International Journal of Innovative Technology and Exploring Engineering (IJITEE)
ISSN: 2278-3075 (Online), Volume-9 Issue-1, November 2019

Model of Bottom Hole Assembly with Rotary Steerable System

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***Abstract*: This article presents a static model of bottom hole assembly (BHA) with rotary steerable system (RSS). This model is aimed at estimation of control actions generated by RSS actuators upon drilling path definition. The model can be also applied for estimation of BHA strength properties.**

***Keywords*: Directional drilling, rotary steerable system, push-the-bit, research, static model, drilling mode, soil strength.**

I. INTRODUCTION

Modernization of oil and gas industry in the frames of strategy of development of power sector is the prioritized trend providing steady economic advance. This strategy solves major problems aimed at increased efficiency of exploration, drilling, engineering and development of new deposits. This should be supported by hi-tech intelligent integrated systems [1-4].

Nowadays drilling of oil-and-gas wells of complicated profile is widely applied (shelf, hard-to-recover reserves, shale oil and gas). Sidetracking is widely applied in order to reduce total capital costs, to increase well yield, to improve drainage of natural oil and gas reservoirs. Construction of such compound wells with inclined and horizontal segments is a difficult problem accompanied by high risks [5].

Directional drilling can be conventionally carried out using several methods: with specialized whipstocks, jet drilling bits, downhole drilling motors with bend adapters or bend bodies, rotary steering systems (RSS): rotary steering drilling (RSD).

The latter method was introduced in the early 2000s aiming at increase in drilling efficiency, it is applied mainly for drilling of compound wells. The main peculiar feature of RSD is generation of rock cutting moment by rotation of overall drilling string, it is especially efficient upon construction of compound wells, in this case drilling bit moves along predefined path together with continuous rotation of drilling string, which significantly improves borehole cleaning and reduces possible freezing [6-8]. Drilling direction is modified by RSS installed in bottom hole assembly (BHA) directly after drilling bit, it is carried out continuously during drilling. Application of RSD significantly decreases drilling time by elimination of drilling tool round trips and formation of smooth (and not piecewise linear) drilling path, which reduces risks upon subsequent well casing.

A practical RSS embodiment is the variant with geostationary whipstock implementing Push-the-Bit procedure when guiding force is provided by striking of elements against well wall, these elements are protruded from whipstock: the so called shoes (Fig. 1).

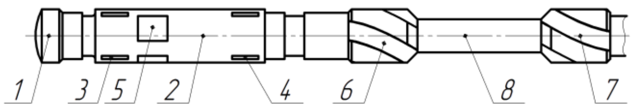

Fig. 1: BHA with geostationary whipstock

The following positions are designated in Fig. 1: the drilling bit (1); the RSS geostationary whipstock (2), which is decoupled with drilling by the radial (3) and the radial thrust (4) bearings; the steerable whipstock shoes (5); the bottom (6) and the top (7) stabilizers; the elastic insertion (8).

The main power section of RSS is located in the geostationary whipstock decoupled from rotating drilling string by means of bearings. The steerable whipstock shoes create force which displaces drilling bit to the required direction according to well design. The bottom and the top stabilizers striking against well walls are separated by the elastic insertion which decreases the influence of remaining drilling string on the forces required for modification (curving) of well path to desired direction.

In assemblies of such type the stabilizers striking against well walls act as thrust points (pivots) and allow to deflect BHA into desired direction. Generally, deflection takes place due to the flexible insertion characterized by lower bending and torsional rigidity. Similar assemblies were studied in [9-14]. However, in these works the subject matter was not equipped with geostationary whipstock, and it requires for decrease in cross section of drilling bit drive shaft.

In addition, the previous studies:

- did not account for spatial position of BHA, in particular, direction of the force of gravity, curvature radius of well segment where it was located;

- did not account for variable rigidity of the assembly stipulated by modification of transversal cross section of BHA;

Revised Manuscript Received on November 30, 2019.
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- did not pay attention to the influence of geometrical and mechanical parameters of the flexible insertion and drilling pipes above the bottom stabilizer on turning angles.

II. METHODS

A. General description

This work presents analytical model of BHA with RSS equipped with geostationary unit. Two variants of BHA with RSS of various dimensions based on this model were studied: for drilling bits of 220.7…250.8 mm (RSS1), and for subsequent stages of well construction using drilling bits of lower diameter of 155.6…188.9 mm (RSS2). These studies were aimed at analysis of capabilities of the considered BHA to modify drilling path in various soils, to determine their rigidity and strength properties.

