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FLEXIBILIZING HYDRAULIC LIMITS FOR OFFSHORE INCLINED WELLS

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Abstract. *The reduction of the number of phases in the construction of an offshore well is a major driver for cost reduction. In order to achieve this goal, phases must be longer, resulting in additional challenges. A critical aspect is related to phase II (no fluid return to surface) reaching high inclinations in order to allow III phase horizontal wells. Such phases are drilled with no carrying capacity fluids, during 1200 m and inclinations as high as 45 degrees, resulting in expressive cuttings accumulation in the wellbore annulus. Drill string trips are frequently obstructed by the cuttings bed. This way, it is necessary to carry on a series of operational procedures to guarantee proper hole cleaning and safe continuation of the drilling operation. This paper details novel design procedures which include the following steps:*
● *Defining cuttings bed height deposited along the wellbore annulus using traditional steady state cuttings transport models. This information is the initial condition for the design of hole cleaning pills pumping.*
● *Estimation of the extension of the cuttings bed through a material balance.*
● *Estimation of drag efforts for drill string movement in the presence of a cuttings bed.*
● *Calculation of the solids removal due to the pumping of hole cleaning pills based on a transient solid liquid model.*
● *Optimization of the frequency, volume and pump rates for the cleaning pills.*
Results obtained by the novel simulation proposed indicate the feasibility of this type of projects.

Keywords: *Drilling of Ultra Slender Wells, Cutting Transport, Drag Efforts, Cleaning Pills*

1. INTRODUCTION

The development of post-salt fields worldwide often considers the strategy of drilling horizontal wells, aiming to maximize the exposure of the reservoir rock to the well and, consequently, its productivity. Traditionally phases I and II of these wells are drilled vertically with sea water and no return. After that, the BOP (blowout preventer) and riser are installed enabling the use of a complete drilling fluid and to handle eventual influx events with the adequate techniques.

The drilling of highly inclined wells is associated with the handling of the problems related with the formation of a cuttings bed, such as additional torque and drag which would impact in tripping operations drilling performance and, in extreme conditions in stuck pipe events, generating expressive nonproductive times.

The push for cost reduction is driven by field development economics and well construction efficiency targets. Originally conceived for 5 phases, the configuration of horizontal wells migrated to slender well concepts of 4 phases. Nowadays the challenge is to make possible the construction of horizontal offshore subsea wells in 3 phases.

To achieve this goal, phase II (still with no return and drilled with sea water) has to be extended and built at inclinations as high as 45 degrees. Due to the non-ability of seawater to transport solids, additional effort must be spent to clean the hole. Frequent pumping of cleaning pills is a common strategy to improve the process.

This paper deals with conception of a new hydraulics design approach which considers the steps of dedicated hole cleaning operations in order to achieve the requirements to conclude a phase. In other words, the proposed methodology was developed to flexibilize extension and inclination limits for drilling a phase of an offshore well. Several other aspects, including the drilling of reactive shale and reservoir rock in the same phase have to be addressed in the project.

2. METHODOLOGY

2.1 Criteria usually used in the hydraulic design of inclined and horizontal wells

The hydraulic design of an oil well comprises 2 different aspects:

• The adequation of annular pressures inside the operational windows formed by the pore pressure (minimum limit) and formation fracture pressure (upper limit). Eventually, collapse events can restrict even more both operational window limits.
• A maximum solids accumulation limit associated to the non-probability of pipe sticking events. Additionally, solids accumulation may result in additional annular pressure, enhancing the risk of fracture formation. In inclined and horizontal wells solids will tend to accumulate in the lower portions of the annular region generating a cuttings bed which may result in additional friction.

For these reasons an accurate well design usually considers a two-phase flow model where solids accumulation affects both pressure terms (hydrostatic and friction losses). There are different steady state approaches for the cuttings transport model, including empirical (Iyoho (1980), Larsen (1990)) or mechanistic (Gavignet and Sobey (1986), Martins (1990)). Normally, transport ratios (used to express the cleaning capacity in vertical sections and corresponds to the ratio between the speed at which the particle is transported and the average speed in the annulus), solids volumetric concentrations and relative bed heights are the dependent variables considered to characterize the hole cleaning efficiency. Usually, solids concentration and transport ratio do not represent the dynamics of cuttings transport in highly inclined wells and the estimation of cuttings bed heights are essential for capturing the stratification phenomena associated to the flow. The continuous use of the model proposed by Martins (1990) indicated that few relevant hole cleaning problems occurred whenever solids concentration is lower than 5% and and/or bed heights are lower than 15% of the hole diameter (Martins et al., 2011).

