where the main steps are listed.

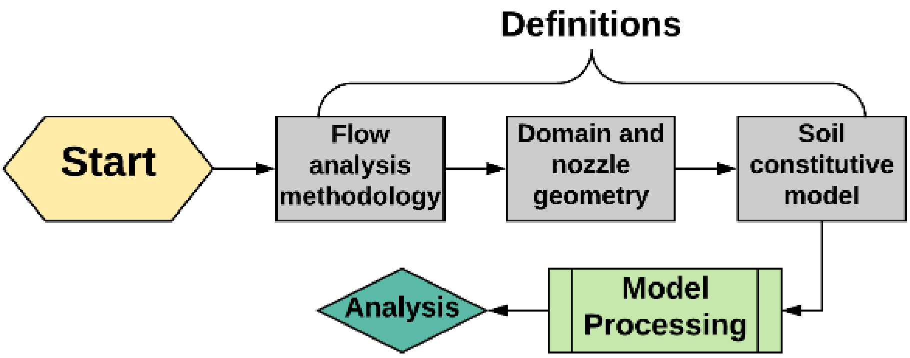

Figure 1. Process flowchart

The process consists of three stages: pre-processing (where the ambient conditions, geometry, soil and jet parameters are defined), processing (with lattice points construction and solution computing), and post-processing (where the qualitative and quantitative results are analyzed). During the displacement of the ground surface in the jetting, there is contact between two fluids, which characterizes multiphase flow. The Volume of Fluid (VoF) approach tracks the volume at the points of the network and is the most suitable for the scale of this study. Besides, the Wall-Adapting Local Eddy turbulence model is the most suitable for this domain.

2.1 Mathematical modelling

In LBM there is no direct discretization of traditional fluid mechanics equations, so it is not directly associated to Navier Stokes equations. The material is represented as a set of particles that move carrying their properties and employing statistical tools. The method has four main elements: the reticulate, its distribution function, the kinetic operator of collision and the equilibrium distribution function [6].

According to Krüger et al. [7], in the distribution function, the particle set f_i moves from a node to the adjacent at $\vec{x} + \vec{e}_i\Delta t$ in a time step $t + \Delta t$, then the original particle and the new particle interact and change their directions according to the collision operator Ω_i and the equilibrium distribution function f_i^{eq}. The external force F_i is stored according to eq. (1):

$$f_i(\vec{x} + \vec{e}_i\Delta t, t + \Delta t) - f_i(\vec{x}, t) = \Omega_i[f_i(\vec{x}, t) - f_i^{eq}(\vec{x}, t)]\ (\vec{x}, t)] + F_i\Delta t. \quad (1)$$

2.2 Soil constitutive model

Undrained clayey soil characteristics defined in this work approaches the behavior of a Herschel-Bulkley fluid, that combines power law fluid characteristics with Bingham's plastic. The Herschel-Bulkley model can be represented by eq. (2), where τ and γ are shear stress and shear rate, respectively; τ_0 is the yield stress, K the consistency index, and n the flow index:

$$\tau = \tau_0 + K \cdot \gamma^n, \ \tau > \tau_0. \tag{2}$$

The Herschel Bulkley model does not deal well with low shear rates ($\gamma \to 0$) since viscosity (τ/γ) tends to infinity, the so-called hard stress zones [8]. To solve such discontinuities, some modifications were proposed, among them the modified Herschel Bulkley model (eq. 3) which includes yielding viscosity (μ_0). μ_0 can be observed experimentally, tangent to flow curve at the yielding point [9].

$$\tau = \tau_0 + K \cdot [\gamma^n - (\tau_0/\mu_0)^n], \ \tau > \tau_0. \tag{3}$$

2.3 Domain and nozzle geometry

The nozzle geometry (Figure 2) consists of a cylinder with a 2 cm radius 20 cm above soil [10]. At bottom of the nozzle, a fluid outlet boundary was determined with water. The nozzle's fluid output velocity was defined as 30 m/s [2]. Soil is composed of an extremely high viscosity YPL fluid.