B. Block diagram

Figure 2 illustrates flowchart of loads considered by the BHA model. It is assumed that BHA is loaded by compressing axial force N, distributed loads of own weight q_1 and q_2 act along the length, and displacing forces F_B and F_C act on the side of geostationary unit in points of contact with bearings. The points E and D are the locations of stabilizers and considered as pivotal points. The point A, location of drilling bit, is also considered as pivotal support. BHA is assumed to be preliminary bent and directed at the angle β to vertical axis.

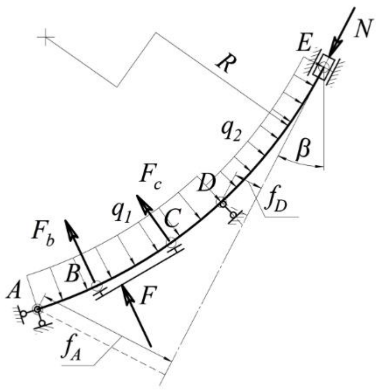


Fig. 2: Analytical model of BHA with RSS

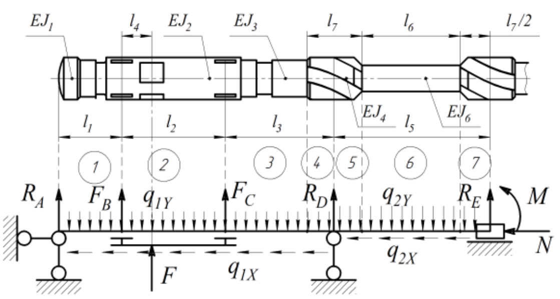


Fig. 3: Analytical model of statically indeterminate BHA beam

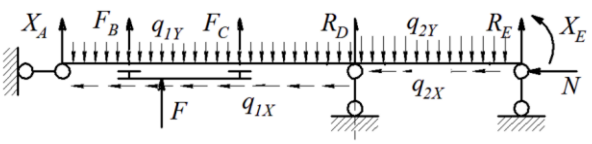


Fig. 4: Analytical model of statically reduced determinate BHA beam

Figure 3 illustrates the BHA analytical model according to which the distributed load is subdivided into constituents q_{1X} and q_{2X} acting along drilling string; and bending constituents q_{1Y} and q_{2Y}. These constituents depending on preset inclination angle β are determined as follows:

$$q_{1X} = q_1 \cdot \cos(\beta);\ q_{1Y} = q_1 \cdot \sin(\beta);\ q_{2X} = q_2 \cdot \cos(\beta);\ q_{2Y} = q_2 \cdot \sin(\beta). \quad (1)$$

The forces F_B and F_C are predicted by preset force F on RSS shoe:

$$F_B = F \cdot \left(1 - \frac{l_4}{l_2}\right);\ F_C = F \cdot \frac{l_4}{l_2}. \quad (2)$$

The beam presenting the BHA analytical model (Fig. 3) is conventionally subdivided into seven segments. Its geometrical properties, thrust conditions, or acting forces are modified at the boundaries of these segments. Each segment is characterized by its bending rigidity EJ_1, EJ_2, EJ_3, EJ_4 or EJ_6 according to Fig. 3.

OZ coordinates are used along the beam axis where respective boundaries of the segments are characterized by own coordinates $z_j (j = 0…7)$.

According to Fig. 1, due to well deflection, the points A and D are displaced with regard to straight axis of drilling string by the distances f_A and f_D. Displacement and rotation angle of beam cross section in the support E are set to zero: $f_E = 0$; $w_E = 0$.

Displacements of thrust points A and D can be determined as follows:

$$f_A = R \cdot \left(1 - \cos\left(\frac{z_0 - z_7}{R}\right)\right)$$

$$f_D = R \cdot \left(1 - \cos\left(\frac{z_4 - z_7}{R}\right)\right) \quad (3)$$

The presented BHA system is two times statically indeterminate (Fig. 3). In this case it is required to determine the responses R_A, R_D, R_E and M using only two static equations.

Eliminating vertical support in the point A and restrictions for rotation of beam cross section in the point E, we obtain equivalent statically determinate system (Fig. 4). This system instead of the eliminated links will be affected by the force X_A and the moment X_E which should be determined upon solution of differential equation of beam bending.

