NUMERICAL SIMULATION OF JET EXCAVATION IN CONDUCTOR JETTING OPERATIONS IN SUBMARINE SOIL: MESH ANALYSIS

a Galindo, D. C.; a Tenório, M. S. C.; b Gomes, A. F. C.; a Marinho, J. L. G.;
   b Barboza, B. R.; a Oliveira, L. M. T. M.; a Santos, J. P. L.

a Federal University of Alagoas, Technology Center, Maceió – AL, Brazil
b Federal University of Alagoas, Scientific Computation and Visualization Laboratory, Maceió – AL, Brazil

Received: 18.08.2021 / Revised: 26.11.2021 / Accepted: 27.11.2021 / Published on line: 05.01.2022

ABSTRACT

The more complex exploration techniques and operations in deepwater environment are, the higher become the financial costs involved in the process. The rent of an offshore rig, for instance, can cost hundreds of thousands of dollars per day. Therefore, improving deepwater drilling efficiency can lead to significant cost savings. The drilling process of an oil well starts with the initial drilling, which is the operation to accommodate the conductor casing. Among the techniques to set the conductor casing, jetting operations have become popular in submarine environments where the seafloor sediments allow the technique to be used. In these environments, the submarine soil consists of a deformable body displaying a behavior that falls between a linear elastic solid and viscous fluid. Therefore, its behavior is governed by general theory of rheology, and it can be described as highly viscous non-Newtonian fluid. Despite the lack of comprehensive investigations, promising works can be carried out by considering cohesive soil behavior as viscous fluid. Problems of this type can be solved using computational fluid dynamics (CFD), a powerful software which solves complex fluid mechanics equations. Thus, this work numerically evaluates the excavation mechanism in conductor jetting operations in submarine soil during the first 30 seconds of examination, considering soil as viscous fluid of Herschel-Bulkley. Ansys Fluent®, which is a CDF software based on the finite-volume method, was applied to simulate the jetting excavation process. The results indicate that all meshes generated in the development of this work have an excellent quality, and they also show that the greater the mesh refinement is, the higher the accuracy and robustness of the model will be. However, the computational cost to simulate the model increases exponentially with the increase in number of elements, highlighting the importance of properly balancing mesh refinement and computational effort. When analyzing the results, we could also identify the excavation profile made by the bit jet, which presented an almost symmetrical shape.

KEYWORDS

drilling; conductor casing; Computational Fluid Dynamics; ANSYS Fluent; soil as viscous fluid

1 To whom all correspondence should be addressed.
   Address: Universidade Federal de Alagoas, Centro de Tecnologia, Av. Lourival Melo Mota – Cidade Universitária, Maceió – AL, Brasil
   ZIP Code: 57072.900 | Phone: +55 21 82 3214-1292 | e-mail: davisson.galindo@ctec.ufal.br
   doi:10.5419/bjpg2021-0010
1. INTRODUCTION

In the past decades, there has been a need to expand oil exploration into more challenging environments, as the demand for oil and its derivatives has increased. In Brazil, offshore exploration began in the 1970s and, over the years, drilling has spread away from the coast. In 2019, oil and gas production reached 3 million barrels, coming mostly from deepwater (ANP 2021; Petrobras, 2019; Thomas, 2004).

This deepwater production led Brazil to become self-sufficient in crude oil. Capital investments in research and development allowed the industry to better understand the influence of the marine environment (such as wave, wind, and sea current) on offshore structures, as well as to improve drilling and exploration techniques to minimize costs and drilling time (Albuquerque, 2019; Petrobras, 2019). According to Malouf (2013), the cost to run operations of a drilling rig at sea can reach hundreds of thousands dollars a day.

In offshore drilling, it is quite common to find seabed sediments in a type of fine mud, which has poor diagenesis and little formation strength. Due to these characteristics, it is fairly common to use the jetting technique for initial drilling in this environment. The technique consists of using a drill bit to circulate fluids with the goal of removing sediments and allowing the conductor casing to penetrate the soil. This technique is usually faster if compared to historical method of drilling a borehole and, then, cementing the casing in place (Akers, 2006; Kan, 2018; Malouf, 2013; Wang & Li, 2014).

