25th ABCM International Congress of Mechanical Engineering
October 20-25, 2019, Uberlândia, MG, Brazil

COB-2019-0543
Modeling the displacement of drill string immersed in cuttings bed

Maryelen Hissae Miyoshi
Cezar O. R. Negrão
Federal University of Technology-Paraná - UTFPR, R. Deputado Heitor Alencar Furtado, 5000, Curitiba, 81280-340, Brazil
mmiyoshi@alunos.utfpr.edu.br
negrao@utfpr.edu.br

Abstract. *Although usually more expensive, drilling and directional well may be useful for targeting a particular oil reservoir. Nevertheless, the more inclined the well towards the horizontal direction, the higher the risk of rock fragment sedimentation at the lower part of the well. When the drill string immersed in the cuttings bed is pulled out of the well, solid particles may accumulate at the drill bit forming a plug that increases the required force to remove the drill pipe. Depending on the cuttings bed height, on the kind of sediment, on the open cross section area, on the drilling fluid viscosity and on the drill pipe speed, the drill pipe may be stuck at the cuttings plug. The current work puts forward a mathematical model to simulate the displacement of a drill string immersed in cuttings bed. The model that is based on lumped mass and momentum conservation equations applied to the solid-liquid two-phase flow is used to predict the cuttings plug length and also the forces acting on the drilling string. The forces due to cuttings bed are determined using theories of granular flow and soil mechanics. This model might help well drilling teams to accurately predict the drill pipe motion so as to minimize well costs and ensure a safe drilling process.*

Keywords: *drag, cuttings bed, mechanical stuck, drilling*

1. INTRODUCTION

The exploration of reservoirs in regions of difficult access and adverse environmental conditions is extremely costly for Oil & Gas Exploration and Production industry. One of the most frequently operational problems that occur during drilling is the pipe stuck (Bradley *et al.*, 1991; Yarim *et al.*, 2007).

The prevention of this problem is a challenge for the petroleum industry. There are studies in the literature about real time systems for monitoring the forces in the drill string to predict stuck pipe (Jardine *et al.*, 1992; Salminen *et al.*, 2017). Those systems use previous data from the field to create a profile of forces during drilling and compare with the real-time field data to predict the drill string stuck. By monitoring the hookload they can identify the force increase when performing operations of Pull-Out-Of-Hole (POOH) or Run-In-Hole (RIH), as may be seen in Fig. 1(b) where the hookload profile over the time is shown, and the operations of POOH and RIH can be observed at the instant of 4 minutes and 36 minutes. Fig. 1(a) shows the elevator position. Among the various mechanisms which induce this increase in force and the pipe stuck, the solids induced pack offs are the most frequent cause.

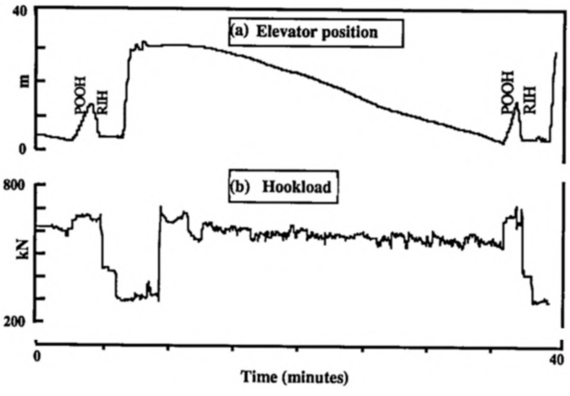

Figure 1. Generation of Pull-Out-Of-Hole (POOH) and Run-In-Hole (RIH) profiles of field drilling data over two connections (Jardine *et al.*, 1992).

Pipe stucking is more common when the drill string moves within a cuttings bed, as shown in Fig. 2(a). The settling of cuttings occurs because of the effect of gravity and the bed's formation is more frequently in horizontal/directional wells.

As illustrated in Fig. 2(b), when drill string is being moved axially inside the well, the stuck may occur depending on the concentration of cuttings, the pull-out velocity and the cross section of the bottom-hole assembly (BHA) elements (Rasi *et al.*, 1994).