Bend of each beam segment will be described by the following differential equation:

$$y_i''(z) = \frac{M(z) - N \cdot y_i(z)}{EJ_i}, \quad (4)$$

where $y_i(z)$ is the function of displacements of beam cross sections with regard to its straight position, $M(z)$ is the bending moment in the cross section, $N \cdot y_i(z)$ is the bending moment generated by active longitudinal force.

Solution of such equation is obtained as the sum of partial and general solutions:

$$y_i(z) = D_{1i}\sin(\alpha_i \cdot z) + D_{2i}\cos(\alpha_i \cdot z) + A_i \cdot z^2 + B_i \cdot z + C_i \quad (5)$$

The terms of partial solution A_i, B_i, C_i are determined by parameters of beam loading as follows:

$$A_i = \frac{\beta_i}{\alpha_i^2};\quad B_i = \frac{\gamma_i}{\alpha_i^2};\quad C_i = \frac{\delta_i - 2A_i}{\alpha_i^2} = \frac{\delta_i}{\alpha_i^2} - \frac{2\beta_i}{\alpha_i^4} \quad (6)$$

where the coefficients α_i, β_i, γ_i, δ_i are defined individually for each beam segment.

The coefficient α_i for each segment is defined as follows:

$$\alpha_i^2 = \frac{N}{EJ_i}.$$

Equations of the remaining coefficients are summarized in Table 1.

Table 1: Equations of coefficients in Eq. (6)

Plot No., i	Coefficients β_i, γ_i, δ_i
1	$\beta_1 = \frac{q_{1Y}}{2 \cdot EJ_1};\ \gamma_1 = \frac{-X_A}{EJ_1};\ \delta_1 = 0.$
2	$\beta_2 = \frac{q_{1Y}}{2 \cdot EJ_2};\ \gamma_2 = \frac{-X_A - F_B}{EJ_2};\ \delta_2 = \frac{F_B \cdot z_1}{EJ_2}.$
3	$\beta_3 = \frac{q_{1Y}}{2 \cdot EJ_3};\ \gamma_3 = \frac{-X_A - F_B - F_C}{EJ_3};\ \delta_3 = \frac{F_B \cdot z_1 + F_C \cdot z_2}{EJ_3}.$
4	$\beta_4 = \frac{q_{1Y}}{2 \cdot EJ_4};\ \gamma_4 = \frac{-X_A - F_B - F_C}{EJ_4};\ \delta_4 = \frac{F_B \cdot z_1 + F_C \cdot z_2}{EJ_4}.$
5	$\beta_5 = \frac{q_{2Y}}{2 \cdot EJ_5};\ \gamma_5 = \frac{-X_A - F_B - F_C - q_{1Y} \cdot z_4 + q_{2Y} \cdot z_4}{EJ_5};$ $\delta_5 = \frac{F_B \cdot z_1 + F_C \cdot z_2 + R_D \cdot z_4 - q_{1Y} \cdot z_4^2/2 + q_{2Y} \cdot z_4^2/2}{EJ_5}.$
6	$\beta_6 = \frac{q_{2Y}}{2 \cdot EJ_6};\ \gamma_6 = \frac{-X_A - F_B - F_C - q_{1Y} \cdot z_4 + q_{2Y} \cdot z_4}{EJ_6};$ $\delta_6 = \frac{F_B \cdot z_1 + F_C \cdot z_2 + R_D \cdot z_4 - q_{1Y} \cdot z_4^2/2 + q_{2Y} \cdot z_4^2/2}{EJ_6}.$
7	$\beta_7 = \frac{q_{2Y}}{2 \cdot EJ_7};\ \gamma_7 = \frac{-X_A - F_B - F_C - q_{1Y} \cdot z_4 + q_{2Y} \cdot z_4}{EJ_7};$ $\delta_7 = \frac{F_B \cdot z_1 + F_C \cdot z_2 + R_D \cdot z_4 - q_{1Y} \cdot z_4^2/2 + q_{2Y} \cdot z_4^2/2}{EJ_7}.$

In the considered equations, the response in R_D is as follows:

$$R_D = \frac{X_E - F_C \cdot (z_7 - z_2) - F_B \cdot (z_7 - z_1) - X_A \cdot (z_7 - z_0) + q_{1Y} \cdot z_4 \cdot (z_7 - z_4)/2 + q_{2Y} \cdot (z_7 - z_4)^2/2}{z_7 - z_4} \quad (7)$$