In situations where this limit conditions are not achievable, additional operational procedures must be adopted, such as ROP (Rate of Penetration) control, hole cleaning pills and/or dedicated wiper trips. Some of these operations, however, are not contemplated by conventional hydraulics simulations imposing restrictions for the approval of several projects.

In the next topics novel simulation strategies are proposed to quantify the effect of hole cleaning strategies and, consequently, to enable the proposition of a consistent hydraulics program to be performed for challenging wellbore configurations. The logics behind the new simulation proposal is to define the frequency of pumping cleaning pills required to avoid pipe sticking events. For that, the following topics must be addressed:

• Estimate the amount of solids generated by the drilling operation;
• Estimate the efforts required to pull the drill string;
• Estimate the amount of solids removable by a cleaning pill.

2.2 Estimating the extension of cuttings bed generated per drilled meter

The initial condition for estimating the extension of the cuttings bed is the relative bed height calculated by the regular steady state simulator based on the model proposed by Martins (1990). This model considers a stratified layered solid liquid flow and is built to reproduce the complete wellbore trajectory. Additionally, a suspension transport model is coupled to represent the low inclination sections of the well.

Once the relative bed height is estimated by the steady state model, the bed cross section is calculated, then a material balance is run to determine the extension of the cuttings bed generated by the drilled of a new portion of the well.

In order to quantify the extension of the cuttings bed along the annular space, the drilled volume V_d is equaled to the volume of the formed bed V_b according to Eq. (1).

$$V_b = V_d \tag{1}$$

The drilled volume is calculated by the Eq. (2), where D_d is the drilled diameter, L_d is the drilled length and Φ_f is the formation porosity.

$$V_d = \pi D_d^2 \, L_d \left(1 - \Phi_f\right)/4 \tag{2}$$

Therefore, the extension of the cuttings bed L_b, is determined by Eq. (3), where Φ_b is the bed porosity and A_b is the bed cross section.

$$L_b = V_d \big/ \left(A_b (1 - \Phi_b)\right) \tag{3}$$

2.3 Effect of the cuttings bed on the efforts to move the drill string

In this item the model developed by Miyoshi (2020) for the drag force prediction while pulling the drill string out of hole in the presence of a cuttings bed is summarized.

In order to account for the efforts on the drill string due to the interaction with the cuttings bed, the drill string together with the amount of cuttings dragged by the string is admitted as a control volume. In Figure 1, the control volume is represented by the dashed red lines.

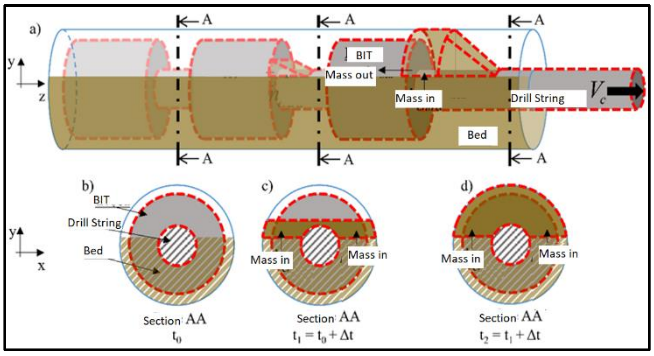

Figure 1. (a) Representation of the evolution of cuttings accumulation in front of the bit with the drill string displacement. Representation of the cross section (b) at the initial instant t_0, (c) at instant t_1 with cuttings accumulation and (d) at the instant t_2 in which there is plug formation.

The main assumptions adopted for the modeling are listed below:

- Drill bit cross-sectional area with constant diameter;
- Constant drill string tripping speed;
- Uniform and constant bed height;
- Perfectly spherical cuttings;
- Anisotropy effects in the granular medium neglected;
- Drill string assembly moves without rotation.

During the displacement of the drill string immersed in a cuttings bed, cuttings accumulate in the region in front of the drill bit, as illustrated in Fig. 1. The accumulated mass of cuttings moves with the drill string set at time t_1 in Fig. 1(c), growing until it obstructs the annular space as shown at time t_2 in Fig. 1(d). The problem is analyzed only in the *z*-direction, as it is the direction of largest contribution of forces opposing the movement, as noted by Ding et al. (2011) when displacing different objects immersed in a granular medium.