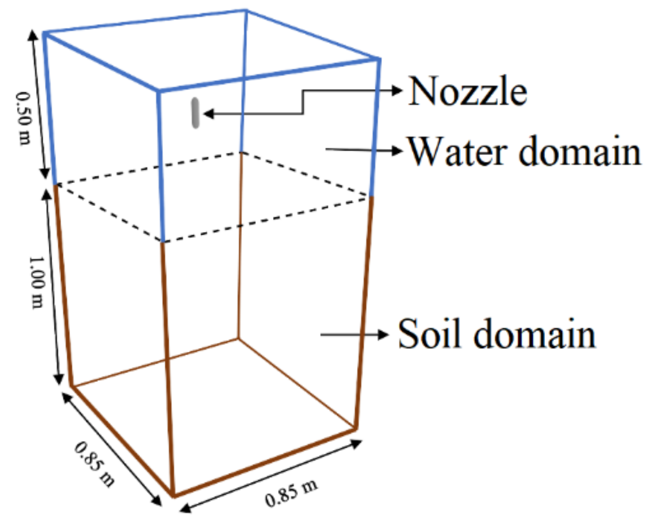

Figure 2. Nozzle and domains with dimensions

3 Results and Discussion

The feasibility of the jetting is governed by its ability to overcome the resistance of soil and thus excavate it. μ_0 is the slope of the flow curve at the point of yield stress. Thus, as described by Qiu and Han [9], there is a relationship between yield stress (τ_0) and yielding viscosity (μ_0) which will depend on the material (in this case the clay composition) and its humidity. Thus, studies on influence of this proportion have been performed.

In order to analyze the behavior of the soil through the variation of μ_0, the analyses were made as percentages of τ_0 and the studied values are shown in the Tab. 1 while the jetted fluid is water with a density equal to 1000 kg/m^3 and viscosity 8.9 e^{-3} $Pa \cdot s$.

Table 1. Soil analysis paramaters

Parameters	Soil
Density (kg/m^3)	2300
Consistency index ($kPa \cdot s^n$)	216.69
Yield stress (kPa)	30
Flow index (-)	0.1
Yielding viscosity (-)	75%, 90%, 100%, 150%, 200%

While yield stress controls the stress required to enable flow, yielding viscosity determines viscosity, i.e. how the material flows after the irreversibility of flow. The proportional increase in yielding viscosity leads to greater soil resistance resulting in lower depths as noticed in Fig. 3. The variation in the depths achieved indicates that yielding viscosity controls considerably the resistance of the soil. It is also possible to notice two distinct phases, where the control factors are different: The widening phase by direct contact with the jet and the widening phase by recirculation fluid.

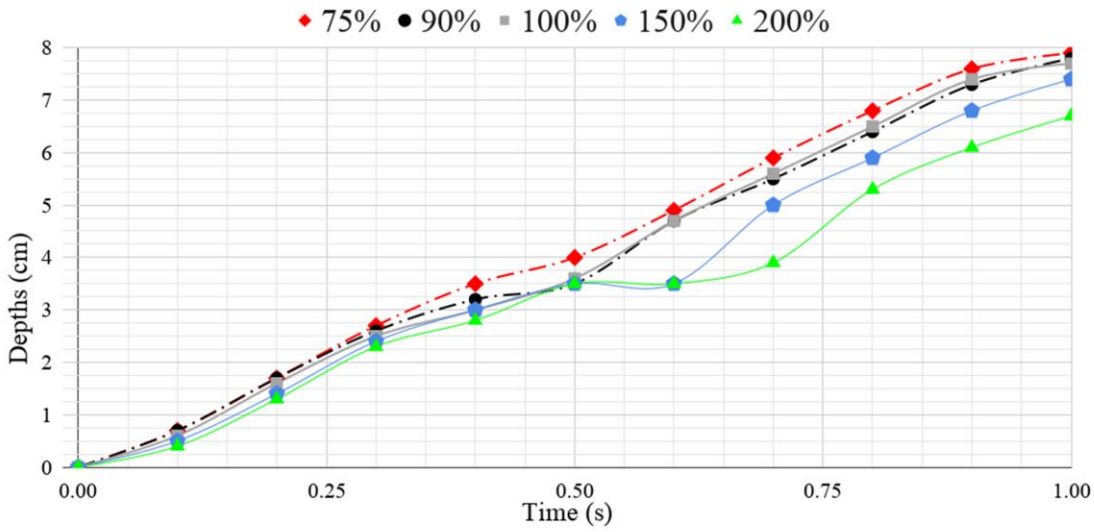

Figure 3. Depths Achieved

In the contact phase, the well lateral excavation is dominated by carrying the soil through direct contact with the jet, where the velocities of the jetting fluid are higher and a large hole diameter gain in a short time. The recirculation phase is dominated by carrying the soil through the re-circulating fluid inside the hole, less energetic and with less erosion capacity, resulting in a slower enlargement.