C. Algorithm

The coefficients D_{1i} and D_{2i} are determined by the set of linear algebraic equations representing the connectivity terms of beam segments and boundary conditions in the points D and E. The respective conditions for boundary points of beam segments are as follows:

the point B: $y_1(z_1) = y_2(z_1)$, $y_1'(z_1) = y_2'(z_1)$;

the point C: $y_2(z_2) = y_3(z_2)$, $y_2'(z_2) = y_3'(z_2)$;

the point between the 3rd and the 4th segments: $y_3(z_3) = y_4(z_3)$, $y_3'(z_3) = y_4'(z_3)$;

the point D: $y_4(z_4) = f_D$, $y_4(z_4) = y_5(z_4)$, $y_4'(z_4) = y_5'(z_4)$; (8)

the point between the 5th and the 6th segments: $y_5(z_5) = y_6(z_5)$, $y_5'(z_5) = y_6'(z_5)$;

the point between the 6th and the 7th segments: $y_6(z_6) = y_6(z_7)$, $y_6'(z_6) = y_6'(z_7)$;

the point E: $y_7(z_7) = f_E = 0$.

The initial statically indeterminate problem is solved on the basis of such forces X_A and X_E at which two additional conditions on the supports A and E are satisfied:

$$y_1(z_0) = f_A;$$
$$y_7'(z_7) = w_E = 0. \qquad (9)$$

The following set of equations should be solved:

$$\begin{cases} X_A \cdot \delta_{AA} + X_E \cdot \delta_{AE} = f_A - f_{A0} \\ X_A \cdot \delta_{EA} + X_E \cdot \delta_{EA} = w_E - w_{E0} \end{cases}, \qquad (10)$$

where δ_{AA} is the increment of beam deformation in the point A upon variation of the force X_A by 1; δ_{AE} is the increment of beam deformation in the point A upon variation of the moment X_E by 1; δ_{EA} is the variation of rotation angle of beam cross section in the point E upon variation of the force X_A by 1; δ_{EE} is the variation of rotation angle of beam cross section in the point E upon variation of the moment X_E by 1; f_{A0}, w_{E0} are the beam deformation in the point A and the rotation angle of beam cross section in the point E, respectively, with initial values of forces X_A and X_E; f_A, w_E are the preset boundary conditions which should be satisfied.

Therefore, the considered statically indeterminate problem can be solved using the following algorithm:

1. Presetting initial forces in the eliminated links $X_A = 0$ and $X_E = 0$.

2. Solving Eq. (8) of statically determinate system under the action of preset system of forces: ($X_A = 0$, F_B, F_C, $X_E = 0$).

3. Determining beam deformation f_{A0}, w_{E0} by equations:

$$f_{A0} = D_{11}\sin(\alpha_1 z_0) + D_{21}\cos(\alpha_1 z_0) + A_1 \cdot z_0^2 + B_1 \cdot z_0 + C_1;$$
$$w_{E0} = D_{17} \cdot \alpha_7 \cdot \cos(\alpha_7 z_7) - D_{27} \cdot \alpha_7 \cdot \sin(\alpha_7 z_7) + 2A_7 \cdot z_7 + B_7.$$

4. Presetting increment of force X_A, for instance: $\Delta X_A = 1$. Solving Eq. (8) of statically determinate system under the action of new preset system of forces ($X_A = \Delta X_A$, F_B, F_C, $X_E = 0$). Herewith, the coefficients D_{1i}, D_{2i}, A_i, B_i, C_i will vary.

5. Finding ratios of beam deformation variations in the point A and the rotation angle of cross section in the point E under the action of the force $X_A = \Delta X_A$ to variation of the force $\Delta X_A = 1$

$$\delta_{AA} = \frac{D_{11}\sin(\alpha_1 z_0) + D_{21}\cos(\alpha_1 z_0) + A_1 \cdot z_0^2 + B_1 \cdot z_0 + C_1 - f_{A0}}{\Delta X_A};$$
$$\delta_{AE} = \frac{D_{17} \cdot \alpha_7 \cdot \cos(\alpha_7 z_7) - D_{27} \cdot \alpha_7 \cdot \sin(\alpha_7 z_7) + 2A_7 \cdot z_7 + B_7 - w_{E0}}{\Delta X_A}.$$

6. Presetting increment of the force X_E, for instance: $\Delta X_E = 1$. Solving Eq. (8) of statically determinate system under the action of new preset system of forces ($X_A = 0$, F_B, F_C, $X_E = \Delta X_E$). Herewith, the coefficients D_{1i}, D_{2i}, A_i, B_i, C_i will vary.