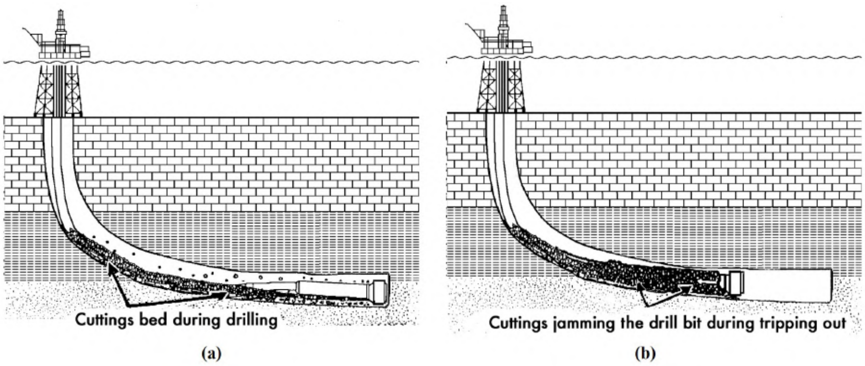

Figure 2. Mechanical stuck of drill string due to formation a cuttings bed. Available from: http://petrowiki.org

Based on the presented context, the current work puts forward a mathematical model capable to predict the drill pipe motion immersed in cuttings bed to determine the forces acting on the equipment. The mathematical model is based on lumped mass and momentum conservation equations applied to the solid-liquid two-phase flow and the forces related to cuttings are determined using theories of soil mechanics and granular flow.

2. DESCRIPTION OF THE PROBLEM

In order to better understand the problem, Peliano (2018) built up an experimental setup which that consists of a cylindrical element, representing the drill bit, attached to a long pipe. This bit-drill pipe assembly was placed inside a horizontal acrylic pipe partially filled with a bed of glass beads, as shown in Fig. 3(a). Water was added to the acrylic pipe to work as the drilling fluid. During the experiments, Peliano (2018) identified the jamming of cuttings near the bit as the drill string is dragged. This jamming may lead to the growth of a cuttings plug in front of the bit, as shown in Fig. 3(c). The continuous plug growth can lead to the stuck of the assembly, Fig. 3(d). If the pipe didn't stuck it was observed just cuttings accumulation near the drill in the final test position, as shown in Fig. 3(e).

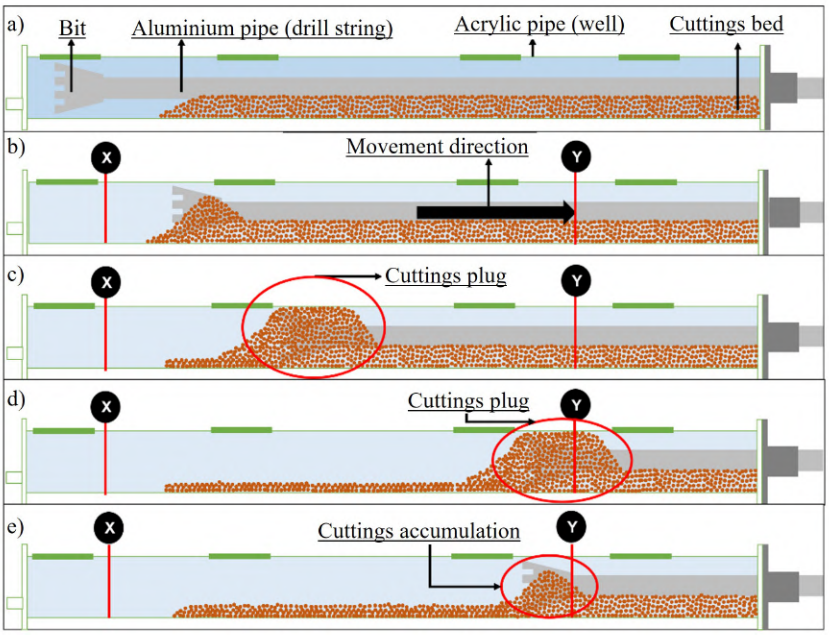

Figure 3. Illustration of the cuttings bed behavior observed by Peliano (2018) during the drill string movement. (a) Initial test position. (b) Cuttings accumulated near the bit. (c) Pipe stuck due to the plug. (d) Plug and drill string in the final test position. (e) Drill string and cuttings accumulated in the final test position. (Adapted from Peliano (2018)).