Equation (4), represents the force necessary for the displacement of the drill string in the presence of a cuttings bed, $\boldsymbol{F_T}$ is obtained through the equation of the momentum applied in the $\boldsymbol{z}$ direction considering that the momentum rate that enters the control volume in the $\boldsymbol{z}$ direction is negligible, $\boldsymbol{F_z}$ are components of the forces on the drill string that are contrary to the movement in the z direction:

$$\boldsymbol{F_T} = \sum \boldsymbol{F_z} \tag{4}$$

The sum of forces $\boldsymbol{F_z}$ represents the different forces on the drill bit and drill string during axial movement, as can be seen in Fig. 2 and by Eq. (5):

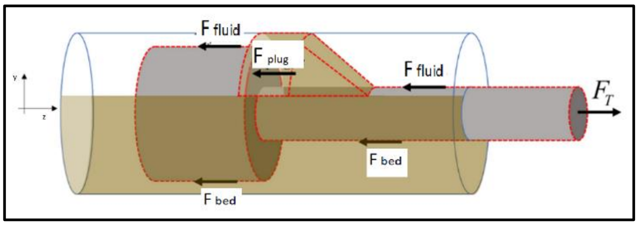

Figure 2. Representation of forces on bit and drill string during axial displacement.

$$\sum \boldsymbol{F_z} = \boldsymbol{F_{fluid}} + \boldsymbol{F_{bed}} + \boldsymbol{F_{plug}} \tag{5}$$

In the sum, the force due to the contact between the string and the cuttings bed (**F_{bed}**), the hydrodynamic drag force due to the flow of the drilling fluid (**F_{fluid}**) and also the forces associated with the plug formation (**F_{plug}**) are present. To calculate each force, models from literature were used. The choice of models for each force is presented below.

The **F_{fluid}** force represents the hydrodynamic drag forces that arise due to the axial movement of the string. Maidla (1987) proposed using surge and swab calculations to obtain the pressures associated with the axial movement of the column. The calculation is based on viscous drag theory for Power Law and Bingham fluids in a well. Therefore, **F_{fluid}** is obtained by Eq. (6):

$$\boldsymbol{F_{fluid}} = (\Delta P A_a/(A_{lw}+A_{lcb}))A_{lc} \qquad (6)$$

Where A_{lw} is the lateral area of the well in contact with the fluid, and the A_{lcb} is the lateral area of the column and bed in contact with the fluid. A_{lc} is the lateral area of the column without the bed, A_a is the open cross-sectional area of the annular space and the pressure variation ΔP is obtained using the concept of friction factor (Fontenot et al., 1974), given by Eq. (7):

$$dP/dz = 2f_a V_{ae}^2 \rho / D_h \qquad (7)$$

Where P is the pressure, ρ is the fluid density, f_a and V_{ae} are the friction factor and the effective flow velocity in the annular region, D_h is the hydraulic diameter, calculated by Eq. (8):

$$D_h = 4A_a/P_a \qquad (8)$$

Where P_a is the perimeter of the open region. For the drill bit region, the hydrodynamic drag force is obtained in the same way.

The **F_{bed}** force is caused by the contact between the set of equipment and the cuttings bed, calculated through the equations developed by Maidla (1987), according to Eq. (9):

$$\boldsymbol{F_{bed}} = C_s \mu_{bed} \boldsymbol{F_N} \qquad (9)$$

Where μ_{bed} is the friction coefficient between the set of equipment and the bed and **F_N** is the normal force generated due to the set of equipment on the bed. The author proposes Eq. (10) below for calculating the correction factor C_s:

$$C_s = (2/\pi)\, tan^{-1}\left(\left(\sqrt{D_{well}^2 - D_{column}^2}\right)/D_{column}\right)(4/\pi - 1) + 1 \qquad (10)$$

For the drill bit region, the column diameter, D_{column}, is replaced by the drill diameter, D_{bit}.

The force due to plug formation, **F_{plug}**, is composed by the sum of the forces **$F_{plug\mu}$** due to friction between the plug and the wall of the well and **$F_{plug\Delta P}$** due to the pressure gradient generated by the fluid flow through the plug.