7. Finding ratios of beam deformation variations in the point A and the rotation angle of cross section in the point E under the action of the moment $X_E = \Delta X_E$ to variation of the moment $\Delta X_E = 1$

$$\delta_{EA} = \frac{D_{11}\sin(\alpha_1 z_0) + D_{21}\cos(\alpha_1 z_0) + A_1 \cdot z_0^2 + B_1 \cdot z_0 + C_1 - f_{A0}}{\Delta X_E};$$
$$\delta_{EE} = \frac{D_{17} \cdot \alpha_7 \cdot \cos(\alpha_7 z_7) - D_{27} \cdot \alpha_7 \cdot \sin(\alpha_7 z_7) + 2A_7 \cdot z_7 + B_7 - w_{E0}}{\Delta X_A}.$$

8. Solving Eq. (10) after determination of the responses X_{A*} and X_{E*} using the equations:

$$X_{E*} = \frac{(w_E - w_{E0}) \cdot \delta_{AA} - (f_A - f_{A0}) \cdot \delta_{AE}}{\delta_{AA} \cdot \delta_{EE} - \delta_{AE} \cdot \delta_{EA}};$$
$$X_{A*} = \frac{f_A - f_{A0} - X_{E*} \cdot \delta_{AE}}{\delta_{AA}}.$$

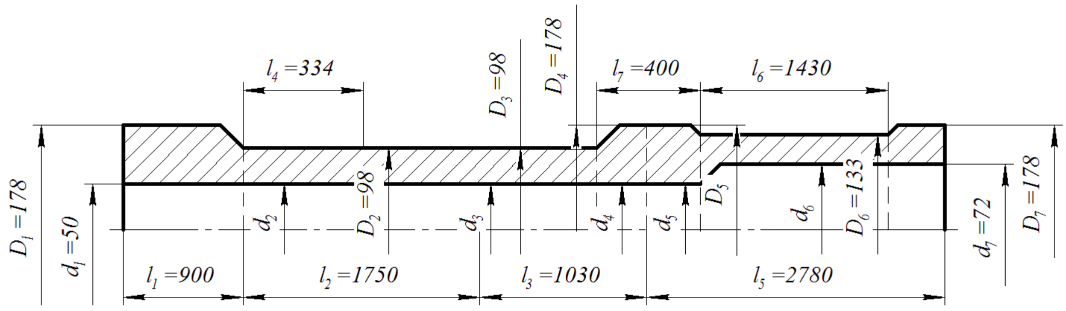
9. The final result can be obtained by solution of Eq. (8) under the action of new forces ($X_A = X_{A*}$, F_B, F_C, $X_E = \Delta X_{E*}$). Therefore, the response $R_A = X_{A*}$ and the moment $M = X_{E*}$ are the required responses of the eliminated links of statically indeterminate system.

The proposed model was used for determination of load properties and substantiation of application of BHA with RSS1 and RSS2 upon directional drilling.

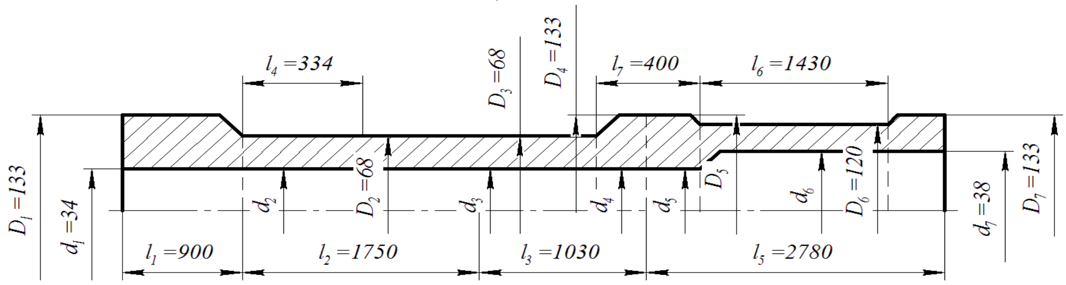
It was required:

- to determine forces which should be generated by the shoes to provide transversal displacement of drilling bit in various soil types;
- to determine rigidity properties of BHA;
- to determine strength properties of BHA upon lateral displacement of drilling bit.