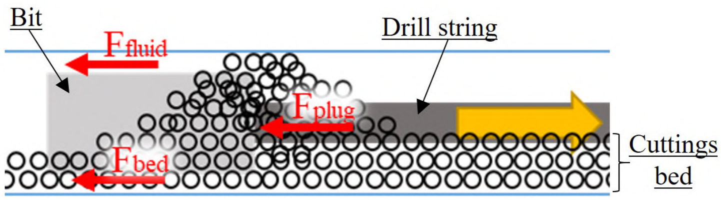

Figure 4. Representation of the most critical situation observed during the movement of bit and drill string, immersed in a bed of cuttings, where the annular space is obstructed and there is growth of a plug in the region in front of bit

In this plug growth condition, several forces acting on the assembly can be identified, as indicated in Fig. 4. There are three main forces: the fluid drag force, F_{fluid}, the friction force between cuttings and equipment, F_{bed}, and the sum of all forces acting on the plug, F_{plug}. The plug forces are divided into: the force due to the pressure drop along the plug due to fluid flow and the friction force between plug and bore hole. The following section presents the model to predict the plug growth and associated forces.

3. MATHEMATICAL MODEL

The problem to be initially considered is the plug growth situation. In the present model, the plug growth can be predicted by the mass conservation applied to the cuttings piled up in front of the drill bit:

$$\frac{\partial M_{\forall C}}{\partial t} = \sum_{in} \dot{m} - \sum_{out} \dot{m} \tag{1}$$

where $M_{\forall C}$ is the mass accumulated in the control volume, drawn in the red dashed lines as shown in Fig. 5, and $\dot{m}$ are the mass flow rates associated with the flow which enters and leaves the control volume.

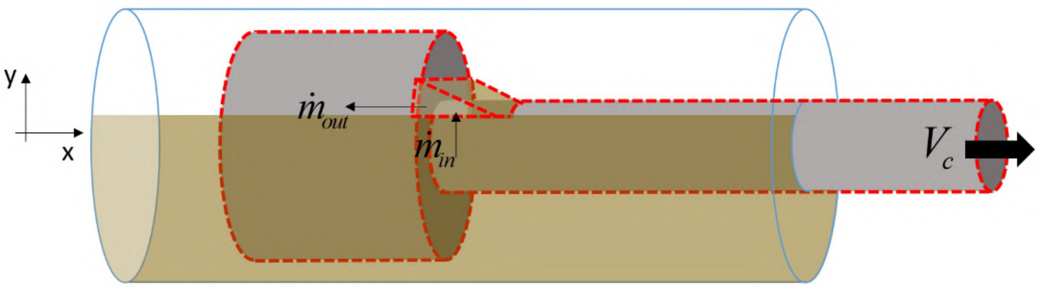

Figure 5. Control volume of cuttings pile up in front of the drill pipe.

The total force required to pull the drill string in x axis is F_T. As illustrated in Fig. 6 and represented by Eq. (2), this force should be equal to the sum of different opposite forces on the drill string during its movement.

$$\frac{\partial (M v_x)_{\forall C}}{\partial t} = F_T - \sum (F_{fluid} + F_{bed} + F_{plug}) - (\sum_{in} \dot{m} v_x - \sum_{out} \dot{m} v_x) \tag{2}$$

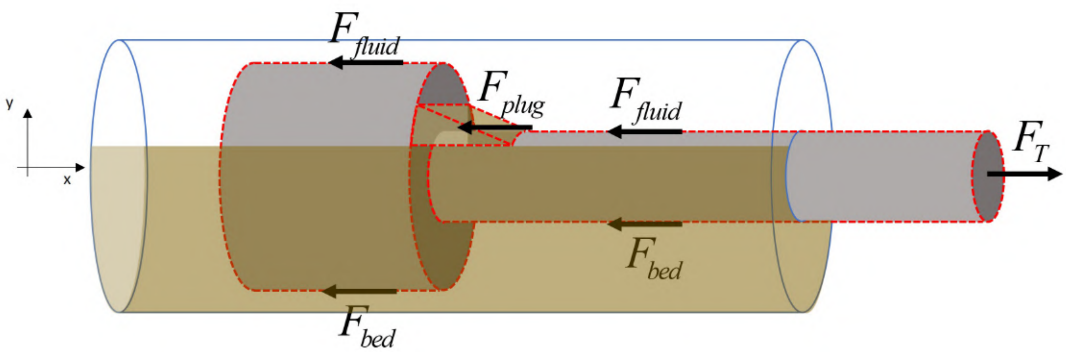

Figure 6. Representation of the forces present during the movement of bit and drill string, immersed in a bed of cuttings. Highlighted in red dashed lines is the control volume of the plug.