According to Wang and Li (2014), the subsea soil is a deformable body, with behavior that ranges between linear elastic solid and viscous fluid, and it can be governed by the general theory of rheology. Boukpeti (2012) and Zhou and Randolph (2011) stated that due to the high shear rate caused by jet pressure, the seafloor can be described as a highly viscous non-Newtonian fluid. Thus, the soil starts flowing only when the applied stress exceeds the yield stress; before this point, it behaves as a solid, which is a typical characteristic of viscoplastic fluids (Wang & Li, 2014; Wang & Song 2018).

According to Gomes (2019), computational fluid dynamics (Computational Fluid Dynamics - CFD) becomes a powerful tool to simulate flow problems with more than one fluid phase, such as the case of the jet and the seabed. The software uses mass and momentum balances through the finite volume method to solve transport phenomena equations when the seabed is also considered as a fluid. Furthermore, the mesh quality plays an important role in obtaining reliable and accurate results. A poor mesh quality can lead to convergence difficulties and poor description of the physical problem.

The present paper aims to evaluate the influence of mesh refinement in marine soil behavior when it is modeled as a viscoplastic fluid, under incidence of bit jets, in jetting operations using a computational fluid dynamics software. We also examined mesh quality and the profile of the excavated soil.

2. METHODOLOGY

We used the software ANSYS® Fluent 2021 R1 for modeling the problem of this work. The CFD program is based on finite volume method, which consists of dividing the computational domain into control volumes, and integrating temporally and spatially each transport equation in each control volume (Fejoli, 2016). All simulations were performed on a computer with an Inter Core i5-9600k processor, with 8 cores, 16 processors and 16 gb RAM.

The problem of this study consists in considering the first few seconds of initial drilling on seabed by conductor jetting, since this operation for deepwater environments is quite common and even a preferred installation method because the seafloor sediments allows this technique to be used (Akers, 2006; Wang & Song, 2018).

Subsea soil is a deformable body that behaves as a linear elastic solid and a viscous liquid, and it can be described by the general theory of rheology. Thus, the soil initiates its flow only when the applied stress surpasses the yield stress. After that point, the soil flows similarly to a highly viscous non-Newtonian fluid and, consequently, its behavior can be described based on fluid mechanics (Zhou & Randolph, 2011; Wang & Li, 2014; Wang & Song, 2018).
2.1 Geometry and domain definition

As the intention of this work is to evaluate the influence of the jet at the beginning of the process near the seafloor, we considered that there was a distance of 20 cm between the drill bit and the mudline. The domain, shown in Figure 1, has 5 meters width by 5 meters height, in which 3 meters is equivalent to the soil domain height. The conductor has 36'' diameter and 1.5'' thickness, and the drill string has 5'' diameter, as described by Akers (2006).

The configuration of the drill bit can be seen in Figure 2. We chose the 17 1/2'' diameter because it is used commonly in this type of operation, according to Akers (2006) and Kan (2018). The selection of 20° for the nozzle inclination with 2 cm diameter and height was based on the studies of Wang & Song (2018). We also considered that the drill bit has a 10 cm height. All geometries in this work were prepared using the SpaceClaim application from Ansys® package.
To generate the numerical meshes, we used the Meshing application from the Ansys® package, as depicted in Figure 3. We imposed maximum element size limits seeking a balance between the number of elements and computational cost.

### 2.2 Mathematical modeling

The equations used to solve the proposed model are described in the following topics.

#### 2.2.1 Mass and momentum conservation equations

The mass and momentum conservation equations describe the behavior of the fluid and are given in Equations 1 and 2.

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \tag{1}
\]

\[
\rho \frac{\partial \vec{v}}{\partial t} + \nabla \cdot [\rho (\vec{v} - \vec{v}_m) \vec{v}] = -\nabla p + \mu \nabla^2 \vec{v} + \rho \vec{g} + \vec{F}_o \tag{2}
\]

where \(\frac{\partial \rho}{\partial t}\) is related to fluid compressibility, \(\vec{v}\) is the velocity vector, \(\frac{\partial \vec{v}}{\partial t}\) is the acceleration, the term \(\nabla \cdot [\rho (\vec{v} - \vec{v}_m) \vec{v}]\) is related to convective acceleration, \(\nabla p\) is the pressure gradient, \(\mu \nabla^2 \vec{v}\) is the viscous term, \(\rho \vec{g}\) is related to the gravitational, and \(\vec{F}_o\) is related to interfacial forces.