Figure 5 exemplifies transversal cross sections of RSS1 and RSS2 used in the predictions. The material is steel with the elasticity module E = 210 GPa. The weight per meter for both cases is set to q1 = 2500 N/m; q2 = 2000 N/m; the well curvature radius is R = 10^8 m (straight segment); the axial force actin on BHA is N = 100 kN.



a) RSS1



b) RSS2

Fig. 5: Geometrical properties of cross sections of BHA with RSS

It is known that cutting drilling takes place when the pressure of drilling tool on soil exceeds minimum force depending on properties of drilled rocks [15]. The same is applicable to lateral drilling. The protruded shoes should generate such force when lateral load exceeds minimum required cutting load. In the model, the lateral load on drilling bit corresponds to the response R_A obtained by solution of the considered model.

The minimum required cutting load is determined as follows [15]:

$$F_{P\min} = 0{,}5 \cdot \sigma_{MD} \cdot S_{FL}, \qquad (11)$$

where σ_{MD} is the ultimate strength of mechanical drilling; S_{FL} is the bit dulling surface area in the range of 0.5–3 cm^2.

In numerical experiments several situations were considered for various soils. Table 1 summarizes the ranges of predicted lateral load on drilling bit for various soil types at preset dulling surface area equaling to S_{FL} = 0.5 cm^2.

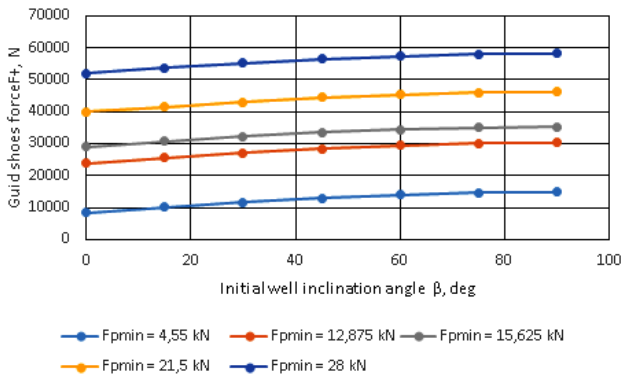
Table 2: Predicted minimum forces of soil cutting

No.	Soil	σ_{MD}, MPa	F_{Pmin}, kN
1	Chalkstone, coal, gypsum	min: 18.2 max: 51.5	4.6 12.9
2	Sandstone, conglomerates	min: 51.5 max: 62.5	12.9 15.6
3	Iron ores, sandy shales	min: 62.5 max: 86	15.6 21.5
4	Granite, marble, dolomite	min:86 max: 112	21.5 28

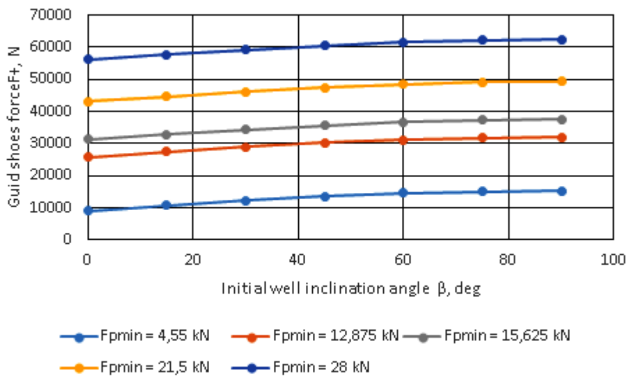
Thus, the numerical experiments determined the force F (see Figs 3, 4) required for creation of response on drilling bit equaling to the forces corresponding to boundaries of rock drillability (Table 2) at various initial BHA inclination angle β (Fig. 1) effecting on load redistribution. The initial angle was set to 0, 15, 30, 45, 60, 75, and 90 degrees.

Since lateral drilling can be carried out both along and against gravity forces, the respective forces F_+ and F_- were determined.