The F_{plug} is a sum of forces acting on the plug composed by: the force due to the pressure drop along the plug, $F_{plug\Delta p}$, and the friction force between the plug and the borehole, $F_{plug\mu}$. These forces are illustrated in Fig. 7

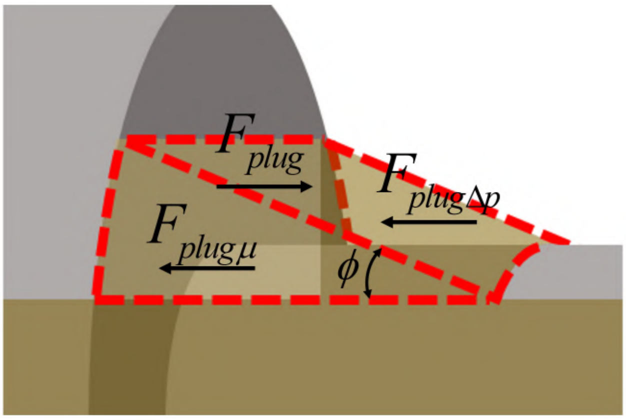

Figure 7. Representation of the forces acting on the plug. $F_{plug\Delta p}$ is the force due to the pressure drop along the plug and $F_{plug\mu}$ is the friction force between the plug and the borehole.

To calculate each of these forces, specific models found in literature were employed. The chosen model for each force are presented below.

The friction force between the equipment and the cuttings bed, represented by F_{bed} in Fig. 6, could be calculated by:

$$F_{bed} = F_N * \mu_{bed} \tag{3}$$

where μ_{bed} is the friction factor and F_N is the normal force due to the buoyancy equipment weight.

The fluid drag effects are calculated by the model proposed by Maidla *et al.* (1987):

$$F_{fluid} = \frac{\pi}{4}\left(\frac{\Delta P}{L}\right)\Delta L d^2 \tag{4}$$

where L is the length of the drill string, d is the drill string diameter and the calculation procedure for the frictional pressure gradient, $\Delta P/L$, is based on the theory of viscous drag in boreholes, developed by Fontenot *et al.* (1974).

The pressure drop along the plug is calculated by the friction factor proposed by (Ergun and Orning, 1949), as:

$$f_{Erg} = \frac{\Delta P}{L_p \rho v_s^2} D_p \frac{\varepsilon^3}{(1-\varepsilon)} = \frac{150}{Re_{Erg}} + 1.75 \tag{5}$$

where ΔP is the pressure drop, L_p is the length of the plug, ρ is the fluid density, D_p is the particle diameter and ε is the fractional void volume. The Ergun's Reynolds number is defined as:

$$Re_{Erg} = \frac{\rho v_s D_p}{\mu(1-\varepsilon)} = \frac{Re_p}{1-\varepsilon} \tag{6}$$

where v_s is the superficial velocity defined by:

$$v_s = \frac{\dot{m}}{\rho A_{cs}} \tag{7}$$

where $\dot{m}$ is the fluid mass flow rate through the plug and A_{cs} is the total cross-sectional area of the packed cuttings bed .

4. PRELIMINARY RESULTS

Two critical cases are analyzed in the current preliminary model, illustrated in Fig. 8. While the first considers that all cuttings reaching the annular space between the bit and the borehole flow freely, as shown in Fig. 8(a), the second, illustrated in Fig. 8(b), assumes that all cuttings are completely retained at the drill bit.

In addition, the cuttings plug growth and the total force to move the drill string are computed for two different drill bits with different cross-sectional areas, as depicted Fig. 9. The cross-sectional area of drill bit 1, Fig. 9(a), is 7.804 mm^2 and drill bit 2, Fig. 9(b), has 13.097 mm^2. For the current model, the cross-sectional area of the drill bit is considered to be circular with a constant diameter, having a constant radius. The results are compared with the experimental work developed by Peliano (2018).