#### 2.2.2 Fluid interface model

The VOF (volume of fluid) method, developed by Hirt & Nichols (1981), allows modeling two or more immiscible fluids by solving a single set of equations of mass conservation and linear momentum, obtaining the volume fraction of each phase throughout the domain, and predicting each position of the interface between the fluids. According to the authors, the major advantage of this method is that it tracks regions instead of surfaces, avoiding logical problems caused by intersecting surfaces, and providing a simple and economical way to locate free boundaries on 2D and 3D meshes. This method is based on the use of an auxiliary variable, called volumetric fraction \(\alpha_i\), which identifies the calculation region where each phase can be found. Thus, the volumetric fraction of \(i\) is defined as: \(\alpha_i = 0\) when there is no fluid \(i\) in the region; \(\alpha_i = 1\) when there is only fluid \(i\); and
0 < α_i < 1 in the interface region. Consequently, the sum of the saturations of each phase must be equal to 1. Figure 4 shows the situation described by the VOF method, for a case of water-soil interaction, in which the soil volume fraction α_1 is shown in each control volume, where the higher the shade of blue is, the higher the soil volume fraction is. The interface between soil and water is represented by the red line.

According to Fejoli (2016), the VOF model can also include the effects of interfacial tension along the interface between the phases. In this work, we adopted the Continuum Surface Force (CSF) model, widely used in engineering problems. This model feeds the interfacial tension term (F_σ) in Equation 2. Hence, this model assumes that the interfacial tension is constant along the interface and only the normal force acts on it.

We adopted CICSAM (compressive interface capturing scheme for arbitrary) as interface discretization scheme, a high-resolution differencing scheme developed by Ubbink (1997). It is indicated for flows with high viscosity ratios between the phases, as is the case of soil phase and water phase.

2.2.3 Turbulence model

In conductor jetting, the jet can reach high Reynolds numbers (which relates inertial and viscous forces) depending on the velocity. We adopted the κ − ε RNG turbulence model, often used in CFD techniques to simulate and achieve average turbulent flow characteristics due to its robustness, economy in calculations, and accuracy (Wang & Li, 2014; Wang & Song, 2018). Derived from a statistical technique called “Renormalization Group Theory,” it allows the Prandtl numbers of turbulent kinetic energy (κ) and its dissipation rate (ε) to be determined through algebraic relationships.

2.2.4 Soil modeling: Herschel-Bulkley model

While the fluid behaves like a Newtonian fluid, that is, there is a linear relationship between stress and shear rate, and its viscosity is constant, the proposed soil model behaves like a non-Newtonian viscoplastic Herschel-Bulkley fluid, represented by Equation 3.

\[ \tau = \tau_0 + k(\dot{\gamma})^n \]  

where \( \tau \) is shear strength, \( \tau_0 \) is the yield stress, \( k \) is the consistency factor, \( \dot{\gamma} \) is the strain rate, and \( n \) is the power-law index.

2.2.5 Simplification hypotheses

Some assumptions were applied in the mathematical model to save computational resources, avoid unrelated complexities to the proposed work, and ensure a good cost-benefit ratio between computational effort and results.
Negligible temperature change:

Since the case under analysis is in a well-defined region, with low temperature variation, considering the simulation as isothermal is a reasonable simplification, as the energy transfer equations in the form of heat would increase the demand for computational effort.

No chemical reactions:

Since the focus of this work is not on chemical interaction between the drilling fluid and the surrounding materials, but a rather physical interaction, and considering that chemical reactions would increase the complexity of the mathematical model, we decided to ignore them.

Constant drilling fluid and soil properties:

Both the drilling fluid and submarine soil were considered to be a homogeneous and isotropic material, with no changes in rheological and physical properties.

2.2.6 Boundary conditions

We assumed the velocity profile of the jet in the drill nozzles to be uniform and the reference pressure in fluid outlet condition in the upper part of the domain to be zero.

We admitted a no-slip wall condition, to have a zero relative velocity between the fluid and the wall.

All simulations were performed in the transient flow, and we simulated 30 seconds of each case with a 0.003 second time step. The simulations took, on average, three hours to run.