The friction force between the plug and the well wall is calculated from Eq. (11):

$$\boldsymbol{F_{plug\mu}} = \boldsymbol{F_{Np}}\, \mu_{plug} \qquad (11)$$

Where μ_{plug} is the coefficient of friction between the plug and the well wall and **F_{Np}** is the normal force generated due to pressure inside the plug, calculated by Eq. (12):

$$\boldsymbol{F_{Np}} = (P_1 - \Delta P/2)A_{lp} \qquad (12)$$

Where, P_1 is the pressure at the beginning of the plug, ΔP is the pressure difference due to the plug, and A_{lp} is the lateral area of the plug.

The force **$F_{plug\Delta P}$** due to the pressure gradient at the plug is calculated by Eq. (13):

$$\boldsymbol{F_{plug\Delta P}} = P_1 A_{oc} - (P_1 - \Delta P)\, A_{ob} \qquad (13)$$

Where A_{oc} is the open area above the bed in the column region and A_{ob} is the open area above the bed in the drill bit region.

2.4 Circulation of cleaning pills

Phase II drilling using seawater as the drilling fluid, without return to the surface, presents insufficient cleaning capacity, as can be seen later in the results presented by the cuttings transport model Martins (1990). Therefore, it will be necessary to take additional actions to minimize solids accumulation, such as controlling the penetration rate, circulation of cleaning pills, and short drill string displacements.

To verify the cuttings bed removal by pumping viscous cleaning pills, simulations were performed using the transient hole cleaning simulator developed by Sansoni Junior et al. (2019).

The transient simulator solves along the annulus a system of equations composed of two continuity equations (solid and liquid), two momentum equations (bed and suspension) and one diffusion/sedimentation equation for suspended solids. The equations are discretized along the well direction and in time, and the resulting nonlinear system is solved using the Newton-Raphson method.

The initial conditions for the solution of the transient problem are the values of total solid concentration and bed height imported from the solution of the steady state cuttings carrying model of Martins (1990). The simulation results are pressure, fluid velocity in the bed, fluid velocity in the suspension, volumetric solid concentration in the suspension and bed height. A detailed description of this transient simulator can be found in Sansoni Junior et al. (2019).

3 RESULTS

As an example of the proposed methodology a case study on a latest generation ultra-slender well currently being implemented in Campos Basin with several challenges to be overcome in its construction. The main topic involving hydraulics is the construction of a buildup section in phase II (no return, seawater as the drilling fluid) from zero to 45 degrees in 790 m. Since very clayish formations are being drilled in this section, it is expected that hole enlargement reaches 50% of the nominal bit area (bit diameter is 0.3746 m or 14.75 in), resulting in a final diameter of 0.4572 m (18 in). This assumption results in additional solids generation and in a new geometric configuration must be considered.

3.1 Determination of steady state Cuttings volumetric concentration and bed height

Table 1 details drilling parameters considered in the case study, while Table 2 shows casing data and Table 3 drill string data.

Table 1. Drilling Parameters.

Fluid	sea water
Particle Diameter (m)	0.0051
Flow rate (m^3/s)	0.0631
ROP (m/s)	0.0056
Sea Depth (m)	1018

Table 2. Casing data

ELEMENT	Internal Diameter (m)	External Diameter (m)	Measured Depth (m)
Casing	0.7461	0.7620	1103
Open Hole - Enlarged	0.4572	0.4572	2190

Table 3. Drill string data

ELEMENT	External Diameter (m)	Length (m)
Directional Tool	0.2413	28
Drill Collar	0.2286	73
Drill Collar	0.2032	75
Heavy Weight Pipe	0.1397	73
Drill Pipe	0.1492	1941

Figure 3 illustrates, for the case study, the hole cleaning simulation provided by the cuttings transport model presented by Martins (1990). Results indicate the presence of one extremely thick cuttings bed around 55% resulting in 39% solids concentration. These values are results of the very poor carrying capacity of the drilling fluids, and by far exceed the conventional hydraulic requirements for project approval.