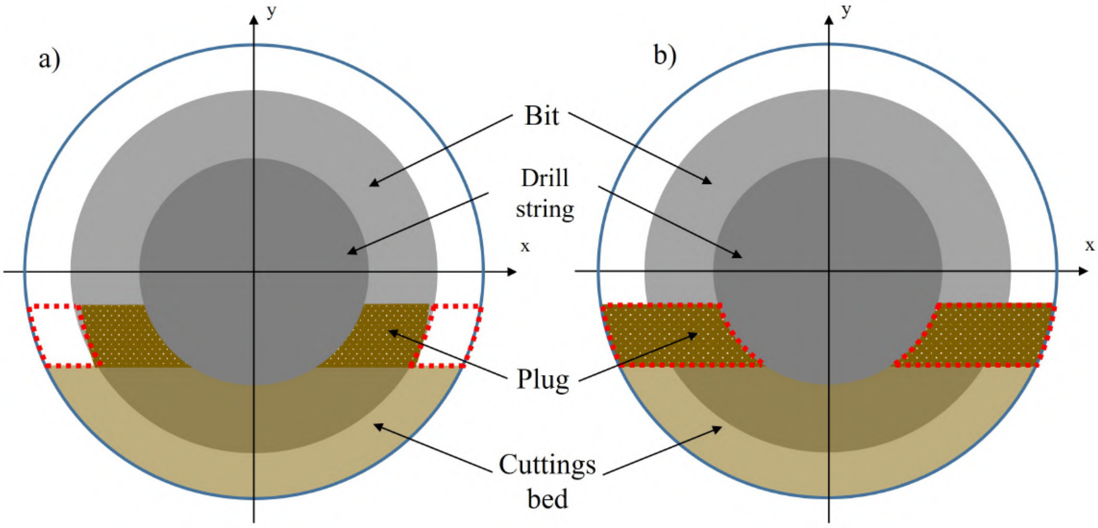

Figure 8. Cross section of the well showing two cases analyzed: a) all the cuttings between bit and well will be carried, b) all cuttings are retained.

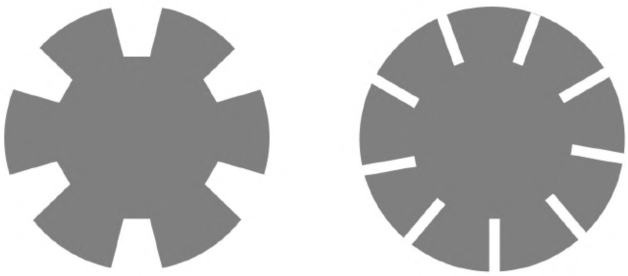

Figure 9. The cross-sectional area of the two drill bits analyzed by Peliano (2018) in his experiments. (a) The drill bit 1 has a cross-sectional area of 7.804 mm^2 and (b) drill bit 2 has 13.097 mm^2

For the cases studied, the well and drill string diameters are, respectively, $0.150\ m$ and $0.076\ m$. It is considered an equivalent radius of $0.0948\ m$ for drill bit 1 and 0.0646 m for drill bit 2. The cuttings bed height is $0.050\ m$, the particles are spherical with $3\ mm$ diameter and density $2610\ kg/m^3$. The fluid's density is $1000\ kg/m^3$ and the viscosity $0.001\ Pa.s$. The friction factor used for μ_{bed} is 0.3, and 0.12 for μ_{plug}. These values and the time of displacement were chosen based on the experiment of Peliano (2018). In the experimental results for drill bit 1 the experiment ended in 30 s without reaching the maximum force allowed for the experimental setup, and for drill bit 2 the test stopped at 17.5 s, reaching the limiting force. The velocity of displacement of the whole set was $0.10\ m/s$.

The final plug length calculated for the two drill bits are compared with the value measured by Peliano (2018) and the results are shown in Fig. 10 and Fig. 11. For both types of drill bit the plug length obtained experimentally is between the two critical values found from the current calculations. These results reveal that in the experiment the amount of cuttings carried were smaller than that considered for the case with exit of cuttings. In addition, it is possible to realise that the case without exit of cuttings does not reliably represents the experiment for the two drill bits, resulting in a longer plug length. This is summarized in Tables 1 and 2, as the percentage relative difference ($\Delta\%$) for the case without exit is larger than for the case with exit of cuttings.

Table 1. Comparison between the final plug length of Peliano (2018) and the current model for the drill bit 2.