The fluid-dynamic approach of the soil favors the modeling of the excavation since it allows the complete movement of the particles. The rheology provides parameters that, if well defined, can represent from Newtonian fluids to clayey soils with the most varied humidities. While the consistency index (K) is a representation of viscosity, i.e., the resistance of the fluid to the flow itself, the yield stress (τ_0) indicates the minimum stress required for irreversible soil movement. With these parameters, it is possible to represent a part of the soil behavior, but it is not feasible for structural representations, where a solid approach is more indicated.

It was possible to identify other patterns in the training stage of the model, with variations of parameters such as consistency index (K) and density (ρ). As expected, the effect of the consistency index is like the effect of yielding viscosity, in terms of limiting soil flow after the impact of the jet. As it is an analogous parameter to viscosity (of Newtonian fluids), representing the slope of the flow curve, the soil resistance is directly proportional to the consistency index (as demonstrated by Wang and Song [10]). The density, on the other hand, has less significant effect, influencing only when at densities closer to those of jetted water.

Two phases of soil jetting were identified: a first phase with faster excavation and subsequent stabilization and a second phase with greater water recirculation (measured in post processing by increased vorticity) caused by deceleration. This vorticity increases, according to preliminary studies, with the growth of yield stress (τ_0).

4 Conclusions

The objective of this work is to study the excavation of the soil under a vertical jetting. There is a lack of studies focusing on soil dynamics at this stage with very little detail on the mechanics of the process. With numerical modeling, it is possible to measure complex behaviors qualitatively and quantitatively. The vorticity of the second stage of jetting is hardly noticeable in empirical studies and it is difficult to quantify the dimensions of the hole formed without computational aids.

The models were developed through a completely CFD approach using the Lattice Boltzmann Method successfully. Good conclusions were reached on the effect of the yielding viscosity parameter on the modified Herschel Bulkley equation. It was determined that the yielding viscosity is the soil parameter that controls the depth reached in relation to a jet with the same speed on all tests and that the characterization of the soils tends to be accurate with values above 100% of yield stress. The installation of the conductor casing takes place with oblique jets close to the pipe. The complexity of this structural interaction should be a step further to the work performed, as well as further parametric analyses.

Acknowledgements. The authors would like to thank Petrobras for the support given in the execution of this work.

Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

References

[1] Malouf, L. R. Drilling operations analysis on onshore and offshore wells. Graduation project, Federal University of Rio de Janeiro, 2013. [In Portuguese]

[2] Wang, T. and Li, H. "Numerical simulation of jet excavation in conductor jetting operations". *Offshore Technology Conference-Asia*. 25-28 March, Kuala Lumpur, Malaysia, 2014.

[3] Vyalov, S. S. *Rheological fundamentals of soil mechanics.* Elsevier, Amsterdan, 1986.

[4] Melo, D. F. M. Rheological behavior of soils subjected to mud run by static liquefaction. Graduation project, Federal University of São Paulo, 2014.

[5] Zhou, B., et al. "Model and experimental study on jetting flow rate for installing surface conductor in deep-water". *Applied Ocean Research*, vol. 60, pp. 155-163, 2016.

[6] He, X. and Luo, L. S. "A prior deviation of the lattice Boltzmann equation". *Physical Review E*, vol. 55, n. 6, 1997.

[7] Krüger, T., et al. *The Lattice Boltzmann method: Principles and Practice*. Springer, New York, USA, 2017.

[8] Soto, H. P. Modeling and simulation via Galerkin minimal-square multibody formulations of Bingham's inertial fluid flows. PhD thesis, Federal University Fluminense, 2010. [In Portuguese]

[9] Qiu, L. C. and Han, Y. "3D simulation of self-compacting concrete flow based on MRT-LBM". *Advances in Materials Science and Engineering*, 2018.

[10] Wang, T. and Song, B. "Study on deepwater conductor jet excavation mechanism in cohesive soil". *Applied Ocean Research*, vol. 82, pp. 225-235, 2019.