The obtained results are illustrated in Fig. 6.



a) typical BHA, load F_+



b) reduced BHA, load F_+

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DOI: 10.35940/ijitee.A4800.119119
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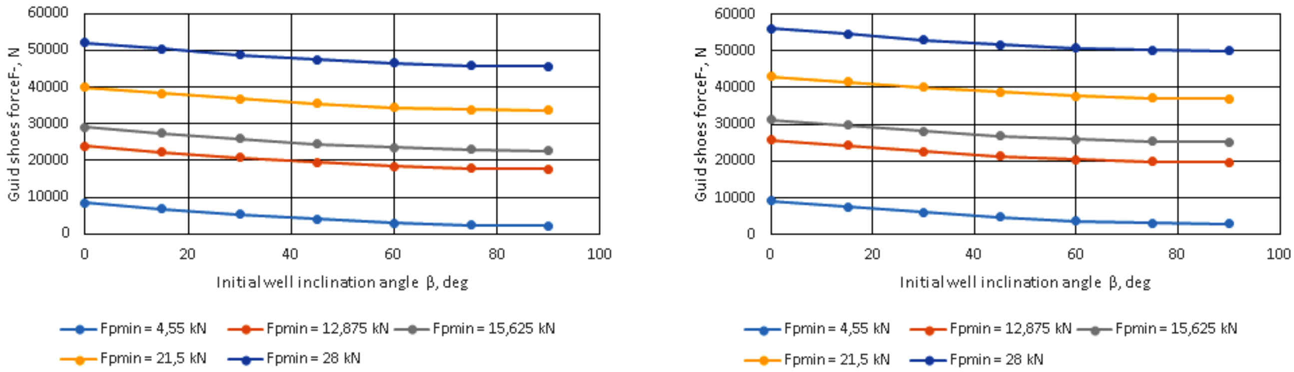


c) typical BHA, load F_- **d) reduced BHA, load F_-**

Fig. 6: Required force on shoes for starting of soil cutting as a function of initial well inclination angles

While analyzing the obtained data, it is possible to conclude that for the required lateral force F_{Pmin} of bit pressure on soil, the force F of shoe striking against well wall should be approximately by 1.7…2 time higher than the force F_{Pmin}. Moreover, with the increase in the initial well inclination angle to vertical, this force slightly varies. For BHA with RSS1, this variation is about 7…10 kN with variation of the inclination angle from 0 to 90 degrees; for BHA with RSS2, due to lower rigidity, this variation is about 5 kN.

Upon drilling against BHA deadweight, as expected, the required force on shoe increases with inclination angle (Fig. 6, a, c), and decreases upon drilling along the gravity forces (Fig. 6, b, d).

The BHA bending rigidity reduced to shoe was predicted as the ratio of increment of the force on shoe to the displacement of free point of bit position caused by this force:

$$C_{BHA} = \frac{\Delta F}{y_A - y_{A0}}, \qquad (12)$$

where y_{A0}, y_A were the initial and final displacements of the point A after variation of load by ΔF. The force increment was set to ΔF = 1 kN**.**

According to the predictions, the bending rigidity of BHA with RSS1 reduced to shoe is: C_{BHA_220}= 114817 N/m; for the design of smaller size with RSS2 the rigidity is: C_{BHA_160}= 47754 N/m, that is, characterized by rigidity lower by 2.4 times.

However, the shoe of smaller BHA should generate the force by 4–8% higher to start drilling.

The BHA strength properties were determined on the basis of maximum normal stresses σ_{MAX} under the action of bending and axial loads from several BHA cross sections. Normal stresses for the j-th cross section were determined as follows:

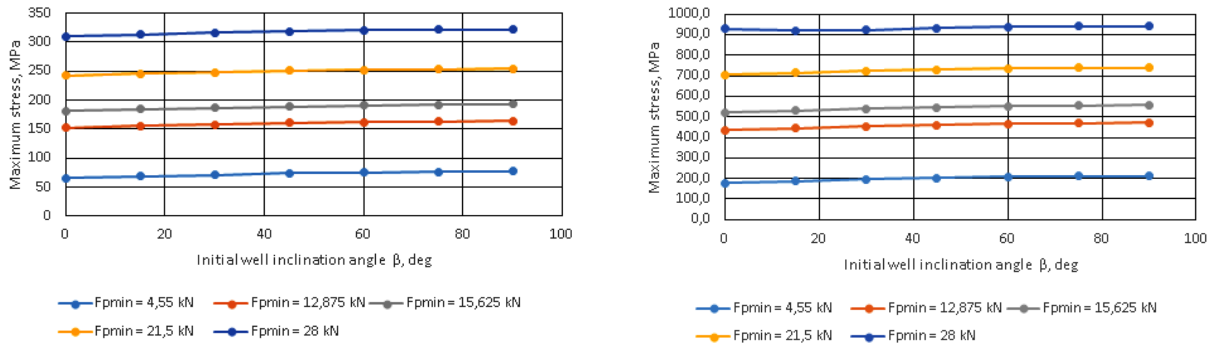
$$\sigma_j = \left| \frac{-N}{A_i} + \frac{M_j}{W_i} \right|; \qquad (13)$$