	Peliano (2018)	w/ exit	w/o exit
Plug length [m]	0.45	0.3853	0.5947
$\Delta\%$	-	12 %	32 %

In the results, the displacement with drill bit 1 was larger than that with drill bit 2, but the plug length of drill bit 1 was smaller. This happened because the open area of drill bit 1 is larger, increasing the amount of cuttings able to exit through

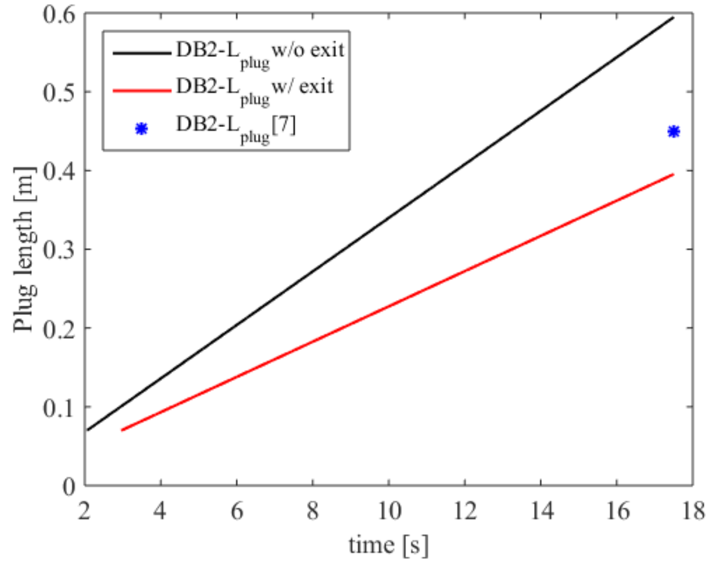

Figure 10. The growth of plug length versus time for the drill bit 2 with exit of cuttings, without exit of cuttings compared to the final experimental value from Peliano (2018)

the annular space. Furthermore, the relative difference ($\Delta\%$) for the final plug length, between the experimental data and the calculated, are larger for drill bit 1 than for drill bit 2, as shown in Table 1 and Table 2. This high difference in the case considering the exit of cuttings could be associated to the shape of the drill bit.

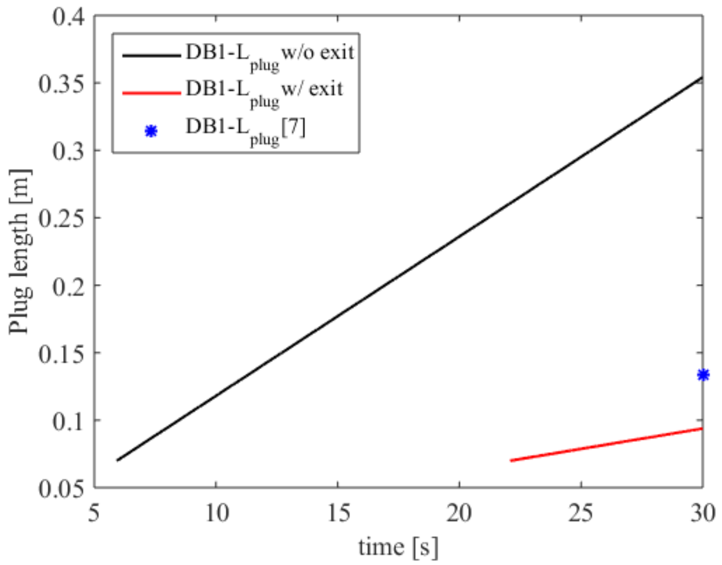

Figure 11. The growth of plug length versus time for the drill bit 1 with exit of cuttings, without exit of cuttings compared to the final experimental value of Peliano (2018)

Table 2. Comparison between the final plug length of Peliano (2018) and results from the current model for the drill bit 1.

	Peliano (2018)	w/ exit	w/o exit
Plug length [m]	0.134	0.0920	0.3471
$\Delta\%$	-	31 %	159 %

The total force, F_T, is also computed for the two critical conditions and compared with the measured values of Peliano (2018). Fig. 12 shows the curves for drill bit 2. The results for retained and non-retained cuttings are depicted in blue and red, respectively. For this drill bit is possible to observe in Fig. 12 that the curve for the case considering the free flow