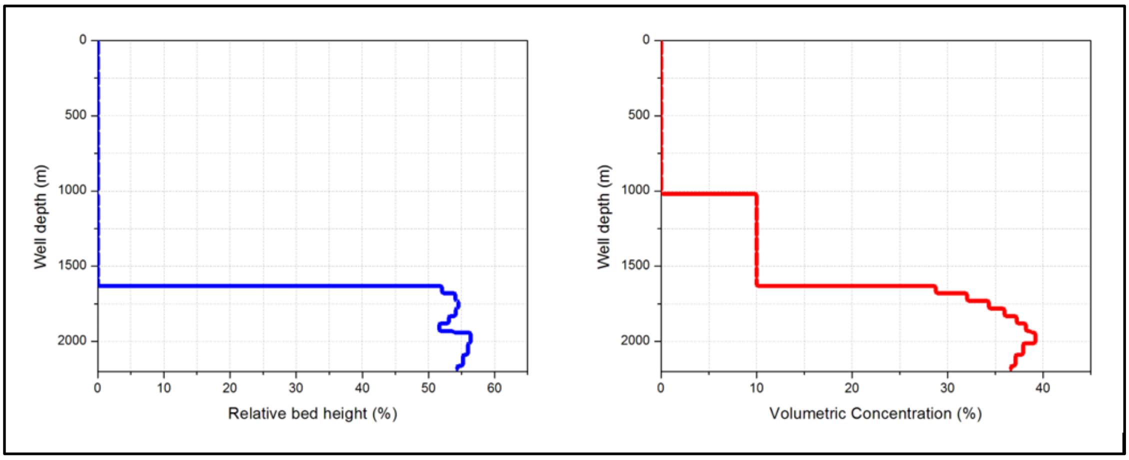

Figure 3. Relative bed height and volumetric concentration of solids.

As stated before, the strategy now is to understand how long we can drill, generating drag efforts which can be handled by the rig equipment before starting dedicated hole cleaning procedures

3.2 Estimating the length of the cuttings beds generated by the drilling activity per drilled section

Starting from the volume of solids generated by the drilling of the last section (30 m) of phase II, where 45 degrees of inclination was reached, at a depth of 2190 m, the length of the cutting bed along the annular space was calculated considering a relative bed height of 55%.

In this calculation, according to section 2.2, the following parameters were considered: formation porosity 0.2, drill string eccentricity 0.8 and cuttings bed porosity of 0.48 (totally compacted). All data combined result in a 146 m long cuttings bed.

3.3 Estimation Drag While Pulling out the drill string

The estimative was based on the model proposed by Miyoshi (2020) which accounts for the formation of a cuttings plug in front of the narrow sections formed by geometry singularities while pulling the drill string. Table 4 summarizes the input data.

Table 4. Parameters for calculating drag force.

PARAMETER	VALUE
Particle Density (kg/m^3)	2696
Particle Diameter (m)	0.0051
Bed Porosity	0.52
Bed Length (m)	146
Particles resting angle (degrees)	20
Fluid Density (kg/m^3)	1018
Fluid Viscosity (Pa.s)	0.001
Plug friction coeficient	0.4
Well Diameter - Enlarged (m)	0.4572
Drill string Velocity (m/s)	0.1

For the current analysis, different values of cuttings bed heights, below the values calculated by the cuttings transport model proposed by Martins (1990) trying to account for different scenarios.

Typical maximum overpull margins for offshore rigs are around 2000 KN (450 Klbf). Fig. 4 details drag forces required to move up to 60 m of drill string in the presence of cuttings beds with different heights. Cuttings beds up to 30% are within the overpull margins.

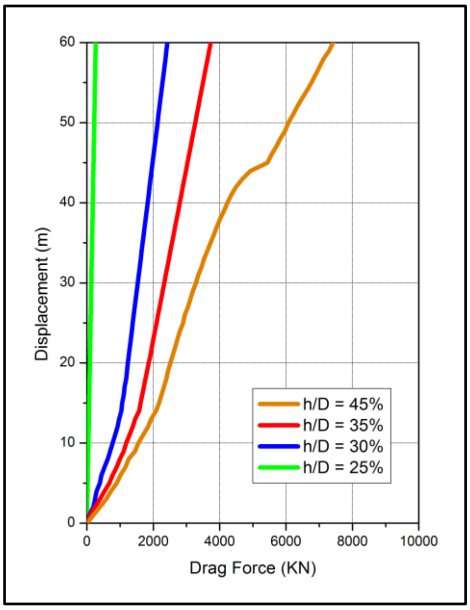

Figure 4. Drag force versus displacement for different bed heights.

3.4 Optimizing Cuttings Removal with Cleaning Pills

As stated previously, the steady state simulation, as proposed by Martins (1990) provided bed heights around 55% and solids concentration of 39 % When the well was drilled with sea water pumped at 0.0631 m3/s (1000 GPM). These results will obviously lead to undesirable stuck pipe events if dedicated hole cleaning procedures are not considered.