2.3 Fluid and soil properties

For the proposed model, we considered a clayey soil with characteristics similar to those found in marine soil with rheological data taken from the studies of Wang and Song (2018). The soil is modeled as a Herschel-Bulkley viscoplastic fluid (Equation 3), being possible to describe the behavior of the soil as an elastic rigid body until the yield stress is reached. After this point, the soil behaves as a viscous fluid. Table 1 shows the Herschel-Bulkley parameters that represent the cohesive soil in this work.

Seawater was adopted as drilling fluid because it is widely used in such operations due being of low cost and abundant. The parameters used to represent seawater behaving as a Newtonian fluid are shown in Table 2.

2.4 Mesh quality and convergence test

In this model, we considered a 17 1/2” drill bit and nozzles with 20° inclination that are jetting seawater at a velocity of 20 m/s (approximately 400 gpm), which it is compatible with the volumetric flow rate pointed out by Akers (2006) considering that the drill bit has 4 nozzles. For this case, we also assumed that there is no relative displacement between the drill and the conductor casing: bit stick-out = 0 cm.

The mesh represents the connection between the subdivided elements, so its efficiency depends

| Table 1. Soil parameters. |
|---------------------------|
| \( \rho \) (kg/m\(^3\)) | \( \tau_0 \) (kPa) | \( k \) (Pa.s) | \( n \) |
|---------------------------|
| 1750.0                    | 40.0               | 18831.3        | 0.09983   |

Source: Wang & Song (2018); Gomes et al. (2020)

| Table 2. Seawater parameters. |
|-----------------------------|
| \( \rho \) (kg/m\(^3\)) | \( \mu \) (Pa.s) |
|-----------------------------|
| 1021.0                      | 0.001             |

Source: Talley et al. (2011)
on its refinement. The mesh quality plays an important role in the accuracy and stability of the numerical simulation, because a mesh with poor quality can lead to convergence difficulties and a misdescription of the physical problem. Within the main attributes associated with mesh quality in Ansys Fluent® are: element quality, aspect ratio, skewness, and orthogonal quality. Each element brings details about the mesh quality by observing a certain aspect, as follows:

- **Element Quality**: gives a metric quality of the element by means of the ratio between the area of the element and the sum of its squared sides. The result of this metric ranges between 0 and 1, where 1 indicates a perfect square/cube.

- **Aspect ratio**: measures the elongation of a cell/surface by means of the ratio between the largest and smallest element edge. The closer the element aspect ratio is to 1, the better the mesh quality. High aspect ratio values can lead to errors in numerical approximation.

- **Skewness**: indicates how close to an ideal surface/cell is the element. The result ranges between 0 and 1, and the closer to 0 this parameter is, the better.

- **Orthogonal quality**: involves the angle between the vector that joins two mesh (or control volume) nodes and the normal vector for each integration point surface associated with that edge. The scale of this parameter also varies from 0 to 1, but the closer it is to 1, the better the quality of the mesh is.

A mesh convergence study was performed. The study consisted of simulating the case until no significant differences in the values of the analyzed variables were found. The parameter used to refine the mesh was the size of each element. Following, we analyzed nine different meshes of the unstructured type to perform the convergence test with a higher density of elements in the drill region, ensuring a better accuracy of the results. The sizes considered in this test are shown in Table 3.

### Table 3. Different mesh element sizes.

| Element size (cm) | Elements | Nodes  |
|-------------------|----------|--------|
| Mesh 1            | 6.0      | 7387   |
| Mesh 2            | 5.0      | 10397  |
| Mesh 3            | 4.0      | 16073  |
| Mesh 4            | 3.5      | 20855  |
| Mesh 5            | 3.0      | 28349  |
| Mesh 6            | 2.5      | 40256  |
| Mesh 7            | 2.0      | 62576  |
| Mesh 8            | 1.5      | 110066 |
| Mesh 9            | 1.0      | 247950 |

### 3. RESULTS AND DISCUSSION

The mesh test was performed to verify the accuracy and reliability of the results obtained through the numerical simulation. We refined the mesh as shown in Table 3 aiming to obtain the best possible results with a low computational effort. Once the model and its variations were established, an extremely refined mesh no longer made sense, since each model has 10000 steps, and would take days to simulate each case.