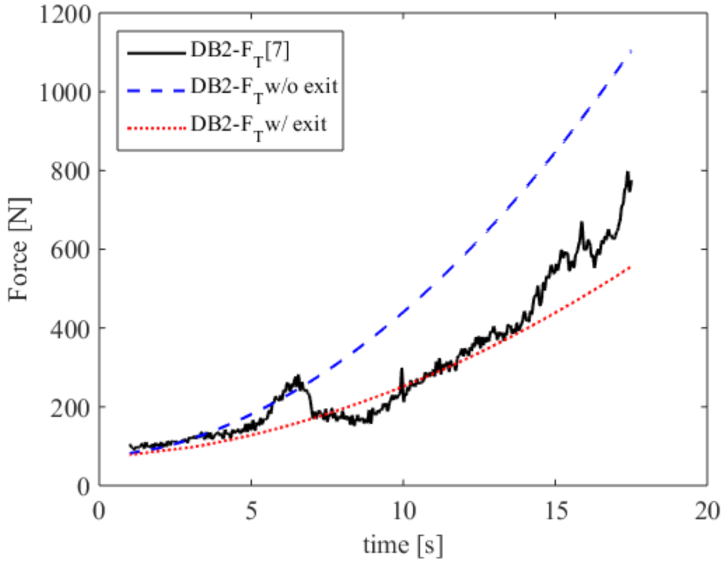

Figure 12. Total force (F_T) to move the drill string versus time for the two cases analyzed compared to the experimental result obtained by Peliano (2018) for drill bit 2 (DB2).

of cuttings has better agreement with experimental result, whereas for the case without exit of cuttings the forces reaches larger values. Table 3 shows the relative differences between the two cases in comparison to the experimental data of Peliano (2018) at $5\ s$, $10\ s$ and $15\ s$. The forces for the case without exit present a difference larger than 27 $\%$, whereas for the case with exit the difference is smaller than 20 $\%$. Even in this case considering the exit of cuttings, which is closer to the results of Peliano (2018), it is possible to notice that the difference increased with time.

Table 3. Comparison between the results of Peliano (2018) and results from the current model for the drill bit 2.

time [s]	$F_T[N]$ Peliano (2018)	$F_T[N]$ w/ exit	$\Delta\%$	$F_T[N]$ w/o exit	$\Delta\%$
5	142.6	128.4	10 %	180.8	27 %
10	224.1	251.8	12 %	440.4	97 %
15	548.6	438.8	20 %	846.6	54 %

The curve for the case considering the free flow of the cuttings follows a trend similar to the experimental curve obtained by Peliano (2018), but the force values have an almost constant difference of $100\ N$. This difference is probably due to the minimum force necessary to move the equipment, as reported by Peliano (2018) in the tests without cuttings. In such tests, the author analyzed only the force for displacement of the apparatus associated with its external elements, such as the friction in the bearings and the force in rack and pinion actuator. If this force due to displacement is added to F_T calculated by the model, it is possible to observe a lower percentage relative difference, as shown in Table 4. This percentage shown in Table 4 exposes a greater difference in the beginning (21 $\%$) and in the end (15 $\%$) of the displacement. This feature is also possible to be observed in Fig 13, where the black and blue curves are the experimental result and the dashed lines red and magenta are the calculated results for drill bit 1 and 2 respectively. As shown in Fig. 13, the calculated curve for the drill bit 1 when added the force of displacement is the one which better matches the experimental results.

Table 4. Comparison between the results of Peliano (2018) and the results of total force and total force added the force of displacement ($100\ N$) from the current model for the drill bit 1.

time [s]	$F_T[N]$ Peliano (2018)	$F_T[N]$ w/ exit	$\Delta\%$	$F_T[N]$ w/ exit + 100	$\Delta\%$
5	114.0	38.2	66 %	138.2	21 %
10	131.8	44.2	66 %	144.2	9 %
15	163.6	50.1	69 %	150.1	8 %
20	166.7	56.1	66 %	156.1	6 %
25	192.3	62.9	67 %	162.9	15 %

However the curve for drill bit 2 does not fit the experimental curve in the beginning of the test, as could be observed in Fig. 13, nonetheless both present a similar trend. This is also verified by the percentage relative difference presented in Table 5. By adding the displacement force, the percentage relative difference increases in the beginning from 10 $\%$ to 60 $\%$, however in the end this difference reduces from 20 $\%$ to 2 $\%$.