A typical operation to improve cuttings transport in inclined wells is the pumping of cleaning pills with superior carrying capacity. The optimization of its properties and the frequency of pumping should be determined with specific simulation.

In this article the authors considered the transient model proposed by Sansoni Junior et al. (2019), starting from the initial conditions stated by the steady state model. The viscous pill considered has the following physical properties: same density as sea water (1018 kg/m^3), and rheological behavior described by the power law coefficients of 0.21 for flow behavior index (n) and 13.32 Pa.s^n for the consistency index *(K)*.

Figure 5 illustrates the cuttings bed removal process due to the action of 15.9 m^3 (100 bbl) of the viscous cleaning pill at 0.0631 m^3/s (1000 GPM), typical parameters in offshore operations. Results indicated that hole cleaning conditions are improved resulting at complete bed removal in the open hole section and 8% of solids concentration in front of the cased portion of the well (region of higher diameter and therefore lower solid transport speeds).

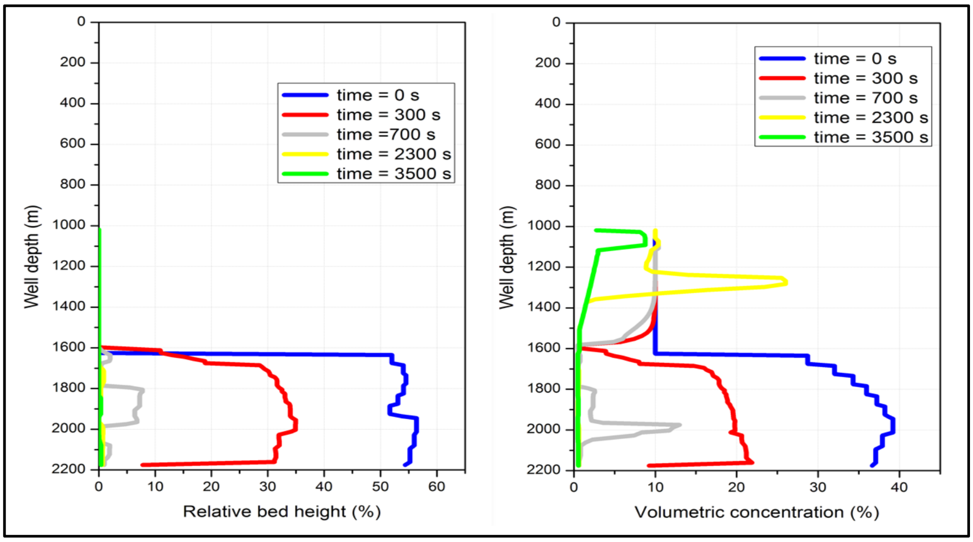

Figure 5. Relative bed height and volumetric concentration of solids in the annular over time, with the passage of the cleaning pills.

4 CONCLUSIONS AND RECOMMENDATIONS

The methodology proposed in this article aims to include a new perspective on the steps to improve a hydraulics project for offshore wells. Whenever traditional requirements, based on steady state flow simulations, do not fulfill the minimum requirements, additional simulations must be performed to account for transient effects resultant from dedicated actions to improve hole cleaning

This strategy allows the detail analysis, optimization and procedures definition to support the approval of challenging projects, such as the drilling of phase II in offshore wells (where seawater is the drilling fluid) in high inclinations and extensions. These projects, considering 3 phase wells, are essential to guarantee the economic attractiveness of mature filed revitalization in the post-salt reservoirs along the Brazilian coast.

Novel information provided by this study include the use of a unique drag model modified to account the presence of a cuttings bed and a transient solid liquid model to represent the effect of cleaning pills in the removal of the cuttings bed.

The conjunction of mechanics models with flow models and optimization techniques proved to be necessary and helpful to propose new design strategies adapted to the complexity requirements of this wells. Once the project is approved a detailed execution project needs to be addressed considering contingency plans and real time monitoring strategies. The validation of the methodology is gradually occurring with the construction of this wells, which have been considered a base configuration for efficient post-salt developments. The frequency of pumping cleaning pills can be flexibilized with the lessons learned from the continuous implementation of the technique.

The proposed methodology can be adapted to other challenging scenarios, such as the drilling of extended reach offshore wells, where dedicated hole cleaning procedures can compensate for flow rate limitations in long sections

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