First, we observed the quality of each mesh, because a poor quality can generate convergence problems and uncertain results. Table 4 shows the quality parameters for each generated mesh.

According to the range of values for studying mesh quality presented by Ansys (2020), shown in the Methodology section of this paper, we can state that the mesh in each case is considered excellent based on the attributes analyzed. Furthermore, we can observe, from the values presented, that the more refined the mesh is, the better its quality is.
After checking the reliability of each mesh, the convergence was tested based on the refinement (increase in the number of elements) to verify the depth and width (main output variables analyzed for the studied model) reached on the soil after 30 seconds of simulation. The values gathered after the simulation are shown in Table 5.

Considering the results found, and taking into account Figure 5, which shows the values reached by the jet in detriment of the required computational effort, we can observe the jump in the required computational time when leaving the least refined mesh (0.187 hr) to the most refined one, which exceeds 26 hours of simulation. By the graphs in Figure 5, we can visualize that the mesh tends to converge to a cutting depth with its refinement, as can be seen in Figure 5-A, in contrast to the time required to perform the simulation, Figure 5-B, which rises exponentially.

In this manner, we observe that mesh 6, with an element size of 2.5 cm, presents a difference of 5.7% in the excavation depth achieved in relation to the mesh with the greatest refinement (with 1.0 cm size), a low difference considering the balance between the quantity of elements and computational cost, taking into account that the simulation time between meshes 6 and 9 is almost 20 times greater. Compared to meshes 7 and 8, mesh 6 was preferred because mesh 7 slightly deviates from the convergence trend while mesh 8 showed close values for excavated depth and width but took about 6 times longer to simulate it.

Figure 6 presents the soil excavation profile using mesh 6, with element size of 2.5 cm, after 30 seconds of simulation, using seawater as drilling fluid. In the image, the seafloor is shown in red, where the volume fraction in this region is equal to 1 (VOF = 1) and equals 0 in the dark blue region, which represents water. The region at the soil-water interface, that is, between the two fluids, has values for VOF greater than 0 and less than 1.
Figure 5. Mesh convergence test: (A) excavated depth, (B) simulation time.

Figure 6. Mesh 6 soil excavation profile at 30 s.
As the aim is to evaluate the depths and widths obtained after the excavation process, we chose to search for the regions with VoF equal to 0.5, representing the median of the interface between the fluids. Therefore, the depth and width obtained at the end of the simulation for this case were 7.41 cm and 76.67 cm, respectively. We can also note that at this early stage of the excavation process, the soil tends to resemble an inverted bell in an almost symmetrical manner, a fact experimentally proven by Wang & Song (2018).

4. CONCLUSIONS

The numerical model evaluated, through finite volume method, the marine soil excavation made by drill bit jets simulating the jetting process. The CFD software chosen to perform the modeling and simulations of the proposed model was ANSYS Fluent® Academic 2021 R1, in which we used the multiphase fluid volume (VoF) method, because the seafloor is modeled as a viscous fluid by the Herschel-Bulkley model.

Based on the meshes analyzed for the proposed model, we verified that all cases presented a good mesh quality according to the criteria observed. Regarding the mesh convergence test, we observed that the mesh with element size of 2.5 cm represented successfully the modeled soil, with a good balance between model accuracy and computational cost.

This type of work is important for the industry because of the possibilities of improving the jetting process, which can reduce well drilling time, consequently reducing operating costs, and also limiting the exposure of workers to risk.

5. REFERENCES

Akers, T. J. Jetting of structural casing in deepwater environments: Job design and operational practices. In: SPE Annual Technical Conference and Exhibition. San Antonio: Society Petroleum Engineers, p. 24-27, 2006. https://doi.org/10.2118/102378-M5

Ansys, Inc. Ansys Fluent – User’s and theory guide, 2020.

Albuquerque, R. D. A. Estudo numérico do jateamento de solos para o assentamento do revestimento condutor de poços de petróleo. Monografia – Universidade Federal de Alagoas, Maceió, 2019. (in Portuguese)

ANP. Ministério de Minas e Energia. Produção de petróleo cresce 5,5% em 2020. Available at: https://www.gov.br/anp/pt-br/canais_atendimento/impressa/noticias-comunicados/producao-de-petroleo-cresce-5-5-em-2020. Accessed on: 25 June 2021.