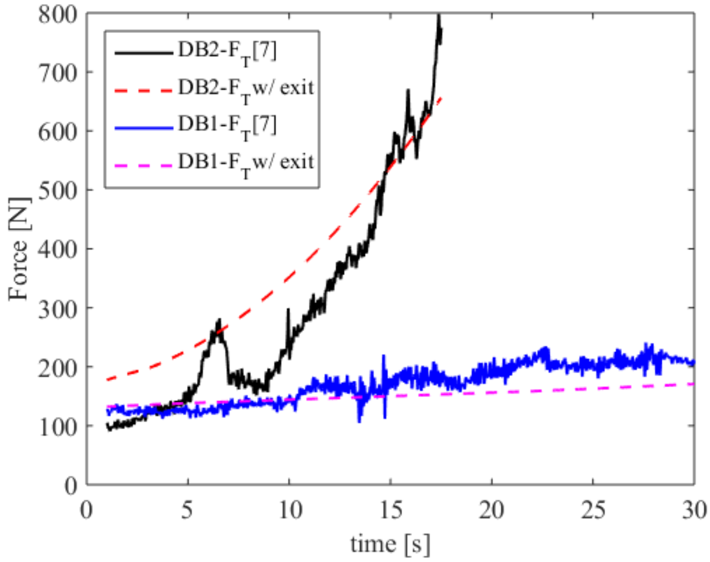

Figure 13. Total force, F_T, added the force of displacement ($100N$) versus time for the two drill bits compared to the experimental results obtained by Peliano (2018).

Table 5. Comparison between the results of Peliano (2018) and results of total force and total force added the force of displacement (100 N) from the current model for the drill bit 2.

time [s]	$F_T[N]$ Peliano (2018)	$F_T[N]$ w/ exit	$\Delta\%$	$F_T[N]$ w/ exit + 100	$\Delta\%$
5	142.6	128.4	10 %	228.4	60 %
10	224.1	251.8	12 %	351.8	57 %
15	548.6	438.8	20 %	538.8	2 %

5. Conclusions

The current work proposed a mathematical model to investigate the forces involved in the pull-out of hole operation, when the drill string is immersed in a cuttings bed.

Based on the results it is possible to note that for both the calculation of plug length and total force, the cases for drill bit 2 presented a smaller difference when compared with the experimental data of Peliano (2018). This may be associated with the drill bit design, because the current model considers the cross-sectional area having a constant radius.

Although the calculated parameters presented significant discrepancies when compared to the experimental results, the current model was able to compute curves with a similar trend to the observed in the experimental work of Peliano (2018). For a real situation a deeper study is necessary to better understand the numerous phenomena inherent to the problem.

Even though, the presented model shows potential in calculation of the forces involving the displacement of the drill string in the presence of a cuttings bed, and can be eventually improved to avoid major financial losses for petroleum industries.

6. ACKNOWLEDGEMENTS

The authors acknowledge the financial support of PETROBRAS S/A, ANP (Brazilian National Oil Agency).

7. REFERENCES

Bradley, W., Jarman, D., Plott, R., Wood, R., Schofield, T., Auflick, R., Cocking, D. *et al.*, 1991. "A task force approach to reducing stuck pipe costs". In *SPE/IADC Drilling Conference*. Society of Petroleum Engineers.

Ergun, S. and Orning, A.A., 1949. "Fluid flow through randomly packed columns and fluidized beds". *Industrial & Engineering Chemistry*, Vol. 41, No. 6, pp. 1179–1184.

Fontenot, J.E., Clark, R. *et al.*, 1974. "An improved method for calculating swab and surge pressures and circulating pressures in a drilling well". *Society of Petroleum Engineers Journal*, Vol. 14, No. 05, pp. 451–462.

Jardine, S., McCann, D., Barber, S. *et al.*, 1992. "An advanced system for the early detection of sticking pipe". In *SPE/IADC Drilling Conference*. Society of Petroleum Engineers.

Maidla, E., Wojtanowicz, A. *et al.*, 1987. "Field comparison of 2-d and 3-d methods for the borehole friction evaluation in directional wells". In *SPE Annual Technical Conference and Exhibition*. Society of Petroleum Engineers.

Peliano, S.V., 2018. *Análise experimental do arrasto em colunas de perfuração parcialmente imersas em leito de cascalhos*. Master's thesis, Universidade Tecnológica Federal do Paraná.

Rasi, M. *et al.*, 1994. "Hole cleaning in large, high-angle wellbores". In *SPE/IADC Drilling Conference*. Society of Petroleum Engineers.

Salminen, K., Cheatham, C., Smith, M., Valiullin, K. *et al.*, 2017. "Stuck-pipe prediction by use of automated real-time modeling and data analysis". *SPE Drilling & Completion*, Vol. 32, No. 03, pp. 184–193.

Yarim, G., Uchytil, R.J., May, R.B., Trejo, A. *et al.*, 2007. "Stuck pipe prevention–a proactive solution to an old problem". In *SPE Annual Technical Conference and Exhibition*. Society of Petroleum Engineers.

8. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.