$$\sigma_{MAX} = \max(\sigma_j), \text{ at } j = 1 \ldots n,$$

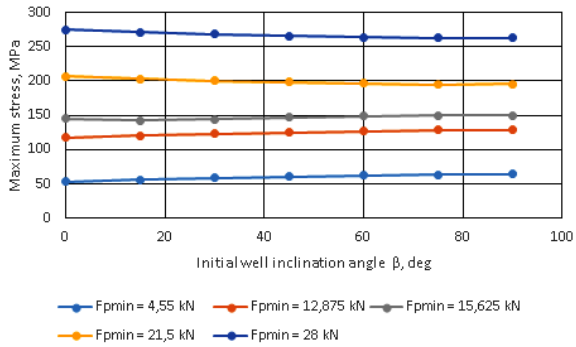
where j was the number of BHA beam cross section; i was the number of BHA beam segment containing the considered cross section; Ai was the surface area of cross section of the respective i-th beam segment $A_i = \pi \frac{D_i^2 - d_i^2}{4}$; Wi was the modulus of the i-th beam segment containing the considered cross section j; Mj was the acting bending moment in the cross section j.

D. Flow chart

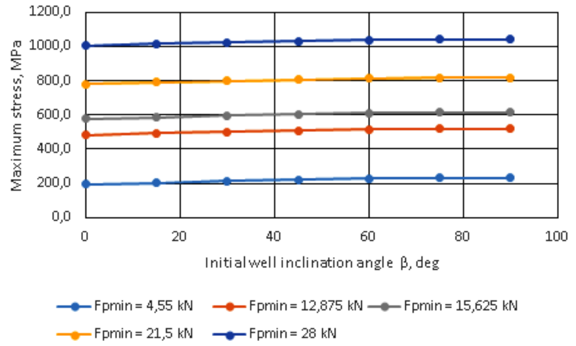
According to Fig. 7, the maximum normal stresses in BHA with RSS2 significantly exceed those in the beam corresponding to BHA with RSS1. Even upon drilling of sufficiently soft rocks, the stresses equal to 180–200 MPa.



a) BHA with RSS1 under load F_+ **b) BHA with RSS2 under load F_+**



c) BHA with RSS1 under load $F_{\_}$



d) BHA with RSS2 under load $F_{\_}$

Fig. 7: Maximum normal stresses in BHA under load on shoe required for starting of soil cutting as a function of initial well inclination angles

III. RESULT AND DISCUSSION

According to the obtained results, the maximum deformation of BHA beam with RSS1 was from 5 to 20 mm depending on acting predicted load. For BHA with RSS2, the predicted deformation is 18–100 mm.

Therefore, the predicted deformation of BHA with RSS2 for provision of effort required for drilling should be higher than the gap with well walls, this should be considered while selecting directional drilling modes using RSS2 depending on soil strength.

IV. CONCLUSION

The proposed model of BHA with RSS made it possible to define the main RSS specifications for provision of reliable controlled drilling. The obtained results demonstrated that the efforts generated by RSS shoes should be by at least two times higher than the minimum effort required for drilling. Due to decrease in rigidity and strength of bottom hole assemblies with RSS of lower diameters, their application should be based on selection of drilling modes with consideration for soil strength.

ACKNOWLEDGMENT

The project was performed by Peter the Great St. Petersburg Polytechnic University in cooperation with Special Design Bureau of Underground Navigation Devices. Project title: Development and research of control principles of path curvature vector upon drilling small diameter wells using rotary steerable systems (Agreement No. 075-15-2019-1403 of June 20, 2019. Unique identifier: RFMEFI57517X0138). This project was financially supported by the Ministry of Education and Science of the Russian Federation.

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