Boukpeti, N.; White, D. J.; Randolph, M. F.; Low, H. E. Strength of fine-grained soils at the solid – fluid transition. Géotechnique, Thomas Telford Ltd., v. 62(3), p. 213 – 226, 2012. https://doi.org/10.1680/geot.9.P.069

Cerqueira, R. F. L. Estudo computacional da transferência de calor e de massa interfacial em partículas fluidas esféricas e deformadas. 164 p. Dissertação de Mestrado. Programa de Pós-Graduação em Engenharia Mecânica, Centro Tecnológico, Universidade Federal de Santa Catarina, Florianópolis, 2015. (in Portuguese)

Fejoli, R. F. Simulação numérica do escoamento de uma gota de óleo em água através de capilares com gargantas. 161 p. Dissertação de Mestrado. Programa de Pós-Graduação em Energia, Centro Universitário Norte do Espírito Santo, Universidade Federal do Espírito Santo, São Mateus, 2016. (in Portuguese)

Gomes, A. F. C.; Barboza, B. R.; Tenório, J. K. F.; Tenório, M. S. C.; Santos, J. P. L.; Dias, R.; Cutrim, F. S. Análise paramétrica de jateamento de revestimento condutor em solo argiloso. In: Rio Oil and Gas, Rio de Janeiro, 2020. https://doi.org/10.48072/2525-7579.rog.2020.120

Gomes. A. F. C. Estudo experimental e numérico do comportamento reológico de um fluido de perfuração. 101 p. Dissertação de Mestrado. Programa de Pós -Graduação em Engenharia Química, Universidade Federal de Alagoas, Maceió, 2019. (in Portuguese)

Hirt, C. W.; Nichols, B. D. Volume of Fluid (VOF) Method for the dynamics of free boundaries. Journal of Computational Physics, v. 39, p. 201-225, 1981. https://doi.org/10.1016/0021-9991(81)90145-5
Kan, C.; Yang, J.; Yu, X.; Xie, R.; Wu, Y.; Li, Y.; Chen, H.; Guan, S.; Liu, H.; Gu, C; Lin, S.; Wang, H.; Abimbola, F. Field experimental investigation of bit stick-out for different soil strengths during deepwater conductor injection. *Journal of Petroleum Science and Engineering*, v. 169, p. 825-836, 2018. https://doi.org/10.1016/j.petrol.2018.04.005

Malouf, L. R. *Análise das operações de perfuração de poços terrestres e marítimos*. Tese de Doutorado. 120 p. Curso de Engenharia de Petróleo, Escola Politécnica, Universidade Federal do Rio de Janeiro, Rio de Janeiro, 2013. (in Portuguese)

Petrobras. *Alcançamos recordes de produção de petróleo e gás em agosto (2019)*. Available at: https://petrobras.com.br/fatos-e-dados/alcancamos-recordes-de-producao-de-petroleo-e-gas-em-agosto.htm. Accessed on: 26 de agosto de 2020.

Talley, L. D.; Pickard, G. L.; Emery, W. J.; Swift, J. H. *Descriptive physical oceanography: an introduction*. Sixth edition. Elsevier, 2011. https://doi.org/10.1016/c2009-0-24322-4

Thomas, J. E. *Fundamentos de Engenharia de Petróleo*. Rio de Janeiro: Petrobras, 2004.

Ubbink, O. *Numerical prediction of two fluid systems with sharp interfaces*. PhD Thesis. Department of Mechanical Engineering, Imperial College of Science, Technology and Medicine, London, England, 1997.

Wang, T.; Li, H. Numerical Simulation of Jet Excavation in Conductor Jetting Operations. In: *Offshore Technology Conference-Asia*, Kuala Lumpur, 2014. https://doi.org/10.4043/24937-MS

Wang, T.; Song, B. Study on deepwater conductor jet excavation mechanism in cohesive soil. *Applied Ocean Research*, Elsevier, v. 82, p. 225 – 235, 2019. https://doi.org/10.1016/j.apor.2018.09.007

Zhou, H.; Randolph, M. F. Numerical analysis of a cylinder moving through rate-dependent undrained soil. *Ocean Engineering*, Elsevier, v. 38 (7), p. 943 – 953, 2011. https://doi.org/10.1016/j.oceaneng.2010.08.005